Development of Open-source Hybrid Pavement Management System for an International Standard

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감사의 글

박사과정에 있는 학생에 있어서 이 부분을 써 내려간다는 의미는 아마도 꿈이라고도 말할 수 있을 것입니다. 이것은 3년간 함께 고생해온 지도교수님, 그리고 항상 고충을 같이했던 가족들에게 주어지는 하나의 결실일 것입니다. 박사학위를 위해 투자한 지난 3년은 아마 인생에서 작은 부분을 차지 하겠지만, 남은 인생을 결정하는 가장 중요한 의사결정이었다고 확신합니다.

먼저, 지도교수이신 Koabyashi 교수님께 감사의 말을 전합니다. 교수님은 제 분에 넘치는 스승이라고도 생각됩니다. 지난 3년간 보여주신 학자로서의 삶은 저의 이상향이 되기에 충분하다고 생각됩니다. 몸소 보여주신, 그리고 들려주신 중요한 교훈들은 절대 잊혀지지 않을 것입니다. 졸업 후에도 깊은 관계가 계속 이어지기를 진심으로 바랍니다.

다음으로, 10년 전부터 스승과 제자의 연을 맺고 있는 또 한 분의 스승, 도명식 교수님께 감사의 마음을 전합니다. 볼 것 없고 평범한 학생이었던 저를 특별하게 만들기 위해 항상 노력하셨고, 이렇게 손수 길도 열어주셨습니다. 저의 박사학위는 교수님 노력에 대한 하나의 결실이라고 생각됩니다. 저는 이미 교수님께 많은 것을 빚졌고, 이제는 하나 둘씩 갚아나가야 할 시기가 된 것 같습니다.

항상 곁에서 많은 도움을 주었던 연구실의 스태프들에게도 감사의 말을 전합니다. Matsushima 교수님, Onishi 교수님, 정하영 박사님, Yoshida 박사님, 그리고 비서인 Fuzimoto 에게도 감사의 말을 전합니다. 특히, 제게 일어났던 모든 문제들에 성심 성의껏 대해주신 정하영 박사님께 진심으로 감사 드립니다.

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Executive Summary

This paper aimed at development of open-source Hybrid Pavement Management System (hereinafter, Hybrid PMS) for establishment of a multilateral international standard that helps sustainable development of Pavement Management System (PMS) models considering heterogeneous PMS situations and insufficient capacity in PMS development. A basic philosophy (also motivation) of this paper is that every road agency should have customized PMS, and the PMS should be developed and improved by themselves along with customized long-term PMS development strategy. This paper may be a useful guide for self-development of customized PMS and establishment of real international standard in PMS development.

The PMS model does very important roles in pavement maintenance and management. The reasons for being of the PMS of each country may be very similar in terms of facilitating maintenance activities and enhancing cost-effectiveness of limited budget. To develop the model, many issues related to inspection, database, management cycle, budget optimization, pavement deterioration forecasting, Life Cycle Cost Analysis (LCCA), long-term management strategy, and even political issues have to be considered. Obviously, all of PMS activities should be conducted under well-grounded Decision Support System (DSS). The PMS model is the heart of the DSS that leads successful road investment. Most countries may be already recognized the importance of the PMS. Nevertheless, we have often found many failure cases on implementation or improvement of the PMS. We need to carefully think about the reasons.

The reason would be started from "*Heterogeneous PMS situations*" surrounding their PMS, such as PMS data and functions, current and desired level of management efficiency (or capabilities), management cycle, main interests, and so on. Those heterogeneous PMS situations naturally lead to appearance of various PMS models having different properties. In brief, most road agencies are pursuing same goals, but their approaches and details are usually different. To reflect their situations, development of customized PMS by each agency is strongly recommended. However, it is never easy because the development of the best PMS demands customized long-term PMS development strategy which is available by comprehensive understanding on current PMS situation, as well as knowledge on overall PMS sector. Besides, a lack of data, and advanced technologies on inspection, theoretical models for pavement deterioration forecasting, LCCA modeling have often tackled for successful development of PMS, particularly in developing countries. However, the PMS is demanded from the construction of road infrastructures. That is why many countries have been preferred to introducing ready-made software such as HDM-4 (Highway Development & Management-4). In such cases, inconsistencies between ready-made system and agency's current capabilities in PMS often become a critical obstacle for successful implementation. The ready-made software sometimes prepares rooms for modification of sub-models by allocating calibration factors and changing model coefficients. However, it is not the real meaning of customization, but it is close to calibration of the ready-made software which is not enough to describe agency's situations in detail. Even if the ready-made software guarantees much easier and cheaper application, it is recommended to reject it for sustainable development of their PMS. As a summary, the problems are started from the heterogeneous PMS situation, and actualized by *"Insufficient capacity in PMS development"*. At this point, we have questions; *"How can we help developing the customized PMS by in-house effort?"* and *"How can we lead successful sustainable development of PMS"*. These two questions were main motivations of this paper. Hence, all considerations in this paper are toward following contributions to the pavement management sector, as well as individual road agency;

- Successful introduction of PMS model
- Sustainable improvement of PMS model
- Cultivating self-reliance for development and improvement of PMS model
- Establishing compatibility among the PMS models

To suggest best alternative, we should first know that the best PMS does not mean a system which has powerful functions, but a system which well describes the road agency's PMS environment and objectives. This is why self-development is essential to ensure flexibility in reflecting the current situation and future demands. Some references described developing customized PMS model guarantees current and future of PMS as the best solution for PMS development. The way is, of course, the ideal solution that has to be pursued by every road agency. However, it is often unrealistic in the reality due to the insufficient capability in PMS development. The second-best alternative could be application of an international standard to everyone. However, it was revealed that unilaterally developed PMS model (*e.g.* HDM-4) cannot satisfy

various unknown users due to heterogeneous PMS situations of each road agencies. Although the second-best alternative is good for establishing compatibilities, most countries properly cannot have a suitable PMS model for their situation. This is a critical limitation of the second alternative. To realize the contributions listed above, heterogeneities among the PMS models should be mitigated, while the heterogeneous PMS situations of each country should be allowed because it is the heterogeneity which is indispensable factors that should be considered. For that reasons, this paper suggests a third-best solution considering the two major problems "Insufficient capacity", and "Essential heterogeneity" as follows;

- Criteria for development and improvement of PMS models
- An open-source PMS model reflecting the criteria

This solution was originated from combining strengths of the best and second-best alternative, while it mitigates problems of each alternative. Here is a reason why this paper uses the term *"Hybrid"*. In case of the best alternative (*i.e.* customized PMS), it has strong benefits that road agencies can have a suitable PMS well matched with their PMS environments. In addition, they can handle it corresponding with their future demands. The second-best alternative also has great benefits from easy introduction, and compatibility among the PMS models. Under the compatibility, road agencies can share important resources related to PMS development also operation, such as pavement performance data, PMS analysis model and methods, research results, system resources (*e.g.* program source code), and even experiences regardless of good or bad practice. In summary, the strategy of this paper is that serving a flexible open/free source PMS model (*i.e.* Hybrid PMS) to unknown users as a basic material. However, serving good enough material is not enough to guarantee sustainable development of the PMS. It requires a guideline (*i.e.* recipe) that shows the best development ways based upon road agencies' heterogeneous PMS situations. Of course, the Hybrid PMS should be developed based on the criteria. That is, the two contents are not separate one, but a pair. Under the strategy, every road agency can easily establish long-term PMS development plan, and actualize their scheme by using the Hybrid PMS. Above all, their customized version could have full or partial compatibility with the other customized Hybrid PMSs. By continuous feedbacks with many users who are in heterogeneous PMS situation, the idea of creating standard criteria brings us closer to bilateral, or multilateral, criteria that could be considered an international standard for PMS development.

This paper defined the Hybrid PMS as follows;

"A prototype open/free PMS system having general PMS functions under easily customizable system architecture to help developing customized PMS model to road agencies who do not have enough capability in PMS development for their heterogeneous PMS situations"

To satisfy the definition, basic properties of the Hybrid PMS were defined as;

- Rich contents
- Free software
- Open-source software
- Easy and flexible system architecture
- Compatibility with current PMS model, and other PMS models

To realize the properties, this paper established following development and customization strategies in multidimensional, while it will be important information for not only establishing long-term PMS development strategy, but also practical application of the Hybrid PMS to road agencies.

- Macroscopic approach for planning phase (definition of system component)
- Mesoscopic approach for implementation phase (composition of system framework)
- Microscopic approach for programming phase (domestication for practical application)

The macroscopic level is to establish overall development plan for developer, while it is important standards to evaluate their current situation, and to draw a blueprint for desired PMS. Although road agencies desire a trustworthy guide that leads to successful PMS development, so far, criteria, standards, or specifications have not been treated as important issues, perhaps because the heterogeneous PMS situations of each country make a universal guide meaningless. However, a PMS development strategy is the most fundamental factor that should be established at the outset of PMS implementation. For sustainable PMS development, firstly road agencies should have a clear grasp of their current PMS situation, and draw blueprints for their desired PMS. To accomplish these processes, it is necessary to express PMS situations with a standardized index, which should be well matched with general (or best) improvement trends of PMS from the beginning stage to a mature level. The PMS evaluation index is useful for self-evaluation, and for the design of methods for future improvement. With the definition of PMS situations, PMS functions satisfying PMS capability levels can be defined. Naturally, a general framework for a PMS model at each level also can be established. After attending to these details, we can discuss data requirements that support desired PMS. This would be a typical procedure of establishment of development scheme of PMS model. As a summary, the macroscopic approach discussed 1) roles of PMS, 2) standardization of PMS capability level, 3) general PMS functions, 4) system framework, and 5) data requirements as main contents of the criteria. An important point in developing the criteria was that the criteria should be a flexible guideline whereby every road agency can apply the standard regardless of their PMS situation and current capability to cover the essential heterogeneity. The criteria were applied for definition of a total framework and system components of the Hybrid PMS by PMS capability levels. While, the guideline will be applied to road agencies in evaluating current PMS situation, and establishing development or improvement schemes of desired PMS. Although, the criteria may be usefully applied to individual cases, a much more important goal is to establish compatibility among PMS models. In addition, the criteria could serve as a foundation for various undertakings in PMS research regarding such matters as PMS databases, PMS cycle management, pavement deterioration forecasting, and life cycle cost analysis.

At the mesoscopic approach, main considerations were *"How to serve flexible system architecture to help easy implementation (or customization)?"* In addition, establishment of compatibility with user's current PMS model was an important challenge. As a solution, this paper introduced following strategies;

- Plug-in system
- Encapsulation (itemization) strategy

This is an important and difficult point that concludes successful development and application. As would be expected, the Hybrid PMS has huge system architecture including sophisticate procedures to serve rich PMS functions. But this architecture can be easily aggregated and disaggregated by introducing a concept of *"Plug-in system"*. The concept is quite simple whereby the system allows composing customized PMS by just input required functions to related functions or database. Because of the property of the concept, someone may consider the Hybrid PMS as a collection of the PMS function, while it also could be said as disaggregated PMS model by functional level. This is another reason why this paper named the general model as the Hybrid PMS. For successful development of plug-in system, determination of unit of PMS functions, and designing exact relationship among the many components are key points of this strategy. Especially, definition of properties of input and output, and their chain are main considerations that require feedback with practical users. However, the plug-in system cannot be realized without *"encapsulation strategy"* for itemization of PMS components. The term, encapsulation, can be defined as;

"Making boundary of functions so that changing the original function (source code) does not make effects to the other functions"

By different viewpoint,

"Itemizing PMS functions as independent modules for flexible composition of desired PMS model or flexible application with their current PMS"

This paper picked up the idea from a concept of *"Object-oriented programming"* which is a jargon in computer programming. In this paper, the objects become units of customization as independent modulus. Thus, definition of the boundary is the most important factor for development of successful customization strategy. The size of capsule has tradeoff relations among system-flexibility, simplicity of customization, and convenience of application. In general, the PMS models have often been taking an integrated format including all of system components. It is easy to use but difficult to be customized. For example, even if a user wants to modify a small part, the user must understand all source codes, and should check all links affecting to the other functions. Perhaps, it would be much difficult than developing new program. On the other hand, the subdivided format divided by smaller capsules can minimize efforts in customization. In brief, road agencies do not have to understand all system resource. This alternative could be the best way to realize the philosophy of the Hybrid PMS that eager to self-customization so that every user can stand on their foot. Besides, the capsulated functions would be useful for supporting internal and external PMS models without additional system building. Lastly, user can get all of intermediate results of simulations. Most cases of simulations, they hide (or do not show) the intermediate results. Hence, users can not check which part has problem when the simulation generates strange results or errors. The encapsulation strategy is good for improving reliability of simulation. The once established PMS structure is fairly difficult to be changed, even if road agencies well recognize critical problems or limitations of their system. The properties of the encapsulation strategy may be helpful to conduct partial improvement or modification.

One more issue in the mesoscopiclevel is compatibilities with current users' system which is a main interest of road agencies. In general, most road agencies, accustomed to their current routines, wish to maintain the status quo and are reluctant to make the troublesome changes that switching PMS systems would require. Since there are many direct and indirect external factors linking with pavement management, nobody can easily discard their current system because their PMS environments are already melted into their PMS. Therefore, the Hybrid PMS system need to go with user's current system by various application ways. The application ways could be divided into three; 1) full introduction, 2) partial introduction, 3) external model. This paper wishes every road agency apply the first alternative, however, it would be unusual application way in the reality. The way is recommended to the beginning stage of the PMS. The second way, partial introduction is supporting useful PMS functions to user's current system by extracting capsulated functions from the Hybrid PMS, such as vehicle speed estimation model, a pavement deterioration forecasting model, and a component of life cycle cost analysis. That is, users can put components of the Hybrid PMS into their current PMS without any system building. This strength can cover the deficiencies of user's PMS. The last, the Hybrid PMS can support user's current PMS by extracting data file from the database so that users can directly apply their current PMS software in use. In brief, user can put their current PMS on the database of the Hybrid PMS. All ways are available because the Hybrid PMS adopts the encapsulation strategy. In the beginning stage of application, road agencies may compare the Hybrid model with their current model, or applies partial functions for their PMS. If they are satisfied with the Hybrid PMS, they can phase the system in step by step. This feature may vitalize appearance of various customized Hybrid PMSs.

The microscopic level is about programming phase which is final stage of development (also customization) of customized PMS. At this stage, this paper defined every detail of the Hybrid PMS, while road agencies should customize pre-defined Hybrid PMS based on their situations. In the paper, following PMS components are mainly described (Of course, the contents were followed by the definitions in the criteria.);

- Database and artificial data
- PMS management cycle
- Pavement deterioration forecasting model
- Life cycle cost analysis model
- Optimization methods
- Etc. (*e.g.* definition of vehicle characteristics)

Although this paper tried to introduce general methods, definitions, and various options, the suggested PMS model would not be matched with road agencies situations and objectives (*e.g.* system interface, main framework, input-output, data properties, estimation or forecasting methods, etc.). In such cases, road agencies have to modify or customize the main body of the Hybrid PMS. For that reason, the Hybrid PMS demands an important property;

- Open-source system

The condition is quite simple, but it has the strongest benefit to realize the concept *"One finds one's own size"* which means real customization. The fundamental purpose of this paper was that every road agency has their customized PMS developed or improved by their hands. It is impossible unless the system is open-source system. Note that road agencies can modify everything corresponding with their customization scheme. However, it is recommended to keep definitions in macroscopic level (*i.e.* criteria for PMS development), and the properties of the input-output which is a nuclear to secure compatibility with the other PMS models. That should be carefully defined by continuous feedback with users.

After development of the criteria and details of the Hybrid PMS, this paper has conducted empirical studies. Since the Hybrid PMS and criteria can be applied for various situations and objectives, this paper introduced only typical application ways as follows;

- Establishment of long-term PMS development strategy to heterogeneous PMS situations (Pilot countries: Korea, Vietnam, and Japan)
- Typical applications of the Hybrid PMS for life cycle cost analysis (divided by different type of

pavement deterioration forecasting models)

The Hybrid PMS would be especially useful for developing countries until they have enough capabilities for self-development. Also, it could be a useful guideline to road agencies who already have their own PMS model for evaluating and extending their management efficiencies. Furthermore, it can do a role of means of communication between road agencies and developer to find a multilateral international standard. The criterion and the Hybrid PMS are still one-sidedly defined a prototype model and guide. It will be empirically tested with members of the asset management implementation group from 19 countries that satisfy variety of PMS situations, economic level, climates condition, and even their interests.

As a brief summary of each chapter,

In the Chapter 1 (Introduction), general introduction regarding research backgrounds, research scope, and expected contributions were discussed. This part mainly explains why we need the criteria of PMS development, and reasons for being of the Hybrid PMS. It is strongly recommended to have deep understanding on research motivations, contributions and philosophies of this paper for better application of the criterions and the Hybrid PMS as they planned.

In the Chapter 2 (Development and customization strategy), development and customization strategies which is an important keyword of this paper were suggested by macro-meso-microscopic approach. This part is a highlight of this paper because it determines all of research streams and details of the Hybrid PMS. The criteria of PMS development were explained as a part of development and customization strategy in macroscopic approach. Further, mesoscopic approach was introduced as strategy to serve much easier customization and application way to road agencies. At the microscopic approach, an important property "open-source system" to allow any modification for customization was suggested. As a detail of the microscopic approach, the Chapters 3 ~ 6 introduced every detail of the Hybrid PMS which is target of customization. Note that the developed Hybrid PMS is a general version for everyone reflecting the criteria which is not a customized version for a specific PMS environment.

From the Chapter 3 to Chapter 6, components of the Hybrid PMS were introduced in detail.

In the Chapter 3 (Database system with artificial PMS data), issues on development of database in PMS were addressed. Since ready-made database generally cannot be applied for another as it is, this chapter mainly treated development methods instead of detail introduction of developed database for the Hybrid PMS. To help easy understanding on data structure, this paper introduced schemes and procedures on generation of artificial pavement inventory data. It could be helpful information for understanding customization or development of database for their PMS. Furthermore, it would be applied as open-source PMS inventory data for various purposes. The feasibility of the artificial data has been tested by empirical studies in the Chapter 7.

In the Chapter 4 (PMS cycle management functions), this paper discussed the PMS cycle management functions that help annual, monthly or dairy activities of PMS managers. To define general procedure of a PMS cycle, this paper applied *"Plan-Do-See"* concept which conducts tactical level of management in PMS. Since it has close relationship with most PMS activities in the reality (*e.g.* maintenance and inspection scheduling, budget estimation, error processing, reporting and so on.), it would be most frequently applied functions throughout the PMS cycle. About all, it should be a fair with database system because the management functions do update function of database. Since the defined PMS cycle follows general (or ideal) procedure, the definition might not be matched with current PMS cycle of road agencies. The procedure can be simplified or sophisticated by customization scheme by users.

The Chapter 5 (Pavement deterioration forecasting models) described pavement deterioration forecasting models hired in the Hybrid PMS. As defaults, simplified regression, multiple regression, Markov exponential hazard model, and local mixture hazard model were included. Those were determined by considerations of properties of models (deterministic or stochastic), data requirement (kind or quantity of data), type of results (state basis or annual basis), and usages of their results (network level or project level). Based upon road agencies' objectives and data situations, they can select model(s) for their various purposes. Of course, they can change default model, and also can input their original model into the Hybrid PMS. At the end of this chapter, this paper suggested localized regression model for compatibilities between forecasting results from the different models.

In the Chapter 6 (Life cycle cost analysis model), a Life Cycle Cost Analysis (LCCA) model developed by this paper was described. This chapter addressed from the definition of LCC contents to their estimation methods in detail. This paper classified the LCC contents from core level to advanced level which includes not only agency costs but also road users and socio-environmental effects. Road agencies can easily compose their suitable LCCA model by aggregating or disaggregating the LCC contents hired in the Hybrid PMS, since every LCC contents of the Hybrid PMS were also developed as independence modulus.

In the Chapter 7 (Empirical application of the Hybrid PMS to Heterogeneous PMS situations), empirical applications to show feasibilities and application procedures of the Hybrid PMS were introduced. For the trials, Korea, Japan and Vietnam who are in a different PMS situation were applied. Due to the huge scale of the Hybrid PMS, there was a limitation to introduce various applications which can be conducted by the Hybrid PMS. For that reason, this paper briefly introduced the procedures for establishing long-term PMS development strategy based on the suggested criteria for PMS development. In addition, demonstrations showing typical applications in LCCA divided into two cases which apply different deterioration forecasting models were explained. The procedure and application ways may be useful for understanding how to apply the each sub-model, as well as the entire system.

The Chapter 8 (Conclusions) is a conclusion part that summarizes overall research contents and results of this paper. Since it is just a preparatory stage before distribution of the Hybrid PMS, opinions from the members of the asset management implementation group could not been reflected. Successive feedbacks reflecting major opinions from them will be main resources for improvement of the criteria of the PMS development, as well as the Hybrid PMS.

This paper suggested the Hybrid PMS and criteria as third-best alternative for development of customized model to every road agency. Even if the Hybrid PMS is well matched with road agencies' situation by simple customization procedures, the self-development is still the best alternative that has to be pursued by every road agency. Note that the criterion is for everyone, while application of the Hybrid PMS is recommended to agencies who do not have enough capability to do self-development.

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APPENDIX

Abbreviations

A

AADT	Annual Average Dairy Traffic
AB	Asphalt Base
AC	Asphalt Concrete
ADB	Asian Development Bank
AM	Asphalt Mix
AMS	Asset Management System
AP	Asphalt Pavement

B

BCR	Benefit Cost Ratio
BOT	Build-Operate-Transfer
BST	Bituminous Surface Treatment

C

CAPE	Cape seal
CO	Carbon Monoxide
CO2	Carbon Dioxide
CM	Cold Mix
CPF	Catalyst Pass Fraction
CRS	CRushed Stone
CS	Cement Stabilization

D

DBSD	Double Bituminous Surface Dressing
DSS	Decision Support System

E

ESALF	Equivalent Single Axle Loads Factor
EUAC	Equivalent Uniform Annual Cost

F

FDA	Full Depth Asphalt
FHWA	Federal Highway Administration
FWD	Falling Weight Deflection

G

GB	Granular Base
GIS	Geographic Information System
GM	Granular Material
GNP	Gross National Product
GPR	Ground Penetrating Radar

H

HC	Hydrocarbons
HCM	Highway Capacity Manual
HDM-4	Highway Development & Management-4
HMA	Hot Mixed Asphalt
HRA	Hot Rolled Asphalt

I

IRI	International Roughness Index
IRR	Internal Return Rate
ITS	Intelligent Transport System

J

K

KICT	Korea Institute of Construction Technology

L

LCC	Life Cycle Costs
LCCA	Life Cycle Cost Analysis
LS	Lime Stabilization
LSE	Least-Squares Estimator

M

MCI	Maintenance Control Index
MESAL	Million Equivalent Single Axle Loads
MLTM	Ministry of Land, Transportation, Maritime affair
MSE	Mean Squared Error
MTP	Markov Transition Probabilities

N

NMT	Not-Motorized Traffic
NOx	Nitric Oxides
NPV	Net Present Value

O

P

PA	Porous Asphalt
Pb	Lead
PC	Passenger Car
PCE	Passenger Car Equivalency
PCU	Passenger Car Unit
PGS	Pain, Grief, and Suffering
PM	Particulate Matter
PM	Penetration Macadam
PMA	Polymer Modified Asphalt
PMS	Pavement Management System
PSCE	Passenger car Space Equivalent factor
PSI	Present Serviceability Index

Q

R

RD	Rut Depth

S

SB	Stabilized Base
SBSD	Single Bituminous Surface Dressing
SDCA	Stepwise Directional Customization Approach
SL	Slurry seal
SNP	Structural Number of Pavement
SMA	Stone Mastic Asphalt
SO2	Sulphur Dioxide
SSE	Sum of Squared Errors
SSR	Sum of Square Residuals

T

TNA	Thin Asphalt surface
TMS	Traffic Monitoring System

U

V

VOC	Vehicle Operating Costs
VRA	Vietnam Road Administration

W

X

Y

Z

CHAPTER 1

Introduction

1.1 General Introduction

The Pavement Management System (PMS) model does very important roles in pavement maintenance and management. The reasons for being of the PMS of each country may be very similar in terms of facilitating maintenance activities and enhancing cost-effectiveness of limited budget. To develop the model, there are so many issues related to inspection, database, management cycle, pavement deterioration forecasting, Life Cycle Cost Analysis (LCCA), accounting by optimization procedures, and even political issues. Obviously, all of PMS activities should be conducted under well-grounded Decision Support System (DSS). The PMS model is the heart of the DSS that leads successful road investment. Most countries may be already recognized the importance of the PMS. Nevertheless, we have often found many failure cases on implementation or improvement of the PMS. We need to carefully think about the reasons.

The reason would be started from "*heterogeneous PMS situations*" surrounding their PMS, such as PMS data and functions, current and desired level of management efficiency (or capabilities), management cycle, and so on. Those heterogeneous PMS situations naturally lead to appearance of various PMS models having different properties. In brief, most road agencies are pursuing same goals, but their approaches and details are usually different. To reflect their original situations, development of customized PMS by each agency is strongly recommended. However, it is never easy because reliable and advanced level of PMS can be established only under well-designed long-term PMS development strategies with rich pavement inventory data. Besides, a lack of advanced technologies on inspection, theoretical models for pavement deterioration forecasting, LCCA and optimization procedures have often tackled for successful development of PMS, particularly in developing countries. However, the PMS is demanded from the construction of road infrastructures. That is why many countries have been preferred to introducing ready-made software such as HDM-4 (Highway Development & Management-4). In such cases, inconsistencies between ready-made system and agency's current capabilities in PMS often become a critical obstacle for successful implementation. The ready-made software sometimes prepares rooms for modification of sub-models by allocating calibration factors and changing model coefficients. However, it is not the real meaning of customization, but it is close to calibration of the ready-made software which is not enough to describe agency's situations in detail. Even if the ready-made software guarantees much easier and cheaper application, it is recommended to reject it for sustainable development of their PMS. At this point, we have questions; *"How can we serve the customized PMS to every users by in-house effort?"* and *"How can we lead successful implementation and sustainable development of PMS"*. These two questions were main motivations of this paper.

It is sure that developing a customized PMS model should be the best alternative for each agency. However, it could be considered as an unrealistic scenario to someone due to the difficulties in self-development. Besides, it has a limitation on compatibilities with other PMS models. As a second-best alternative, establishing an international standard is considerable. However, it is difficult to satisfy various unknown users by one PMS model. Although the system has powerful functions, road agencies cannot put successive steps for sustainable development under the ready-made software. Therefore, we have to contrive a third-best alternative that covers limitation of the best and second-best alternative. The third-best alternative should mitigate heterogeneity among the PMS models while the heterogeneity of PMS situation should be allowed as it is. It is somewhat contradictory or unrealistic. However, it should be realized for not only individual road agency but also PMS sector. This is a main challenge of this paper.

1.2 Research Backgrounds

The pavement management system treats the past, present and future of pavement. It systemically accumulates pavement history data (past), and operates management cycle (present). Based on the maintenance history, the better maintenance strategy (future) can be established. To apply the benefits of the PMS, road agency should invest sufficient time and effort for defining the best PMS from the first implementation. Obviously, the best PMS does not means a system which has powerful functions, but a system which is well describing road agency's PMS environments and objectives. That is why self-development is essential to ensure flexibility to reflect current situation and future demands. However, when road agencies try to develop their PMS, they have often been confused due to a lack of long-term PMS development strategy. For that reason, many road agencies have been relied on other's experiences or ready-made software which is not well matched with their PMS situations. Once they got a wrong choice, they have to back to the start line and invest enormous budget and time which is one of social costs. The PMS model should be developed step by step with long-term PMS development strategy. In brief, helping sustainable development of customized PMS model by their hands is a fundamental research background of this paper. It can be reinterpreted in detail by following contents;

- Successful introduction of PMS model
- Sustainable improvement of PMS model
- Cultivating self-reliance for development and improvement of their own PMS model
- Establishing compatibility among the PMS models

All contents are very important and difficult issues. The successful PMS introduction and improvement is not a simple matter because it demands comprehensive understanding on overall knowledge on PMS sector and their current situations. However, issues on PMS development have not been treated as important issues. This is maybe because heterogeneous PMS situations of each country make it meaningless. A researcher, Uddin (2006) described that developing customized PMS guarantees current and future of PMS as the best solution. The way is, of course, the ideal solution that has to be pursued by every road agency. However, it is often unrealistic in the reality due to on a lack of data, budget, time, technologies, and even interest in Asset Management System (AMS). The second-best alternative may be application of an international standard to everyone. However, it was revealed that one-sidedly developed PMS model cannot satisfy various unknown users who are in the different situations. Although the second-best alternative is good for establishing compatibilities, most countries cannot have a suitable PMS model. Therefore, we needs much flexible criterions of PMS introduction, evaluation and future improvement way considering heterogeneous PMS situation of each road agency.

The criterions are not a physical PMS model but information in system level that guides how to make future development plan considering past, present and future. Since every element of PMS requires very detailed methods, research results and various field data, some road agencies who do not have enough capability to develop their customized PMS may be encountered to many problems. For such cases, we need a pre-designed general PMS model having easily customizable system architecture reflecting the criterions. The general version would be quite helpful so that everybody has a customized PMS model, regardless of their current capability. One more important research motivations is establishing compatibility among the PMS models. Due to the heterogeneous PMS situations, most PMS models have different properties in terms of roles of PMS model, kinds of functions, data definition, type of pavement forecasting model, approaches on LCC etc. Under these situations, it is difficult to share any information each other because they are applying different system and definitions. If we have a general criterion and PMS model, road agencies can share PMS data, research results, and experiences on application of the criterion and PMS model regardless of good or bad practices. In brief, footprints of the frontiers could be significant lessons to the followers since every road agency is in a route of PMS development. The criteria for PMS development and customizable PMS will do the role. Finally, it could be closed to the real international standard in PMS by the continuous feedback with road agencies who are under various PMS situations. As a summary, the demands of the general PMS model can be summarized into following three contents;

- Demand of a total system that covers general demands in PMS
- Difficulties in self-development of customized PMS model
- Necessity of establishing compatibility among PMS models

The demands are for following contributions of this paper.

- Helping sustainable development and improvement of customized PMS model considering heterogeneous PMS situations
- Establishing compatibility of PMS models by 'both-sided international standard'

1.3 Research Scopes

As discussed in the Chapter 1.2, research scopes have already defined by these two contents;

- Suggestion of criterions of PMS development
- Development of a general PMS model (called as the Hybrid PMS)

There are so many issues that have to be treated in the criterions. However, roles of the criterion are quite simple that shows what road agency have to do. The tasks could be determined by differences between their current PMS and their desired PMS. To define the differences, the criterion should include evaluation method that classifies PMS capability level based upon PMS functions. It can help having a clear grasp of current PMS situation, and it is also useful for drawing a blueprint for their desired PMS. With the definition of the PMS situations, PMS functions satisfying the PMS capability levels can be defined. Naturally, a general framework of PMS model by each capability level also can be established. After fixing all of details, we can discuss about data requirement by the PMS capability level. An important point is that the criterions should be suggested by the PMS capability level. It is essential to consider heterogeneity of PMS situation. In fact, the contents related to criterions of PMS development account for very small part of this paper. However, it is a basement of all of contents of this paper.

The next research content, the general PMS model should be a total system considering general demands in PMS to appease unknown users. Therefore, it must have rich contents from the data requirements, database system, PMS cycle management functions, pavement deterioration forecasting models, advanced LCCA model, accounting functions and optimization methods. A key point is designing easily customizable system framework, and simplifying complex relationship among the sub-models to be a user-friendly system. In addition, empirical studies using actual field data are also required for their feasibility. The main research contents of this paper for the two main research contents are summarized in the Table 1.1.

Table 1.1 Summary of research scope

Main contents	Sub contents	Brief description	For details
Criteria for PMS development and improvement way	Evaluation method of PMS capability level	Development of PMS evaluation indicator based upon general or best improvement way of PMS development	Chapter 2
	Definition of general PMS functions	Standardization of PMS functions demanded in PMS sector based upon the PMS capability level	
	Definition of general PMS frameworks	Definition of general PMS framework based upon the PMS capability level and their PMS functions	
	Definition of data requirements	Definition of the data requirements to support each the PMS capability level	
Development of the general PMS model	Definition of basic system framework and functions	· Definition of PMS functions and results · Definition of required system components · Definition of system architecture and properties	
	Customization and improvement strategy	Strategies on system properties for easy customization and improvement	
	Development of database system & Artificial PMS data	· Development of database system · Issues on development of database in PMS · Development of artificial pavement inventory data	Chapter 3
	Development of management functions	Standardization of a pavement management cycle Development of sub-functions	Chapter 4
	Development of pavement deterioration models	Suggestion of various deterioration forecasting models having different properties for various applications	Chapter 5
	Development of life cycle cost analysis model	· Definition of LCC contents · Development of LCC estimation methods · Development of sub-models for vehicle speed and generation of traffic data	Chapter 6
	Accounting with optimization procedures	· Development of budget optimizations method in maximizing NPV (Net Present Value), condition recovery, and finding best maintenance timing · Development of accounting function	Chapter 6
Empirical study	Application of the criterion and general PMS model	· Applying the criterions for establishing PMS development strategy to Japan, Korea and Vietnam · Demonstration of typical application of the general PMS	Chapter 7

An ultimate goal of this paper is establishing “both-sided” international standard of criterion and PMS model so that every road agency applies same PMS model under same criterion, and shares everything each other. It is quite interesting, but seems to be impossible. Even if the task would be time-consuming or impossible mission, this paper believes it is a meaningful challenge.

Note that the contents of the criterion are limited to system and function level only. Even though details of programming level were treated in the progress of developing the general PMS, it is just a (one-sidedly defined) suggestion that has to be calibrated or customized by road agencies. Besides, issues related to road construction were out of scope of this paper.

1.4 Expected Contributions

Herewith remarkable contributions to individual and international level (PMS sector) by successful development and distribution of the criterion, and the general PMS model;

For individual level;

- The criterion will be a useful guideline that leads successful introduction, self-evaluation, and improvement of PMS model
- The general PMS model can help road agencies who do not have enough capability for self-development.

That is, contributions to individual level can be summarized in a sentence;

- Every road agencies can have their customized PMS with well-designed long-term PMS development strategy regardless of their current PMS capability.

For PMS sector;

- The criterion and general PMS model push every road agency into the best route in PMS development so that they can share every PMS resources and experiences for much better and practical implementation.
- The general PMS model does a role of a mean of communication between road agencies and developer to establish ‘both-sided international standard” of PMS model.
- The criterions could be a basement of various PMS researches, such as PMS database, PMS cycle management, and life cycle cost analysis models.

The contributions to PMS sector can be summarized in a sentence.

- The criterion and general PMS model establishes compatibility among PMS models.

1.5 The Origin of the Hybrid PMS

There are two reasons why this paper named the general PMS model as *“Hybrid PMS”*;

- By mixed strategy of the PMS implementation ways
- By mixed concept of ways of system composition

This paper hybridized properties of the best alternative (development of customized PMS) and second-best alternative (applying international standard to everyone) of the PMS implementation ways. In case of the best alternative (*i.e.* customized PMS), it has strong benefits so that road agencies can have a suitable PMS well matched with their PMS environments. In addition, they can handle it corresponding with their future demands. However, they have to develop it by their hand. The second-best alternative also has great benefits from compatibility among the PMS models. Under the compatibility, road agencies can share important resources related to PMS development. An important property is that everybody uses a same PMS model. This paper is taking a mixed strategy of the two alternatives. In brief, road agencies will receive (pre-defined) the Hybrid PMS model. Then, they will develop “*Customized version of the Hybrid*

PMS" by their hands based upon schemes of their desired PMS.

Regarding the customization way, the Hybrid PMS is taking flexible system framework by the encapsulation strategy. Simply, each sub-model was developed as independent module so that it can make function as a separated model. Under the property, the customization works for system composition can be simplified, also it diversifies implementation way of the Hybrid PMS, such as full-application, partial application or using external model. Because of the properties, the Hybrid PMS could be seen as a collection aggregating PMS functions, while someone may consider it as a disaggregated PMS model. This is also a mixed strategy (or an ambiguous concept).

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CHAPTER 2

Development and Customization Strategy

2.1 General Introduction

This chapter serves information of development and customization strategy whereby the Hybrid PMS to be much flexible and user-friendly system. It is a highlight of this paper. It is strongly recommended to have deep understanding about both strategies for better implementation or improvement of PMS model.

This paper devised the multidimensional approach by viewpoints of road agencies, as well as developer. It will be called as macroscopic level, mesoscopic and microscopic level. Main considerations at the macroscopic approach are about system and functional level of application which is a useful guide in planning phase. It guides introduction, evaluation, and improvement way of PMS model of each country. To consider their heterogeneous PMS situation, this paper suggested an evaluation method of PMS capability, general PMS functions, system framework, and data requirement by the PMS capability. That is, a summary of the contents becomes the criteria for the PMS development which was introduced as a main research scope of this paper. Based upon the contents, road agencies can evaluate their current PMS situation, and establish long-term PMS development plan corresponding with their PMS situations.

The mesoscopic approach describes considerations to make flexible system structure to guarantee much easier customization or improvement. It would be useful information in implementation phase. Someone may think such considerations should be done by the system developer. However, the strategy has direct relationships to the application ways of the Hybrid PMS. It would be the most important information for application of the Hybrid PMS.

At the microscopic level, it treats every detail of sub-models of the Hybrid PMS. It is related to programming phase. Following chapters (Chapters 3 ~ 6) describes its details. In fact, the applied methods, models, or specifications are one-sidedly defined contents by this paper since it is difficult to consider all of heterogeneous PMS situations by a PMS model. As a solution, this paper imbued an important property, "Open-source software". This is a keyword of this paper.

2.2 Philosophies of PMS Development

Before introducing of main contents, this paper advocates following two important philosophies for the sustainable PMS development;

- Taking long-range view
- Cultivating self-reliance

Above all, this paper advocates taking a more long-term view, whereby standard PMS would be universally applied as a matter of course. In reality, however, it is very difficult to realize this goal. Most road agencies, accustomed to their current routines, wish to maintain the status quo and are reluctant to make the troublesome changes that switching PMS systems would require. Properly, their interests and perspectives remain at past or present levels. One good example is data policy. PMS development depends on the definition of 1) the roles of PMS, 2) PMS functions supporting the roles of PMS, and 3) data conditions supporting the PMS functions. Therefore, it can be said that data conditions govern the overall PMS development scheme. If road agencies cannot satisfy the data requirements of their desired PMS, it is imperative that they change their scheme, unless they make alternate plans for data acquisition. However, if a PMS manager suggests a data inspection plan on unnecessary data content in the current PMS, road administrators may (properly) refuse the suggestion. This is a foreseeable scenario. To continue the development plan uninterrupted, road agencies need to envision preconditions in advance. Because it is already too late when road agencies realize certain data were essential, they should have not only comprehensive understanding of their current situation but also sufficient knowledge of the overall PMS sector.

The second consideration is "Who develops the PMS?" Regarding this issue, this paper compares two concepts: "One size fits all" and "One finds one's own size." The former concept, whereby everyone wears same-sized, or "free-size" clothing, could be compared to the HDM-4 (Highway Development and Management-4) model developed by the World Bank, which tries to push all users under one sufficiently large umbrella (that is, one with enough PMS functions). On the contrary, the latter concept, whereby individuals seek their own sizes, emphasizes having sufficient skills to satisfy particular demands. To use an analogy, based upon demands and skill, fabric can be made not only into apparel but also into various other items such as bags or curtains. Note that sustainable development is attainable when a road agency has sufficient capacity for self-development. Therefore, implementation of ready-made software is not recommended. Even if ready-made software guarantees much cheaper and easier application, it should be excluded from the alternatives for the future because ready-made software is usually a unilaterally developed "black box" that hides all system resources and does not allow any modification. If necessary, it is recommended that such software be applied as an external model for special demands, such as comparison with domestic models, and for research purposes.

It is believed that the two concepts should be understood to every PMS manager and even road administrator. Otherwise, this paper does not have any meaning.

2.3 Basic Properties and Definition of the Hybrid PMS

Since the PMS structure is very difficult to change once it is established, the decision for the PMS model should be determined at the beginning stage of the PMS development or implementation plan. This part will discuss about properties which are essential for the Hybrid PMS.

To define basic properties for establishing the best strategy, this paper have firstly reviewed about the PMS implementation issue. A researcher, Uddin (2006) classified implementation strategies into three;

- Application of ready-made PMS model
- Modification of ready-made PMS model
- Development of customized PMS model

Based upon his descriptions, and field experiences in some countries, this paper redefined and compared strengths and weaknesses of the alternatives in the Table 2.1.

Table 2.1 Comparison of strengths and weaknesses of implementation ways in PMS

	Ready-made software	Modifying ready-made software	Customized software
Strength	· Cheap · Easy to apply · Good at outset of PMS implementation	· Cheap · Minimizing effort to develop (near) customized PMS software	· Best adaptation for present and future · Easy improvement without copyright problem
Weakness	· Could be expensive · Technical dependence · Inflexibility · Compatibility	· Could be expensive · Difficult to customize · Very rare case due to copyright · Unstable situation	· Most expensive · Technical problems · System maintenance
Evaluation	· Suitable for small to medium size government or developing country · Technical and funding problems · Good at initial stage of PMS	· Suitable for developing or developed country · Problems on being under unstable situation · Second-best alternative but unstable	· Good for every country · Useful for unusual situation, and special objectives · Should be the preferred alternatives

Maybe someone think that starting with the customized software would be the best strategy. However, it has critical limitations to be realized by some countries who are in the beginning stage. The other alternatives also have limitations disturbing sustainable development of the PMS. As a solution, this paper devised a hybrid concept that gathers only strengths also removing weaknesses from each alternative. Its basic properties of the Hybrid PMS should be;

- Rich contents
- Free software
- Open-source software
- Easy and flexible customization
- Compatibility with current PMS model
- Self-reliance

Considering the properties, the Hybrid PMS could be defined as;

"A prototype open/free PMS system having general PMS functions under easily customizable system architecture to help developing customized PMS model to road agencies who do not have enough capability in PMS development considering their heterogeneous PMS situations"

In brief, this paper distributes free/open software (general version) having rich PMS functions which can be easily customizable by road agencies regardless of their current situation. Afterward, the road agencies conduct customization works by their hand to make their customized PMS. Referring their opinions and experiences, the general version also can be improved. By continuous feedback, the general version could be closed to real international standard.

The strategy of the Hybrid PMS is partially similar with the first alternative by the viewpoint of supporting ready-made software to users. A usual problem of the first alternative is the software already has developer-specified model framework and functions which cannot be modified. It may disturb successful settlement of the ready-made software to users. For the problems, the Hybrid PMS should serve rich PMS functions by referring general demands in PMS to appease every road agency. In addition, the customization works for detaching useless functions, modifying details of function, and adding user-developed function by their demands) needed to be simple. In summary, the Hybrid PMS should have rich and general PMS functions, and also all system resources should be distributed as a free and open-source software. This feature may cover the weaknesses of the first alternative.

The second alternative also has similar point with the Hybrid PMS so that the user can modify the ready-made PMS model. By the second alternative, efforts to develop customized PMS software could be minimized. This alternative might be considered as a second-best way among the alternative. Nevertheless, it is very difficult to be customized by road agencies because the user must understand developer-specified all resources in the model. Above all, the case allowing modifications of the original resources is not so usual (usually applied for business model). Worst of all, the road agency is being under technical dependence and unstable condition. As an example, the Vietnam Road Administration (VRA) is applying order-made PMS software of the RoSy SYSTEMS by investing enormous budget. It was designed for every branch office in the country. However, only several engineers can apply the system from all over the country due to complex system environment. It is, of course, impossible to modify by them. Undoubtedly, this is a failure case of the second alternative. About these problems, the Hybrid PMS should suggests much easy and flexible system structure.

The last alternative, developing customized software, should be preferred alternative. However, road agency should sacrifice many things to carry out (and keep) the alternative for new development and continuous feedback. As a solution, the Hybrid PMS serves free/open source software including predesigned PMS functions. By the modification or customization, each road agency could find suitable PMS model that well describes their current situation.

2.4 Macroscopic Approach for Planning Phase

When road agencies make plan to introduce, evaluate or improve their PMS, there are often confusions due to a lack of long-term PMS development strategy. Although road agencies desire a trustable guide that leads successful development of PMS, its criterions, standards or specifications have not been treated as important issues. For the reason, they have often tried to refer to others' experiences, or relied on ready-made software. It often results many problems caused by inconsistencies between their situation and characteristics of the ready-made software. Therefore, we need criteria that show development of PMS is desired. The issues will be treated in the macroscopic approach. Note that the term "criteria of PMS development" is equal to the macroscopic approach.

2.4.1 Contents of the Criteria of PMS Development

The demands of system improvement to extend management efficiency are successively happened because the PMS model could not be perfect by just first introduction. The advanced PMS (or desired PMS) which guarantee much better management efficiency demands rich historical pavement inventory data.

The point is that definition of the best PMS could be differed by each country. Some road agencies may prefer much simplified model dedicating only road agency cost and maintenance work, while someone may eager to have much advanced PMS model that covers demands of project, programming, and strategy level of analysis. Simply, the best PMS is not their desired PMS, but the desired PMS is their best PMS. Following the level of the desired PMS, PMS functions, system framework, and required inventory data become differed. It implies that road agencies require much flexible criteria for PMS development which satisfies different PMS situation.

By the definition of the criterion, its scope could be totally different. However, roles of the criterion in this paper are quite simple that shows "What road agency have to do". Their tasks could be determined by differences between their current PMS and their desired PMS. To define the differences, the criterion should suggest evaluation method that classifies PMS capability level based upon PMS functions. It can help having a clear grasp of their current PMS situation, and it is also useful for drawing a blueprint for their desired PMS. To do the processes, the PMS situations are needed to be expressed by standardized index, and the index should be well matched with general (or best) improvement trends of PMS from the beginning stage to mature level. The PMS evaluation index would be useful for self-evaluation, and designing future improvement way. With the definition of the PMS capability level, PMS functions satisfying conditions of each PMS capability levels can be defined. Naturally, a general framework of PMS model by each level also can be established. After fixing all of details, finally we can discuss about data requirement. In summary, this paper treats following issues as contents of the criterions;

- Standardization of PMS capability level
- Definition of PMS functions
- General PMS frameworks
- Data requirements

Much literature has treated the details of asset management, infrastructure management, or facilities management (Hudson *et al.,* 1997; Goodman and Hastak, 2006; Shahin, 2005; Huang, 2004; Nam, 2009; Fwa, 2006; PIARC, 2000; MLTM, 2009). As major references in the PMS sector, Hudson *et al.* (1997), Goodman and Hastak (2006) and Fwa (2006) well describe overall concepts and concerns of infrastructure management, and summarize general methodologies used in PMS. They present a huge amount of information on detailed methods and experiences related to infrastructure management. However, instruction regarding PMS development strategy has been inadequate. Huang (2004) and Shahin (2005) introduce very practical information in works similar to field manuals, which could serve as valuable references facilitating the operation of the PMS management cycle. Nam (2009) suggests advanced stochastic optimization methods for infrastructure management. The models would be useful in the development of pavement deterioration forecasting models in various cases. The MLTM (2009) is a national guideline for investment in road infrastructure in Korea, treating a wide range of Life Cycle Cost (LCC) evaluation methods related to road infrastructure. This kind of guidebook makes it easy to define PMS models. Among the references, Shahin (2005) suggests pavement management implementation steps based on ready-made PMS analysis software, the Micro PAVER. The steps are widely divided: 1) obtain map, 2) define network, 3) collect inventory data, 4) create database, 5) collect condition data, 6) develop deterioration models, 7) verify data, 8) obtain localized and global M&R (Maintenance and Rehabilitation) costs, 9) develop PCI (Pavement Condition Index) vs. cost models, 10) perform condition analysis and work planning analysis, 11) formulate M&R project and establish priorities. While the noted steps are sufficient to cover the basic procedures of road agency-oriented PMS analysis, they would be insufficient to cover various objectives extended to road user costs and socio-environmental issues. In addition, the steps treat only agency-oriented PMS analysis.

As noted above, most references well summarize essential PMS components and present details on various methods, models and technologies. Nevertheless, it is difficult to find suitable references about PMS development strategy at the system level, since references are usually dedicated to individual components at the functional level. However, all references would be useful for designing PMS functions after a PMS development strategy is defined.

2.4.2 Standardization of PMS Capability Levels

While the purpose of what we have termed "PMS" may be similar among organizations—to facilitate maintenance work and to enhance cost-effectiveness amidst budget constraints—the PMS of each road agency usually differs from others in system framework, components, functions, and even definitions of the same content. In fact, it is difficult clearly to define the term PMS because each road agency has a different image of PMS based on its own current system. Regarding this issue, this paper aims clearly to define the term according to PMS capability levels, the most fundamental standard affecting other criteria.

The general objectives of PMS development could be divided into the initial introduction of PMS, the domestication of the introduced PMS model, or the improvement of current PMS capabilities. Properly, the demands occur successively, beginning with the initial implementation. Road agencies may have different distances between two points indicating the current and desired level of PMS capability. Although the distances differ, agencies' efforts are focused on progressing toward the desired PMS from their current PMS. This implies that PMS development has direction, and the development strategy also should have a formal (or general) direction based on the stream of improvement of PMS capabilities. Therefore, establishing evaluation standards for various PMS situations and leading them in the best direction must be the main considerations when PMS capability levels are defined.

For this purpose, this paper suggests *"Stepwise Directional Customization Approach (SDCA)"* defined as *"A formal (or the best) direction of development of PMS considering user's current and desired PMS capabilities level"*. With well-designed standards regarding the data level, required function, PMS components and their results, users can incorporate successive steps into long-term development plans for their PMS. This is well matched with the concept of sustainable development. The basic development strategy, the SDCA, could have three important benefits: 1) assessing the current PMS situation by standardized index, 2) showing the best development scheme with regard to any PMS situation, and last 3) getting every country on track toward PMS development (*i.e.* toward having compatibility with others). The step indices could be used as indicators characterizing the PMS situations of each country. If many countries follow the steps, the indicator could be an international standard for evaluating and comparing levels of management capabilities. The SDCA is comprised of 2 phases divided into 5 general stages and 2 mature stages as follows:

- ***General stage A: Expert system dependent level A - Without data and system:*** At this stage, there is no data, no system, or even any interest in maintenance and management. The agency does not conduct inspection work to check pavement conditions and inventory data. Decisions for maintenance are made in a very reactive manner based on the experience of road managers during poorly conducted patrols.

- ***General stage B: Expert system dependent level B – With (incomplete and limited) data:*** Some inventory and condition data are available. However, the data are not vividly applied for systematic decision making processes due to the lack of a long-term PMS development plan. Moreover, incomplete or limited data make the situation unstable. Decisions for maintenance at this stage also follow the expert system in a reactionary way. At this level, usually the "Worst-First" strategy is used for decision making, taking into consideration budget limitations.

- ***General stage C: Database dependent level:*** This is the most typical level of PMS. Road agencies at this level operate a procedural pavement maintenance cycle, and have a reasonable dataset to support maintenance work and budget estimation. In brief, this is an agency-oriented level (or PMS cycle-oriented level) focused on maintenance work only. Since at this level there is a basic framework for pavement management, there is the potential for increasing management efficiency with minimal effort. However, it is unknown to agencies at this level whether or not their current strategy is optimal, and they may be eager to enhance cost-effectiveness by optimizing their PMS strategy.

- ***General stage D: Modeling level A – Pavement deterioration forecasting models:*** This is also one of the typical types of PMS. The pavement deterioration forecasting model (hereinafter, deterioration model) should be the first step in modeling for PMS because it is the foundation of every PMS analysis. At this level, a road agency can conduct various pavement performance analyses and simplified economic analysis by the What-if analysis. This stage is attainable to agencies with enough performance history (or time-series) and inventory data. This level may have higher cost-effectiveness because data demand could be minimized for long-term economic analysis. However, the definition of LCC at this level has limitative meaning that considers only road agency cost. Although road agency cost is the most important factor in the decision making process, this might be incomplete information because it is road agency-oriented information.

- ***General stage E: Modeling level B – Full life cycle cost analysis model with optimization procedure:*** Stage E could be considered the maximum level of PMS capabilities. At this stage, much comprehensive information on the socio-environmental cost incurred by road investment is used in the decision making process with budget optimization procedures. The life cycle cost at this level could be considered as (a part of) total transport cost because it assumes that most costs occur when road users are on road sections. As objective functions of the optimization, minimizing NPV or maximizing condition recovery can be applied. This stage is realized by compiling detailed life cycle cost contents and optimization procedures at stage D. Since the additional life cycle cost contents consider vehicle operating cost (fuel, tires, engine oil, vehicle maintenance and depreciation cost), travel time cost, accident cost, work-zone effects, and emission costs, various and meaningful information can be used in decision making. Although the PMS model in stage E can produce a great deal of powerful and interesting information, there are not many cases manifesting this level because it requires a considerable number of sub-models, a huge amount of data, and specification data (*e.g.* vehicle characteristics, accident rate, various unit costs, etc.). To maintain this level, additional budget resources for PMS application are required for inspection and Research and Development (R&D) projects.

- ***Mature stage F: Feedback / Improvement / Customization phase:*** After each user reaches its desired stage (not necessarily stage E), road agencies must jump to this stage. Though the PMS physically reaches the desired level, the PMS needs feedback, improvement and customization in a continuous manner to satisfy heterogeneous environments. The main efforts would be 1) improving or modifying pavement deterioration models following data accumulation, 2) elaborating on or simplifying the life cycle cost analysis model, 3) eliminating useless items of the current PMS, or adding useful items from another stage, 4) modifying current components and structures for special demands (*e.g.* changing the database to a visualized DB, web-based PMS operating system) and 5) developing unique functions for special purposes (*e.g.* Hidden Markov for measurement error (Kobayashi *et al.,* 2009), and local mixture hazard model (Nam *et al.,* 2009) for defining heterogeneity of deterioration speed among road groups.

- ***Mature stage G: Specification / Documentation / Legislation:*** When enough feedback and improvement have occurred, core standards for pavement maintenance and management can be specified, documented and legislated. The results serve as official guidelines at the national level, facilitating decision making with regard to every PMS activity. This is the ultimate goal of PMS. Main contents to be specified are 1) surface and basement materials, 2) pavement design method (*e.g.* thickness of each layer), 3) engineering method of construction and maintenance, 4) definition of data requirements, 5) specifications of inspection work regarding interval, contents, and methods, 6) definition of economic analysis method (LCC contents and estimation models), 7) pavement deterioration forecasting models, and 8) decision making process defining mandatory analysis work.

Of course, the guidelines should also be endlessly improved by the tasks noted in stage F. As described in the beginning of this chapter, this paper classifies PMS situations into general stages (A, B, C, D and E) and mature stages (F and G). The stages are not separate, but are in a hierarchical relationship in the best direction. In brief, the order of the stages shows implementation or improvement steps. The relationships of the 7 stages are described in Figure 2.1 and Table 2.2.

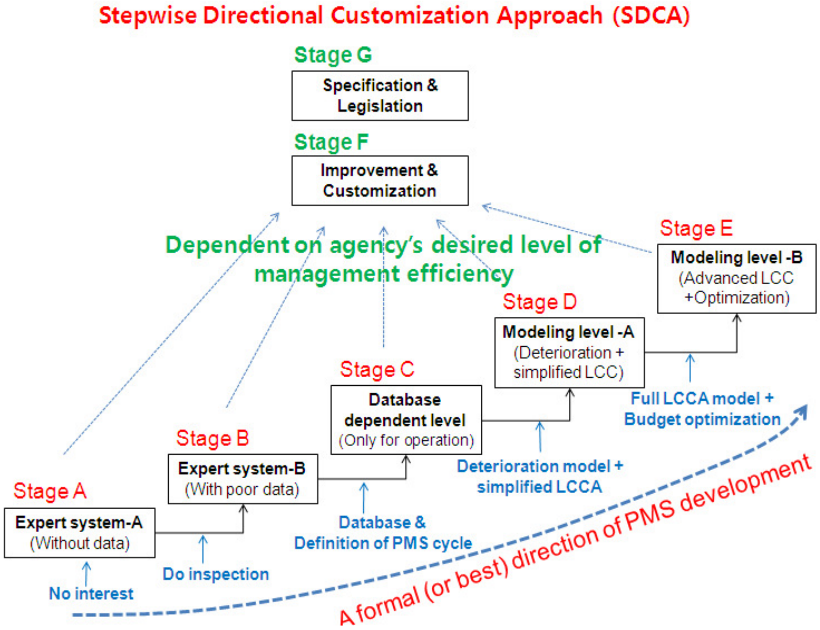

Figure 2.1 Suggestion of general implementation and improvement steps of the PMS by the SDCA

Table 2.2 Description of PMS capability levels

PMS capabilities	Descriptions	Requirements to advance to next stage	Main functions of PMS (Capability of PMS)	Additional system components	Core data
Stage A	· Expert system dependent level without data	· Inspections for pavement condition and inventory data	· No function and system	· N/A	· N/A
Stage B	· Expert system dependent level with (incomplete) data	· Database + definition of PMS cycle and activities · Securing general data requirement in PMS	(For a PMS cycle) · Maintenance schedule · Inspection schedule · Budget estimation	· Data tables	· Pavement condition indices · Minimized inventory data
Stage C	· Database dependent level or PMS cycle-oriented level	· Pavement deterioration forecasting model(s) · LCC model for agency cost	(For a PMS cycle) · Overall PMS activities plan · Basic database function · Support external models · Data error processing · Maintenance design · Budget estimation	· Database · Internal PMS model · External PMS model (if necessary)	· Additional data to be general dataset · Unit costs by maintenance types
Stage D	· Modeling level A - Pavement deterioration forecasting model (Performance analysis + estimation of agency cost)	· Full LCCA models · Optimization functions	(During analysis period) · Performance analysis · Comparison of maintenance strategies · Economic analysis on road agency cost · Accounting function	· Forecasting model (s) · Functions estimating road agency cost	· Enough time-series performance data · Explanatory PMS variables
Stage E	· Modeling level B – LCC (road user and socio-environmental cost +optimization)	· Domestication · Customization · Elaboration	· Economic analysis with additional LCC contents · Optimization functions which maximize NPV or condition recovery	· LCC models · Optimization functions	· LCC related data · Unit costs for additional LCC contents · Model coefficients
Stage F	· Feedback level	· Continues feedback	· Feedback, improvement, and customization of current PMS	· Case by case	· Case by case
Stage G	· Specification, documentation and legislation level	· Ultimate stage but needs continuous feedback corresponding with new demands	· Documentation & application to real field work	· Case by case	· Case by case

Note: Data requirements differ according to desired stage of road agencies, type of deterioration models, estimation methods of LCC and customization results.

When road agencies attempt initial implementation of the PMS, they can define a suitable stage by referring to the PMS functions and data requirements of each stage. The desired level need not be the maximum capability (*i.e.* stage E) but should be chosen according to agencies' environments and objectives. A road agency can choose as its desired PMS level a lower stage if that agency faces current budget or technical limitations, later adjusting its level in accordance with its increased capability. In the case where a current

PMS system is improved, pre-conditions of previous levels should be fully institutionalized as the system reaches a more advanced stage. It is suspected that many countries have been skipping important procedures and missing critical points at previous stages. If a current PMS does not satisfy the preconditions of previous stages, the model must return to those previous stages to achieve sustainable development. Thus, in order to define their desired level of PMS, road agencies would need key information about what qualifications must be met at each stage before advancement to the next PMS level.

As would be expected, because all criteria are based on the definition of PMS capability levels, that definition is the focus of this paper. While certain details in Table 2.2 can be revised and improved in the future, the basic concepts for PMS evaluation will remain fixed.

2.4.3 Definition of PMS Functions by PMS Capabilities

There are many functions that facilitate PMS operations and analysis. This paper attempts to classify general functions by PMS capability levels. By determining suitable PMS capability levels, road agencies can provide important information that would create links with PMS framework and data requirements. General functions have been subjectively classified into 6 categories according to the main roles of PMS, and level of importance. The definitions are presented in Table 2.3.

In Table 2.3, the PMS functions are classified first according to data requirements, database, management, pavement deterioration forecasting, economic analysis and accounting function. Then, the functions are once more subdivided according to the level of demand.

Users may choose reasonable functions to build their customized PMS model by considering their data conditions and objectives. It is recommended that a suitable level be determined by observing the horizontal axis (from bottom to top) of Table 2.3, which is related to the main roles of PMS (or PMS capability level), and then checking the vertical axis (from left to right) to find a suitable level of functions. The main considerations regarding the use of this procedure would be 1) to decide whether or not to include PMS analysis procedures (*i.e.* pavement deterioration model, economic analysis and optimization), 2) to define the scope of LCC (road agency cost only VS. adding various LCC contents), 3) to determine whether data are sufficient to cover the desired PMS functions and lastly, 4) to see if there is a hierarchical relationship among the functions. For example, long-term economic analysis is not available without the pavement deterioration forecasting function.

Table 2.3 Definition of general functions in PMS

Functions	Core level	Semi-core level	Recommended level	Advanced level	Available stage(s)
(Near) Optimization	･Optimization – I Work scheduling by user-specified priority ranking	･Optimization-II Maximizing condition recovery	･Optimization-III Maximizing NPV	･Optimization-IV Best maintenance strategy by long-term accounting concept	E, partially D
Economic analysis	･Minimized LCCA - I Maintenance cost only (by deterministic or stochastic approach)	･Minimized LCCA - II User-specified agency cost only (*e.g.* adding inspection cost)	･Simplified LCCA Agency cost + (user-specified) simplified road user cost	･Advanced LCCA Full road user costs and socio-environmental cost Accounting function	E, partially D
Pavement deterioration forecasting	･Deterministic - I Empirical-mechanistic model (for beginning stage only)	･Deterministic - II (*e.g.* Single and multiple regression)	･Stochastic - I (*e.g.* Markov hazard model)	･Stochastic – II (*e.g.* Local mixture hazard, Hidden Markov chain, etc.)	D, and E
PMS cycle management	･Finding work demands (inspection & maintenance) ･Data error processing	･Work effect models ･Work design models ･Budget estimation	･Reporting function (summary of activities during a cycle)	･Near-optimization of agency cost (by changing current plan)	C, D, and E
Database	･Basic database function ･Data exportation	･Reporting function (network condition, simple statistics)	･Support for internal and external models (*e.g.* HDM-4)	･Visualized database ･Web-based system ･Link with other road facilities or systems	
Data requirements	(For stage A and B) ･Identification ･Simplified inventory & condition data ･Unit costs for agency cost	(For stage C) ･General inventory that includes pavement condition indices and PMS variables	(For stage D) ･Enough time-series pavement condition ･(special) PMS variables	(For stage E) ･Detail data for LCC modeling ･Unit costs for socio-environmental cost ･Subsidiary data	A, B, C, D, and E

The data requirement becomes totally different according to the definition of desired functions and their properties (*i.e.* estimation methods). For that reason, the data requirement should be defined at the last stage after all other details are defined. Taking into account the results of the data definition, road agencies must establish additional strategies regarding data inspection. This will be discussed in detail in Chapter 2.4.4.

The database is a tool for saving all historical data, and it should have general database functions, such as searching, deleting, modifying and exporting. To facilitate daily or annual activities of the road agency, reporting functions that show a summary of network conditions and simple statistics are recommended. A function supporting internal or external models is recommended for direct and easy applications. Since such functions could change the database structure due to the normalization procedure of data tables, these functions should be considered from the outset. Because layers of data can be easily managed in the GIS system, a visualized database at the advanced level is useful in cases where road agencies must manage various road related facilities. Sometimes, developing web-based systems or linking with other road related systems can aid the practical operation of PMS between headquarters and branch offices. Note that designing a database demands more time than expected so as to take into consideration the wide range of factors related to PMS operation, analysis and even relationships among systems.

As main functions for PMS cycle management, this paper suggests 1) the estimation of work demands on inspection and maintenance, 2) work design, 3) work effect, 4) error processing, 5) budget estimation and reporting function, and 6) near-optimization procedure during a PMS cycle. These functions can be inserted as part of the current PMS cycle, if necessary. The management function should be paired with the database because it has a close relationship with database updates. These paired functions are minimum requirements for PMS operation.

The pavement deterioration forecasting function is a core element for economic or performance analysis. So far, many theories and models with different properties have been developed for various purposes (Bhattacharya and Majumdar, 2007; Lancaster, 1990; Yang *et al.,* 2005, 2006; Kobayashi *et al.,* 2008, 2009, 2010; Nam, 2009; Tsuda *et al.,* 2006; Odoki and Kerail, 2000; Jiang *et al.,* 1989; Jido *et al.,* 2008). The models can be divided into deterministic and stochastic, or empirical and mechanistic. Although stochastic models are preferred over deterministic models due to uncertainty about the pavement deterioration process, their applications are not for everyone. Since pavement deterioration forecasting is totally dependent upon the historical performance data affected by many kinds of PMS variables, there are many limitations to establishing the forecasting models, especially for road agencies in the beginning stage of PMS. In the case of the initial implementation of PMS, road agencies may have to apply mechanistic models like HDM-4, or apply another's forecasting functions. However, road agencies can update their models based on the Bayesian concept as data accumulates. In the long run, the road agency will have the capability of developing its own customized deterioration forecasting functions. One important consideration regarding properties of the forecasting model is whether it can satisfy objectives, and whether it can be satisfied by the data conditions of road agencies.

The main role of the pavement deterioration model is to show the performance of road pavements. To extract meaningful information for various purposes, an economic analysis based on pavement performance and investment level is essential. In general, economic analysis in the PMS sector follows the concept of LCC to enhance budget cost-effectiveness. In the economic analysis, cost streams by user-specified alternatives are empirically simulated, and various economic decision criteria are estimated to help in decision making. For this procedure, most road agencies have focused only on the agency cost. However, the analysis has the weakness of not taking into account the entire LCC affected by the road investment level. According to reviews of the definition of LCC contents in the PMS sector, the main contents were Vehicle Operating Costs (VOC), travel time costs, accident costs, and vehicle emission costs. Included as components of VOC were fuel consumption, tire wear, engine oil cost, vehicle maintenance cost, and vehicle depreciation cost (Winfrey, 1963; de Weille, 1966; Bonney and Stevens 1967; AASHTO, 1978; FHWA, 1998; MTBC 2005; Goodman and Hastack, 2006; Uddin and Torres-Verden, 1998; MLTM, 2009). In fact, the agency cost may account for a very small ratio of the total transport cost. Nevertheless, cases treating the advanced LCCA are not very common in reality because the money is invisible, and such cases demand too much data for their estimations. To consider only agency cost might be enough to satisfy general objectives in the practical operation of PMS. However, we must recognize that a revolution in PMS will not be the result of any change in application methods (*i.e.* management strategy), but of many fundamental factors related to hardware, such as pavement material, design methods, etc. The advanced LCCA may be useful for research regarding these matters.

One strong recommendation is to acquire the accounting function, which could be a bridge between PMS managers and administrators, who have different viewpoints. This function provides accounting information to assess whether repair is sufficiently realized for maintaining the service level of road pavement (Kobayashi *et al.,* 2008). The budget level, an important policy parameter, can be determined while maintaining the agency-specified pavement service level of the entire road network. This function allows PMS managers to show the importance of the budget directly to administrators and to make more persuasive cases for funding when long-term budget plans are drawn up. For a detailed description of accounting functions, refer to Kobayashi *et al.* (2008).

The last component is the (Near) optimization function for maximizing the cost-effectiveness of a constrained budget. This function finds the best maintenance alternative based on budget limitations, and would be useful for defining better maintenance criteria under a specific budget level. Optimization principals can be classified as maximizing NPV (Net Present Value) or maximizing condition recovery. This function can determine the best maintenance strategy based on the long-term accounting concept. Moreover, the solution can be applied at the individual section level, as well as at the network level. In brief, every individual section could have a different optimal maintenance standard based on deterioration speed and LCC scale. Note that the term, 'Optimization' is, strictly speaking, incorrect. A more appropriate expression might be "Near-optimization," which more accurately conveys the idea that the optimized solution means the best alternative among applied alternatives in the simulation.

2.4.4 Data Requirements and Management

This chapter should be highlighted as the most important of this paper. The matter of data governs the overall development plan, as well as every detail of the estimation models. Most road agencies have a deep interest in this issue because it is directly linked to the volume of PMS work and to budget requirements. While we treat data content (or requirements) as an important issue, we also wish to focus on the additional issue of data management. To avoid failures in data policy, it is necessary to have a deep understanding of these two issues.

2.4.4.1 Data Management

According to lessons learned from past failures, strategic data management is the key to successful PMS operation and development. In some cases, due to poor management strategy, road agencies have had to discard valuable data, the loss of which costs a considerable amount of both money and time.

Among the many issues related to data management, this paper emphasizes identification (ID) management. Simply, the ID involves units of data saving. In the PMS sector, we often use the term "Section." However, its definition has a very close relationship with pavement maintenance and data management. In many countries, it is common for road agencies to have section units pre-defined according to administrative, physical or operational characteristics, and these usually become the agencies' basic units for data saving. Road agencies conduct inspection work by dividing a section into many inspection units. In the end, the inspection units are integrated to obtain pavement condition data for the section. Sometimes, several section units are further integrated as a homogeneous section unit, and the homogenous section unit has often been used for analysis work. Road agencies usually base maintenance work on the section unit. After maintenance work is conducted, data tables are updated to reflect the results. The most serious problem with this scheme is that partial maintenance may occur within a section because of the inability to reflect maintenance effects exactly, especially in cases involving a rehabilitation level of maintenance. An additional problem in reality is that the definition of the sections or of the homogenous section is often changed. Frequent changes in definition can cause an inverse condition whereby a road section is deemed to have improved even though no maintenance work has been done. This problem is considered one of the most serious in PMS data management, as it implies that previous data becomes obsolete and should be discarded. Experience has shown that road agencies must be careful when defining the basic unit of the PMS.

Identification rules could be based on inspection, maintenance or analysis. The ideal definition is, of course, conducting management and analysis work by using the inspection unit. Accordingly, it is necessary for the inspection unit to be short (maybe less than 100m) to reduce any bias due to partial deterioration and maintenance. However, such short units might be unrealistic or inefficient due to the size of the population, the preservation of homogeneity in pavement design, or coordination with administrative units. Therefore, applying multiple units is recommended. Of course, the management unit should be the center of units usually called “sections”. For defining homogeneities of widely distributed sections in the network, it would also be useful to include grouping information about such matters as road class, pavement material, physical pavement design, traffic load level, and climate conditions. This could be considered as another identification rule useful for various research purposes, especially in showing significant explanatory variables in different PMS environments, and establishing better maintenance design standard considering PMS variables.

Vietnamese PMS is a worst-case scenario, with road officials saving their data according to different ID rules (even creating rules) with every inspection. For this reason, data cannot be linked as time-series data. Maintenance history cannot be properly or exactly reflected, one of the main reasons being that Vietnamese PMS is committed to HDM-4 application. Presently, the HDM-4 model is applied every fiscal year only to budget estimation. Since Vietnamese road managers are now applying the default pavement deterioration model inside the HDM-4 model, there has been no need to build time-series data for calibration of the deterioration model. In brief, road managers have been discarding previous inspection data. Recently, they have realized the many limitations of the unaltered HDM-4 model and have become interested in developing a customized PMS. However, there is a lack of time-series data, essential for building the forecasting function. Meanwhile, for the past 10 years, the Vietnamese have invested enormous budget resources in acquiring rich data contents for HDM-4 application, data that nevertheless cannot be used to create a customized PMS. This unfortunate case well describes the importance of data management.

Another issue related to the data management scheme is inspection strategy, the first concern about which is interval. In most cases, a 3-4 year interval has been chosen as the frequency at which inspection should be conducted for accumulating data and finding maintenance objects. However, the inspection interval determines the quantity of additional deterioration (over maintenance criteria), which significantly affects road users and the environment. Depending on the results of maintenance retardation, a change in maintenance design might become necessary, resulting in worse cost-effectiveness than in the scheme originally established by the road agency. Since road agencies cannot conduct maintenance work unless they find that the road condition meets their maintenance criteria, actual maintenance criteria in reality are determined by the combination of “official maintenance criteria” and “delays in maintenance” generated by the function of pavement deterioration speed, inspection interval, and budget limitations. Sensibly, the network having a faster deterioration speed needs to apply a shorter inspection interval to minimize the quantity of deterioration. With economic analysis, the optimal inspection interval in relation to deterioration speed can be determined.

The second concern is about the long-term inspection scheme. Simply put, the question is whether the inspection work of an entire network should be conducted all at once or divided over several years (*i.e.* inspection interval). The properties of PMS data may change according to which type of inspection scheme is used. Accordingly, the type of inspection scheme has significant effects on actual maintenance plans, as well as on PMS research.

2.4.4.2 Data Requirement

Data requirements cannot be defined before fixing all other types of details related to PMS. Even if this paper were subjectively to suggest a pre-defined dataset based on a specific PMS situation, such a dataset would not be suited to various PMS situations. For that reason, it is necessary that data requirements for each PMS be determined by individual road agencies, taking into account the following three factors: 1) the desired level of PMS capability, 2) the external or internal PMS model in use, and 3) domestication procedures (see Figure 2.2).

Since the factors 2) and 3) in the previous paragraph are heterogeneous factors by each road agency, this chapter will discuss data requirements based upon the desired PMS capability level. To define the data requirement, data categories should be firstly defined. The general categories and main data are summarized in Table 2.4. Besides, this paper suggests 4 pre-defined datasets supporting each PMS capability level respectively, a simple summary of which can be found in Table 2.5.

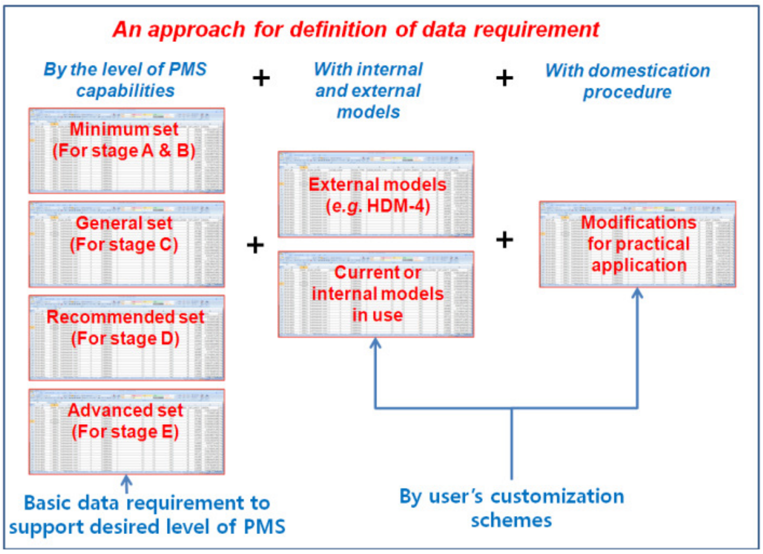

Figure 2.2 Definition of data requirement in PMS

Table 2.4 General categories and main data in PMS

Classification	Description	Main data
Identification	Definition of road networks by agency, network, link (homogeneous section), section, and inspection unit.	· Identified by -Analysis unit, Management unit, Inspection unit
Physical and operational road characteristics	Describing physical characteristics of road sections required for budget estimation, and forecasting pavement deterioration Describing operational road characteristic	· Section length (km) · Carriageway width (m), number of lane · Slope (%), curvature (degree/km) · Type of road (*e.g.* bridge, tunnel,) · Speed limit (km/h) (for advanced LCCA only)
Pavement design variables	Describing details of the pavement design affecting pavement strength and maintenance works	· Pavement materials · Thickness of each layer (mm)
Maintenance & inspection history	Recording all of maintenance and inspection histories with age indicators[4)]	· History of (re)construction, rehabilitation, repair, routine maintenance, and inspection
Explanatory variables	Significant PMS variables that affect to pavement deterioration speed, and M,R&R activities (could be differed by road agencies)	· Traffic: AADT[1)], vehicle composition (%) · Climate conditions: Temperature(C^o), rainfall(mm/yr) etc. · Etc.
Pavement condition data	Various deterioration indices that characterize pavement conditions.	· Minimum: crack(%), rutting(mm), IRI(m/km), and pothole(n/km) · Optional: types of crack, raveling area(%), edge break (m^2/km), texture depth(mm), skid resistance (SCRIM 50km/h)
Vehicle characteristics	Describing properties of vehicle types in use	· Size, num. of wheels, axles, and tires, fuel type · PCSE[2)], ESALF[3)] · Unit costs for LCCA
Subsidiary data	Subsidiary data to conduct performance and economic analysis	· Interest, model coefficients, unit costs and so on.

Note: 1)AADT (Annual Average Dairy Traffic)
2) PSCE (Passenger car Space Equivalent factor)
3) ESALF (Equivalent Single Axle Loads Factor)
4) AGE0 ~ AGE4 (0 = inspection, 1 = preventive level, 2 = repair level, 3 = rehabilitation level, 4 = construction level)

Table 2.5 Definition of datasets based on PMS capabilities

Definition	PMS stages	Descriptions	Data requirement
Dataset A	All stages	***Minimum level*** to support the "Expert system" that follows "Worst-first" concept of maintenance strategy	· Identification · Minimum level of physical road characteristic · Pavement conditions · Core subsidiary data
Dataset B	C, D, E	***General level*** to support "database dependent level" for typical PMS operation	· General inventory data to support operation of a PMS cycle
Dataset C	D, E	***Recommended level*** to support "Modeling level-A" that estimates pavement deterioration and agency cost	· Enough time-series pavement related data for establishing pavement deterioration functions · Enhancing special considerations (*e.g.* climate factors)
Dataset D	E	***Advanced level*** to support "Modeling level-B" that applies advanced level of LCCA and optimization for decision making	· Enough inventory data for application of road user and socio-environmental cost

Table 2.6 Data requirement of minimum level

Classification	Contents
Identification	ID (saved by inspection, maintenance, or analysis unit), location information
Pavement condition indices	User-specified condition indices for maintenance works of agency
Physical road characteristics	Section length, number of lane, width of lanes
Subsidiary data	Unit costs of maintenance types and inspection

Table 2.7 Additional data contents to be general level

Classification	Contents
Traffic related data	Traffic volume in AADT, vehicle composition ratio
General pavement condition indices	Crack, rutting, IRI, Pothole (or more, if necessary)
Pavement design variables	Current pavement type, surface material, thickness of each layer,
Maintenance and inspection history	Conducted year (and elapsed time), details of conducted maintenance work
PMS activities	Record of conducted (and delayed) maintenance and inspection as planned Executed budget by each activity
Additional subsidiary data (or information)	Detailed unit costs related to pavement design, ESALF of each vehicle type, maintenance criteria, error processing mechanism, maintenance codes etc.

The minimized dataset is to support stages A and B, which follow the "Expert system" based on the concept of a "Worst-first" maintenance strategy. The general functions of this level are defined as estimating maintenance and inspection work, and the required budget during a PMS cycle. For the two functions, the following data summarized in Table 2.6 are adequate to satisfy the data requirements of stages A and B.

The general dataset is to support stage C, a database-dependent level at which the tactical "Plan-Do-See" management cycle is conducted. Distinguishing it from the minimum set, the general dataset has traffic related data, general pavement deterioration indices, pavement design variables, maintenance and inspection history, records of PMS activities during a cycle, and much detailed subsidiary data. Table 2.7 summarizes the contents. Note that the "General pavement condition indices" in the Table 2.7 are for bituminous pavement. If desired PMS of road agency want to treat additional pavement materials, the dataset should have additional indices corresponding with the materials. The "Current pavement type" is for characterizing properties of basement and surface layer. The index considers history of previous maintenance works for much practical design of maintenances (Odoki and Kerali 2000; NDLI 1995a). The "Maintenance codes" is an optional requirement to design maintenance work determined by PMS variables (*e.g.* traffic volume, temperature, road class). It may be quite helpful for objective maintenance design. However, establishing such standards requires enormous data, and time. Above all, it is impossible without strategic PMS development plan.

The general dataset provides most data necessary for PMS operation. Besides, many kinds of useful data can be estimated (or calculated) from the dataset, such as pavement strength characterized by SNP (Structural Number of Pavement), and traffic road level expressed by MESAL (Million Equivalent Single Axles Load). Since the general dataset contains minimum data for the general level of PMS, it could be called a separate level of the minimum dataset.

Although the general dataset can support the basic framework of PMS, it cannot be considered the recommended dataset, which ideally should have additional PMS variables to be used in the modeling of the pavement deterioration process. In brief, the recommended dataset is defined as a combination of the "general dataset + user-specified PMS variables". The determination of user-specified PMS variables should reflect significant factors that affect pavement deterioration speed or practical PMS operation. Significant variables may differ in type with each road agency due to heterogeneous environments. For example, if there are many bridges and tunnels in the network due to mountainous topography, it is necessary to strengthen data contents about the objects. In cases where road networks are spread over huge areas with various climate conditions, climate data could be considered a significant factor affecting deterioration speed. In brief, user-specified PMS variables are for establishing better maintenance or management strategies with regard to the unique PMS situations of each road agency. Since the general dataset has most of the important data, improvement from the general level to the recommended level would not be very difficult in most cases and would depend to a large extent on the interest and capability of the PMS manager.

Although datasets A, B and C can support the estimation of road agency costs, they may be inadequate for conducting advanced level LCCA, which includes various LCC contents. Estimation regarding road users and socio-environmental cost has usually followed deterministic methods based on an empirical and mechanistic approach. This implies that estimation models are composed of many model coefficients developed under specific road conditions (or countries). Road agencies will be able to use the default model as it is. However, obtaining reliable estimation results often requires model calibrations. For advanced LCCA, many subsidiary data and standards to support estimation models should be prepared. Even if the advanced level of dataset has many benefits, its cost-effectiveness is still questionable, as this level requires huge research efforts to develop customized models, to find model coefficients, or to establish standards. For this reason, there are few cases that apply the advanced LCCA. Since the advanced dataset is totally dependent on the LCC contents and their estimation models, we are unable to give detailed descriptions in this paper. Regarding estimation models on road users and socio-environmental cost, refer to Bennett and Greenwood (2003) for an example.

2.4.5 General Framework of PMS by Capability Level

So far, PMS capability level, PMS functions, and data requirements have been discussed. Based on the contents, a PMS framework can be established according to PMS capability level, summarized in Table 2.8 and Figure 2.3. Note that Table 2.8 and Figure 2.3 could be reorganized (or customized) according to a user-specified PMS development plan at a system level as well as at a functional level.

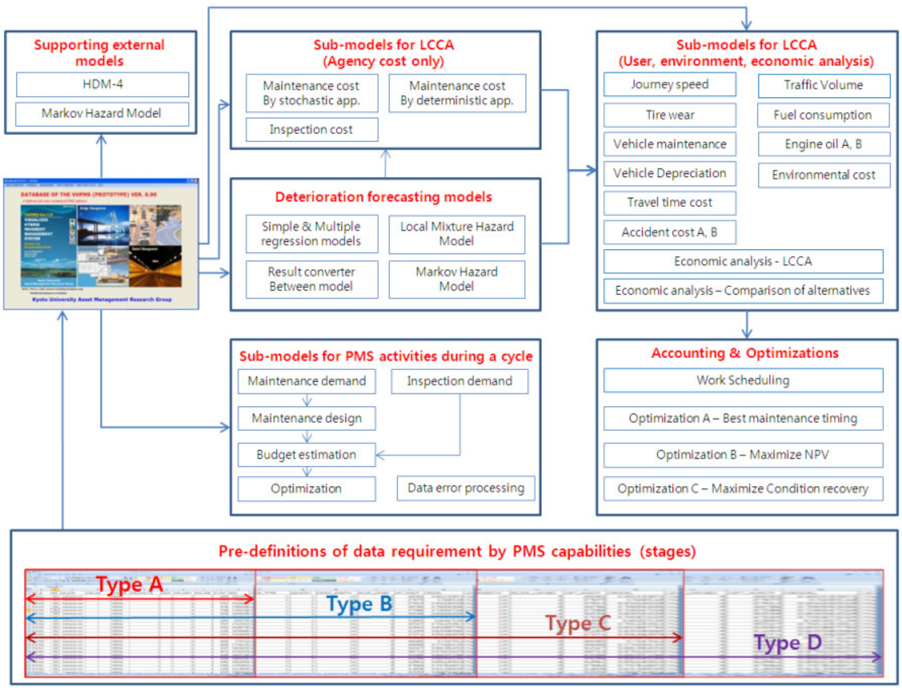

Figure 2.3 Suggestion of a general framework of PMS (full version)

Table 2.8 Summary of PMS components

Categories	Roles of PMS	Roles (name) of components	Description	Level of demands
Data definition	Data management	Core set	Identification, simplified inventory & condition data, unit costs for maintenance	Core
		Semi-core set	General level of inventory & condition data	Recommended
		Recommended set	Enough time-series data + user-specified PMS variables	Recommended
		Advanced set	Detail data for establishing advanced LCC models, subsidiary data and rich grouping information	Optional
Database		Integrated database	Database based on user-specified data definition and database functions	Core
Management	Operation of PMS cycle	Maintenance demands	Finding maintenance demands by maintenance types	Core
		Inspection demands	Finding inspection demands by inspection types	Optional
		Data error processing	Finding errors data, and processing it by user-specified algorithm	Core
		Maintenance design	Deciding suitable maintenance code corresponding with levels of PMS variable	Recommended
		Budget estimation	Estimating budget requirement of agency-specified maintenance alternative	Core
		Near optimization	Finding better work schedule by control of current management schemes under budget constraint	Recommended
Deterioration forecasting	Performance analysis & Economic analysis	Empirical-mechanistic models	Ready-made deterioration models developed by laboratory experiments or specific field data.(*e.g.* deterioration models in the ready-made software)	Not recommended
		Simplest models	Deterioration models that can be established by minimum data (*e.g.* single or multiple regression)	Core
		Advanced models – General	Deterioration models that serve critical information for pavement management based upon the stochastic approach (*e.g.* Markov chain, hazard models)	Recommended
		Advanced models – Special	Deterioration models for special issues on pavement management (*e.g.* Hidden Markov Chain (Kobayashi *et al.*, 2010), Local mixture hazard (Nam, 2010))	Optional
LCCA model	Economic analysis	Maintenance cost	A part of agency cost for maintenance work that can be estimated by deterministic or probabilistic approach	Core
		Inspection cost	A part of agency cost for inspection that can be estimated by inspection rules (depended on the definition of road agency cost)	Optional
		Travel time cost	Option 1: Estimating total travel time cost Option 2: Estimating additional travel time cost due to workzone	Optional
		Vehicle Operating Cost (VOC)	Option 1: Estimating the total VOC (composed by fuel, tire, engine oil, vehicle maintenance and vehicle depreciation) Option 2: Estimating additional VOC due to workzone	Optional
		Accident cost	Option 1: Applying hazard exposure based method Option 2: Applying pavement condition based method	Optional
		Environmental cost	Economic evaluation of substances from the vehicles emission (The substances: HC, CO, CO2, NOx, SO2, Pb, and PM)	Optional
		Sub-models	Sub-models to support the advanced LCCA (*e.g.* traffic volume generation method, vehicle speed model, etc.)	Optional
		LCCA-cost stream	Estimating cost stream of each analysis year considering interest	Core
		Decision criteria	Estimating economic decision criteria (*e.g.* NPV, IRR, NPV/Cost ratio, and EUAC)	Recommended
		Sub-models	Traffic volume generation, Vehicle speed model	Optional
		Accounting function	Providing accounting information (*i.e.* budget level) to maintain specific service level with minimized LCC	Recommended
Optimization		Work scheduling	Summarizing the work schedule by priority ranking	Optional
		Optimizations	Finding optimal work schedule which maximizes objective functions (*e.g.* NPV or condition recovery) under budget constraint, or finding optimal budget under accounting concept	Optional

The core information of this paper is embodied in Table 2.8, where functions are classified according to the level at which they are recommended. Selection of functions depends on road agencies' development schemes, and it should be noted that road agencies can increase their PMS capability in the future.

2.4.6 Establishment of Development Scheme

To establish a development scheme, the first procedure should be to gain a clear grasp of the characteristics of a country's PMS, and to define the desired level of its PMS. Road agencies must have sufficient time for this procedure. Basically, a road agency must first define "What we have to do," which depends on the difference between the desired and the current level of PMS. Note that differences should be checked not only forward but also backward for sustainable development. To draw a blueprint for the desired level, road agencies must check the current situation and roles of PMS from various viewpoints, which we classify into three: the system level, the functional level, and the programming level.

The system level concerns "What the desired PMS can do" that determines the overall system framework and components. Of course, this question is contingent upon the PMS's main roles, which are divided into three categories: 1) data management, 2) management of the PMS cycle, and 3) PMS analysis. Afterward, detailed functions fulfilling selected roles should be specified (see Table 2.3 and Table 2.8). If the suggested functions in this paper are insufficient to satisfy the demands of the desired PMS, road agencies must develop new functions at this level. Further, road agencies must check subordinate relationships among the functions. After identifying the system level, PMS functions, the overall framework, and physical system components are determined.

At the functional level, selected functions at the system level should be designed in detail, taking into consideration factors shown in Table 2.9.

Table 2.9 Considerations for PMS development in functional levels

Contents	Descriptions
Data definition	· Following general definition in PMS sector (*e.g.* definition of contents, unit, estimation way) · Supporting all of desired PMS functions as well as future demand. However, it is recommended to get general data requirement defined in the Table 5 and 6
Database	· Considering database type (*e.g.* texted or visualized) · Defining detail database functions reflecting demands of actual users so that the database can directly helps annual, monthly and dairy activities of PMS managers · Considering special usages, such as supporting ready-made software or internal models
PMS cycle	· Reorganizing overall procedure by adding useful procedures or simplifying useless procedures
Deterioration models	· Defining type of forecasting method by considering actual application and data condition (*e.g.* deterministic *vs.* stochastic, annual basis *vs.* state basis, or network basis *vs.* section basis)
Economic analysis	· Defining type of results, LCC scope, estimation methods on each LCC contents, economic decisions criteria, and optimization methods
Heterogeneous factors	· Special considerations due to heterogeneous PMS situations of each road agencies (*e.g.* integrating other road facilities or systems into a system, demand of web-based system, generating special report)

At the programming level, all details should be addressed. For example, the main tasks at this level include determining kinds of programming language, determining system interfaces, and elaborating on or simplifying estimation models, all of which may depend on the particular tastes of road agencies and their PMS situations.

2.5 Mesoscopic Approach for Implementation Phase

At the macroscopic approach, criteria for PMS development have been treated. Based on the criteria, road agencies may draw a blueprint for application of the Hybrid PMS. At the mesoscopic approach, this chapter mainly describes strategies to realize following two properties of the Hybrid PMS introduced in the Chapter 2.3.

- Easy and flexible customization
- Compatibility with current PMS model

Basic objective of the mesoscopic approach is devising easily applicable system framework to help composing desired PMS of each road agency. Therefore, having clear understanding on system architecture of the Hybrid PMS is essential for application of the Hybrid PMS.

2.5.1 Flexible System Architecture by Plug-in System

After establishing the application plan of the Hybrid PMS, users may be confused because they do not know well about the system inside. At the moment, they may make a question "How to use this?". This chapter will give a answer against the question.

This is an important and difficult point that concludes successful development and application. As would be expected, the Hybrid PMS has very huge architecture including sophisticate procedures to serve rich functions and easy customization environment. But this architecture can be easily disaggregated and aggregated by introducing a concept, *'Plug-in system'*. Figure 2.4 shows the concept of the Plug-in system of the Hybrid PMS.

The concept of the plug-in system is quite simple whereby the system allows composing customized PMS by just input required functions to the database. Because of the property of the concept, someone may consider the Hybrid PMS as a collection of the PMS function, while it also could be said as disaggregated PMS model by functional level. This is a reason why this paper named the general model as the "Hybrid PMS".

For successful development, determination of unit of PMS functions, and designing exact relationship among the many components are key points of this strategy. Especially, definition of properties of input and output of each function is important point.

As an example for life cycle cost analysis, it firstly requires application of the pavement deterioration forecasting function. At the moment, the database supports its (predefined) data requirement to the deterioration model. Afterward, the deterioration model inputs its output to LCCA model as a partial data requirement. If the road agencies do not want to apply the LCCA model, they can ignore (or put off) the LCCA model from the main body of their desired PMS. However, it is impossible to apply LCCA model without the deterioration model because the system framework cannot satisfy the data requirement of the LCCA model. Therefore, users have to understand the subordinate relationship among the function.

The plug-in system cannot be realized without "encapsulation strategy" for itemization of PMS components which was basically assumed in the concept. It will be treated in the next chapter (see Chapter 2.5.2)

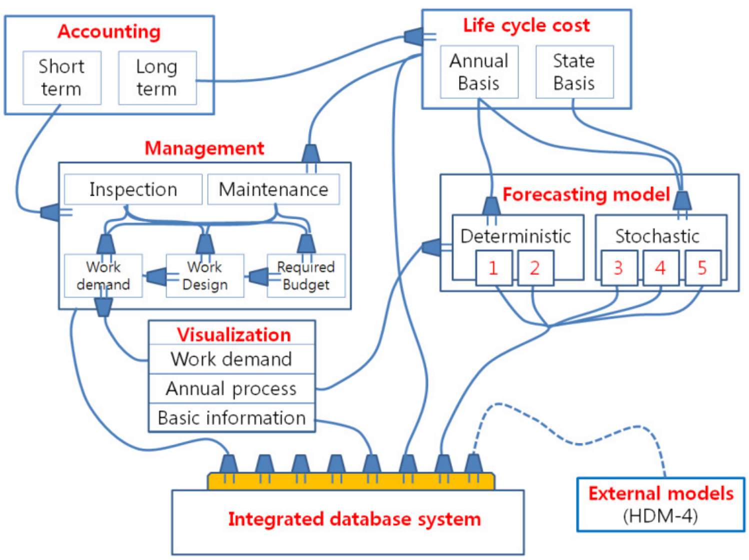

Figure 2.4 Concept of *'Plug-in system'* of the Hybrid PMS for flexible system architecture

2.5.2 Itemization of PMS Functions by Encapsulation Strategy

The flexible system architecture can be realized by the Plug-in system. However, the Plug-in system is impossible without the encapsulation strategy. The term, encapsulation, can be defined as;

"Making boundary of functions so that changing the original function (source code) does not make effect to the other functions"

By different viewpoint,

"Itemizing PMS functions as independent modules for flexible composition of desired PMS model or flexible application with their current PMS"

In brief, this is a unit of customization. Thus, definition of the boundary is the most important factor for successful customization strategy. The size of capsule has a tradeoff relation among system flexibility, simplicity of customization, and convenient application (see Figure 2.5).

The Hybrid PMS has many functions, and even each function has many sub-models and routines. In general, the system in PMS takes an integrated format including all of system components. It is easy to use but difficult to be customized. For example, even if a user wants to modify a small part, the user must understand all source codes, and should check all links affecting to the other functions. Maybe it could be much difficult than developing new program. On the other hand, the subdivided format divided by smaller capsules can minimize efforts for customization by modifying small amount of source code within a capsule. In brief, road agencies do not have to understand all system resource. This alternative could be the best way to realize the philosophy of the Hybrid PMS that eager to self customization so that every user can stand on their foot. Besides, the capsulated functions can be applied for supporting external PMS models (*e.g.* user's current system, or HDM-4) without additional system building. Lastly, user can get all of intermediate results of simulations. Most cases of simulations, they hide (or do not show) the intermediate results. Hence, users can not check which part has problem when the simulation generates strange results. The encapsulation strategy is good for improving reliability of simulation.

The once established PMS structure is fairly difficult to change, even though road agencies know critical problems or limitation of their system. The properties of the encapsulation strategy may be helpful to conduct partial improvement or modification.

2.5.3 Application Ways for Compatibilities with Current PMS

This is the most critical issue for practical application. If agencies do not consider the Hybrid PMS as an alternative, there is no meaning. This is anticipatable scenario. Usually, most road agencies have a tendency to keep their current system because they think introducing new system may cause too much trouble. In reality, there are many direct and indirect external-factors linking with pavement management. For those reasons, nobody can easily discard their current system. Therefore, the Hybrid PMS system need to go with user's current system by various application ways. The strategy is illustrated in the Figure 2.6.

Figure 2.5 Tradeoff relationships between capsulation strategies

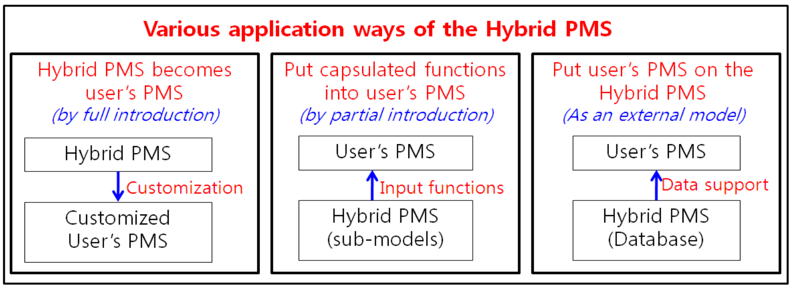

Figure 2.6 Flexible application ways of the Hybrid PMS

The application ways could be divided into three; 1) full introduction, 2) partial introduction, 3) external model. This paper wishes every road agency apply the first alternative, however, it would be unusual application way in the reality. It could be recommended to the beginning stage of the PMS. The second way, partial introduction is supporting useful PMS functions to user's current system by extracting capsulated functions from the Hybrid PMS, such as vehicle speed estimation model, a pavement deterioration forecasting model, and a component of life cycle cost analysis. That is, users can put the components of the Hybrid PMS into their current PMS without any system building. Since the every function in the Hybrid PMS are designed as independence modulus, each function can cover the deficiencies of user's PMS. This is available since the Hybrid PMS adopts the encapsulation strategy. The last, the Hybrid PMS can support user's current PMS by extracting data file from the database so that users can directly apply their current PMS software in use. In brief, user can put their current PMS on the database of the Hybrid PMS. As a default, the database of Hybrid PMS supports the HDM-4 system which is the most widely applied to pavement management field (used in over 100 countries (Kerali, 2000)). The function could be customized for supporting data requirement of their desired PMS.

In the beginning stage of application, road agencies may compare the Hybrid model with their current model, or applies partial functions for their PMS. If they are satisfied with the Hybrid PMS, they can phase the system in step by step. This feature may vitalize appearance of various types of Hybrid PMS.

2.6 Microscopic Approach for Programming Phase

The microscopic level is about programming phase which is final stage of development of customized PMS. Although this paper tried to introduce general methods, definitions, and various options, the suggested PMS functions would not be matched with road agencies situations and objectives (*e.g.* system interface, main framework, input-output, data properties, estimation or forecasting methods, etc.). In such case, road agencies have to modify or customize the main body of the Hybrid PMS. For that reason, the Hybrid PMS demands an important property;

- Open-source system

The condition is quite simple, but it has the strongest benefit to realize the concept "One finds one's own size" which means real customization not the calibration. The fundamental purpose of this paper was that every road agency has their customized PMS developed or improved by their hands. It is impossible unless the system is open-source system.

Note that road agencies can modify everything corresponding with their customization scheme. However, it is recommended to keep the properties of the input-output of each PMS function to secure compatibility with the other PMS models. The definition is nuclear of the PMS model that should be carefully defined by continuous feedback with users.

2.7 Operation Strategy for Improvement of the Hybrid PMS

One limitation of the criteria and the Hybrid PMS is that they are still unilaterally developed standards and PMS model. They will likely be improved by the continuous feedback of many road agencies in various PMS situations. Finally, the idea of creating standard criteria and model brings us closer to bilateral, or multilateral, definitions that could be considered an international standard for PMS development

We have to recognize that establishing the multilateral PMS model can make a great benefit by the joint ownership among users. After distribution of the first general version of the Hybrid PMS, maybe many customized versions would be appeared developed under different PMS situation. Even if they have different PMS model, they can share experiences on customization procedures, know-how, even newly developed capsulated functions. If there are very useful functions which are newly developed or modified by users, or major opinions eager to improve current definitions, the general version and criteria also can be improved. Afterward, the upgraded version will be served to new users. As time goes by, their customized PMS model would be similar, or several standardized versions representing specific conditions would be appeared by continues feedback among users. Every user has a different customized PMS model, but they can share their model under joint ownership. This is a final goal of the Hybrid PMS.

For the processes, many users from the 19 countries (Korea, Japan, Vietnam, Singapore, Thailand, Malaysia, India, etc.) (see Figure 2.7) are registered as expected users of the Hybrid PMS. The distribution of countries is good for making examples of various customized PMS model representing different characteristics in terms of data condition, economic level, climate condition, and technical level. Main contents that have to be discussed with the pilot countries would be details of criteria, Hybrid PMS, and their experiences. Following contents will be main subjects;

Related to criteria for PMS development

- Definition basic roles of the PMS
- Definition of PMS capability level
- Definition of the PMS functions
- System framework and procedures
- Definition of inputs-output of each PMS function

Related to the Hybrid PMS

- Basic components
- Shape of the Hybrid PMS (*e.g.* by an integrated model, or sub-divided ready-made versions)
- Essential or useless functions that has to be excluded or added
- Details of applied models, methods, specifications of the functions and sub-subsidiary data
- Typical application ways and results

Related to their current PMS situation and experiences

- Current PMS situations and remarkable experiences
- Implementation strategy of the criterion and Hybrid PMS
- Customized or newly developed functions by users
- New demands and functions

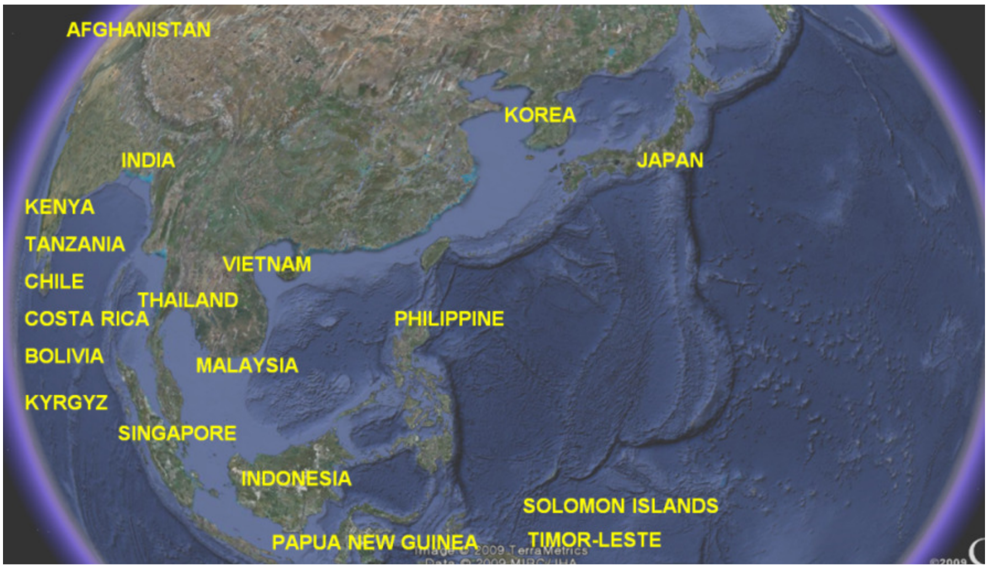

Figure 2.7 Distribution of the expected users of the Hybrid PMS

2.8 Summary and Recommendations

This chapter described development and customization strategy of the Hybrid PMS. It should be highlighted because the contents became a root of the Hybrid PMS, also it shows application ways from the planning to programming phase to road agencies.

At the beginning, this paper has emphasized following two basic philosophies for sustainable PMS development;

- Taking long-range view
- Cultivating self-reliance

As properties of the Hybrid PMS, this paper has defined following contents for much flexible and easy customization and application;

- Rich contents
- Free software
- Open-source software
- Easy and flexible customization
- Compatibility with current PMS model

To realize the properties, this paper has suggested a multidimensional approach;

- Macroscopic approach for planning phase
- Mesoscopic approach for implementation phase
- Microscopic approach for programming phase

At the macroscopic approach, criteria of the PMS development have been suggested for introduction, evaluation, and improvement of the PMS model. Based on the contents, road agencies can make a application plan of the Hybrid PMS. The criteria treated following contents;

- Standardization of PMS capability level
- Definition of PMS functions
- General PMS frameworks
- Data requirements in PMS

At the mesocsopic approach, strategies to design much easy and flexible system architecture have been addressed. For the purposes, following strategies have been discussed.

- Plug-in system
- Encapsulation strategy
- Various application way

As the microscopic approach for programming phase, this paper suggested an important property of the Hybrid PMS;

- Open-source system

At the end of this chapter, improvement strategy of the Hybrid PMS with the expected user from 19 countries were explained.

As an executive summary, this chapter defined basic properties of the Hybrid PMS, than established a development and customization strategy to realize the properties. As recommendations for further research, following contents could be considerable;

- The criteria for PMS development used for the macroscopic approach need to be much concreted.
- Feedback with road agencies is essential to secure reality.
- Finding much better strategy to serve user-friendly system (minimizing application steps)

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CHAPTER 3

Database System with Artificial PMS Data

3.1 General Introduction

The database system plays important roles for pavement management, as well as maintenance. It is an essential component of PMS that systemically accumulates essential data to support all of PMS activities from the inspection to economic analysis. Well-designed database functions and system interface are important to be user-friendly system. However, much important thing for sustainable development of PMS is data contents, and definition of their relationship. The data contents (or data requirement) have already been discussed in the Chapter 2.4.4.2, it is time to develop the database system.

In narrow meaning, the database is a tool showing the saved data by the developer-specified ready-made forms. Nevertheless, developing database system demands (deep) expert knowledge on system development. It can be simplified, while it also can be sophisticated by development scheme. Since it is very difficult to change database system once it is established, road agencies have to invest sufficient time to consider all of related factors at the designing stage. In general, composition of the data tables which are resources of the database system is different with the other's PMS databases. Although the Hybrid PMS serves pre-defined data tables and programmed database system, it is almost impossible to use as it is; because system components and architecture could be totally changed by even minor modification. Therefore, road agency may have to develop their system by themselves. For that reasons, this chapter will let focus following two contents, instead of introducing developed database of the Hybrid PMS;

- Development way of database in PMS
- Generation of artificial pavement inventory data

To develop database, there are so many issues and procedures that have to be taken into consideration beyond our expectation. This chapter will explain the development procedures to help self-development of PMS database step by step.

There are two reasons why this paper generates artificial PMS inventory data.

- No (permitted) PMS inventory data for the Hybrid PMS
- To serve open-source PMS inventory data for various purposes

Usually, maintenance of road pavement is a national duty. And its history data is not opened to the public. For that reason, researchers have often been encountered limitations due to a lack of data. If we have common open-source inventory data, it could be useful for various purposes, such as common research resource, academic purposes and so on. It also can be renewed or improved by response of unknown users. These are motivations of the generation of artificial data. The artificial data should reflect reality, especially in relationship between pavement deterioration speed and its explanatory variables, such as pavement material, traffic load level, climate condition, and so on. On the contrary, it also should have uncertainty in deterioration process which is an important property. To reflect the properties, this paper suggested a pavement condition generation model. Above all, the data generation process would be a good reference that shows how to compose their data tables.

The developed database for the Hybrid PMS also applied the plug-in system based on encapsulation strategy. The system framework guarantees easiest application and modification in functional level. As a viewpoint of total system, there is no main interface that integrates the sub-models because the sub-models of the Hybrid PMS were developed as independent modulus. For that reason, the database system will play a role of a main interface of the Hybrid PMS.

Note that simplicity in application also programming is a very important characteristic because it would be used by many users (*i.e.* local PMS managers). The system must be simple to be easily understood, modified, and operated. In brief, it must be user-friendly system. In this Chapter, following focal points will be discussed for successful development of database;

- Establishment of development plan of database system in PMS
- Database functions in PMS
- Normalization of data
- Strategy and methodology for generating artificial PMS data
- Customization issues

3.2 Establishment of Development Plan of Database System in PMS

3.2.1 Development Procedures of Database System

Through the steps described under below occur in different order, the following list summarizes the order that is most typical. These could be added, removed, and rearranged as necessary (Stephan, 2009(revised));

- Make a list of questions for system development
- Think who will be the main user, and who will affect to the system.
- Pick the main user's brains (Suppose the detail application way and preferences)
- Grasp the current operations
- Brainstorm with related persons
- Look to the future
- Understand the user reasoning
- Learn what the user really need
- Fix and prioritize the data contents and functions to be included
- Make use cases (describe system's behavior by detailing scenarios-driven thread though functional requirement)
- Decide feasibility

As noted, the functions of database are just showing the data saved in tables. However, the task is not so simple because it has to consider and expected users' willingness and preferences even future demands. Improvement or modification of database may be much complex tasks than new development. Therefore, we need check what should be considered. It will be addressed in next chapter.

3.2.2 Main Considerations in Planning Phase

Road agency has to prepare many important key questions related with the procedures listed in the Chapter 3.2.1. The essential questions are mainly related to functionality, data needs, data integrity, and system environment. This chapter serves list of the general questions in development of database (Stephan, 2009).

About functionality;

- What should the system do?
- Why are you building this system? What do you hope it will accomplish?
- What should it look like? (about interface)
- What reports (result) are needed?
- Who are the players?

About data needs;

- What data is needed for the user interface?
- Where should that data come from?
- How are those pieces of data related?
- How often the database should be updated?

About data integrity;

- Which fields are required?
- What values are allowed in which fields?
- Which fields should be primary key or should refer to foreign keys?

About system environment;

- Does this system enhance or replace an existing system?
- Are there other systems which this one must interact?
- Is it customized (or modified) by the user?

Except for above list, additional questions could be made as necessary. More questions guarantee better system.

3.2.3 Main Database Functions for PMS

The basic functions of database are, of course, searching data. The general information and corresponding database function in pavement management can be summarized as follows;

- ***Searching by ID (By hierarchical concept*)**:** This is the most fundamental function of database by using user-granted ID (Identification). As noted in the Chapter 2.4.4.1, it is recommended to have multiple identification rules for inspection, maintenance, and management (analysis) under the hierarchical concept. This is an important customization point of database.

- ***Searching data by variables and pavement condition:*** This is also a typical function of database in PMS. This is good for research purposes, as well as maintenance work. The contents to be used as standards for searching would be a customization point.

- ***Searching time-series data:*** Extracting time-series data is very useful function in PMS. It will help easy data building for research purposes.

- ***Searching maintenance and inspection target:*** This function shows maintenance and inspection target screened by user-defined maintenance criteria. It is a core function for operating PMS cycles. Based on the result, users can easily estimate budget demand for a PMS cycle. By changing the criteria of maintenance and inspection, user may find suitable PMS activities considering budget constraint.

- ***Searching maintenance history:*** This function shows conducted maintenance histories from first construction to most recent work. From the data, elapsed time from last maintenance which is the most important information for deterioration progress modeling can be collected. It is recommended that the elapsed time should be saved by type (or level) of maintenance.

- ***Searching traffic volume (and load) data / vehicle characteristic:*** The traffic volume or load data is an external data which is not direct information of pavement and road characteristics. However, it has often been required for research purpose. Since the traffic monitoring data is essential explanatory variable of deterioration speed, it should be intensively managed. Besides, the traffic volume collected by vehicle types is essential for life cycle cost analysis especially in estimation of user and socio-environmental cost.

- ***Searching PMS standard and budget expenditure:*** This is just showing previous history of applied standard and budget expenditure. It may be useful for understanding relationship between budget stream and recovery of pavement condition.

- ***Exporting files for other applications:*** Basically, all information searched by users should be extracted. In addition, users have to consider additional applications for PMS analysis such as implementation of ready-made software. In case of the database of the Hybrid PMS, it is designed to support HDM-4 model. Of course, the functions could be changed by user's customization plan.

- ***Visualization:*** The text-based database is much simple to develop, and cheaper than visualized database. Because the text-based database is available without customized digital map and expensive GIS program, it may be good for initial stage of PMS. However, it has limitation on grasp characteristics of whole network condition by in-house effort. The characteristic can be found by additional analysis procedures. On the other hand, the visualized database gives overall information with the positioning data, and colors which present the pavement condition. Besides, it is very useful for integration of the other road infrastructure systems, such as BMS (Bridge Management System), TMS (Tunnel Management System), TMS (Traffic Monitoring System), RFMS (Road Facilities Management System) and so on. Recently, the visualized database is trending. Especially, it is indispensable to road agencies who manage overall road infrastructures.

3.2.4 Definition of Data Contents and Normalization

This is the most critical procedures in development, since the database could be said "TABLES" in narrow meaning. An important thing is that normalization results (*e.g.* number of tables and columns, kind of the data, data arrangement) could be changed by user-specified database functions and options. Hence, it is recommended that the developer should have knowledge on system programming.

3.2.4.1 Definition of Data Contents

Definition of data requirement is a complex issue because it should satisfy the past, present and future demands of the PMS. As addressed in the Chapter 2.4.4.2, it requires comprehensive understanding of the desired level of PMS (internal demands), external model (external demands), and current situations (demands for domestication). For details about the issues, refer to the Chapter 2.4.4.2.

In case of the database of Hybrid PMS, the data contents were determined by integrating data requirement of the "General dataset + HDM-4". It has several hundred contents. However, the number of contents in the general dataset is not so much but from the HDM-4 accounts for most parts. Detail contents and their descriptions can be found in the APPENDIX A.

3.2.4.2 Data (or table) Normalization

The technical term, data normalization, is an issue about "How to define data tables and their contents?" It is the most critical issue in development of database. Although many technical references on database have introduced general methodologies for data normalization with simplified examples (Stephan, 2009), it should be flexibly applied for successful development of database. Simply put, if users just follow the instructions on references, required functions might be not realized. The normalization procedure and results has to be followed to user-defined database functions.

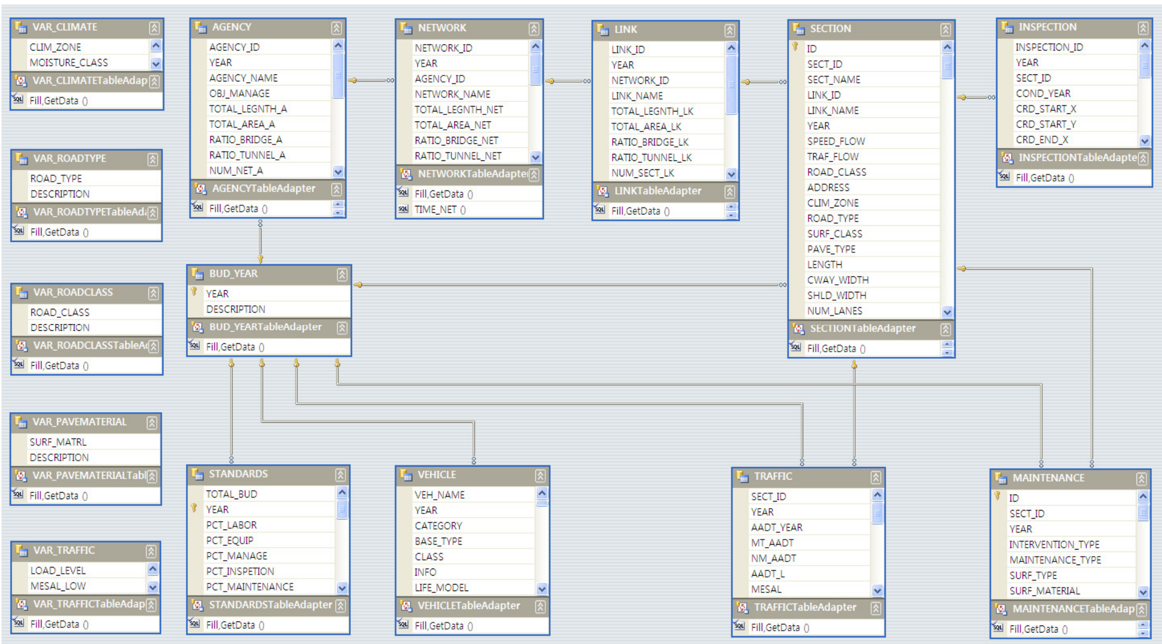

Figure 3.1 Normalization results having multiple identification units

The Figure 3.1 is showing an example of the normalization procedure focused on managing multi-identification units (Agency, network, homogeneous section, normal section and inspection unit). The unit could be applied for different purposes in inspection, maintenance works, and analysis works. The detail contents of the Figure 3.1 are attached in the APPENDIX A.

3.2.5 Design of System Framework and Interfaces

There are two important factors that define overall system framework and interface.

- Defining of inspection, maintenance and analysis unit
- Number of (and kinds of) desired functions

In case of the Hybrid PMS, it applied five identification standards by agency, network, homogeneous section, normal section and inspection unit, than have classified them into inspection, maintenance and analysis unit in management viewpoint. The database system saves the homogeneous, network and agency unit and national unit as analysis unit respectively. And the section unit was considered as a basic unit of database system which is reflected by maintenance works. Of course, integrated results of corresponding inspection units become values of the section units.

The database of the Hybrid PMS has most functions addressed in the Chapter 3.2.3 (except for the visualization). To realize the functions, 15 forms have been required. Since each function has been designed by independent modulus (by a form), system building is very easy and flexible. The system framework of the database of Hybrid PMS is showing at Figure 3.2.

Properly, each function has to be linked to corresponding data unit. For example, the form supporting HDM-4 should be linked to a table that can support its data requirement. If a road agency wants to apply homogeneous section unit for HDM-4 application, the table saving homogenous sections' data should prepare data requirement of the HDM-4. If the road agency wishes to change the unit to the section unit, they have to modify the structure of data table. A critical problem is that such changes can destroy other functions. Further, some PMS data is difficult to aggregated or disaggregated. Re-normalization process would be very complex and troublesome work. That is why this paper noted that the customization of database is almost impossible, also the effort would be the same (or more) with the new development.

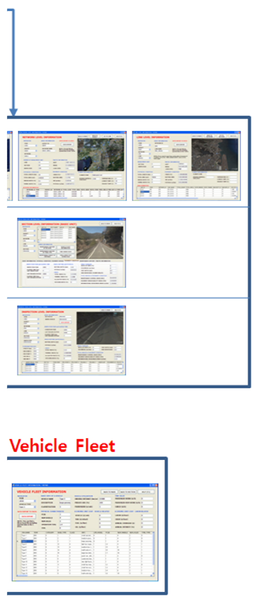

Figure 3.2 Database structure and functions of the Hybrid PMS

3.3 Generation of Artificial Pavement Inventory Data

3.3.1 Strategy of Generation of Artificial Data

As noted in the Chapter 3.1, the main purposes why artificial pavement inventory data is required in this research can be summarized as follows;

- No (permitted) PMS inventory data for the Hybrid PMS
- To serve open-source PMS inventory data for various purposes

The point of the artificial data is, of course, reflection of reality. This paper was focusing following characteristics in the reality;

- Uncertainty of the deterioration processes
- Relationship between deterioration speed and its explanatory variable
- Definition of data contents (general dataset + HDM-4 application)
- Different roles of data in inspection, maintenance, and analysis
- Demands of time-series data

To consider listed characteristics, this paper generated a pavement inventory dataset having multiple road agencies and networks under different characteristics in terms of geometry, climate, pavement design, traffic condition, and road class. In brief, the paper assumed a PMS data under a virtual country for data generation.

Besides, a pavement condition generation model satisfying pavement deterioration characteristics both uncertainty and relationship between deterioration speed and its explanatory variable was suggested. The generated data was used as resource of database, also was applied for a case study to show feasibility of the LCCA model of the Hybrid PMS.

The physical road characteristics and basic deterioration characteristics are summarized in the Table 3.1.

Table 3.1 Strategy for generation of artificial data

Contents	Description
Object of database	National level of the PMS database
Administrator/manager	Under hierarchical structure composed by; ・1 national government ・4 regional governments ・1 private company managing expressway
Number of analysis unit	Under hierarchical structure composed by; ・Agency level: 5 units ・Network level: 37 units ・Link level: 444 units ・Section level: 2,220 units ・Inspection unit: 11,100 units
Duration of data accumulation	・10 years (2001~2010) by annual-basis time-series data. (*i.e.* each unit has 10 data sets)
Physical characteristic of road sections	・Same standard was applied to all section on length, number of lane, width of carriageway. ・The difference of the life cycle cost of each section is occurred by only deterioration characteristic (with maintenance strategy)
Deterioration speeds	・It follows allocated road environments in network level characterized by geometry, climate, pavement design, traffic condition, and road class
Deterioration process	・Every unit has different characteristic defined by random process ・However, the deterioration speed is affected by combination of level of explanatory variables. ・The effects to deterioration speed were assumed, and are independent each other

3.3.2 Procedures for Data Generation

To develop artificial database, many assumptions or definitions are required. Required procedures are as follows (the order of some steps could be changed, or can be excluded);

1. Definition of the deterioration factors
2. Subdividing the deterioration factors by the level
3. Definition of properties of each subdivided deterioration factors
4. Definition of the standard condition among subdivided deterioration factors
5. Definition of methodology generating deterioration process
6. Definition of deterioration speed of the standard condition
7. Definition of weighting factors of deterioration speed
8. Definition of physical characteristic and analysis unit
9. Definition of characteristic of traffic flow
10. Definition of properties of each vehicle type
11. Definition inspection scheme and maintenance history
12. Definition of period of data accumulation

A. Step 1&2: Definition of the deterioration factors and subdividing their level
Main factors that affect deterioration speed are defined as environment (climate), traffic condition (traffic load), geometry (slope, physical classification), pavement design (material), and road classification. Based on those definitions, the number of networks can be determined. Table 3.2 shows its details.

Based on the classification of the variables shown in the Table 3.2, 37 road networks were required to imbue different characteristics each other. APPENDIX B attached in the last of this paper is showing their combination and degree of effect to deterioration speed.

B. Step 3&4: Definition of properties of subdivided deterioration factors and a standard condition
Assumptions about detail properties, and their default having default deterioration speed among the standards have to be defined. It is summarized in Table 3.3.

Table 3.2 Definition main deterioration factors

Category	Variables in database	Subdividing variables by levels (or contents)	Number of network (accumulated)
Environment	Temperature	Cold, normal, and hot	3 (3=1*3)
Traffic condition	Traffic load	High, middle, and low	3 (9=3*3)
Geometry	Slope, road type	Flat land, mountains area expressed by including uphill, downhill, tunnel, and bridge	2 (18=9*2)
Pavement design	Material	Normal asphalt, super-pave	2 (36=18*2)
Road classification	Road design	National highway, and expressway	+1 highway net (37=36+1)

Table 3.3 Definition of characteristic of deterioration factors (with default standard)

Main factors	Classification	Details	Basic condition[1)]
Environment	Hot	Tropical (20~35 C^o)	
	Normal	Subtropical-cool (-10~30 C^o)	X
	Cold	Temperate-freeze (-40~20 C^o)	
Traffic condition	High	MESAL (~0.2)	
	Middle	MESAL (0.2~0.5)	X
	Low	MEASL (0.5~)	
Geometry	Flat	No slope, tunnel and bridge	X
	Mountain	Slope (50%), tunnel (5%), bridge (10%), Flat (35%)	
Pavement design (material)	HMA	Conventional hot-mix asphalt	X
	Super	Superpave (e.g. SMA, PMA)	
Road classification	National Highway	4 lanes, normal speed (discrete flow)	X
	Expressway	8 lanes, high speed (continues flow)	

Note: 1)The basic condition is assumed to have default deterioration speed (weight = 1.00)

C. Step 5: Definition of methodology generating deterioration process

This is the most important procedure for pavement condition data. Deterioration process usually includes noise, but also it also has a correlation with the level of assumed deterioration factors (Note that there are so many cases that shows low correlation even opposite tendency in the reality). To generate deterioration speed following random process, definition of the standard condition of network and its deterioration speed, $\overline{\beta_d^k}$, should be firstly defined. Then, speeds of the other networks are defined by the weighting factors considering level of the deterioration factor. Next, an uncertainty factor should be added to the process to adjust dispersion of deterioration speed of sections in a network. Basically, the deterioration speed follows the linear function. However, the estimation parameter of each year, $\widehat{\beta_i^k}$, is randomly changed by complex relationship among the random estimation factors. It can be simply expressed by following equations;

$$DI_i^k = \alpha_i^k + \widehat{\beta_i^k}x + e_i^k \tag{3.1}$$

Where,

$$\alpha_i^k = DI_{i-x}^k \tag{3.2}$$

$$\widehat{\beta_i^k} = \overline{\beta_n^k}\varepsilon_i^k\rho_i^k \tag{3.3}$$

$$here, \varepsilon_i^k \sim rnd[0,1)$$

$$\overline{\beta_n^k} = \overline{\beta_d^k}\,[1 + \textstyle\sum_{s=1}^{S} w_s^k] \tag{3.4}$$

Where,

DI_i^k = condition of a deterioration index k in year i $(k = 1 \dots K; i = 1 \dots J)$

α_i^k = condition of a deterioration index k in previous inspection year i, thus DI_{i-x}^k

x = inspection interval $x = [1, \infty)$

e_i^k = inspection error of a deterioration index k in year i, (default=1.0)

$\widehat{\beta_i^k}$ = (unknown) random estimation parameter of a deterioration index k in year i

$\overline{\beta_n^k}$ = estimation parameter of a deterioration index k in a network n $(n = 1, \dots, N)$

$\overline{\beta_d^k}$= estimation parameter of a deterioration index k in a network d under standard condition

ε_i^k= random coefficient generated by $\varepsilon_i^k \sim random[0,1)$

ρ_i^k = uncertainty parameter representing dispersion of deterioration speeds of sections, $\rho_i^k = [1, \infty)$ (but default ρ_i^k = 2.00)

w_s^k = a weighting factor adjusting deterioration speed determined by summation of weighting factors of deterioration factor s, $(s = 1, \dots, S)$

The main factors determining deterioration process are the ε_i^k, ρ_i^k, and w_s(also with the $\overline{\beta_d^k}$). The ε_i^k generates small random wave being increment value of each year i (or inspection interval) in the deterioration process. By adjusting range of this factor, the wave size can be controlled. In case of the uncertainty parameter ρ_i^k, it determines variance of deterioration speed among samples belonged in a group. Lastly, the weighing factors w_s^k which are determined by the level of deterioration factors affect deterioration speed of section groups. The Figure 3.3 shows the concept with a simple example under the standard condition.

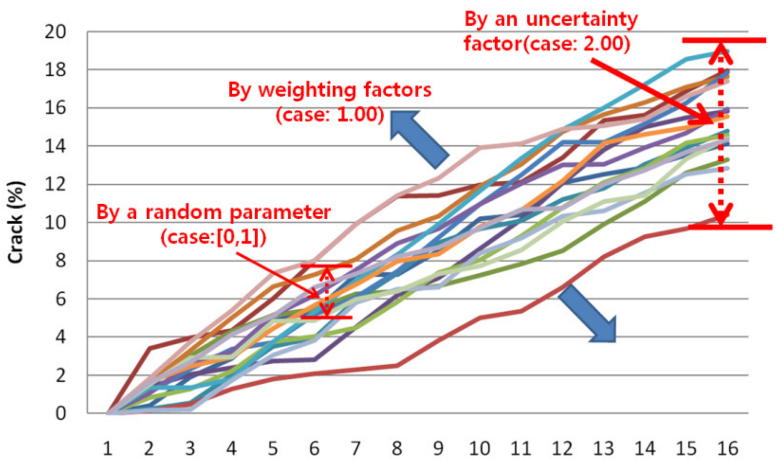

Figure 3.3 Generation of artificial deterioration process by parameters ε_i^k, ρ^k, and w_s^k

As shown in the Figure 3.3, suggested methodology can satisfy both conditions that 1) the deterioration processes are following random process, 2) deterioration speed should be reflected by explanatory variables. By using this method, every section has different deterioration process in every year, even if two networks have same explanatory variables and same weighting factors. Their deterioration speed also could be different. Nevertheless, their benchmarked deterioration processes of the two networks would be similar because every network has enough sample scale.

D. Step 6: Definition of deterioration speed of the standard condition

Next step is determination of deterioration speed of basic condition $\overline{\beta_d^k}$ (see Eq. 3.5 and Table 3.3). It can be estimated by combination of assumed design life which is considered as typical life expectancy of maintenance (usually, overlay level) and maintenance criteria of each deterioration index. To find the speed, initial (or reset) condition of pavement after construction or rehabilitation IC^k should be defined. By using three variables, typical deterioration speed can be simply estimated by linear function (see. Eq. 3.5).

$$\overline{\beta_d^k} = \frac{MC^k - IC^k}{DL_m^k} \tag{3.5}$$

Where,

$\overline{\beta_d^k}$ = an estimation parameter of a deterioration speed of index k of network d which in a basic condition
MC^k = an maintenance criteria of a deterioration index k
IC^k = initial condition of a deterioration index k after maintenance
DL_m^k = design life of construction or maintenance of a deterioration index k by maintenance method, m ($m = 1,\dots,M$)

Using the Eq.3.5 with assumptions of each element, the deterioration speeds of basic condition have been estimated. The assumptions and results are summarized in the Table 3.4.

Additional assumptions on pothole and alligator crack are also required. In general, types of crack are divided into transverse thermal crack (linear type crack) and alligator crack (area type crack). In addition, pothole is occurred by progression of the alligator crack. The basic assumptions relevant to progress of crack and pothole are followed by;

- All crack area is determined by summation of transverse thermal crack and alligator crack
- Thermal / longitudinal crack is evolved into crack
- Alligator crack is evolved into pothole. (thus, pothole is occurred in only crack occurred section)
- Severe crack makes higher composition ratio of alligator crack
- Number of pothole is based on degree of alligator crack (*e.g.* 1 pothole by 10%)

Standards for crack properties based on above assumptions are summarized in Table 3.5.

Table 3.4 Determine of the basic speed parameter $\overline{\beta_d^k}$ (in the Eq. 3.5)

Deterioration index	Initial condition (IC^k)	Maintenance criteria (MC^k)	Design life of maintenance work (DL_m^k) in year (case: overlay)	Speed parameter ($\overline{\beta_d^k}$)
Crack	0.00 (%)	15 (%)	15	1.000
Rutting	2.00 (mm)	25 (mm)	15	1.533
IRI	1.00 (m/km)	3.5 (m/km)	15	0.167

Table 3.5 Assumptions of deterioration progress between crack and pothole

Total crack area (%)	Ratio of transverse thermal / longitudinal crack (%)	Ratio of alligator crack (%)	Number of pothole (n/km) (pothole / alligator crack %)
0~5	90	10	1 / 10
5~10	80	20	1 / 8
10~30	50	50	1 / 5
30~50	30	70	1 / 3
50~100	10	90	1 / 2

E. Step 7: Definition of weighting factors to define deterioration speed

The factor w_s of each deterioration index could be determined by analyzing performance data. However, this paper allocated it by assumptions. Applied assumptions related with deterioration speed to determine w_s are showing at Table 3.6.

By summation of the five weighting factors of a network, the w_s^k representing relative deterioration speed factors of each network can be calculated. Estimated weighting factor of each deterioration index will be used for adjusting deterioration speed by combination with the basic estimation parameter. The estimated coefficients of each network corresponding explanatory variables can be found in APPENDX B with a table that shows network conditions.

F. Step 8: Definition of the physical characteristic and analysis unit

Definition of physical condition of network has also been followed by assumptions. However, it should be carefully determined, because these characteristics affect to deterioration speed, life cycle cost and so on. Effects of physical characteristics of road section to PMS are simply summarized in Table 3.7.

Table 3.6 Assumptions between deterioration factors and speed to determine the w_s

Main factors	Classification	Assumptions	w_s^k	
Environment	Cold	Cold weather accelerates deterioration speed of crack and IRI	w_e^c = 0.2 w_e^i = 0.1	
	Normal	Standard condition	$w_e^{c,r,i}$ =0.0	
	Hot	Hot weather accelerates deterioration speed of rutting and IRI	w_e^r = 0.3 w_e^i = 0.3	
Traffic condition	High	Higher traffic load accelerates deterioration speeds of all deterioration indices	w_t^c = 0.2 w_t^r = 0.3 w_t^i = 0.3	
	Middle	Standard condition	$w_t^{c,r,i}$ =0.0	
	Low	Lower traffic load decelerates deterioration speeds of all deterioration indices	w_t^c = -0.2 w_t^r = -0.3 w_t^i = -0.3	
Geometry	Flat	Standard condition	$w_g^{c,r,i}$ =0.0	
	Mountain	Uphill, downhill has higher deterioration speed of all indices (50% of network)	w_g^c = 0.2 w_g^r = 0.1 w_g^i = 0.1	Average: w_g^c = 0.13 w_g^r = 0.05 w_g^i = 0.08
		Tunnel has higher deterioration speed of crack (5% of entire network)	w_g^c = 0.2	
		Bridge has higher deterioration speed of crack and IRI (10% of network)	w_g^c = 0.2 w_g^i = 0.3	
Pavement design	HMA	Standard condition	$w_p^{c,r,i}$ =0.0	
	Super	Super-pave has slower deterioration speed of all indices	$w_p^{c,r,i}$ = -0.3	
Road classification	National Highway	Standard condition	$w_f^{c,r,i}$ = 1.0	
	Expressway (continues flow)	Expressway has slower deterioration speed of all indices (But it has high maximum speed, more lanes, and higher unit cost)	$w_f^{c,r,i}$ = -0.2	

Table 3.7 Effects of physical characteristic of road network

Objects of road network	1st effect	2nd effect	3rd effect
Classification of road section	Number of analysis unit	Sample scale of analysis	Reliability of stochastic model
Length of section	Total size of network	Scale of agency cost	Changing economic result (NPV, B/C, IRR, etc.)
Number of lane, shoulder, and width of both	Traffic load	Deterioration speed	Scale of agency cost
	Road capacity (volume/capacity ratio)	Vehicle speed (in free or congested)	Travel time (cost), Work-zone cost
Construction year (with maintenance history)	Elapsed time from last construction (or maintenance over rehabilitation level)	Deterioration speed	Scale of agency cost

Table 3.8 Definition Physical characteristic and analysis unit

Objects	Standards	Note
Classification of road section in the network	- Network = 1 - Homogenous section unit = 12 - Section unit = 60 - Inspection unit = 300	By hierarchical relationship; 1 homogenous section has 5 section, and 1 section has 5 inspection unit Definition of highway network; - inspection unit = 300 - length of inspection unit = 1km - 8 lanes (total width=28m) - shoulder = 2.0m
Length of section	- Total length of network = 60km - A homogeneous section = 5km - A section = 1km - An inspection unit = 0.2km	
Number of lane	- 4 lanes (both-way)	
Shoulder, carriageway width	- Shoulder = 1.5m (total 3m) - Carriageway width = 14m (3.5m/lane)	
Construction year	- Constructed in 2000	AGE1=AGE2=AGE3=AGE4

However, physical characteristics of each section should be same (except for highway network) by one standard condition because the strategy of artificial data was that the difference of the life cycle cost has to be occurred by difference of deterioration characteristic. If physical conditions of network are randomly assigned, the comparison would not be simple because it is difficult to judge whether the difference of the LCC between two objectives is generated from the deterioration characteristic or the physical road condition. Applied physical characteristic as a default condition is summarized in Table 3.8.

G. Step 9: Definition of characteristic of traffic flow

Usually the term, characteristic of traffic flow, has condensed meaning including many kinds of properties of road traffic condition. However, the traffic flow in the pavement management is usually defined by just AADT with composition ratio of the vehicle types, and traffic load characterized by MESAL and ESALF. In general, the number of vehicle, AADT has close relationship to scale of road user cost, while road agency cost is mainly affected by level of traffic load. To generate traffic data, assumptions on above three variables are essential. The basic objective of traffic data generation is for determination of traffic load level of each road section by allocating traffic volume and vehicle type ratio to match with assumed the MESAL of each network. The traffic load level could be determined by Eq.3.6 and Eq.3.7.

$$MESAL_i = \sum_{k=1}^{K} MESAL_i^k \tag{3.6}$$

$$MESAL_i^k = \frac{AADT_i \times VR_i^k \times ESALF^k / 1{,}000{,}000}{LANE_i} \tag{3.7}$$

Where,

$MESAL_i$ = million Equivalent Single Axle Loads in section i

$MESAL_i^k$ = million Equivalent Single Axle Loads of a vehicle type k in section i

$AADT_i$ = annual Average Dairy Traffic of section i

VR_i^k = ratio of a vehicle type k in section i

$ESALF^k$ = equivalent Single Axles Load Factor of a vehicle type k

$LANE_i$ =number of lane of a section i

The five elements, number of lane, number of vehicle type, vehicle composition ratio, AADT, ESALF of each vehicle type are main properties. Applied assumptions on above variables are summarized in Table 3.9.

Table 3.9 Assumption of traffic flow for determination of traffic load and volume

Variables of traffic flow	Assumption	Note
Number of lanes	4 lane	3.5m/lane
AADT	1,000~40,000	Highway: 2,000~80,000 (Randomly generated)
Number of vehicle type	16 types (see Table 3.10)	Same with default classification of the HDM-4
Vehicle composition ratio		Motorbike and Non-Motorized Traffic (NMT) were excluded in the definition. (But 16 vehicle types was applied in DB)
ESALF		Referring HDM-4 default
MESAL	0.00~1.00	Low: ~0.2, Middle:0.2~0.5, High:0.5~

Table 3.10 Assumed ESALF and vehicle composition ratio

Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$ESALF^k$	0.00	0.00	0.00	0.04	0.70	0.80	0.80	0.01	0.02	0.01	0.01	0.10	1.25	2.28	4.63	0.0
VR^k	0.50	0.04	0.05	0.01	0.02	0.02	0.05	0.05	0.05	0.06	0.04	0.05	0.02	0.03	0.01	0.0

Note: ESALF values has been referred to default value of HDM-4 (saved in the HDM-4 program version 1.30)

Time-series data generation of traffic volume will be discussed in the Chapter 6.9.2 as a sub-model of the life cycle cost analysis model.

H. Step 10: Definition of properties of each vehicle type

Each country may have standardized vehicle types. It they have it, it could be use as it is for convenience in application. However, the classification sometimes would not be reasonable for PMS since the standards are usually focused on traffic management or toll pricing and so on. In PMS, traffic load related factors, such as number of axles and wheels, operating weight, is core information. For the reason, it is recommended to do re-classification by focusing the issues. Of course, the number of vehicle types could be simplified by definition of vehicle class. It would be depended upon standard of traffic monitoring system of agencies.

About the issues, the HDM-4 suggested vehicle classification standard divided into 16 types for motorized vehicles. It has very sub-divided standard, also serves detail property data of each vehicle. It could be flexibly applied for many fields. The database of the Hybrid PMS has also followed the standard to support HDM-4 application. Table 3.11 shows vehicle classification with a part of property data of each vehicle type of the HDM-4 model. Even though the standard in the Table 3.11 is from the World Bank, road agencies do not have to follow the classification. However, if a user has to apply the HDM-4 model, the database should have a table for description of vehicle fleet which has same data contents of a HDM-4 input file.

Table 3.11 Vehicle classification and properties (the World Bank standard)

Vehicle type	Description of vehicle type	Class	PCSE[1)]	Num. of wheel	Num. of axles	Operating weight	ESALF
Type 1	small passenger cars	1	1.00	4	2	1.00	0.00
Type 2	medium passenger cars	1	1.00	4	2	1.20	0.00
Type 3	large passenger cars	1	1.00	4	2	1.40	0.00
Type 4	light bus (approximately < 3.5 tons)	4	1.40	4	2	2.50	0.04
Type 5	medium bus (3.5 - 8.0 tons)	4	1.50	6	2	6.00	0.70
Type 6	multi-axle or large two-axle bus	4	1.60	10	3	10.00	0.80
Type 7	large bus designed for long distance travel	4	1.70	10	3	15.00	0.80
Type 8	panel van, utility, or pickup truck	2	1.00	4	2	1.50	0.01
Type 9	Land-rover/Jeep type vehicle	2	1.00	4	2	1.80	0.02
Type 10	very light truck for carrying goods (4 tires)	2	1.00	4	2	1.50	0.01
Type 11	small bus based on panel van chassis (4 tires)	4	1.20	4	2	1.50	0.01
Type 12	small two-axle rigid truck (approx. < 3.5 tons)	3	1.30	4	2	2.00	0.10
Type 13	medium two-axle rigid truck (> 3.5 tons)	3	1.40	6	2	7.50	1.25
Type 14	multi-axle rigid truck	3	1.60	10	3	13.00	2.28
Type 15	articulated truck or truck with drawbar trailer	3	1.80	18	5	28.00	4.63
Type 16	motorcycle or scooter	0	0.50	2	2	0.20	0.00

Note: 1)PCSE (Passenger Car Space Equivalency),
Source: HDM-4 data input file (ver.1.30) (Christopher et al., 2000)

I. Step 11 & 12: Definition inspection scheme, maintenance history, and period of data accumulation

The period of data accumulation was assumed to 10 year, and inspection of all sections has performed in every year. That is, the artificial database will have 10 sets of pavement data. About the maintenance history, this database does not allocate any maintenance work because the accumulation period was too short. No maintenance activity makes simple extraction of time-series pavement performance data for research purposes. It is also good for modeling of deterioration process, maintenance timing and effect of retardation of maintenance activities, since the database could have the condition over the maintenance criteria.

3.4 Update of the Database

The pavement database has different properties with general database system. The database system must record all previous data instead of update. Of course, there are many PMS activities (e.g. inspection result, maintenance effect, traffic volume, budget expenditures and so on) changing data saved in the table. The updating the PMS activities can be done with the PMS cycle management function which is a sub-function of the Hybrid PMS. By using the function, previous year's condition can be renewed. The update is possible to add the renewed data upon the existing table. The concept is showing at Figure.3.4.

3.5 Customization of the Database

So far, issues on development of database for PMS have been discussed. Even if the Hybrid PMS serves well-designed database as a prototype model, it must be customized based on the data conditions and function of the database. This chapter will discuss the objects to be customized. Main objects and procedures of the database customization are summarized in Table 3.12

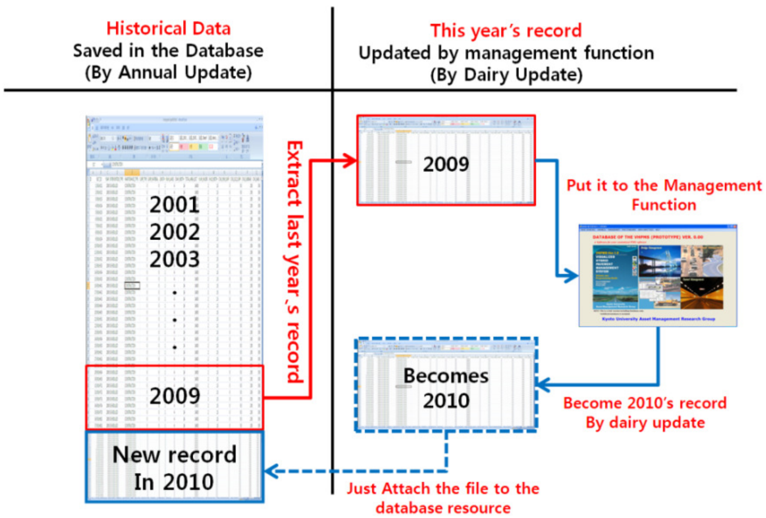

Figure 3.4 Concept of updating database by the PMS cycle management function

Table 3.12 Customization objects and procedure of database

Classification	Customization points	Note
Structure customization (overall system planning)	·Desired system functions ·Units for data recording (inspection, maintenance and analysis unit) ·Relationship between functions and tables	·If the user has different table structures among inspection, management, and analysis. It should be saved in separated tables. ·Normalization result could be changed by characteristics of the desired functions. ·If users want to apply external model, it is recommended that one table having same structure with the designated format should be separately designed by a table
Tables customization (data normalization)	·Kinds of the tables ·Data requirement (columns) in the table ·Relationship between tables, and between data contents	
User interface customization	· Based on the desired functions · Based on the taste of main user · Others (e.g. visualization, change language in the vernacular)	

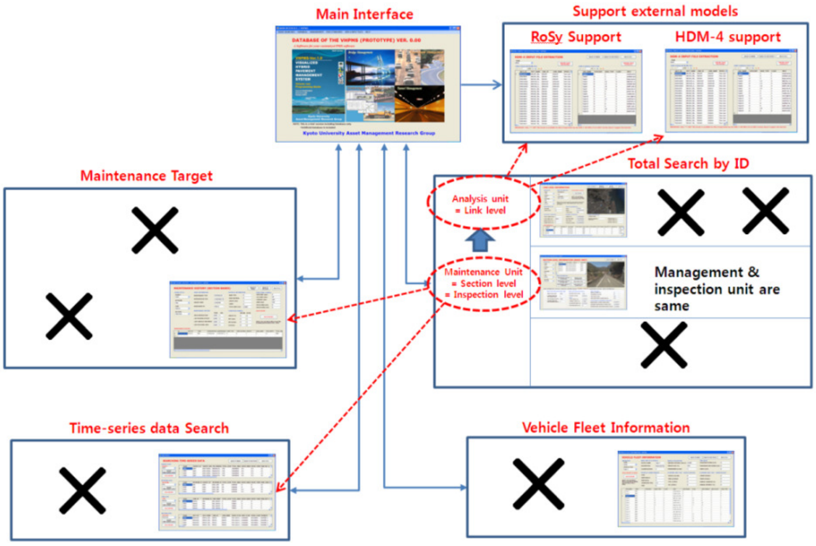

Figure 3.5 Database structure of the customized version (Assumed case: Vietnam)

As shown above, the customization procedure of database is close to new development. But it is indispensable. In fact, the database of the Hybrid PMS suggests the basic framework and methodology. For easy customization, the interfaces have been designed by a form unit (or class unit). This means the database can be divided by functional units. This characteristic facilitates customization of database structure. As a simple example of structural customization, Vietnamese case has been introduced. Assumed PMS conditions are,

- They must apply two external models, the HDM-4 and the RoSy Systems.
- They collect pavement data by unit kilometer. This standard is applied as inspection unit and management unit
- The analysis unit of the HDM-4 and the RoSy is the link (homogeneous section) aggregating the inspection units
- They do not collect applied PMS standard, maintenance history,
- They do not want to include the "Variable/condition based searching function"

Based on above assumptions, database framework could be determined. The Figure 3.5 shows customization result in functional level (see with Figure 3.2 for comparison with the general definition).

3.6 Summary and Recommendations

The database is the most important system component that supports every maintenance and management work. The other components, such as pavement deterioration forecasting, life cycle cost model, could be option, but the database is essential component that has to be firstly developed. Although the database is just a tool showing the saved data in the tables, its development is not simple matter. Also, it is difficult to be compatible with the others' database, road agencies have to develop it by hands. For that reason, this chapter has mainly discussed following two research contents;

- Development way of database in PMS
- Development of artificial pavement inventory data as an open-source

To develop well-grounded database system, road agencies have to consider so many issues surrounded their PMS. Also, modification is fairly difficult once it is developed. Hence, they must invest sufficient time to establish development plan. To help the activities, this paper explained the development way of database with following focal points;

- Development procedure of database
- Main considerations in planning phase
- Main database function for PMS
- Normalization procedure (definition of tables)

- System framework

Note that the contents would be helpful for development of the database. However, the details of development method of the database are not fixed one. It is always case by case depended on development scheme. Therefore, it is recommended to have some technical knowledge on database programming.

There are two reasons why this paper generates artificial PMS inventory data.

- No (permitted) PMS inventory data for the Hybrid PMS
- To serve open-source PMS inventory data for various purposes

Since the pavement inventory data is usually hidden to the public, researchers have often been encountered limitations to their research works. This paper has also encountered same problem. If we have common open-source inventory data, it could be useful for various purposes, such as common research resource, academic purposes and so on.

This paper has tried to reflect reality as much as possible. This paper was focusing following characteristics in the reality;

- Uncertainty of the deterioration processes
- Relationship between deterioration speed and its explanatory variable
- Definition of data contents (general dataset + HDM-4 application)
- Different roles of data in inspection, maintenance, and analysis
- Demands of time-series data

To consider listed characteristics, this paper generated a pavement inventory dataset having multiple road agencies and networks under different characteristics in terms of geometry, climate, pavement design, traffic condition, and road class. In brief, the paper assumed a PMS data under a virtual country for data generation. Besides, a pavement condition generation model satisfying pavement deterioration characteristics both uncertainty and relationship between deterioration speed and its explanatory variable was suggested. The data generation processes explained in this chapter would be a good reference that shows how to compose their data tables.

The developed database for the Hybrid PMS also applied the plug-in system based on encapsulation strategy. The system framework guarantees easiest application and modification in functional level. As a viewpoint of total system, there is no main interface that integrates the sub-models because the sub-models of the Hybrid PMS were developed as independent modulus. For that reason, the database system will play a role of a main interface of the Hybrid PMS.

Note that simplicity in application also programming is a very important characteristic because it would be used by many users (*i.e.* local PMS managers). The system must be simple to be easily understood, modified, and operated. In brief, it must be user-friendly system.

As recommendation for further researches, following contents are considerable;

- Development of a virtual city using real pavement data by cooperation with road agencies
- Estimation of deterioration speed parameters by level of explanatory variables from real field data (It has been relied on assumptions)
- Development of various types of artificial dataset by focusing specific purposes (*e.g.* definition of deterioration speed, estimation of life cycle cost, optimization, accounting information etc.)

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CHAPTER 4

PMS Cycle Management Functions

4.1 General Introduction

Road agencies must establish annual PMS activities at the beginning of the year (or end of the last fiscal year), and do the works as scheduled. At the end of the year, they have to report their activities to road administrator. Usually, the activities are preceded by a specific order as a cycle. This paper named the routine as *"PMS Cycle"*.

This chapter addressed PMS cycle management functions that can facilitate practical road maintenance activities from establishing annual PMS plan to reporting work. Since these functions can cover dairy, monthly even annual activities of PMS, it would be most frequently applied by road agencies. Generally, the works have been manually conducted without any automated system. In addition, the management works are conducted by many persons who are concerned in road inspection, maintenance, data management, PMS planning, and system management. For that reason, their procedures cannot be systemically or exactly applied. Naturally, human errors also could be accumulated. As a summary, developing PMS cycle management functions has important meanings as follows;

- Facilitating dairy, monthly and annual PMS activities of PMS manager by automated system
- Reducing human errors caused by many related person who are engaged in different fields
- Standardization of PMS cycle (*i.e.* criteria for PMS operation)

So far, many researches in pavement management have been dedicated to PMS analysis, especially in finding characteristics of deterioration process under specific conditions, and estimation life cycle cost by maintenance alternatives under competitive relationship. The research results are important for improving management strategy or establishing specifications of engineering method. Such kinds of research might be required once in several years, or when PMS manager feels its necessity. Although such PMS analysis is important for better maintenance policy, we should know the main tasks of the PMS manager are planning annual schedule, and carrying out the management and inspection as scheduled. If we say the database system treats the *'Past'*, the management function is for *'Present'*.

The PMS cycle management function (hereinafter, management function) does a tactical level of management cycle classified by three phases; *"PLAN, DO, and SEE"*. In the process, road agency have to establish annual PMS plan including target of maintenance and inspection, maintenance design, data error processing, and updating conducted activities for a PMS cycle. It also should have short-term accounting functions to estimate budget demands to conduct user-specified management plan. For the case when allocated budget is not enough to cover their annual plan, its optimization methods also demanded. As a summary, the roles of the management functions could be defined by the "Plan-do-see" concept as follows;

At the Planning phase:

- Determining maintenance and inspection target during a PMS cycle
- Work design, inspection type
- Budget estimation
- Optimization (when budget goes over its constraint)

At the Do phase;

- Updating pavement conditions changed by the maintenance and inspection
- Recording budget expenditures
- Error processing (e.g. inversed pavement condition)

At the See phase:

- Summarizing annual PMS activities (conducted and un-conducted work)
- Summarizing executed budget
- Analyzing network condition
- Updating and reporting

Someone may consider that the updating data is core function of the database. But, the database of the PMS has a different property with general database that annual historical data should be saved without any modification. For that reason, the management function should be designed as separated modules. It implies that database system and the management function should be a pair for update. In addition, some functions (*e.g.* error processing or work effect estimation) are required for complex calculation procedures that cannot be done by the database. It is believed that the management functions would be most frequently used for practical PMS operation among the functions of the Hybrid PMS.

Since all functions in the Hybrid PMS are independent module, road agencies can apply the management function for operation of their PMS as an external model even they do not have database. This is available by the encapsulation strategy of the Hybrid PMS.

4.2 Definition of PMS Cycle and Sub-functions

To maintain huge road networks, road agency has to consider many things regarding priority of maintenance and inspection target, maintenance (and inspection) design based on level of explanatory variables, data qualities, and budget expenditure. The road agency has to establish the best PMS plan by harmonizing those considerations under budget limitation.

Simply put, the definition of the PMS cycle is just definition of PMS activities that have to be carried out by road agencies during a cycle. Although all agencies pursue the same goal, their processes and methods to define the activities are usually different. This chapter tries to suggest better procedures, and corresponding sub-functions.

The definition of the best PMS cycle should follow the concept of 'Plan-Do-See' which plays strategic level of management. Each step requires many sub-functions. Those sub-functions are described in the Table 4.1. And, the main stream of the management cycle based on the definition in the Table 4.1 is illustrated in the Figure 4.1.

Table 4.1 Description of sub-functions of the management functions

Classification	PMS activities	Description	Result	Time to do
Plan	Maintenance target	Selecting maintenance target section (including type)	Annual PMS schedule	At beginning of a PMS cycle
	Inspection target	Selecting inspection target section		
	Work design	Design of the detail maintenance work by consideration of the PMS variables		
	Budget estimation	Total budget required for the maintenance and inspection		
	Budget optimization	Adjustment of determined work scheduled by the user-specified budget constraint		
Do	Update maintenance result and its budget expenditure	Estimating physical change, pavement condition change by the designed maintenance work, and recording executed budget	Update of conducted PMS activities	In the middle of a year
	Update new inspection record	Updating new conditions by the inspection		
See	Summary of budget expenditures	Summarizing executed budget for a PMS year by the PMS activities	PMS report, and renewed table for saving database	At the end of a year
	Summary of PMS activities	Result of conducted and un-conducted PMS activities as planed		
	Updating and reporting	Renewing tables including latest record of current PMS year		

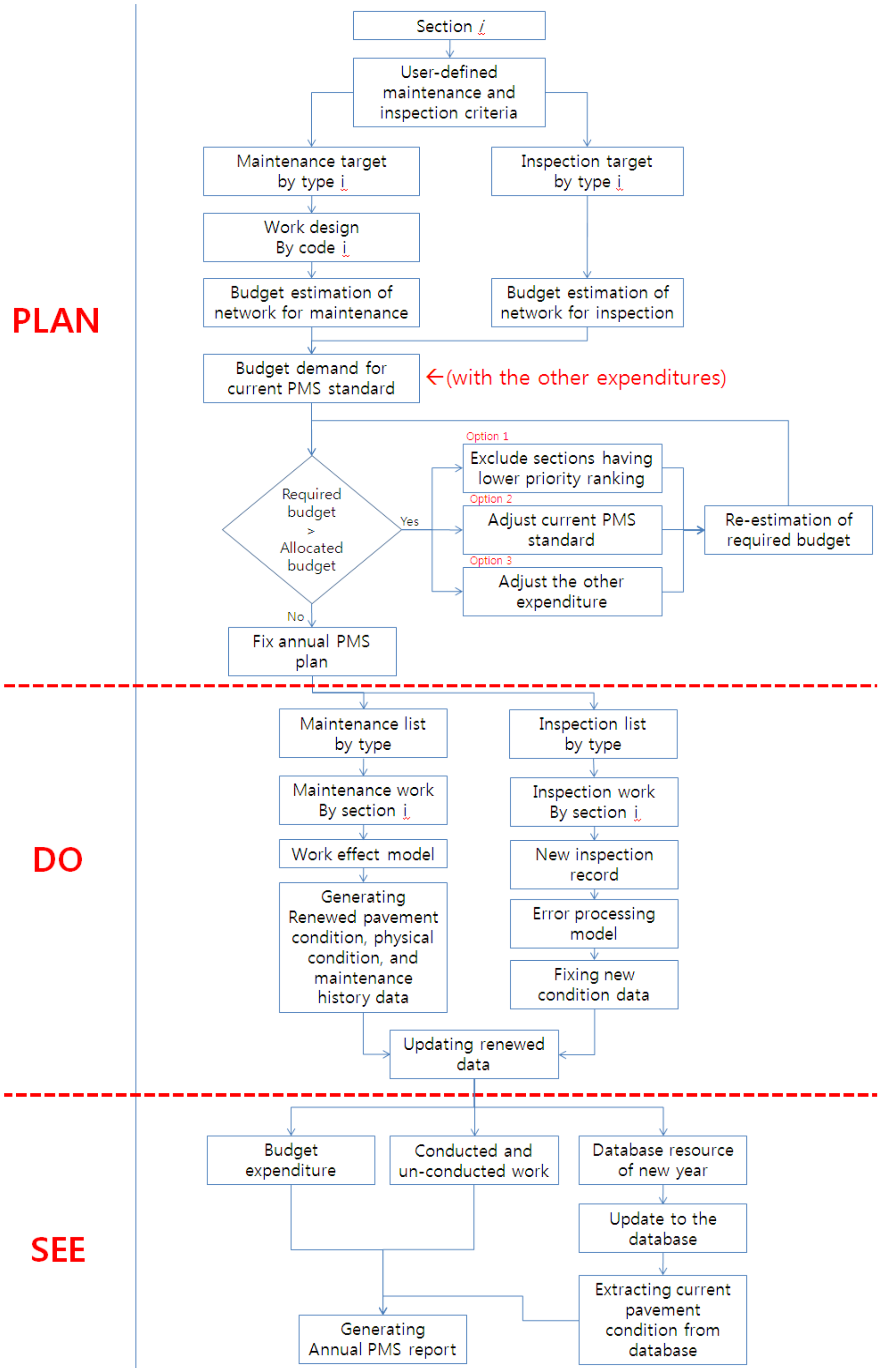


Figure 4.1 Suggestion of the management cycle for PMS

4.3 Sub-functions for Planning Phase

4.3.1 Searching Maintenance & Inspection Target

This function searches target sections matched with user-specified maintenance or inspection criteria. In fact, the function can be realized by the database system by using simple query statements. However, this function needs to be separately developed for the management function because every element should be independent module to keep the encapsulation strategy. There are core factors that determine details of maintenance works.

- ***Maintenance type***: Kinds of maintenance works against level and kinds of deterioration. As a default, reconstruction, cutting overlay, overlay, surface treatment, pothole patching, crack patching, and crack seal are applied for the Hybrid PMS.
- ***Maintenance criteria***: User-specified maintenance criteria (*e.g.* overlay = IRI 3.5m/km, crack 20% or rutting 25mm).
- ***Pavement conditions***: Deterioration indices, design indices, traffic volume level, pavement age etc.

In the reality, there are many maintenance types against various deterioration types and their degree. Although the Hybrid PMS has limited maintenance types, this could be customized by road agencies

In case of inspection target, the system will find sections matching with user-specified standard for inspection. It demands data on 'elapsed time' from last inspection or last (over) rehabilitation (*i.e.* AGE 0). If the elapsed time of a section is longer than the user-specified periodical inspection period, the section will be classified as a target section. In case of much advanced types of inspection, such as FWD (Falling Weight Deflectometer), GPR (Ground Penetrating Radar) or coring pavement, has been excluded from the consideration because the inspection types are not for usual situations. However, it could be considered by customization as necessary.

4.3.2 Designing Maintenance Work

The maintenance target function has treated the condition-timing of maintenances, so to speak, *"When"*, while the work design function is issues about *"How"* regarding maintenance method of the target section corresponding conditions of road sections. To do reasonable maintenance works, the maintenance design should be based on standardized maintenance modules with primary deterioration factors by one-to-one correspondence. About the issue, the Hybrid PMS recommends applying *"Design codes"* by subdividing maintenance work. The design codes are standardized maintenance works against various conditions of a road section. By scanning the various road conditions of a section, the function results an appropriate design code with estimated budget.

The definition of the code can be customized. The number of the design codes is determined by the combination of the maintenance type, design options and variables. Examples of definition of the design codes by maintenance types are showing at Table 4.2 ~ Table 4.8.

Table 4.2 Standardization of work design (case: reconstruction)

Type	Code	Basement	Code	Material-Pave	Code	Pavement thickness	Code	Example of final code name
Reconstruction	RC	Normal	MBn	Normal	MPn	50mm	PT5	RC_MBn_MPn_PT5
	RC	Advanced-a	MBa	Advanced-a	MPa	100mm	PT10	RC_MBa_MPa_PT5
	RC	Advanced-b	MBb	Advanced-b	MPb	150mm	PT15	RC_MBb_MPb_PT5
				Advanced-c	MPc			

Table 4.3 Standardization of work design (case: cutting-overlay)

Type	Code	Cutting level	Code	Material-Pave	Code	Pavement thickness	Code	Example of final code name
Cutting-overlay	COL	All	CA	Normal	MPn	50mm	PT5	COL_CA_MPn_PT5
		Patial-50mm	CP5	Advanced-a	MPa	100mm	PT10	COL_CP5_MPa_PT10
		Patial-100mm	CP10	Advanced-b	MPb	150mm	PT15	COL_CP10_MPb_PT15
				Advanced-c	MPc			

Table 4.4 Standardization of work design (case: normal overlay)

Type	Code	Preparatory work(Patch)	Code	Material-Pave	Code	Pavement thickness	Code	Example of final code name
Normal overlay	OL	All	PrA	Normal	MPn	50mm	PT5	OL_PrA_MPn_PT5
		Pothole only	PrP	Advanced-a	MPa	100mm	PT10	OL_PrP_MPa_PT10
		Crack only	PrC	Advanced-b	MPb	150mm	PT15	OL_PrC_MPb_PT15
				Advanced-c	MPc			

Table 4.5 Standardization of work design (case: surface treatment)

Type	Code	Preparatory work(Patch)	Code	Material-Pave	Code	Pavement thickness	Code	Example of final code name
Surface treatment	ST	All	PrA	Normal	MPn	20mm	PT2	ST_PrA_MPn_PT2
		Pothole only	PrP	Advanced-a	MPa	30mm	PT3	OL_PrP_MPa_PT3
		Crack only	PrC	Advanced-b	MPb	40mm	PT4	OL_PrC_MPb_PT4
				Advanced-c	MPc			

Table 4.6 Standardization of work design (case: pothole patching)

Type	Code	Material-Pave	Code	Cutting area	Code	Example of final code name
Pothole patch	PP	Normal	MPn	$1m^2$	C100	PP_MPn_C100
		Advanced-a	MPa			PP_MPa_C100
		Advanced-b	MPb	$0.25\ m^2$	C25	PP_MPb_C25
		Advanced-c	MPc			

Table 4.7 Standardization of work design (case: crack patching)

Type	Code	Object of crack	Code	Material-Pave	Code	Example of final code name
Crack patch	CP	Alligator crack only	AC	Normal	MPn	CP_AC_MPn
		All crack	ALC	Advanced-a	MPa	CP_ALC_MPa
				Advanced-b	MPb	CP_ALC_MPb
				Advanced-c	MPc	CP_ALC_MPc

Table 4.8 Standardization of work design (case: crack seal)

Type	Code	Material-Pave	Code	Object of crack	Code	Example of final code name
Crack patch	CP	Normal	MPn	All crack	AC	CP_MPn_AC
		Advanced-a	MPa	Alligator crack only	ALC	CP_MPa_ALC
		Advanced-b	MPb			CP_MPb_ALC
		Advanced-c	MPc			

These work design codes should be allocated to user-specified road conditions. The main factors characterizing the road condition are following conditions;

- ***Type of deterioration (deterioration indices):*** Crack (Transverse thermal crack, alligator crack), rutting, IRI, and pothole.
- ***Degree of deterioration***: Preventive, general, retarded.
- ***Traffic volume (or load):*** Low, Medium, High
- ***Current pavement structure (thickness and material):*** Poor, Reasonable, Advanced
- ***Preparatory works**:*** Necessary (for pothole, and alligator crack) or unnecessary
  **Note: the overlay or surface treatment work without the cutting current layer needs the preparatory works against alligator crack, wide structural crack, rutting, and surface irregularities. However, the Hybrid PMS has considered only pothole and alligator crack which can be recovered by the patching.*

By allocating the compounded above conditions to the design codes, maintenance design and corresponding budget requirement can be easily and objectively defined. The simplest application way of this function may be applying current maintenance standard of each agency. Of course, finding the best allocation between road conditions and the design code would be a hard challenge. For well-grounded definition, pavement performance analyses are essential. However, it requires not only systemically accumulated inventory data but also advanced pavement deterioration forecasting models. Due to the difficulty of such researches, the issues on compatibilities among PMSs could have significant contributions. Deterioration forecasting models of the Hybrid PMS may be useful for the researches (if agency has enough data).

4.3.3 Budget Estimation for a PMS Cycle

Budget can be easily estimated by multiplying scale of target area and unit cost of each design code. In case of reconstruction, cutting overlay, overlay and surface treatment target total carriageway area as an object of maintenance, while the patching and crack seal is based on partial maintenance following their percentage. With consideration of the issues, budget requirement can be simply calculated by following equations;

$$AC_i = [MC_i^{entire} + MC_i^{part}] + IC_i + \alpha \quad (4.1)$$

For the types of entire maintenance*: Reconstruction, cutting-overlay, overlay and surface treatment,*

$$MC_i^{entire} = \sum_{y=1}^{Y}\sum_{s=1}^{S}[Lng_s \times W_s] \times UC_d \tag{4.2}$$

***For partial maintenance**: Alligator crack, transverse thermal crack, and potholes,*

$$MC_i^{part-C} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\left[\frac{Lng_s \times W_s}{PC_s}\right] \times UC_d \tag{4.3a}$$

$$MC_i^{part-P} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\left[\frac{Lng_s \times W_s}{NP_s * UAP}\right] \times UC_d \tag{4.3b}$$

***For inspection cost:** normal type only (GPR, FWD, Coring are excluded)*

$$IC_i = \sum_{y=1}^{Y}\sum_{s=1}^{S}[Lng_s \times NL_s] \times UC_{isp} \tag{4.4}$$

Where,
AC_i = agency cost of an alternative i
MC_i^{entire} = maintenance cost for the reconstruction, cutting-overlay, overlay and surface treatment
MC_i^{part-C} = maintenance cost for crack related maintenance type (=crack seal, crack patching)
MC_i^{part-P} = maintenance cost for pothole related maintenance type (=pothole patching)
IC_i = inspection cost for an alternative i
α = additional user-specified contents for agency cost
Lng_s = length of a section s in kilometer
W_s = width of a section s in meter
UC_d = unit cost of design code d
PC_s = percentage of crack of a section s
NP_s = number of potholes of a section s
UAP = unit area of a pothole in square meter (m^2)
NL_s = number of lane of a section s
UC_{isp} = unit cost of inspection in km/lane

In summary, road agency can simulate budget requirement for their current (or future) PMS strategy by using the maintenance and inspection target with design codes, and physical road conditions. The Eq. 4.2 ~ Eq. 4.4 have been applied for the LCCA models.

4.3.4 Budget Optimization for a PMS Cycle

If current PMS scheme is encountered to budget limitation, a procedure for budget optimization is required. To establish PMS plan satisfying limited budget, users have to modify their current scheme. In order to adjust their plan, the Hybrid PMS suggests three alternatives as solutions (see with the Figure 4.1).

- Adjusting user specified the other expenditures (if user applies other expenditures into the system)
- Adjusting PMS standards on work demands and/or work design
- Determining sections to be delayed by priority rules

The first option is for a case that user wants to keep their PMS standard related with inspection and maintenance by reduction of the other expenditures. For example, postponement of the plan for purchasing new inspection equipment, reduction of staff (or salary), or cancellation of research projects could be the ways for first option. However, it might be difficult because most expenditure are usually fixed cost, also the budget scale in the total PMS budget is not so huge compared with maintenance and inspection cost. The second option is a way changing current PMS standards about maintenance criteria, and redefinition of the design codes or maintenance criteria. If the government wants to keep current PMS standard strictly, this option should be excluded from the alternatives. The last option is also for the case keeping the current PMS standard by excluding a part of work demands from the maintenance objects which have lower priority ranking. Maybe this option is usual for budget optimization. However, this option makes maintenance retardation that makes worse effect to road user cost. Once delayed, the work demands add an extra weight to next year's PMS plan which causes a vicious circle. In fact, there is no recommendable option. The best way is increasing the amount of budget. In order to steer to the way increasing budgetary, much critical information showing budget power is required to press decision maker.

The first option and second option can be easily applied by just modifying application options at the interface without any additional programming. However, the third needs priority ranking of sections about maintenance and inspection respectively. If agency has rules of prioritization resulted by the LCCA, it could be applied. Otherwise, there is no room for choice except for applying user-specified priority rules. The default priority rules of the Hybrid PMS are summarized in Tables 4.9 and 4.10. Users can select and adjust the priority rules, and also can make combination.

By using these priority rules, work demands on inspection and maintenance has priority ranking. After that, cumulated cost from the first rank is calculated until the cost beyond the allocated budget. A sub-routine applying the third alternative is presented in Figure 4.2.

Table 4.9 Priority rules for inspection demand

Steps	Description	Type
1st priority	User defined sections	Duplicable with 3rd
2nd priority	Delayed inspection of previous term	Duplicable with 3rd
3rd priority	Having longer elapse time since last inspection	Basic standard
4th priority	Having worse condition in last inspection	Optional[1)]

Note: 1)If inspection budget is enough to cover the objects by 3rd standard, additional sections can be added by 4th standard.

Table 4.10 Priority rules for maintenance demand

Steps	Description	Type
1st priority	User defined sections	Duplicable with 3rd or 4th
2nd priority	Delayed maintenance of previous term	Duplicable with 3rd or 4th
3rd priority	Maintenance type[1)]	A basic standard (Selectable)
4th priority	Deterioration index[2)]	A basic standard (Selectable)

Note: User can select a basic standard either 3rd or 4th priority.
1) Default order: Reconstruction cutting overlay, overlay, surface treatment, pothole patching, crack patching and crack seal
2) Default order: Pothole, IRI, rutting, crack (changeable)

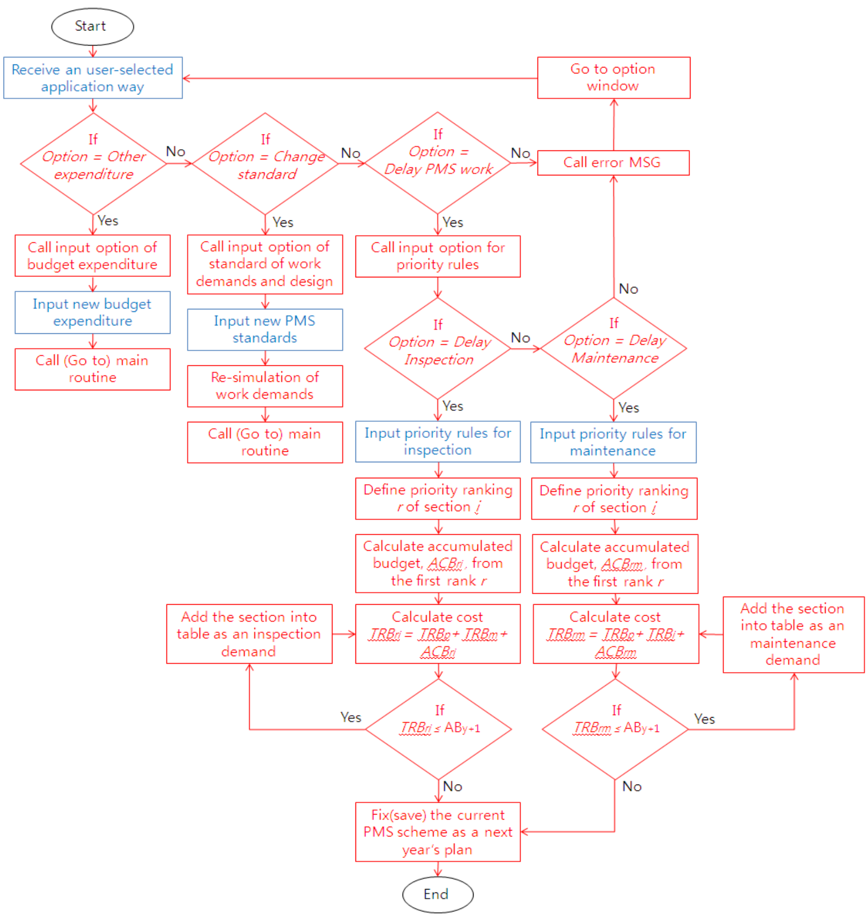


Figure 4.2 A flowchart of budget optimization for a PMS cycle

The equations in the Figure 4.2 are represented in Eq. 4.5 ~ Eq. 4.7.

$$TRB_r^I = TRB_p + TRB_m + ACB_r^I \quad (4.5)$$

$$TRB_r^M = TRB_p + TRB_I + ACB_r^M \quad (4.6)$$

Where,

$$ACB_r^I = \sum_{r=1}^{R} RB_r^I \quad (4.7a)$$

$$ACB_r^M = \sum_{r=1}^{R} RB_r^M \quad (4.7b)$$

Where,
TRB_r^I = total required budget adjusting inspection demand I by referring priority ranking r $(r = 1, \dots, n)$
TRB_r^M = total required budget adjusting maintenance demand M by referring priority ranking r
TRB_p = total required budget of the user-defined other expenditure
TRB_m = total required budget for maintenance work
ACB_r^I = accumulated required budget adjusting inspection demand I by referring priority ranking r
ACB_r^M = accumulated required budget adjusting maintenance demand M by priority ranking r
RB_r^I = required inspection budget of a section which is ranked as r
RB_r^I = required maintenance budget of a section which is ranked as r

The routine will be stopped when the TRB_r^I or TRB_r^M is bigger the allocated budget for next year AB_{y+1}. If user applies this option, the delayed sections would be listed for next PMS cycle.

4.4 Sub-functions for the Operation (Do) Phase

During a PMS cycle, PMS managers conduct maintenance and inspection, and have to record the activities and results. The conducted PMS activities change information in the data tables not only pavement condition but also other inventory data such as surface type, elapsed time, and pavement structure. The changes should be systemically defined for PMS operation and analysis in future. The sub-functions for the operation phase are essential for refreshing previous data (last PMS cycle). The results of these functions are used for update of database. That is, database and management function is a pair which is minimum requirements for the general level of PMS.

Obviously, different types of maintenance works make different effects to data contents. This chapter will discuss about *"What should be changed?"* and *"How much changed in pavement condition?"* From now, the all kinds of changes will be noted as a term *"Work effects"*

4.4.1 Work Effects on Database Contents

The contents changed (or added) by maintenance work can be summarized as following contents;

- Applied design code
- Conducted year, and elapsed time from the last maintenance work (by types)
- Pavement structure (thickness)
- Refreshed deterioration indices
- Surface types
- Executed budget
- Special notes

Firstly, the effects of different type of maintenance works should be standardized. It is presented in the Table 4.11.

Table 4.11 Definition of work effects by different maintenance works

Works type	Physical changes			Maintenance history	Deterioration indices	
	Target area	Class of Pavement structure[1)]	Changing thickness	Affected Age(s)[4)]	Affected deterioration indices	Reset conditions by maintenance types
Crack seal	Partial section	-	-	Age 1	Crack	User-specified[3)]
Crack patching	Partial section	-	-	Age 1	Crack, IRI	Crack=User-specified IRI=Modeling
Pothole patching	Partial section	-	-	Age 1	Pothole, IRI	Crack=User-specified IRI=Modeling
Surface treatment	Entire section	X	X	Age 0, 1, 2	Crack, IRI, pave type[5)]	Crack=User-specified IRI=Modeling
(Cutting) overlay	Entire section	X	X	Age 0, 1, 2, 3	Crack, Rut[2)], IRI[2)], Pothole, pave type	Crack, rutting, pothole = User-specified IRI = modeling
Reconstruction	Entire section	X	X	Age 0, 1, 2, 3, 4	Crack, Rut, IRI, Pothole, pave type	Reset as user-specified constant

Note: 1) including underground layer (sub-base, base layer)
2) Quantity of condition recovery is reflected by pavement condition before maintenance
3) By two options, 1) being user-defined constant 2) being user-defined percentage (%)
4) AGE indicators related with elapsed time corresponding types of maintenance work and inspection
5) Pavement type indicator considering pavement material and base type

Table 4.12 Reset condition of pavement ages

Work types	Classification	AGE0[1)]	AGE1	AGE2	AGE3	AGE4
Crack seal	Preventive type	-	X[2)]	-[3)]	-	-
Crack patching	Preventive type	-	X	-	-	-
Pothole patching	Preventive type	-	X	-	-	-
Surface treatment	Repair type	X	X	X	-	-
(Cutting) overlay	Rehabilitation	X	X	X	X	-
Reconstruction	Construction	X	X	X	X	X

Note: 1) AGE0 = Elapsed time from the latest data
2) X = Reset to an user-specified condition or an estimated condition
3) "-"= Keeping the age

4.4.2 Age Indicators

The age indicators in the Table 4.11 are to define the number of years since preventive maintenances (AGE1: crack seal, patching), repairs (AGE2: Surface treatment), rehabilitations (AGE3: (cutting) overlay), and first or reconstruction (AGE4: (re)construction including base parts). It is essential to calculate the elapsed time for PMS analysis. The concept has been referred from the HDM-4's definition (Odoki and Kerali, 2000). However, the Hybrid PMS added one more indicator for elapsed time from the latest data, the "AGE0". Since the maintenance work over the rehabilitation level recovers deterioration indices into user-specified or estimated conditions, road agencies can have the condition information. Thus every maintenance work resets the AGE 0, as well as inspections. By the adding the AGE 0 into the age indicators, inspection plan for a PMS cycle could be changed. Rules of managing age indicators are summarized in the Table 4.12.

4.4.3 Pavement Structure after Maintenance

As work effects over rehabilitation level (surface treatment, overlay and reconstruction), pavement structure could be changed. It also has to be recorded for maintenance and analysis works. The pavement structure can be characterized by combinations of material of surface and base layer. The general classification is showing in the Table 4.13.

Various types of material for surface and basement layer shown in the Table 4.13 can be standardized by 8 types of combination (see the Table 4.14). In summary, all of pavement structures can be characterized by 8 types of combination. Based on the maintenance types, pavement structure after maintenance could be changed. It is summarized in the Table 4.15. This classification could be applied as a grouping variable to show the heterogeneity on deterioration speeds among the groups.

Table 4.13 Classification of bituminous pavement structure

Surface type	Surface material (Abbreviation/description)	Base type	Base material	Pavement type
AM (Asphalt Mix)	AC (Asphaltic Concrete)	GB (Granular Base)	CRS (Crushed Stone)	AMGB
	HRA (Hot Rolled Asphalt)		GM (Granular Material)	
	PMA (Polymer Modified Asphalt)	AB (Asphalt Base)	AB (Asphalt Base)	AMAB
	RAC (Rubberized Asphalt Concrete)	SB (Stabilized Base)	CS (Cement Stabilization)	AMSB
	CM (Cold Mix)		LS (Lime Stabilization)	
	PA (Porous Asphalt)	AP (Asphalt Pave)	TNA (Thin Asphalt Surface)	AMAP
	SMA (Stone Mastic Asphalt)		FDA (Full Depth Asphalt)	
	Xx			
ST (Surface treatment)	CAPE (CAPE seal)	GB (Granular Base)	CRS (Crushed Stone)	STGB
	DBSD (Double Bituminous Surface Dressing)		GM (Granular Material)	
	SBSD (Single Bituminous Surface Dressing)	AB (Asphalt Base)	AB (Asphalt Base)	STAB
	SL (Slurry seal)	SB (Stabilized Base)	CS (Cement Stabilization)	STSB
	PM (Penetration Macadam)		LS (Lime Stabilization)	
	Xx	AP (Asphalt Pave)	TNA (Thin Asphalt Surface)	STAP
			FDA (Full Depth Asphalt)	

Source: Odoki and Kerali, 2000 (revised)

Table 4.14 Default classification of bituminous pavement

Pavement type	Surface type	Base type	Description of pavement types
AMGB	AM	GB	Asphalt Mix on Granular Base
AMAB	AM	AB	Asphalt Mix on Asphalt Base
AMSB	AM	SB	Asphalt Mix on Stabilized Base
AMAP	AM	AP	Asphalt Mix on Asphalt Pavement
STGB	ST	GB	Surface Treatment on Granular Base
STAB	ST	AB	Surface Treatment on Asphalt Base
STSB	ST	SB	Surface Treatment on Stabilized Base
STAP	ST	AP	Surface Treatment on Asphalt Pavement

Source: Odoki and Kerali, 2000

Table 4.15 Reset conditions of pavement structure after the maintenance work

Maintenance type	Current pavement type							
	AMGB	AMSB	AMAB	AMAP	STGB	STSB	STAB	STAP
Crack seal	AMGB	AMSB	AMAB	AMAP	STGB	STSB	STAB	STAP
Patching	AMGB	AMSB	AMAB	AMAP	STGB	STSB	STAB	STAP
Overlay	AMAP	AMAP	AMAP	AMAP	AMGB	AMSB	AMAB	AMAP
Cutting overlay Option A[1)]	**AP	**AP	**AP	**AP	N/A[2)]	**SB	**AB	**AP
Cutting overlay Option B[1)]	**GB	**SB	**AB	**AP	**GB	**SB	**AB	**AP
Reconstruction	****	****	****	****	****	****	****	****

Source: NDLI, 1995a (revised)

Note: 1) Option A = cutting to intermediate surface layer, then overlay
Option B = cutting to base layer, than overlay
2) Not applicable
*** Indicators, two character variables, which are dependent on the user-specified (or system determined) works type*
***** Indicators, four character variables, which are dependent on the user-specified (or system determined) works type*

4.4.4 Maintenance Effects Models

The term, maintenance effect, has different meaning with the work effect in this paper. While the work effects include all kinds of changes by maintenance work, the maintenance effect has narrow meaning limited to condition recovery of pavement surface. The maintenance effect has often been assumed by user-specified condition based on field experiences. Of course, the best way would be surveying pavement condition before and after maintenance. However, it is not usual manner in PMS due to limited budget.

Most researches or simulations have just simply assumed the reset conditions of deterioration indices. However, in the reality, the surface conditions are affected by condition before maintenance. By the maintenance 7 types of the Hybrid PMS, the maintenance effect has been modeled. It will be used as an option for the management function but also the LCCA model. A flowchart of the main routine of the maintenance effect model is illustrated in the Figure 4.3.

Every routine has own procedure. The flowcharts of each maintenance type will be separately addressed.

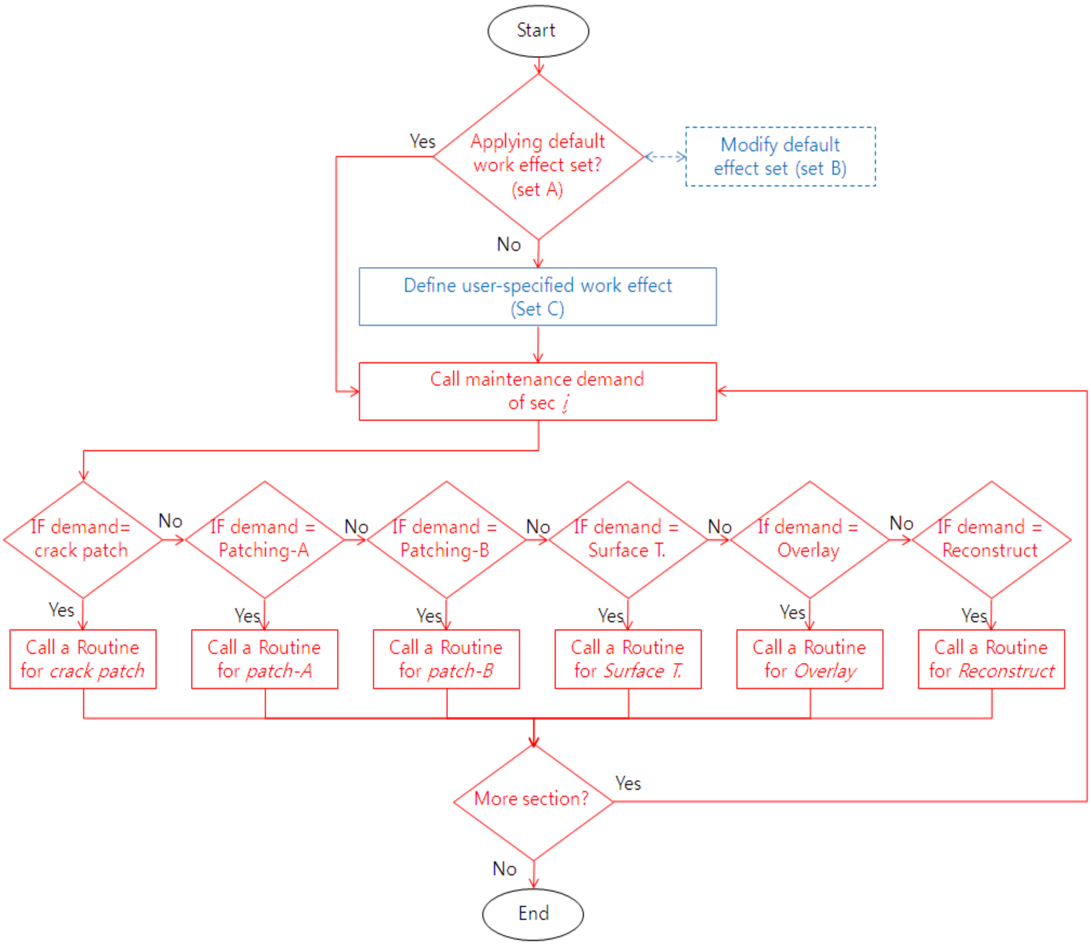


Figure 4.3 A flowchart for maintenance effect model

A. Crack seal

As noted in the Table 4.12, it was assumed that the crack seal makes effects to only crack area. And the effect can be defined by user-defined constant, or percentage of condition before maintenance. The options are expressed by simple equations in Eq. 4.8 and Eq. 4.9.

$$CI_a^p = CI_b - \left[CI_b \times \frac{RP_{ur}}{100}\right] \tag{4.8}$$

$$CI_a^C = CI_{ur}^C \tag{4.9}$$

Where,

CI_a^p = condition of a deterioration index after maintenance work by application of percentage option

CI_b = condition of a deterioration index before maintenance work

CI_a^C = condition of a deterioration index after maintenance work by application of user-specified condition (constant)

CI_{ur}^C = user specified condition for the after maintenance work

RP_{ur} = target area of maintenance work, in percentage (user-specified)

The definition of the maintenance of the crack seal is as follows,

- Resetting (or reducing) transverse thermal crack area (linear crack)
- Update maintenance history: Record objective year, Set the AGE 1 to zero

Usually, default value of the RP_{ur} is recommended as '100%'. Also, the second equation (Eq. 4.9) for applying user-specified constant is also assumed that all deteriorated area is considered as a target of maintenance work. The value of the RP_{ur} is required for estimation of total cost of maintenance. The flowchart to design sub-routine is shown in the Figure 4.4.

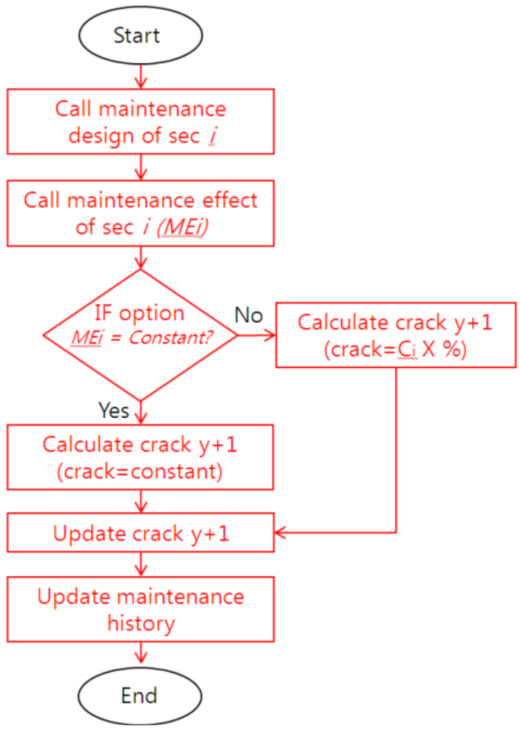


Figure 4.4 A flowchart of maintenance effect model - crack seal

B. Crack patching

Usually patching work is usually conducted for crack and pothole. This section will address the patching for alligator (or fatigue) crack. The transverse thermal crack is not the objective of this work type. The effects are divided into two factors related to crack and IRI condition. Definition of the effects is;

- Resetting (or reducing) alligator crack area.
- A positive effect to IRI due to removing the crack area
- Updating maintenance history: Record conducted year, and set the AGE 1 to zero

The effect of removing the crack area can be simply estimated by using the Eq. 4.8 or the Eq. 4.9. In case of the positive effect to IRI due to removing crack area can be estimated by Eq. 4.10 (Morosiuk *et al.*, 2000).

$$\Delta RI_i^{CP} = -a_0 \left[C_b \times \frac{RP_{ur}}{100} \right] \quad (4.10)$$

Where,

ΔRI_i^{CP} = change in IRI by crack patching area of analysis year i in m/km IRI

a_0 = model coefficient (default = 0.0066)

Next year's IRI condition for the case without forecasting model (Eq. 4.11), and with forecasting model (Eq.4.12) is determined by,

$$RI_i^m = RI_{i-1} + \Delta RI_i^{CP} \quad (4.11)$$

$$RI_i^{LC} = RI_{i-1} + \Delta RI_i + \Delta RI_i^{CP} \quad (4.12)$$

Where,

RI_i^m = IRI of an analysis year i (i=patching for crack applied year) in Management function, in m/km

RI_i^{LC} = IRI of an analysis year i in LCCA, accounting function, in m/km IRI

RI_{i-1} = IRI of an analysis year $i-1$, in m/km IRI

ΔRI_i = change in IRI estimated by deterioration model in an analysis year i, in m/km IRI

ΔRI_i^{CP} = change in IRI condition due to crack patching, in m/km IRI

However, the patched area is not considered as removing the crack area permanently. Since the patched area has often been considered as crack area, the area should be separately recorded in the database. Of course, the database also should prepare a column for the information. A flowchart is showing in the Figure 4.5.

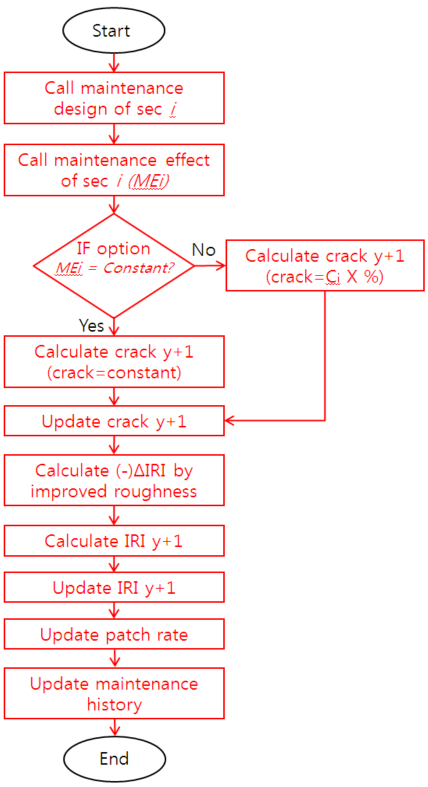


Figure 4.5 A flowchart of maintenance effect model - crack patching

C. Pothole patching

Application of potholes patching requires a little bit sophisticate approach. Unlike most of maintenance works, many countries are considering the pothole patching should be immediately conducted when it is happened even during a PMS cycle. However, the Hybrid PMS did not consider this option since the difference between instant repair and annual basis strategy is not so significant under a viewpoint of the final simulation result (e.g. deterioration speed and economic result). Pothole patching has one more effect than crack patching. The effects related to crack and IRI condition are defined as,

- Resetting (or reducing) number of potholes
- Positive and negative effects to IRI due to removing the potholes, and number of patching
- Update maintenance history (Record objective year, Set the AGE 1 to zero)

The effect of removing the crack area also can be estimated by Eq. 4.8 or Eq. 4.9. The positive and negative effect to IRI is estimated by integration of two effects. It can be expressed by the Eq. 4.13.

$$\Delta RI_{i+1}^{PP} = [a_0(NPT_i)] - \left[\frac{a_1}{10} \times \frac{0.11(NPT_i)}{(WID \times LEN)}\right] \quad (4.13)$$

Where,
ΔRI_{i+1}^{PP} = change in IRI by potholes patching, in m/km IRI
NPT_i = number of pothole units per km
WID = total width of carriageway, in meter (default = 3.5m)
LEN = unit length of section, in meter (default = 1,000m)
a_0 = model coefficient (default = 0.000006)
a_1 = model coefficient (default = 0.42)

The first term, $a_0(NPT_i)$, in the Eq. 4.13 is increase in IRI determined by a function of the number of patching, and the last term, $\frac{a_1}{10} \times \frac{0.11(NPT_i)}{(WID \times LEN)}$, is amount of decrease in IRI by reducing the number of pothole in the section. The estimation coefficient was found under assumptions that the standardized size pothole is 0.1 m^2, a typical pavement width is 7 meters, and unit length of section is 1 km (1,000m). In this case, the term, $'WID \times LEN'$ in the Eq. 4.13 becomes 7,000. Next (or current) year's IRI condition also can be estimated by the Eq. 4.11 and Eq. 4.12. A flowchart of pothole patching is addressed in the Figure 4.6.

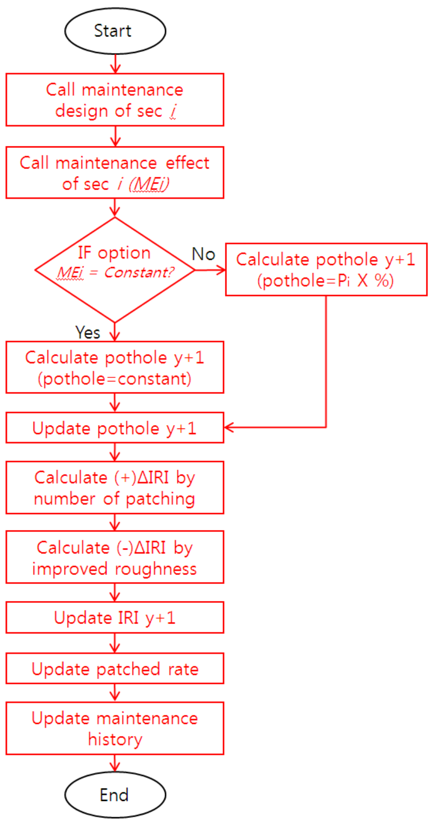


Figure 4.6 A flowchart of maintenance effect model - pothole patching

D. Surface treatment

Bituminous Surface Treatment (BST) is used mainly on low-traffic roads, but also as a sealing coat to rejuvenate an asphalt concrete pavement. It generally consists of aggregate spread over sprayed-on asphalt emulsion or cut-back asphalt cement. The aggregate is then embedded into the asphalt by rolling it, typically with a rubber-tired roller. BSTs of this type are described by a wide variety of regional terms including “Chip seal”, "Tar and chip", "Oil and stone", "Seal coat" or "Surface dressing" (Gransberg and Douglas, 2005). The BSTs supports following three types,

- Slurry Seals and Cape seal
- Reseal with Shape Correction, and
- Single or Double Surface Treatment

The BSTs target entire section like with overlay or reconstruction. It adds thickness of pavement layer, removes crack, and decrease the IRI. However, it is considered that BSTs do not have effect to rutting in general. In addition, BSTs require preparatory work before main surface treatment work, such as pothole patching, and repairing edge break. Hence, the maintenance effect model in the Hybrid PMS has defined the effects by BSTs to crack and IRI only. The effects of BSTs are summarized under below;

- Changing thickness of pavement layer (expect for single or double surface treatment)
- Resetting crack area
- Resetting pothole area
- A positive effect to IRI due to removing the pothole and crack area
- Update maintenance history (Recording objective year, Set AGE 0, 1, and 2 to zero, Changing pavement type)

The first content, adding thickness of pavement layer, is simply calculated by user-specified option in work design option (see Eq. 4.14)

$$T_{PL_{i+1}} = T_{PL_i} + T_{PL_i}^{BST} \tag{4.14}$$

Where,

$T_{PL_{i+1}}$ = thickness of pavement layer after surface treatment applied year i in mm

T_{PL_i} = thickness of pavement layer in year i in mm

$T_{PL_i}^{BST}$ = thickness of surface treatment in year i in mm

The second and third contents can be assumed to being user-specified reset condition (crack=0.00%, the number of pothole = 0). This is, because, pothole patching is usually performed as a preparatory work before surface treatment. Besides, crack is covered after treatment work. The last content was considered for IRI reduction after the application of surface treatment.

Three methods related with surface treatment are considering reducing the IRI by application of pothole patching as a preparatory work described in the Eq.4.13. Models by the types of surface treatment are addressed in Eq. 4.15,

In case of slurry seals and cape seals,

$$RI_a = RI_b + min\{0, max[0.3(4.6 - RI_b), -0.09(Hsl)]\} - 0.0066(ACX) \tag{4.15a}$$

In case of reseal with shape correction,

$$RI_a = RI_b + min\{0, max[-0.0075(Hsc)(RI_b), -0.0225(Hsc)\max(RI_b - 4,0)]\} - 0.0066(ACX) \tag{4.15b}$$

And the case of the single or double surface treatment,

$$RI_a = RI_b + min\{0, max[0.3(5.4 - RI_b), -0.5]\} - 0.0066(ACX) \tag{4.15c}$$

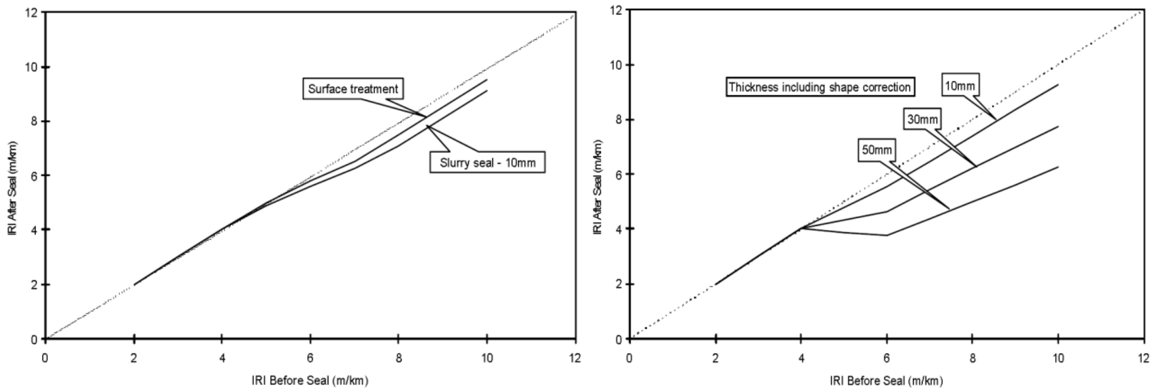
Where,

RI_a = IRI condition after seal, in m/km IRI

RI_b = IRI condition after pothole patching and before seal, in m/km IRI
Hsl = thickness of slurry seal, in mm
Hsc = thickness of reseal including shape correction layer, in mm (that is, $min\,(Hsc, 50)$)
ACX = area of indexed cracking, in percent

These models show a relatively small reduction in roughness for surface treatment (refer to Figure 4.7). Around 0.5m/km IRI reduction is generated when the pre-seal roughness is more than 5 m/km. 5 mm slurry seal gives roughly the same effect while 10 mm slurry is predicted to give a reduction of about 1.0m/km IRI when pre-seal roughness is more than 7m/km. At lower levels of roughness, as would be found on a well-developed highway network, seals are modeled as having no effect on roughness.

However, the real objective of surface treatment is to slow down deterioration speed by applying it at appropriate timing, particularly in low volume. Also, one more important difference with an overlay is the thickness. If the total thickness of such a treatment were 50 mm, it should surely be considered and modeled as an overlay. A flowchart for surface treatment is showing in the Figure 4.8.



Source: Morosiuk et al., 2000

Figure 4.7 Effects of surface treatments and slurry seals (left) and reseal with shape correction (right) on roughness (related with Eq. 4.15)

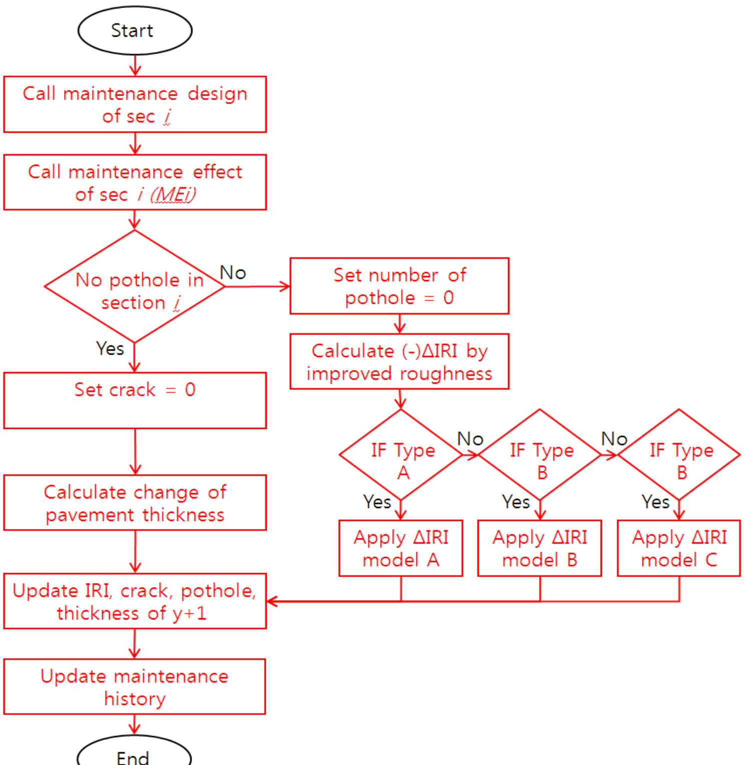


Figure 4.8 A flowchart of maintenance effect model – Surface treatment

E. Overlay

Generally, the overlay is classified by a rehabilitation level of maintenance work that changes pavement structure, and reset deterioration indices. The overlay is usually performed when the permanent type of deterioration indices reaches to maintenance level. There were many researches related with the overlay effects to IRI (Djarf, 1995; Corne, 1989; NDLI, 1991, 1993, 1994a, 1994b) conducted in Sweden, Indonesia, Nepal, Barbados and Thailand. Most studies had suggested estimation models by the function of before maintenance condition. However, these research results could not be considered as a universal result covering every environment because each country has very different design, properties of material, and maintenance standard. In order to apply much flexible model, the Hybrid PMS has improved a maintenance effect model for IRI in the HDM-4 (Odoki *et al.,* 2001). The definition of overlay effects in the Hybrid PMS is listed under below;

- Changing thickness of pavement layer
- Resetting crack area
- Resetting (or reducing) rut depth
- Resetting pothole area
- A positive effect to IRI due to overlay
- Update maintenance history (Record objective year, Set AGE 1,2 and 3 to zero, change pavement type)

Until surface treatment (AGE 2: repair level), its concept was modifying current IRI by the types. However, the overlay makes (near) reset condition. User can adjust crack, rutting, pothole, and even IRI condition by user-specified constant, or by percentage of before overlay. The overlay also requires preparatory works. The relationship between overlay and IRI condition by overlay thickness is represented in the Figure 4.9.

The reduction in roughness after overlay, ΔRI, can be estimated by the sum of $dR2$ and $dR2$. And this is expressed by equations.

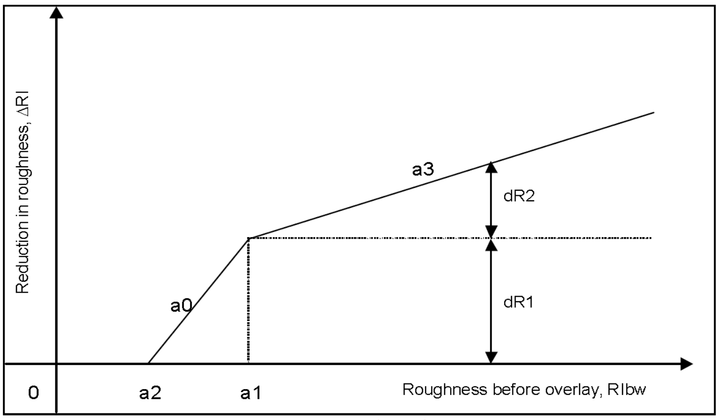
$$\Delta RI = max\,\{0, a_0[min(a_1, RI_{bw}) - a_2] + a_3\,max[0, (RI_{bw} - a_1)]\} \quad (4.16a)$$

$$RI_{bw} = max\,(1.0, RI_{ap}) \quad (4.16b)$$

$$RI_{aw} = RI_{bw} - \Delta RI \quad (4.16c)$$

Where,

ΔRI = reduction in IRI condition after overlay, in m/km IRI
RI_{bw} = IRI condition before overlay, in m/km IRI
RI_{ap} = IRI condition after overlay, in m/km IRI
RI_{aw} = adjusted roughness after preparatory work (patching patching), in m/km IRI
a_0 = slope of the first line, default = 0.9
a_1 = IRI condition before overlay at which the two lines meet, in m/km IRI
a_2 = minimum roughness after overlay, m/km IRI (That is, the best condition)
a_3 = slope of the second line



Source: Morosiuk et al., 2000

Figure 4.9 Effects of overlay on roughness

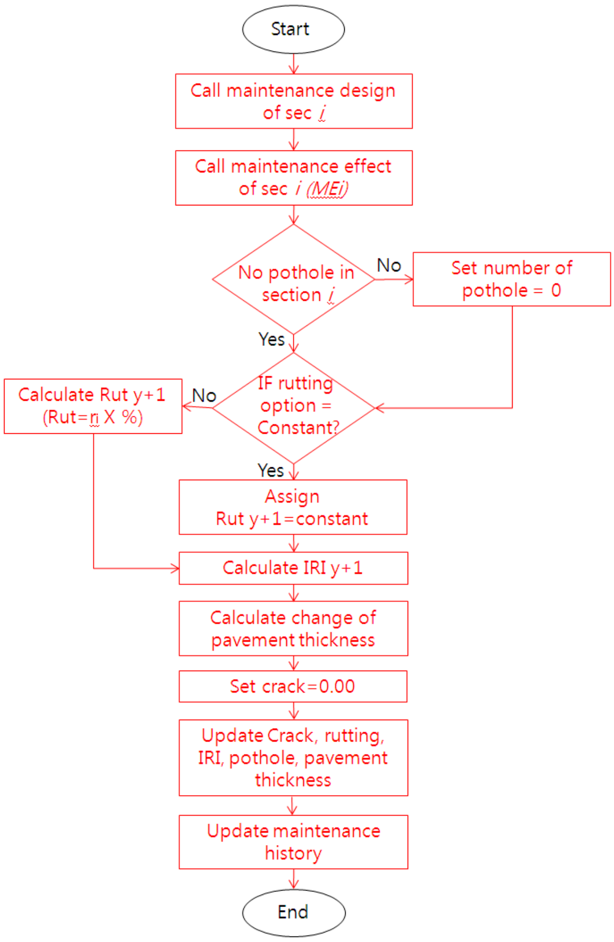


Figure 4.10 A flowchart of maintenance effect model – Overlay

As shown above equations, the IRI condition after overlay is flexible by adjusting constants a_0, a_1, a_2, and a_3. These factors are user-definable in the Hybrid PMS, and computable as a function of the thickness of overlay as follows,

$$a_1 = max\,\{4.0{,}2.1\,exp[0.019(HSNEW_{aw})]\} \qquad (4.17)$$

$$a_2 = 1 + 0.018\,max\,[0\,,(100 - HSNEW_{aw})] \qquad (4.18)$$

$$a_3 = min\,\{a_0, max[0, (0.01(HSNEW_{aw}) - 0.15)]\} \qquad (4.19)$$

Where,
$HSNEW_{aw}$ = thickness of overlay, in mm

The flowchart for overlay effect model is showing in the Figure 4.10.

F. Reconstruction
Unlike with the overlay, all of the deterioration indices are independent when reconstruction is applied. All indices should be user-specified constant value which represents the best condition. The effect of reconstruction can be defined as;

- Resetting all indices to the user-specified best condition
- Updating maintenance history (Recording objective year, set AGE 0,1,2,3 and 4 by zero, changing the pavement type of new design)

Therefore, a sub-routine for the reconstruction type becomes simple (see Figure 4.11).

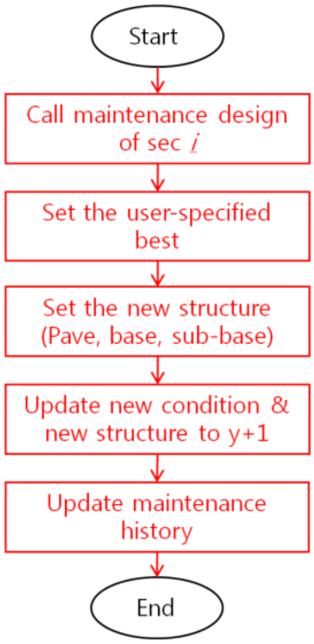


Figure 4.11 A flowchart of maintenance effect model – Reconstruction

There is an inherent limitation of the best condition of some deterioration indices even after reconstruction. In general, IRI cannot reach to IRI 0.00m/km even if the highest quality of pavement material with very strict design specification is applied. The usual case is around from IRI 1.00 m/km to IRI 2.00 m/km. It may be as high as IRI 2.5m/km for surface treatments (Morosiuk *et al.*, 2000). In case of the HDM-4 system, a default value of IRI asphalt mix type for IRI is 2.00m/km, and surface treatment is IRI 2.8m/km (Odoki and Kerali, 2000). However, so far as private experiences in developed country, usually it reaches around IRI 0.90~1.10 m/km. It is, of course, might be differed from type of material (e.g. hand laid surfacing), design and specifications for construction work. Surveys of local roads in Indonesia have shown an average IRI for new penetration macadam surfacing to be around 8m/km, and in India the IRI of hand laid premix asphalt is typically around 6m/km. The Hybrid PMS suggests the best condition of each pavement deterioration index for the case of bituminous pavement as follows;

- Crack: 0.00%
- Rutting: 2.00mm (usually, 2.00~5.00mm)
- IRI: 1.00m/km (usually, 0.90m/km~1.1m/km)
- Pothole: 0 n/km
- Edge break: 0.00m^2
- Raveled area: 0.00%
- Skid resistance: 0.5 SCRIM (at 50km/h)

In fact, modeling of maintenance effect is not so simple because mechanism between road pavement including underground layer and explanatory variables is not so clear. In addition, there are too many sub-divided maintenance works.

4.5 Sub-functions for See Phase

This chapter will discuss about results of PMS activities during a PMS cycle. Simply, it could be compared to “A report of PMS”. This would be an important work to PMS managers at the end of a PMS cycle. The key information in PMS operation could be following contents;

Applied standard and options;

- All of applied options in the management function
- All of applied PMS standards (user-defined)

Inspection & maintenance demand / Conducted works;

- Details of scheduled inspection and maintenance work planned at the beginning
- Details of conducted (and delayed) inspection and maintenance work as scheduled

Budget related;

- Compilation and execution of budget

Pavement condition related;

- Average conditions of each deterioration index by entire network / agency / pavement groups / etc.
- Time-series network condition along with allocated budgets history
- Effect of maintenance work (improved road condition)
- Etc.

Examples of the report are showing in the Table 4.16 and Table 4.17.

Table 4.16 An example of final report (A summary of simulation options and results)

User-selected or specified options	Applied PMS standard	Brief summaries of work demand	Brief summaries of Budget expenditure
1. Error processing (1) Type-A: Rutting:100mm, IRI 16m/km, pothole 50n/km (2) Type-B: Option 2 (Believe previous data) **2. Inspection** (1) Type: Normal type, Advance type (FWD only) (2) Priority rule: By Longer elapsed time (3) Applied standard: Scheduled scheme **3. Maintenance** (1) type: 9 types (2) Priority rule: By maintenance type (3) Applied standard: Reactive scheme **4. Work Design** (1) type: By variable based type **5. Work effect** (1) Type: By model application **6. Accounting** (1) Type: Total accounting (2) Budget condition: Constraint (3) Optimization way: Option 3 (delay section)	**1. Maintenance standards** (1) Reconstruction: Crack 50% or Rutting 50mm or IRI 8.0m/km (2) Overlay: Rutting 25mm or IRI 3.5m/km (3) Cutting overlay: Rutting 25mm or IRI 3.5m/km & thickness of pave layer 150mm (4) Overlay: Rutting 25mm or IRI 3.5m/km (5) Surface treatment – type A : Crack 25% and traffic load less than 0.01 (6) Crack Patching : Alligator crack 10% (7) Pothole patching: Pothole 1 (8) Crack sealing: Line crack 5% **2. Inspection standards** (1) Normal : 4year's interval (2) Advanced type: FWD, Object of reconstruction **3. Priority rule for work demand** (1) Inspection: Longer elapsed time since last inspection (2) Maintenance: Reconstruction, cutting overlay, overlay, surface, surface treatment, pothole patching, crack patching, crack seal	**1. Maintenance demands** (1) Total number of section and area -Reconstruction: 8 sections, (149,000m^2) -Cutting overlay: 4 section (248,000 m^2) -Overlay: 15 sections (2,848,000 m^2) -Surface treatment: 10 sections (1,258,000 m^2) - Crack Patching : 21 sections (1,087m^2) - Pothole patching: 19 sections (189 n) - Crack sealing: 29 sections (1,239 m^2) **2. Inspection demands** (1) Total number of section - Normal: 2597 sections - Advanced: 3 sections (2) Total length - Normal: 3,950km - Advanced: 21.0km - Crack sealing: 29 sections (1,239 m^2) **3. Delayed work** (1) Inspection : N/A (2) Maintenance: Crack seal 31 section	**1. Allocated budget** $ 68,259,458 **2. Required budget** (1) Unconstraint: $72,048,458 (2) Constraint (After optimization): $68,258,259 **3. Budget expenditure** (1) Maintenance: Total $56,589,129 - Reconstruction: $925,974 - Cutting overlay: $1,486,308 - Overlay: $2,384,028 - Surface treatment: $283,182 - Crack Patching: $15,199 - Pothole patching: $25,896 - Crack sealing: $198,479 (2) Inspection: Total $2,251,130 -Normal: $2,001,989 -Advanced: $249,131 (3) The other: Total $5,562,258 -Overhead: $4,400,000 -PMS operation: $80,000 -R&D: $520,000 -Equipment: $562,258

Table 4.17 An example of final report (A summary of maintenance demands)

Section ID	Required Work	Condition				Location			Physical characteristic			Pavement structure					Maintenance history		Priority ranking	Cost for a section ($).	Cum. cost ($)
		Crack (%)	Rut (mm)	IRI (m/km)	Pot (n/km).	Start	End	Address	Length (km)	Width (m)	Lane	Pave Type	Material	Pave (mm)	Sub (mm)	Base (mm)	First/Last Const.	Last Overlay			
A01d1	Recon.	15.2	42.2	7.3	3	A03481	A03542	No.9	1.2	7	2/4	AMAP	AC	100	150	250	1978	1995	1	198,248	198,248
A05d2	Overlay	2.5	31.2	4.5	0	A02680	A02674	No.9	1.4	14	4/8	AMSB	SMA	100	150	250	1988	2001	2	96,458	294,706
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
A12c4	Patching	11.4	2.1	3.3	12	A09481	A09581	No.24	2.4	7	2/4	STBG	AC	100	150	250	2000	N/A	106	1,875.	7,987,954

4.6 Summary and Recommendations

This chapter addressed PMS cycle management functions as criteria for PMS operation. The functions can facilitate practical road maintenance activities from establishing annual PMS plan to reporting work. Generally, the works have been manually conducted by PMS manager without any automated system. In addition, the management works are conducted by many persons who are concerned in road inspection, maintenance, data management, PMS planning, and system management. Under the situation, the procedures cannot be exactly applied unless everybody exactly knows the procedures and every detail. Properly, human errors could be accumulated. As a summary, developing PMS cycle management functions has important meanings as follows;

- Facilitating dairy, monthly and annual PMS activities of PMS manager by automated system
- Reducing human errors caused by many related person who are engaged in different fields
- Standardization of PMS cycle as criteria for PMS operation

For developing management function, above all, definition of a general PMS cycle should be first step. As a solution, this paper introduced a tactical level of management cycle classified by three phases; *"PLAN, DO, and SEE"*. Details works of each phase were defined as follows;

At the Planning phase:

- Determining maintenance and inspection target during a PMS cycle
- Work design, inspection type
- Budget estimation
- Optimization (when budget goes over its constraint)

At the Do phase;

- Updating pavement conditions changed by the maintenance and inspection
- Recording budget expenditures
- Error processing (e.g. inversed pavement condition)

At the See phase:

- Summarizing annual PMS activities (conducted and un-conducted work)
- Summarizing executed budget
- Analyzing network condition
- Updating and reporting

The management functions have deep relationship with update of database. Since the database of the PMS has a different property with general database that annual historical data should be saved without any modification, it must have a role for data update as an independent module. In addition, some functions (*e.g.* error processing or work effect estimation) are required for complex calculation procedures that cannot be done by the database due to a nature of system. That is, the management functions should be paired with the database. The paired functions could be considered as minimum requirements for PMS operation.

Since these functions can cover dairy, monthly even annual activities of PMS, it would be most frequently applied by road agencies. Of course, it might be not exactly matched with road agencies' current PMS cycle. By the comparison with suggested general PMS cycle, they can modify their cycle as necessary. For the cases, every sub-function was developed as independent modules by the concept of encapsulation strategy. Any modification is available for customization. As recommendation for further researches, following contents are considerable;

- ***Much practical definitions of PMS cycle and their functions:*** Current definitions for general PMS cycle and details of each sub-function were developed under theoretical viewpoints to appease everybody. From the experiences, it was recognized that real situations are somewhat different. Usually, most agencies applied simplified procedure and details by many assumptions. Improvement (or simplification) of the management function could be realized by feedback with many road agencies.

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CHAPTER 5

Pavement Deterioration Forecasting Models

5.1 General Introduction

At the Chapters 3 and 4, this paper has discussed database system, and PMS cycle management which are related to issues on the "*Past*" and "*Present*". The two components described as tools for operation of current road management policy as a minimum requirement of PMS. However, the components cannot produce better solutions to enhance cost-effectiveness of their budget. If a road agency operates only the two components, they do not know whether or not their current management policy and specification is optimized. A solution could be introducing PMS analysis procedures. The PMS analysis generally treats optimization of management strategy regarding pavement performance analysis, maintenance method and timing, better material or engineering methods, economic analysis and so on. If there are some differences in PMS analysis results between countries, it is surely oriented from the pavement deterioration characteristics. It means that starting point of introduction of the PMS analysis should be developing pavement deterioration forecasting model (hereinafter, deterioration model) which is the heart of the PMS. As a basic function, the deterioration model estimates future pavement conditions based on deterministic or probabilistic variables. This function is a basement of every pavement performance analysis, and simulation for LCCA. It is strongly recommended to settle in their PMS to find better solution at every situation. Note that the roles of pavement deterioration model in this paper do not include economic analysis procedure, but it just estimates deterioration process without maintenance effects.

Although the deterioration model is desired for everyone, its application is not for everyone. Since the pavement deterioration forecasting is totally depended upon the time-series pavement performance data and explanatory variables, road agencies may be encountered many problems, unless they did not prepare the rich data contents from the initial stage of road construction. In general, there is much noise in the pavement performance history data. For that reason, usually stochastic models have been preferred than deterministic models. However, the simplified deterministic model that requires minimized data is also demanded for users who do not have enough data. As a solution, the Hybrid PMS serves various deterioration models by considerations of data requirement, usage, even properties of forecasting (or estimation) models. The road agencies in a beginning stage of PMS development may prefer the simplest model due to data limitation. However, as time goes by, their data would be accumulated, then finally they can use the much better (also much more) models in future. The strategy having various deterioration models is good for easy introduction and improvement of the Hybrid PMS to various unknown users who have different data condition and objectives, as well as preparation of future demands.

Note that the introduced deterioration models or theories were not developed by this paper, but generally applied in PMS sector. The most important concern of this chapter is not introducing various deterioration models, but how to compose deterioration models to satisfy various PMS situations and objectives

5.2 Determination of Deterioration Forecasting Models in the Hybrid PMS

An objective of forecasting model is to define deterioration process characterized by deterioration speed and shape of curve. There are many kind of forecasting models applied in the pavement management field. The forecasting models could be classified by the following factors:

- Data requirement
- Property of forecasting model
- Usage of result (Network level or Project level)

Data requirement is most critical factor for application of deterioration model. Even if someone develops very powerful model, it could be considered as useless one to others who cannot satisfy its data requirement.

Thus, Hybrid PMS should have simple models that demands minimum data. Of course, advanced models should be settled for road agencies who are in a mature level.

The property of deterioration model can be classified into deterministic or stochastic model. Due to uncertainty in the pavement deterioration processes, usually stochastic models have been preferred than deterministic models in PMS sector. However, the deterministic model which developed by empirical or mechanistic approaches are also demanded for special cases for users who do not have enough capability to develop own model.

The usage of result could be distinguished by network level and project level. Network level application is usually for budget estimation or benchmarking approach on pavement deterioration process of network, while project level targets individual road section for specific purpose. The composition of deterioration model in the Hybrid PMS should cover both purposes.

As a result, following models which are generally used in PMS sector has been selected as member of deterioration model in the Hybrid PMS;

- Simplified linear regression
- Multiple regression
- Markov exponential hazard model
- Local mixture model

Simple descriptions about the models are presented at the Table 5.1.

Table 5.1 Pavement deterioration forecasting models of the Hybrid PMS

Model	Model type (result type)	Main data	Description & recommendation
Simple regression	Deterministic (year basis)	· Elapsed time · Condition change	Simple regression analysis by function of elapsed time or a single variable : The country which has only pavement condition data (no applicable explanatory variables)
Multiple regression	Deterministic (year basis)	· Elapsed time · Condition change · Explanatory variable(s)	Estimated by multiple regression analysis by user defined multi-variables : The country which has enough pavement condition and explanatory variables to make estimation functions
Multi-state Markov exponential hazard model	Stochastic (state basis)	· Elapsed time · Condition change · Explanatory variable(s)	Based on the Markov Transition Probability (MTP) matrix disaggregated by multi-state exponential hazard model with maximum likelihood estimators (good for strategic or macro level) : The country which has enough pavement condition data to compose the MTP matrix, and wants to get probabilistic result with consideration of explanatory variables : For network level of analysis, and research purpose by a concept of the benchmarking approach.
Local mixture hazard	Stochastic (state basis & heterogeneity factor)	· Elapsed time · Condition change · Explanatory variable(s) · Grouping information	Estimated by the Markov chain with the Local mixture mechanism to find not only deterioration process but also heterogeneity factors to find better strategy by comparison of deterioration properties of the road groups (good for strategic or macro level) : The country who wants to compare deterioration characteristic of road groups having different properties. (*e.g.* the best technology of pavement design, pavement material, climate effect, etc.)

Since the four basic internal models have been developed as independent modules in the Hybrid PMS, road agencies could find the best model for their original PMS condition and objectives with understanding on properties of the models regarding the input, output, and forecasting procedures. Note that the best deterioration model is not a model which has powerful functions and theories, but a model which is well matched with road agencies' current data situations and purpose of application.

5.3 Description of Pavement Deterioration Forecasting Models

5.3.1 Simplified Linear Regression Model

This model estimates annual road condition by the linear regression by a function of elapsed time. This may be useful for countries which have only pavement condition and maintenance history data. The demands may be considered as minimum requirement for all of forecasting models. However, from the experience, it is expected that the regression model cannot well describe deterioration progress due to an uncertainty of pavement deterioration progress. However, the model has important meaning to satisfy the philosophy of the Hybrid PMS, the "Everybody". This chapter delivers simple description of simple linear regression.

Regression analysis treats the relationship between a dependence variable and one or more independent variable (or explanatory variable). In detail, regression analysis gives the result how the dependent variable is affected when the independent variables is varies. Most commonly, regression analysis forecasts the conditional expectation of the dependent variable given the independent variable(s). The main target of regression analysis is focused on a function of the independent variables. In brief, the regression function is defined by a finite number of unknown parameters estimated from the historical performance data.

Classical assumptions for regression analysis include (Wikipedia, 2000a);

- The sample must be representative of the population for the inference prediction.
- The error is assumed to be a random variable with a mean of zero conditional on the explanatory variables.
- The variables are error-free. If this is not so, modeling may be done using errors-in-variables model techniques.
- The predictors must be linearly independent, i.e. it must not be possible to express any predictor as a linear combination of the others. (An Issue related to the Multicollinearity))
- The errors are uncorrelated, that is, the variance-covariance matrix of the errors is diagonal and each non-zero element is the variance of the error.
- The variance of the error is constant across observations (homoscedasticity). If not, weighted least squares or other methods might be used.

These are sufficient (but not all necessary) conditions for the Least-Squares Estimator (LSE) to possess desirable properties, in particular, these assumptions imply that the parameter estimates will be unbiased, consistent, and efficient in the class of linear unbiased estimators. The linear regression model basically demands the following variables;

- The unknown parameter, generally denoted as "β"
- The independent variables, generally denoted as "X"
- The dependent variable, generally denoted as "Y"

By using above variables, the regression model for estimating Y by a function of the X and the β can be defined as $Y \approx f(X, \beta)$. The approximation is usually formalized as:

$$E(Y|X) = f(X|\beta) = \beta_0 + \beta_1 X_i + \varepsilon_i \quad (i = 1, \dots, n) \tag{5.1}$$

Here, the dependence variable X can be the elapsed time from last rehabilitation or (re)construction or condition change between inspection points. In case of multiple linear regression, several independent variables are added by terms in $X_i^2, X_i^3, \dots, X_i^n$.

$$\mathrm{y_i} = \beta_0 + \beta_1 X_i + \beta_2 X_i^2, \dots, \beta_n X_i^n + \varepsilon_i \ \ (i = 1, \dots, n) \tag{5.2}$$

Although the right side of the Eq.5.2 are taking quadratic, cubic function or more, this is still linear regression, because it is linear in the parameters, $\beta_0, \beta_1, \dots, \beta_n$.

The ε_i in the Eq.5.1 and Eq.5.2 are the error term. Given a random sample from the population, we estimate the population parameters and obtain the sample linear regression model;

$$\hat{y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_i + e_i \tag{5.3}$$

The term e_i is the residual, that is, $\varepsilon_i = y_i - \hat{y}_i$. A method of estimation is the ordinary least squares. The method gains parameter estimates that minimize the Sum of Squared Errors (SSE);

$$SSE = \sum_{i=1}^{N} \varepsilon_i^2 = \sum_{i=1}^{N} (Y_i - \beta_0 - \beta_1 x_i)^2 \tag{5.4}$$

To minimize of the SSE, a set of simultaneous linear equations are required for finding the $\widehat{\beta_0}$, $\widehat{\beta_1}$. For the case of simple regression, the following formulas estimate the least squares estimates.

$$\hat{\beta}_1 = \frac{\sum_{i=1}^{n}(x_i - \overline{x_i})(y_i - \overline{y_i})}{\sum_{i=1}^{n}(x_i - \overline{x_i})^2} \quad and \quad \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \tag{5.5}$$

Where,
$\bar{x}$ = mean of the independence variable x
$\bar{y}$ = mean of the dependence variable y

The regression line estimated by the least square method has following properties:

- Sum of the residuals equals to zero, that is, $\sum_{i=1}^{n} e_i = 0$
- Sum of squared error becomes minimum
- The weighted sum by independence variable x_i equals to zero, that is, $\sum_{i=1}^{n} x_i e_i = 0$
- The weighted sum by estimates $\hat{y}_i$ equals to zero, that is, $\sum_{i=1}^{n} \hat{y}_i e_i = 0$
- The regression line always has an estimation point $(\bar{x}, \bar{y})$

Thus, the estimates gained by the least square method has properties *"linear"*, *"unbiased"* and *"minimum variance"*, called as the *"Gauss-Markov theorem"*.

By graphing the data representing relationship between dependence and independence variable, a precision of the regression model related to $\hat{\beta}_0$ and $\hat{\beta}_1$ roughly can be checked. However, it is not a précised way expressing its precision. For the case, usually standard error of estimate and coefficient of determination are widely used.

First, the variance σ^2 which is biased estimates from the regression line, the Mean Squared Error (MSE), can be estimated by:

$$MSE = \frac{1}{n-2} \sum_{i=1}^{n} e_i^2 = \frac{1}{n-2} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 = \frac{1}{n-2} \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_i)^2 \tag{5.6}$$

So that, the standard error of estimates, S_e are given by:

$$S_e = \sqrt{MSE} = \sqrt{\frac{1}{n-2} \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_i)^2} \tag{5.7}$$

That is, the regression line having S_e which is closer to zero well explains relationship between independence variable x_i and dependence variable y_i. After the construction of a regression model, a coefficient of determination and statistical significance of the model should be check. For the purpose, the R-square value is commonly used to check the goodness of fit. If total deviation is defined as difference between measurement y_i and $\bar{y}$, the total deviation can be disaggregated by the SSE and SSR(Sum of Square Residuals),

$$(y_i - \bar{y}) = (y_i - \hat{y}_i) + (\hat{y}_i - \bar{y}) \tag{5.8}$$

By denoting each term as;

- the total variation (SST) = $\sum_{i=1}^{n}(y_i - \bar{y})^2$,
- the sum of squared error (SSE) by residual = $\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$ and,
- the sum of squared error by regression (SSR) is = $\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2$

The total deviation can be rewritten by;

$$SST = SSE + SSR \tag{5.9}$$

By dividing every term in Eq. 9 by the SST, we can get the variation ratio of the explained and unexplained variation, respectively.

$$\frac{SST}{SST} = \frac{SSE}{SST} + \frac{SSR}{SST} \ or \ 1 = \frac{SSE}{SST} + \frac{SSR}{SST} \tag{5.10}$$

Here, the $\frac{SSR}{SST}$ is called as the sample coefficient of determination, denoted as R^2. This can be simply rewritten by:

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} = \frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}, \ here, \ 0 \le R^2 \le 1 \tag{5.11}$$

If all estimation points on the regression line,

$$SSE = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 = \sum_{i=1}^{n} e_i = 0 \ \ then \ \ R^2 = 1.00 \tag{5.12}$$

The R^2 is always positioned between 0~1, and higher correlation coefficient has higher R^2. Since the R^2 representing the contribution ratio of the total variation by sample regression line, the R^2 is called as the contribution ratio of sample regression line.

Data requirement of the simple linear regression model in pavement management is generally elapsed time from last rehabilitation or (re)construction, or interval between two inspection points as an independence variable. As a dependence variable, of course, condition change during the period. If users use a pair of inspection record, it does not matter. In case of referring the maintenance history (*i.e.* section has only one inspection point), the condition changes can be estimated by an assumption of the reset condition by maintenance the work.

Note that the simple linear regression model also can be applied to explain other explanatory variables for research purposes, such as accumulated axle load characterized by the MESAL.

5.3.2 The Multiple Regression Model

Many research fields have often applied the multiple regression. The general premise of multiple regression is similar to that of simple linear regression. However, there is most important difference that the multiple regression allows more than one predictor variable. Often this is done to determine whether the inclusion of additional independence variables leads to increased prediction of the dependence variable. In the pavement field, there are too many explanatory variables that affect pavement deterioration process. Therefore, the Multiple regression may be much useful than simplified linear regression model. Understanding significant factor of pavement deterioration are very important for establishing better pavement management strategy because the effect of variables and their degree to deterioration speed could be different among countries, even every road section). The general form of the multiple regression equation having *n*-variables is,

$$\hat{Y}_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 +, \dots, + \beta_n X_n + \varepsilon_i \tag{5.13}$$

The basic form of the multiple regression is similar with the simple linear model. The β_0 is the intercept which indicates the point at which the regression plane intersects the y-axis when the values of the predictor scores are all zero. The $\beta_1, \dots, \beta_n$ is partial regression slope coefficients which are used as multipliers for the corresponding predictor variables $X_1, \dots, X_n$. The ε_i is a residual associated with the i the observation.

The computation for the regression coefficient in multiple regression analysis is much more complex than in simple regression. In simple regression, the regression weight includes information about the correlation between the predictor and criterion plus information about the variability of both the predictor and criteria. In multiple regression analysis, the regression weight includes all this information, however, it also includes information about the relationships between the predictor and all other predictors in the equation and information about the relationship between the criterion and all other predictors in the equation.

The Eq. 5.13 can be rewritten as a system of equations,

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} \beta_1 & \beta_2 X_{21} + & \beta_3 X_{31} + \cdots + & \beta_n X_{n1} & \varepsilon_1 \\ \beta_1 & \beta_2 X_{22} + & \beta_3 X_{32} + \cdots + & \beta_n X_{n2} & \varepsilon_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \beta_1 & \beta_2 X_{2n} + & \beta_3 X_{3n} + \cdots + & \beta_n X_{nn} & \varepsilon_n \end{pmatrix} \tag{5.14}$$

The Eq. 5.14 also can be rewritten by,

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} 1 & X_{21} & X_{31} & \cdots & X_{n1} \\ 1 & X_{22} & X_{32} & \cdots & X_{n2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & X_{2n} & X_{3n} & \cdots & X_{nn} \end{pmatrix} \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix} \tag{5.15}$$

The normal equations which is needed to differentiate with respect to the unknown "β"s,

$$SSE = e'e = (Y - X\beta)'(Y - X\beta) \tag{5.16}$$

Matrix form of the normal equation is given by,

$$(X'X)\beta = X'Y \tag{5.17}$$

For the solution of the "β"s, it should be apparent how to solve for the unknown parameters. Pre-multiply by the inverse of $X'X$ is,

$$(X'X)^{-1}(X'X)\beta = (X'X)^{-1}X'Y \tag{5.18}$$

From the properties of inverses,

$$(X'X)^{-1}(X'X) = I \tag{5.19a}$$

$$I\beta = (X'X)^{-1}X'Y \tag{5.19b}$$

$$\beta = (X'X)^{-1}X'Y \tag{5.19c}$$

The coefficient of determination can be estimated by same concepts explained in the Eq. 5.9 and 5.10. The equation can be rewritten by considering the SSE (refer to the Eq. 5.16):

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE^2}{SST} = 1 - \frac{(Y-\hat{Y})'(Y-\hat{Y})}{(Y-\bar{Y})'(Y-\bar{Y})} \tag{5.20}$$

The Multiple regression also has same assumptions explained in the Chapter 5.3.1. However, the Multiple regression model needs one more assumption about the *Multicollinearity* related to correlation between independence variables. It is not unusual for a researcher to use 4 or 5 predictors because generally speaking, the more predictors you have, the more accurately the criterion will be predicted. In Multiple regression, it is quite common that around two or three predictor variables capture some of the same variability in the criterion variable. That is, some of the variance that the first predictor explains in the criterion is the same variability that is explained by the second predictor variable. The more is that two predictor variables are correlated with each other, the more likely it is that they capture the same variability in the criterion variable. In fact, if two predictor variables are perfectly correlated, then the variance that the first predictor explains in the criterion is exactly the same variability that the second predictor variable explains. In other words, the addition of the second predictor does not increase the ability to accurately forecast the criterion beyond what is accomplished by the first predictor. When the two predictors are perfectly correlated, then neither predictor adds any predictive value to the other predictor, and the computation of R^2 is meaningless.

5.3.3 Multi-state Markov Exponential Hazard Model

5.3.3.1 Introduction

The pavement condition forecasting models are usually classified into deterministic and stochastic (or probabilistic) approaches. The deterministic models, such as the simple or multiple regression which were introduced in the Chapters 5.3.1 and 5.3.2 are useful for microscopic or mesoscopic approach for project level of analysis (also reasonable for network level) because it can have annual-basis result. However, it has often been confronted with problems on reliability of the result due to the uncertainty of pavement deterioration processes. For that reason, stochastic models are usually preferred.

A Markov chain model is a statistical model used to forecast the deterioration process of pavement deterioration indices. In this model, a rank order as results of pavement inspections represents the pavement conditions, and Markov Transition Probabilities (MTP) matrix is estimated to characterize the deterioration process between two consecutive states. In many of applications, the Markov transition probabilities are simply estimated using the relative transition frequency by converting the inspection data into the condition state. However, there are many cases in which the information obtained from inspections does not make reference to differences, such as pavement design, road alignment and slope, traffic load or even time intervals between inspections, compromising the accuracy of the MTP estimation (Tsuda *et al,* 2006). Basically, the traditional Markov chain model demands same inspection interval, besides, it cannot consider independence variables to explain deterioration processes.

The Markov hazard model in the Hybrid PMS is an advanced type of the traditional Markov chain model that has been improved for weaknesses of practical application in PMS. It is also based on the condition ranks by changing inspection data. However, The MTP matrix is estimated after characterizing the deterioration process of each state by multi-state exponential hazard model. The most important strengths of the Markov hazard model for practical application are that;

- Consideration of explanatory variables using unknown parameters estimated by maximum likelihood estimators
- Adjustment of different time interval of two consecutive conditions under assumption of holding property of defined transition probability matrix

Practically, there are many cases in which the time interval between inspections is differed by each section. Besides, there are so many independent variables have to be considered for explaining deterioration process. Those strengths are available by introduction of the hazard model to establish the MTP matrix, and Maximum likelihood estimator to consider explanatory variables. The strengths are good for practical application of pavement management field. Overall procedures of the Markov hazard model are illustrated in the Figure 5.1.

The main result of the Markov hazard model is the deterioration process from the best condition to maintenance criteria based on inspection data and explanatory variables. Related to the results, the Markov hazard model makes following results;

- Markov transition probabilities matrix
- Expected hazard rate of each state
- Unknown parameter with t-value of each state
- Benchmarked (average) life expectancies of whole network

The Markov hazard model requires not so many data. However, it demands enough sample scale for reliable transition probability matrix.

Figure 5.1 Procedures of Markov exponential hazard model (Benchmark approach)

5.3.3.2 Markov Transition Probability

To compose Markov transition probability matrix, it is necessary to accumulate time-series data to describing the condition changing from each section. In reality, uncertainty of deterioration progress of pavement is very serious. Moreover, the condition state is restricted by just each inspection point. The concept of deterioration process with a periodical inspection scheme is presented in the Figure 5.2.

In the Figure 5.2 the τ represents real calendar time. The deterioration is immediately occurred from at time point τ_0. The condition state is expressed by a rank J representing a state variable ($i = 1, \ldots, J$). A value of $i = J$ indicates that a section has reached its maintenance standard. Usually, Information about the deterioration process of a pavement section is acquired by periodical inspection points at times τ_A and τ_B. The Figure 5.2 shows four possible sample paths. The 'path 1' shows no transition in the condition state i during an inspection interval. In the 'path 2' and 'path 3' the condition state has advanced to one upper state condition at the times τ_i^2 and τ_i^3 respectively. The condition state of these two paths observed at time τ_B become $i+1$. In a periodical inspection scheme, the point times τ_i^2 and τ_i^3 in which the condition state has changed from i to $i+1$ are not determined. In addition, 'path 4' shows transitions in the condition state during the inspection interval at times τ_i^4 and τ_{i+1}^4. The condition state observed at time τ_B becomes $i+2$. That is, in spite of the transitions in the condition state being observable at the time of periodical inspection. It is not possible to obtain information about the times in which those transitions occur. The time length between two inspections is expressed by Z.

Source: (Left) ***Kobayashi et al., 2010****, (Right)* ***Tsuda et al., 2006***

Figure 5.2 Change of the condition states (left), and possible paths between two inspections (right)

The Markov transition probability is used to represent the uncertain transition of the condition state of a section during two points in time. The observed condition state of the component at time τ_A is expressed by using the state variable $h(\tau_A)$. If the condition state observed at time τ_A is i, then the state variable $h(\tau_A) = i$. A Markov transition probability is defined by the probability that the condition state changes from $h(\tau_A) = i$ to a future condition to $h(\tau_B) = j$. That is;

$$Prob[h(\tau_B) = j | h(\tau_A) = i] = \pi_{ij} \tag{5.21a}$$

$$\begin{cases} \pi_{ij} \geq 0 \\ \pi_{ij} = 0 (when\ i > j) \\ \sum_{j=1}^{J} \pi_{ij} = 1 \end{cases} \tag{5.21b}$$

The Markov transition probabilities matrix can be defined by using the transition probabilities between each pair of condition states i to j.

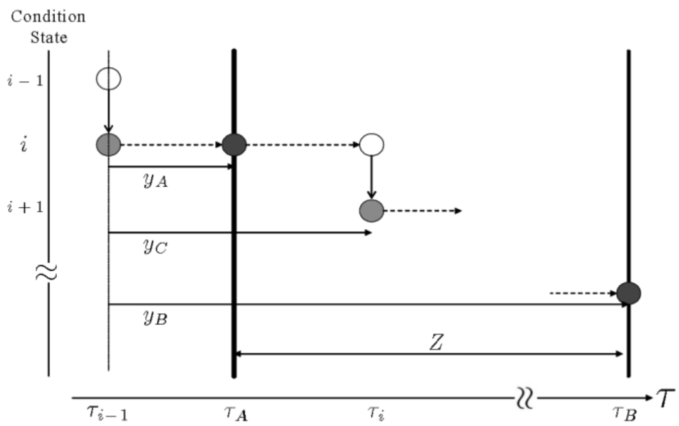
$$\Pi = \begin{bmatrix} \pi_{11} & \cdots & \pi_{1J} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ} \end{bmatrix} \tag{5.22}$$

The highest level of deterioration condition is expressed by the condition state J, which remains as an absorbing state in the Markov chain as long as no repair is carried out. That is, $\pi_{JJ} = 1$.

5.3.3.3 Disaggregation of Markov Transition Probability

The Markov transition probability can be defined by using a multi state hazard model representing the deterioration process of an individual road section. In order to estimate Markov transition probabilities based on explanatory variables, it is desirable to develop an estimation methodology that considers specific characteristics of each section. The purpose of the hazard model is to determine the transition probabilities that characterize the deterioration process of each pavement section. Markov transition probabilities determined by means of hazard models are referred to as disaggregate Markov transition probabilities.

For the deterioration process of a road section in the Figure 5.3, it is assumed that the condition level at the time τ_{i-1} has changed from $i-1$ to i. The time τ_{i-1} is assumed to be the origin $y_i = 0$ of the time axis, referred to in this paper as the sample time-axis. The time represented by the sample time-axis is referred to from now as a 'time point' and differs from the time axis. It can be seen that $y_A = \tau_A - \tau_{i-1}$, $y_B = \tau_B - \tau_{i-1}$. Information on the condition state i at the beginning of the time τ_{i-1} cannot be obtained in a periodical inspection scheme. Therefore, time points y_A and y_B in the sample time-axis cannot be correctly obtained either. Nevertheless, it is possible to use the information contained in $z = y_C - y_A \in [0, Z)$. For convenience of description, it is assumed that the information at the time points are known in order to develop the model, despite this assumption is not necessarily essential. The following paragraph discusses the fact that even without information at time points y_A and y_B an exponential hazard model can be estimated.



Source: Tsuda, et al., 2006

Figure 5.3 Deterioration process with inspection scheme

In the case that the condition state of a road section at time τ_i (time point y_C) is assumed to change from i to $i+1$, the period length in which the condition state has remained at i (referred to as the life expectancy of a condition state i) is represented by $\zeta_i = \tau_i - \tau_{i-1} = y_C$. The life expectancy of a condition state i is assumed to be a stochastic variable with probability density function $f_i(\zeta_i)$ and distribution function $F_i(\zeta_i)$, being ζ_i defined in the domain $[0, \infty)$. The distribution function $F_i(y_i)$ is defined as,

$$F_i(y_i) = \int_0^{y_i} f_i(\zeta_i) d\zeta_i \tag{5.23}$$

The distribution function $F_i(y_i)$ represents the cumulative probability of the transition in the condition state from i to $i+1$ when i is set at the initial time point $y_i = 0$ (time τ_A) and for a time interval measured along the sample time-axis to the time point y_i (time $\tau_{i-1} + y_i$). Therefore, using the cumulative probability $F_i(y_i)$, the probability $R_i(y_i)$ of a transition in the condition state i during the time points interval $y_i = 0$ to $y_i \in [0, \infty)$ is defined by $R_i(y_i)$;

$$R_i(y_i) = prob\ \{\zeta_i \geq y_i\} = 1 - F_i(y_i) \tag{5.24}$$

By using the exponential hazard function it is possible to represent a deterioration process of a road section that satisfies the Markov condition (Tsuda *et al.,* 2006; Chung *et al.,* 2006). The probability density $\lambda_i(y_i)$ which is referred to as the hazard function is defined as;

$$\lambda_i(y_i) = \frac{f_i(y_i)}{R_i(y_i)} = -\frac{\frac{dR_i(y_i)}{dy_i}}{R_i(y_i)} = \frac{d}{dy_i}\left(-log\ R_i(y_i)\right) \tag{5.25}$$

In this paper, it is assumed that the deterioration process of a road section satisfies Markov conditions and that the hazard function is independent of the time point y_i of the sample time-axis. Using the hazard function $\lambda_i(y_i) = \theta$, the probability $R(y_i)$ that the life expectancy of the condition state i becomes bigger than y_i is expressed by the following;

$$R_i(y_i) = exp\left[-\int_0^{y_i} \lambda_i(u) du\right] = exp\ (-\theta_i y_i) \tag{5.26}$$

The probability density function $f_i(\zeta_i)$ of the life expectancy of the condition state i is given by the following;

$$f_i(\zeta_i) = \theta_i exp\ (-\theta_i \zeta_i) \tag{5.27}$$

5.3.3.4 Determination of Markov Transition Probabilities

The Markov transition probabilities based on the exponential hazard model are expressed by three cases based on deterioration speed.

A. Case 1: Keeping the current condition until the next inspection time
The probability $prob\ [h(y_B) = i|h(y_A) = i]$ is nothing but the Markov transition probability π_{ii}. For a condition state i obtained by inspection at time point y_A the probability that the same condition state will be observed by a subsequent inspection at the time point $y_B (= y_A + Z)$ is expressed by the following;

$$\pi_{ii} = prob\ [h(y_B) = i|h(y_A) = i] = \frac{R_i(y_A+z_i)}{R_i(y_A)} = \frac{exp\{-\theta_i(y_A+z_i)\}}{exp\ (-\theta_i y_A)} = exp(-\theta_i z_i) \tag{5.28}$$

where Z expresses the interval between two inspection times. When an exponential hazard function is employed, the transition probability π_{ii} is dependent only on the hazard rate θ_i and the inspection interval Z. Even more, without using deterministic information on the time points y_A and y_B, it is still possible to estimate transition probabilities.

B. Case 2: the condition changes from i to $i+1$ during the interval Z
Using an exponential hazard function the probability that the condition state at the inspection time points y_A and y_B changes from i to $i+1$ can be obtained. This transition can occur if 1) the condition state i remains constant between a time point y_A to a time point $R_i = (y_A + z_i), (z_i \in [0, Z))$, 2) the condition state changes to $i+1$ at the time point $y_A + z_i$, and 3) it remains constant between $y_A + z_i$ and y_B.

Although the exact time in which the condition state transition from i to $i+1$ cannot be traced by periodical inspection, it can be temporarily assumed that the transition occurs at the time point $(y_A + \bar{z}_i) \in [y_A, y_B)$. However, the explanation above has been applied for a fixed value $\bar{R}_i = y_A + \bar{z}_i$. The life expectancy ζ_i of a condition state i i is in fact a stochastic variable, so $\bar{z}_i$ may change in range $[0, Z)$. The Markov transition probability that the condition state change from i to $i+1$ during the time points y_A and y_B is expressed by the following;

$$\begin{aligned} \pi_{ii+1} &= prob[h(y_B) = i+1 | h(y_A) = i] \\ &= \int_0^Z q_{i+1}(z_i|\zeta_i \geq y_A) dz_i \\ &= \int_0^Z \theta_i exp(-\theta_{i+1}Z) exp\{-(\theta_i - \theta_{i+1})z_i\} dz_i \\ &= \frac{\theta_i}{\theta_i - \theta_{i+1}} \{-exp(-\theta_i Z) + exp(-\theta_{i+1}Z)\} \end{aligned} \quad (5.29)$$

where $\pi_{ii+1} > 0$ is satisfied regardless of the relative size between θ_i and θ_j. The assumption $\theta_i \neq \theta_{i+1}$ implies $\pi_{ii+1} < 1$. For more detailed description it is suggested to readers to look at the references (Tsuda *et al.,* 2006). The distribution function and the probability density function of a period length in which a condition state j remains constant is denoted by $F_i(y_i)$ and $f_i(y_i)$ respectively. The hazard function related to the condition state j is denoted by $\lambda_i(y_i) = \theta_i$.

C. Case 3: the condition changes from i to $j (j \geq i+2)$ during the interval Z

The transition of the condition state from i to j during the time interval $[y_{A,} y_B)$ can occur if 1) the condition state i remains constant during the time interval $y_{A,}$, $\bar{R}_i = (y_A + \bar{z}_i) \in [y_A, y_B)$, 2) the condition state changes to $i+1$ at time point $\bar{R}_i = y_A + \bar{z}_i$, 3) the condition state $i+1$ remains constant during the time interval $\bar{R}_i = y_A + \bar{z}_i$, $\bar{R}_{i+1} = y_A + \bar{z}_{i+1} (\leq y_B)$, and at this time point changes to $i+2$. After repeating the same process 4) the condition level changes to j at some time point $\bar{R}_{j-1} (\leq y_B)$ remains constant until the time point y_B. Therefore, the Markov transition probabilities π_{ij} that a transition in the condition state from i to $j (j \geq i+2)$ occurs between the inspection time points y_A and y_B becomes;

$$\begin{aligned} \pi_{ij} &= prob\,[h(y_B) = j | h(y_A) = i] \\ &= \int_0^Z \int_0^{Z-z} \cdots \int_0^{Z - \sum_{m=i}^{j-2} z_m} q_j(z_i, \cdots, z_{j-1} | \zeta_i \geq y_A) dz_i, \cdots, dz_{j-1} \\ &= \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} exp\,(-\theta_k Z) \end{aligned} \quad (5.30)$$

It is possible to conclude that $0 < \pi_{ij} < 1$ is independent of the relative size between (θ_m and θ_k) and (θ_{m+1} and θ_k) by looking at the Eq. 10. Note that $\prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} = 1$ is satisfied when $k = i$ and $\prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} = 1$ is satisfied when $k = j$. π_{ij} is arranged using the Markov transition probabilities conditions as follows;

$$\pi_{iJ} = 1 - \sum_{j=1}^{J-1} \pi_{ij} \quad (5.31)$$

The summary of Markov transition probability based on exponential hazard model becomes;

$$\pi_{ii} = exp(-\theta_i Z) \quad (5.32a)$$

$$\pi_{ii+1} = \frac{\theta_i}{\theta_i - \theta_{i+1}} \{-exp(-\theta_i Z) + exp(-\theta_{i+1}Z)\} \quad (5.32b)$$

$$\pi_{ij} = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} exp\,(-\theta_k Z) \quad (5.32c)$$

$$\pi_{iJ} = 1 - \sum_{j=1}^{J-1} \pi_{ij} \quad (5.32d)$$

5.3.3.5 Time Adjustment of Markov Transition Probability Matrix

As shown in Eqs. 5.32a ~ 5.32d, Markov transition probabilities depend on the inspection interval value Z. For clarity of expression, the Markov transition probability is expressed as $\pi_{ij}(Z)$, so the Markov transition probabilities matrix related to the inspection time interval Z becomes,

$$\Pi(Z) = \begin{bmatrix} \pi_{11}(Z) & \cdots & \pi_{1J}(Z) \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ}(Z) \end{bmatrix} \tag{5.33}$$

For an integer value n two inspection intervals Z and nZ are considered. The Markov transition probabilities matrices $\Pi(Z)$ and $\Pi(nZ)$ describe the same deterioration process for two different time intervals. Therefore, the Markov transition probabilities matrix $\Pi(nZ)$ is expressed in terms of the Markov transition probabilities matrix as $\Pi(nZ)^n$. The condition expressed above is referred to as the time adjustment conditions of a Markov transition probability matrix. In order to satisfy this condition, a fixed mathematical structure between the Markov transition probabilities π_{ij} must be held.

5.3.3.6 Estimation of Markov Transition Probabilities

A. Contents of periodical inspection data

Suppose homogeneous periodical inspection data on K road sections is available. An inspection sample $k(k = 1, \cdots, K)$ describes two continuous periodical inspections carried out at times τ_A^k and τ_B^k and the respective condition states ratings $h(\tau_A^k)$ and $h(\tau_B^k)$ measured at those times. Differences in the inspection intervals of the samples are not inconvenient. Based on the above inspection data, the inspection interval of a sample k is defined as $Z^k = \tau_A^k - \tau_B^k$. In addition a dummy variable based on the deterioration progress patterns between two inspections times is defined for each $\delta_{ij}^k(i,j = 1, \cdots, J; k = 1, \cdots, K)$ by;

$$\delta_{ij}^k = \begin{cases} 1 \quad when\ h(\tau_A^k) = i\ and\ h(\tau_B^k) = j \\ \qquad 0 \quad otherwise \end{cases} \tag{5.34}$$

Furthermore, the structural characteristics and using conditions of a road section that affect the deterioration speed of a component are represented by the vector $x^k = (x_1^k, \ldots, x_M^k)$, where $x_M^k(m = 1, \cdots, M)$ represents the value of a characteristic variable m observed in the sample data k. The information contained in the inspection sample data k can be rearranged as $\Xi^k = (\delta_{ij}^k, Z^k, x^k)$. On the other hand, the exponential hazard function of the deterioration process for a sample data $k(k = 1, \ldots, K)$ is $\lambda_i^k(y_i^k) = \theta_i^k(1, \cdots, J-1)$. Since the condition state J is the absorption state of a Markov chain and $\pi_{JJ} = 1$ the rate of the hazard is not defined. The hazard rate $\theta_i^k(1, \ldots, J-1; k = 1, \cdots, K)$ characterizing the deterioration process of a road section is considered to change in relation to the vector x^kas follows;

$$\theta_i^k = x^k \beta_i' \tag{5.35}$$

Where $\beta_i = (\beta_{i,1}, \cdots, \beta_{i,M})$ is a row vector of unknown parameters $\beta_{i,M}(m = 1, \cdots M)$ and the symbol $'$ indicates the vector is transposed. In order to obtain Markov transition probabilities the first step consists in estimating the exponential hazard function $\lambda_i^k(y_i^k) = \theta_i^k$ based on the inspection sample information $\Xi^k(k = 1, \cdots, K)$. In the following section, the estimation of the exponential hazard function is described. As a second step, Markov transition probabilities are estimated using the exponential hazard functions found in the previous step. The methodology proposed by this paper permits estimating Markov transition probabilities for every individual section. However, determining an optimal repair strategy for every individual road section can complicate its application to the pavement management practice. For this reason, it can be more convenient in many cases to assume an average Markov transition probability analog to that of the sections. The estimation of the average Markov transition probability using the exponential hazard model estimated is explained in the following chapter. In addition, using exponential hazard models a risk management index for pavement management can also be derived. The expected elapsed period from the time the rating in question is reached until the following rating is attained as a result of the deterioration progress (referred to as the expected life expectancy of a rating) is defined by using the survival function $R_i(y_i^k)$ as follows (Lancaster, 1990).

$$RMD_i^k = \int_0^\infty R_i(y_i^k) dy_i^k \tag{5.36}$$

By defining the survival function $R_i(y_i^k)$ in terms of the exponential hazard function as in Eq. 26, the expected life expectancy of a rating is expressed by the following;

$$RMD_i^k = \int_0^\infty exp(-\theta_i^k y_i^k) dy_i^k = \frac{1}{\theta_i^k} \tag{5.37}$$

B. Estimation of the Hazard Rate

Information $\Xi^k = (\bar{\delta}_{ij}^k, \bar{Z}^k, \bar{x}^k)$ can be acquired in relation to the inspection sample k, where the symbol '-' indicates an actual measurement. The Markov transition probabilities can be expressed in terms on the hazard functions. Although the hazard rate $\theta_i^k (i = 1, \cdots, J-1; K = 1, \cdots, K)$ of each condition is contained in the Markov transition probabilities, it can be represented by the Eq. 5.15 when using the vector $\bar{x}^k$ of a road section. Moreover, the deterioration transition probability also depends on inspection interval $\bar{Z}^k$ in which the data was observed. For clarity of expression, the transition probability π_{ij} is expressed as a function of the measured data $(\bar{Z}^k, \bar{x}^k)$ obtained from inspection and the unknown parameters β_i as $\pi_{ij}(\bar{Z}^k, \bar{x}^k : \beta_i)$. If the deterioration progress of the road sections in sample K is assumed to be mutually independent, the log-likelihood function expressing the simultaneous probability density of the deterioration transition pattern for all inspection samples is expressed by the following (Tobin 1958; Amemiya and Boskin, 1974);

$$ln[\Gamma(\beta)] = ln\left[\prod_{i=1}^{J-1}\prod_{j=1}^{J}\prod_{k=1}^{K}\left\{\pi_{ij}(\bar{Z}^k, \bar{x}^k : \beta)\right\}^{\bar{\delta}_{ij}^k}\right] \\ = \sum_{k=1}^{K}\sum_{i=1}^{J}\sum_{j=1}^{J}\bar{\delta}_{ij}^k \, ln[\bar{Z}^k, \bar{x}^k : \beta] \tag{5.38}$$

where $\bar{\delta}_{ij}^k, \bar{Z}^k$ and $\bar{x}^k$ are all determined by inspection values and $\beta_i = (i = 1, \cdots, J-1)$ are parameters to be estimated. Estimations of the parameters β can be obtained by solving the optimality conditions that result from maximizing the log-likelihood function (see Eq.5.38).

$$\frac{\partial ln\,[\Gamma(\hat{\beta})]}{\partial \beta_{i,m}} = 0, (i = 1, \cdots, J-1; m = 1, \cdots, M) \tag{5.39}$$

The optimal values $\hat{\beta} = (\hat{\beta}_{1,1}, \cdots, \hat{\beta}_{J,M})$ are then estimated by applying a numerical procedure such as the Newton Method for the $(J-1)M$ nonlinear simultaneous equations. Furthermore, the estimator for the asymptotical covariance matrix of the parameters is given by $\hat{\sum}(\hat{\beta})$.

$$\hat{\sum}(\hat{\beta}) = \left[\frac{\partial^2 ln\{\Gamma(\hat{\beta})\}}{\partial\beta\partial\beta'}\right]^{-1} \tag{5.40}$$

The $(J-1)M \times (J-1)M$ inverse matrix of the right-hand side of the above formula, composed by the elements $\left[\frac{\partial^2 \ln\{\Gamma(\hat{\beta})\}}{\partial\beta\,\partial\beta'}\right]$ results to be the inverse matrix of the Fisher information matrix.

C. Average Markov Transition Probability

Given the vector x^k and the inspection interval Z^k the Markov transition probabilities of a road section can be estimated by using Eqs. 5.32a ~ 5.32d. Markov transition probabilities satisfying time adjustment conditions can be estimated for arbitrary inspection intervals by changing the value Z^k. As proposed in this paper, a Markov transition probability matrix characterizing every road section can also be estimated. However, when forecasting the deterioration pattern of many road sections as a whole, in many cases, it is more convenient to search an average transition probability rather than a transition probability for every section. For that purpose, it is necessary to develop a methodology to estimate the average transition probability matrix that also satisfies at the time adjustment conditions. The methodology presented in this chapter pays attention to the hazard rates $\theta_i^k (k = 1, \cdots, K)$. The distribution function of the pavement characteristics for the sample of road sections is expressed as $\Lambda(x)$. For this case, the expected value of the hazard rate $E[\theta_i]$ for the sample is defined as;

$$E[\theta_i] = \int_{\Theta} x\beta_i' d\ \Lambda(x) \tag{5.41}$$

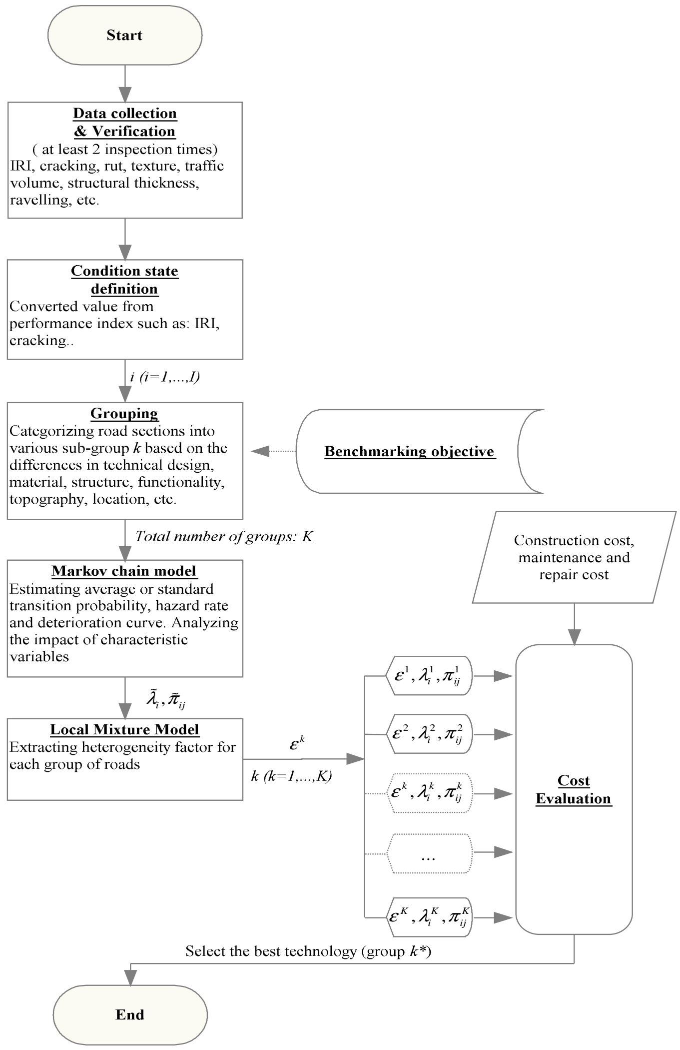
where $'\Theta'$ makes reference to the sample. A Markov transition probabilities matrix is said to satisfy the time adjustment conditions if 1) Markov transition probabilities are estimated by using the exponential hazard functions (refer to Eqs. 5.32a ~ 5.32d), and 2) the Markov transition probabilities matrix for each sample is defined by the hazard rates $\theta_i^k (i = 1, \cdots, J-1; k = 1, \cdots, K)$. Therefore, a Markov transition probabilities matrix estimated by using the averaging the Eq. 5.41 is said to also satisfy the time adjustment.

5.3.4 Local Mixture Hazard Model

5.3.4.1 Introduction

Another stochastic model in the Hybrid PMS is the local mixture hazard model estimating heterogeneity factors of each individual pavement category based on local mixing mechanism. The Markov hazard model introduced in the Chapter 5.3.3 dedicated for forecasting the average life expectancy of the whole network or whole sample. This was called as the benchmarking approach. The further explore benchmarking application in order to select the best alternatives for standardization by making groups having different characteristics on pavement design method, material, climate condition, geometric conditions etc. Good examples have been introduced by Nam (2009) about the national road in Vietnam where the entire road system is comprised of many different technologies. Since Vietnam government have often borrowed budget and technologies from abroad, most of their national standards for design and construction practices are copied from developed countries. Nam (2009) investigated pavement performance of various technologies applied in the national highway, and found best technology among the materials. In addition, the paper compared regional groups of pavement sections under different environmental conditions. It was a meaningful trial because Vietnam is vertically long country having different climate conditions by regions.

Like the practices, a main role of the local mixture hazard model is to find difference of deterioration speed of road section groups having different road characteristics. Such trials can help standardizing PMS specifications for better management work enhancing cost-effectiveness. Hence, in view of long term and strategic management, this model would be useful to PMS as time goes on. The following section gives an overview of mixture hazard model. The Figure 5.4 shows overall procudures of the mixture hazard model.



Source: NAM, 2009

Figure 5.4 Benchmarking flowchart by the Mixture hazard model

5.3.4.2 Markov Transition Probability and Heterogeneity Factor

In general, the deterioration speed of every road section is very different from each other even though they have same conditions affecting pavement deterioration speed, such as thickness of layers, material, slope, etc. About the deterioration speed of the sections having similar characteristics, only one deterioration curve is drawn based upon their hazard rate. The Markov hazard model is used to estimate this average.

In reality, deterioration process varies differently among pavement groups due to dynamic factors. Thus, it is hard to grant a homogenous sampling population in estimation. To express this inhomogeneous sampling population, many literatures in liability modeling employ the term *"Heterogeneity factor"*. In pavement system, we assume the entire road system comprising of K group of road according to their technological difference. In each group $k(k = 1, \ldots, K)$, total road section is S_k. And ε^k is referred as the heterogeneity factor, which infers the change of characteristic of a peculiar hazard rate $i(i = 1, \ldots, J-1)$ to a pavement section s_k $(s_k = 1, \ldots, S_k)$. Thus, the mixture index hazard function can be further expressed as;

$$\theta_i^{s_k} = \tilde{\theta}_i^{s_k} \varepsilon^k \tag{5.42}$$
$$(i = 1, \ldots, J-1; k = 1, \ldots, K;\ s_k = 1, \ldots, S_k)$$

Where the $\tilde{\theta}_i^{s_k}$ is average hazard rate. And the ε^k is always non-negative which is the higher value of ε^k means the faster deterioration speed of road section s_k. Within the one group of road sections (or one technology), the index hazard of all ratings hold the same value of heterogeneity factor ε^k. Counting all road sections as the whole, the distribution of ε^k is exactly representing the influence of individual group of road sections on the overal deterioration process. Depending on structural characteristic of each system, heterogeneity factor ε^k can be in form of a function or stochastic variable.

For measurable representation, we denote a set of value of $\varepsilon^k(k = 1, \ldots, K)$ as a vector $\bar{\varepsilon}^k$. The bar, [-], indicates measurable value. As a result, we can further expressed survival probability in the Eq. 5.26 by means of mixed hazard rate in the Eq. 5.42 for a pavement group k.

$$R_i(y_i^k) = exp\,(-\tilde{\theta}_i\ \bar{\varepsilon}^k\ y_i^k) \tag{5.43}$$

Siminarly, Markov transition probability expressed in the Eqs. 32a ~ 32d are derived as follows.

$$\pi_{ii}^k(z^k : \bar{\varepsilon}^k) = exp(-\tilde{\theta}_i\, \bar{\varepsilon}^k z^k) \tag{5.44a}$$

$$\pi_{ij}^k(z^k : \bar{\varepsilon}^k) = \sum_{l=i}^{j} \prod_{m=i}^{j-1} \frac{\tilde{\theta}_m^k}{\tilde{\theta}_m^k - \tilde{\theta}_l^k} exp(-\tilde{\theta}_i\, \bar{\varepsilon}^k z^k) \tag{5.44b}$$
$$= \sum_{l=i}^{j} \psi_{ij}^l(\tilde{\theta}^k)\, exp(-\tilde{\theta}_i\, \bar{\varepsilon}^k z^k)$$
$$(i = 1, \ldots, J-1; j = j+1, \ldots, J; k = 1, \ldots, K)$$

Where,

$$\psi_{ij}^l(\tilde{\theta}^k) = \prod_{m=i}^{j-1} \frac{\tilde{\theta}_m^k}{\tilde{\theta}_m^k - \tilde{\theta}_l^k} \tag{5.45}$$

5.3.4.3 Local Mixing Mechanism

A great deal of past resarch has revealed the difficulties in defining the heterogeneity factor ε^k. The assumption of the hetrogeneity factor to be in the form of a function or a stochastic variable crucially depends on the characteristics of the system itself and the availability of inspection data (Lancaster, 1990). This section focuses on applying mixture model the case that the value distribution of heterogeneity factor ε^k has a small dispersion.

In other words, the departure of heterogeneity factor from homogeneity is in small scale. This type of mixture model is named as local mixture model. In exponential family form $f(x;\epsilon)$ (where x and ϵ are variable and heterogeneity respectively) as similar to Markov hazard model, local mixing mechanism is defined via its mean parameterization δ^k.

$$g(x;\mu) := f(x;\epsilon) + \sum_{i=2}^{r} f^k(x;\epsilon) \tag{5.46}$$

Where,

$$f^k(x;\epsilon) = \frac{\delta^k}{\delta\epsilon^k} f^k(x;\epsilon)$$

Another class of local mixture model that captures the behavior of scale dispersion in mixture of function $f^k(x;\epsilon)$, is defined as local scale mixture model.

$$g(x;\mu) := f(x;\epsilon) + \sum_{i=2}^{r} \frac{\epsilon^k}{k!} f^k(x;\epsilon) \tag{5.47}$$

Expansion of series in the Eq.5.46 and Eq.5.47 can be observed to follow Taylor series. Since likelihood function of Markov transition probability in Eq.5.46 and Eq.5.47 belongs to exponential family. We are able to approximate in the form of local mixture distribution.

$$\tilde{\pi}_{ij}(z) = \int_0^\infty \pi_{ij}(z:\varepsilon) f(\varepsilon) d\varepsilon \quad (i = 1, \dots, J-1) \tag{5.48}$$

For convenience of mathematical manipulation, we assume local mixture transition probability as exponential function $f_{mix}(\varepsilon, z, \theta)$ with the "*mix*" indicating the meaning of mixture. As the sequent, a true behavior of mixture function $f_{mix}(\varepsilon, z, \theta)$ can be described by means of standard function $f_{mix}(\varepsilon, z, \theta)$ and distribution $H(\varepsilon)$. The Eq. 5.48 can be simplified as,

$$f_{mix}(\varepsilon, z, \theta) = \int f_{mix}(\varepsilon, z, \theta) dH(\varepsilon) \tag{5.49}$$

Where $f_{mix}(\varepsilon, z, \theta) = \exp(-\varepsilon\theta z)$. Function, $f(\varepsilon, z, \theta)$ is likely a function of ε about its mean. Without no loss of generality, and as long as the mean exist, we can further decompose the Eq. 5.47 as follows.

$$exp(-\varepsilon\,\theta\,z) = e^{-\theta z}\left(1 + (\epsilon - 1)(-\theta z) + \frac{(\epsilon-1)^2}{2!}(-\theta z)^2 + \cdots\right. \tag{5.50}$$

This is the Taylor series. And thus, quadratic form (when $r = 2$) is acceptable for accurate approximation. Consequently, a very attractive and explicit form of approximation can be derived for Markov transition probability.

$$E\left(e^{-\varepsilon\theta z}\right) \approx e^{-\theta z}\left\{1 + \frac{(\sigma\theta z)^2}{2}\right\} \tag{5.51}$$

And,

$$\tilde{\pi}_{ii}(z) = e^{-\tilde{\theta}_i z}\left\{1 + \frac{(\sigma\tilde{\theta}_i z)^2}{2!}\right\} \tag{5.52a}$$

$$\tilde{\pi}_{ij}(z) = \sum_{l=i}^{j} \psi_{ij}^{l}\left(\tilde{\theta}^k\right) e^{-\tilde{\theta}_i z}\left\{1 + \frac{(\sigma\tilde{\theta}_i z)^2}{2!}\right\} \tag{5.52b}$$
$$(i = 1, \dots, J-1; j = i+1, \dots, J)$$

5.3.4.4 Likelihood Estimation Approach

The estimation for Markov transition probability and heterogeneity factor requires collective information from two inspections. Supposing that periodical inspection data on S_k road sections according to technological aspect is available. An inspection sample s_k (a road section) has two consecutive discrete periodical inspections at times $\bar{\tau}_A^{S_k}$ and $\bar{\tau}_B^{S_k} = \bar{\tau}_A^{S_k} + \bar{z}^{S_k}$ with its respective condition states $h(\bar{\tau}_A^{S_k}) = \mathrm{i}$ and $h(\bar{\tau}_B^{S_k}) = j$. Based on inspection data of $\sum_{k=1}^{K} S_k$ samples, $\bar{\delta}_{ij}^{S_k}(i = 1, \dots, J-1, j = i, \dots, J; S_k = 1, \dots, S_K; k = 1, \dots, N_k)$, is defined to satisfy the following conditions:

$$\bar{\delta}_{ij}^{S_k} = \begin{cases} 1, & h(\bar{\tau}_A^{S_k}) = i \; and \; h(\bar{\tau}_B^{S_k}) = j \\ 0, & Otherwise \end{cases} \tag{5.53}$$

The range of dummy variable, $= (\bar{\delta}_{ij}^{S_k}, \dots, \bar{\delta}_{J-1,J}^{S_k})$ is denoted by using vector $\bar{\delta}^{S_k}$. Furthermore, the structural characteristic and environmental condition of road components that effect the deterioration speed are represented by the row vector $\bar{x}^{S_k} = (\bar{x}_1^{S_k}, \dots, \bar{x}_M^{S_k})$ with $\bar{x}_M^{S_k}(m = 1, \dots, M)$ indicating the observed variable m for the sample s_k. The first variable $x_1^{s_k}=1$ is a constant term. Thus, the information concerning inspection data of the sample k can be described as $\Xi^{s_k}=(\delta^{s_k},\bar{z}^{s_k},\bar{x}^{s_k})$.

The hazard rate of condition state i of sample s_k can be expressed by using mixture hazard function $\theta_i^{s_k}(y_i^{s_k})=\tilde{\theta}_i^{s_k}\varepsilon^k(i=1,\dots,J-1)$. The J is absorbing condition state satisfying transition probability $\pi_{JJ}^{s_k}=1$ and $\tilde{\theta}_J^{s_k}=0$. The hazard rate $\tilde{\theta}_i^{s_k}(i=1,\dots,J-1;s_k=1,\dots,L_k)$ depends on the characteristic vector of pavement section and suppose to change to the vector s_k as follows

$$\tilde{\theta}_i^{s_k}=x^{s_k}\beta_i' \tag{5.54}$$

where $\beta_i=(\beta_{i,1},\dots,\beta_{i,M})$ is a row vector of unknown parameters $\beta_{i,M}(m=1,\dots,M)$ and the symbol $[\,']$ indicates the vector is transposed. From the Eq.5.52a and Eq.5.53b, the standard hazard rate of respective condition states can be expressed by means of $\tilde{\theta}_i^{s_k}(i=1,\dots,J-1;s_k=1,\dots,L_k)$ and the hetrogeneity paremeter ε^k. Average Markov transition probability is expressible by the Eq. 54b when using row vector $\bar{x}^{s_k}$. In addition, the transition probability also depends on inspection time interval $\bar{z}^{s_k}$.

For clarity of presentation, the transition probability π_{ij} is expressed as a function of measured data $(\bar{z}^{s_k},\bar{x}^{s_k})$ and unknown parameter $\theta=(\beta_1,\dots,\beta_{J-1},\sigma)$ as $\tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k},\bar{x}^{s_k}:\theta)$. If the deterioration progress of the road sections l_k in the entire samples L_k are assumed to be mutually independent, the likelihood function expressing the simultaneous probability density of the deterioration transition pattern for all inspection samples is defined as (Tobin, 1958 ; Amemiya and Boskin, 1974).

$$L(\theta,\Xi)=\prod_{i=1}^{J-1}\prod_{j=1}^{J}\prod_{k=1}^{K}\prod_{s_k=1}^{S_k}\left\{\tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k},\bar{x}^{s_k}:\theta)\right\}^{\bar{\delta}_{ij}^{s_k}} \tag{5.55}$$

By means of heterogeneity factor expressed by Taylor series, we further express the explicit form of Markov transition probability as follows;

$$\tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k},\bar{x}^{s_k}:\theta)=e^{\bar{x}^{s_k}\beta_i'\bar{z}^{s_k}}\left\{1+\frac{(\sigma^{s_k}\bar{x}^{s_k}\beta_i'\bar{z}^{s_k})^2}{2\,!}\right\} \tag{5.56}$$

$$\tilde{\pi}_{ij}(\bar{z}^{s_k},\bar{x}^{s_k}:\theta)=\sum_{l=i}^{j}\psi_{ij}^{l}(\theta)e^{\bar{x}^{s_k}\beta_i'\bar{z}^{s_k}}\left\{1+\frac{(\sigma^{s_k}\bar{x}^{s_k}\beta_i'\bar{z}^{s_k})^2}{2\,!}\right\} \tag{5.57}$$
$$(i=1,\dots,J-1\,;J=J+1,\dots,J)$$

Where $\psi_{ij}^{s}(\theta^{l_k})$ is referred to the Eq. 5.45. Since $\bar{\delta}_{ij}^{s_k},\bar{z}^{s_k},\bar{x}^{s_k}$ are known from inspection, thus, $\hat{\theta}(\hat{\beta},\hat{\sigma})$ can be estimated by the maximum likelihood approach. For computational convenience, the Eq. 5.55 can be rewritten by means of logarithm.

$$L(\theta,\Xi)=\prod_{i=1}^{J-1}\prod_{j=1}^{J}\prod_{k=1}^{K}\prod_{s_k=1}^{S_k}\left\{\bar{\delta}_{ij}^{s_k}\tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k},\bar{x}^{s_k}:\theta)\right\} \tag{5.58}$$

The estimation of the θ can be obtained by solving the optimality conditions;

$$\frac{\partial\ln L(\theta,\Xi)}{\partial\,\theta_i}=0,\qquad(i=1,\dots,(J-1)M+1) \tag{5.59}$$

The optimal $\hat{\theta}=\left(\hat{\theta}_1,\dots,\hat{\theta}_{(J-1)M+1}\right)$ are then estimated by applying a numerical iterative procedure such as Newton Method for the $(J-1)M+1$ order nonlinear simultaneous equations (Isota and Ono, 2005). Furthermore, estimator for the asymptotical covariance matrix $\sum(\hat{\theta})$ of the parameters is given by;

$$\sum(\hat{\theta})=\left[\frac{\partial^2\ln L(\hat{\theta},\Xi)}{\partial\theta\partial\theta'}\right]^{-1} \tag{5.60}$$

The $\big((J-1)M+1\big)(J-1)M+1)$ order inverse matrix of the right-hand side of the formula, composed by the elements $\frac{\partial^2\ln L(\hat{\theta},\Xi)}{\partial\theta\partial\theta'}$, results to be the inverse matrix of the Fisher's information matrix.

5.3.4.5 Estimation of Heterogeneity Factor

Information on inspection sample s_k of pavement group k is denoted as $\zeta^{s_k}(s_k = 1, \ldots, S_k)$. To describe the condition states of individual sample, the first and cecond condition states of sample are assumed as $i(s_k)$ and $j(s_k)$. It is supposed that the parameter set $\theta = (\beta_1, \ldots, \beta_{J-1}, \hat{\sigma})$ is available. If we consider the distribution of heterogeneity factor ε^k expressed by function $\bar{f}(\varepsilon:\hat{\sigma})$, the probability density accounting for the transition pattern of each inspection sample ζ^{s_k} can be obtained by;

$$\rho^{s_k}(\varepsilon^k:\theta,\zeta^k) = \left\{\pi^{s_k}_{i(s_k)j(s_k)}(\bar{z}^{s_k},\bar{x}^{s_k}:\beta,\varepsilon^k\right\}^{\bar{\delta}^{s_k}_{i(s_k)j(s_k)}} \bar{f}(\varepsilon:\hat{\sigma}) \tag{5.61}$$

where function $\bar{f}(\varepsilon:\hat{\sigma})$ follows the local mixing mechanism as previously described. Further consideration for the entire sampling population in pavement group k, it is able to expressed the simultaneous occurrence probability density function concerning heterogeneity factor ε^k as,

$$\rho^{S_k}\left(\varepsilon^k:\hat{\theta},\zeta^k\right) = \prod_{s_k=1}^{S_k} \rho^{s_k}\left(\varepsilon^k:\hat{\theta},\zeta^k\right) \propto$$
$$\prod_{s_k=1}^{S_k}\left\{\sum_{i=i(s_k)}^{j(s_k)} \psi^l_{i(s_k)j(s_k)}\left(\tilde{\theta}^{s_k}(\hat{\theta})\right) exp\left(-\tilde{\theta}^{s_k}(\hat{\theta})\varepsilon^k z^{s^k}\right)\right\}^{\bar{\delta}^{s_k}_{i(s_k)j(s_k)}} \left\{1+\frac{\left(\sigma\tilde{\theta}^{s_k}z^{s_k}\right)^2}{2!}\right\}^{S_k} \tag{5.62}$$

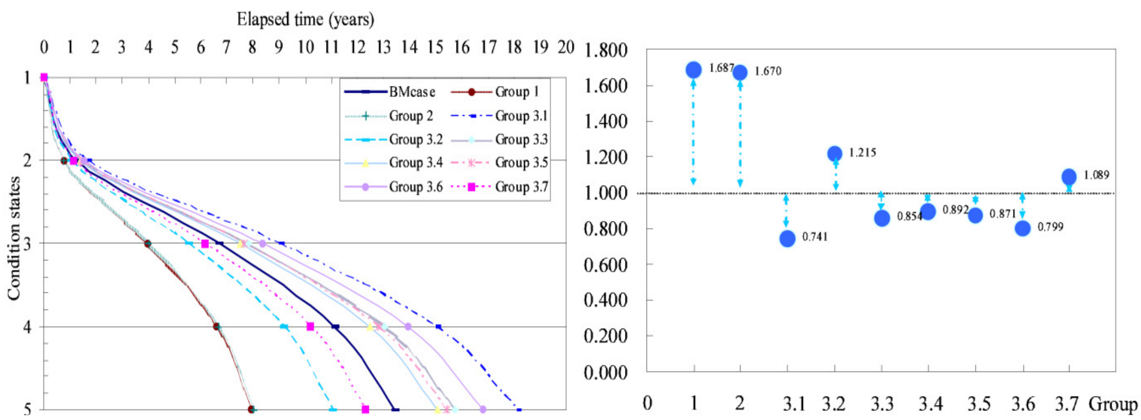
The standard or average hazard rate is expressible by mean of vector $\tilde{\theta}^{s_k}(\hat{\theta}) = \{\tilde{\theta}^{s_k}_i(\hat{\theta}), \ldots, \tilde{\theta}^{s_k}_{J-1}(\hat{\theta})\}$. Thus, average hazard rate $\tilde{\theta}^{s_k}_i$ is understood to depend on the parameter $\hat{\theta}$. To gain the explicit form of probability density function in the Eq. 5.62, patial logarithm was applied as follows,

$$ln\, \rho^{S_k}\left(\varepsilon^k:\hat{\theta},\zeta^k\right) \propto \sum_{s_k=1}^{S_k} \bar{\delta}^{s_k}_{i(s_k)j(s_k)}\, ln\left\{\sum_{m=i(s_k)}^{j(s_k)} \psi^l_{i(s_k)j(s_k)}\left(\tilde{\theta}^{s_k}(\hat{\theta})\right) exp\left(-\tilde{\theta}^{s_k}(\hat{\theta})\varepsilon^k z^{s^k}\right)\right\}$$
$$+s_k ln\left\{1+1+\frac{\left(\sigma\tilde{\theta}^{s_k}z^{s_k}\right)^2}{2!}\right\} \tag{5.63}$$

Optimal solution to get the value of heterogeneity factor $\varepsilon^k(k = 1, \ldots, K)$ can be evaluated through maximizing the Eq. 5.63 with respect to ε^k as variable and $\hat{\theta} = (\hat{\beta}_1, \ldots, \hat{\beta}_{J-1}, \hat{\sigma})$.

$$max_{\varepsilon^k}\left\{ln\, \rho^k\left(\varepsilon^k:\hat{\theta},\zeta^k\right)\right\} \tag{5.64}$$

The mixture hazard model is structurally similar with the Markov hazard model. But the mixture hazard model makes one more result on the heterogeneity factors of road section group $k(k = 1, \ldots, K)$. However, we can compare their deterioration speeds by comparing of the heterogeneity factor directly. As an example, the Vietnamese case study performed by Nam (2009) is introduced in the Figure 5.5.



Source: Nam, 2009

Figure 5.5a (left) Comparison of life expectancies of different road group

Figure 5.5b (right) Comparison of heterogeneity factors ε^k of road group (in the Fig. 5.5a)

5.3.5 Issues on Sample Scale and Inversed Condition

This paper introduces a flexible dataset structure for maximizing the sample scale for various purposes. Each interval between maintenances has more than one inspection point. Using this characteristic, data can be disaggregated by the "Inspection-based dataset (I-set)" and the "Maintenance-based dataset (M-set)." The difference between the two concepts is the condition of the initial state. The concept is illustrated in the Figure 5.6.

The M-set is started from the initial condition after (re)construction or rehabilitation level of maintenance (usually, higher than overlay level) assumed by the user, while the condition changes of the I-set is determined by two inspection points. Of course, the two sets can be applied at the same time (denoted as 'A-set') to maximize the data set. If a user wants to apply the M-set, an assumption of the initial condition is essential (see Figure 5.6). In the application, an assumption of the reset condition has important meanings. This assumption makes difference on deterioration speed. The difference could lead to biased deterioration modeling, and makes an effect to life cycle cost analysis, especially in a long-term analysis. Furthermore, sometimes it becomes a reason of the inverse condition which is being better condition without any maintenance work from last inspection. Accordingly, the I-set is better for the deterioration modeling because it does not need to assume the initial condition. Besides, establishing a time-series data set (I-set) has great benefit for research purposes. Above all, the actual deterioration history can be derived without any estimation or assumption. Moreover, the sample scale is increased in a geometric progression because many data sets can be additionally generated by combinations by using every inspection point. This may facilitate the application of the stochastic model, which requires a huge amount of historical pavement condition data. The inversed condition can also be ignored under the I-set.

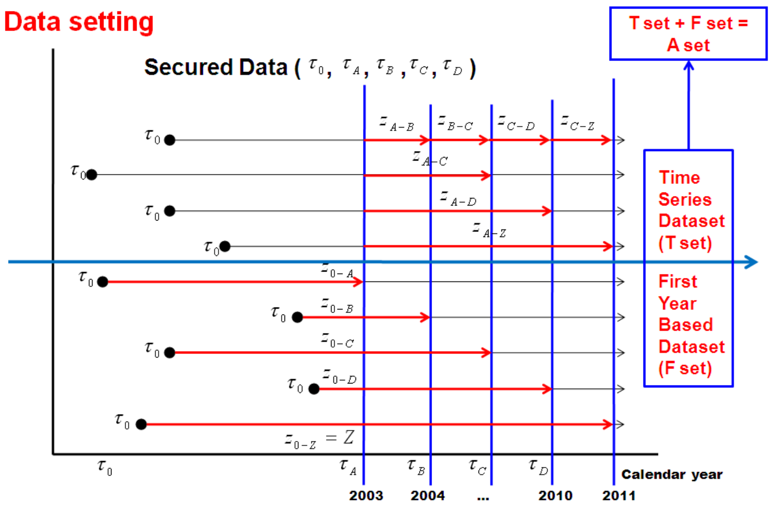


Figure 5.6 Structure of pavement performance data

As noted above, the time-series data has much strength for PMS. Nevertheless, building the I-set is not so easy because of budget constraints. Even though the M-set is much more viable than the I-set for the practical PMS situation, the I-set is recommended for pavement deterioration modeling in a strict sense.

5.4. Compatibility of Forecasting Results between Deterministic and Stochastic Models

As described in the Chapter 5.2, the forecasting models in the Hybrid PMS have different type of results, and different properties. In summary,

- State basis result VS. annual basis result
- Network basis result VS. section basis result

In case of the Markov hazard model, fixed standard of the condition state should be firstly defined by users, than the model finds the time point when the road condition reaches the user-specified condition. And the forecasted benchmark process represents deterioration process of a network. On the contrary, the annual basis model (single and multiple regression model) estimates annual basis condition. For that reason, it is difficult to compare their result directly. Much practical problem in the Hybrid PMS is that it is impossible to apply state basis model for life cycle cost analysis model because the LCCA models of the Hybrid PMS are following annual basis framework under deterministic approach. Thus, an additional function that converts the state based result into year-based result is demanded. The method has a concept which has several regression models reflecting deterioration speed of each state. Besides, a method converting annual basis result into state basis result) can help direct comparison between models. By a simple method under simple assumptions, the conversion can be readily done. This Chapter will describe both ways.

5.4.1 Compatibility between Annual-basis Result and State-basis Result

5.4.1.1 Converting Annual Basis Result into State Basis Result

The way converting annual basis into the state basis is can be easily done by linear interpolation. The method is to find exact time points $P(H_i)$ that deterioration indices k passes condition state state i $(i = 1, \ldots, J-1)$. In brief. $\widehat{H}(P_i) \;>\; H_i$, $P(H_i)$ is given by;

$$P(H_i) = P(H_{i-1}) + \frac{Obj(i)}{CD(i)} \tag{5.65}$$

where, the passing zone $CD(i)$, and target interval to be adjusted $Obj(i)$ in the Eq. 5.65 can be estimated by,

$$CD(i) = H(P_{i+1}) - H(P_i) \tag{5.66}$$

$$Obj(i) = H(i) - H(P_i) \tag{5.67}$$

By the Eqs. 5.65 ~ 5.65, $P(H_i)$ can be estimated by a number of condition states. The linear interpolation is quick and easy, but it is not very precise. Another disadvantage is that interpolation is not differentiable at the point (Wikipedia, 2010b). Of course, the linear interpolation can be substituted by the other type of interpolation, such as polynomial type or Gaussian process. However, the disadvantage would be not so huge for this case, since the states to explain deterioration process of pavement are usually defined by 5-6 state, thus the bias is not so significant when we consider the fact that usual life expectancy of a maintenance work is around 10-20 years.

5.4.1.2 Converting State Basis Result into Annual Basis Result

As noted in the beginning of the Chapter 5.4, the method converting state basis result into annual basis result has much important meaning due to the application of state based results into LCCA model of the Hybrid PMS. The method converting state basis result into annual basis result has opposite meaning with the method described in the Chapter 5.4.1.1. Simply, this function is to find condition of year. The is another sub-model that results annual basis condition by using the state basis condition when a user applies state based result to the life cycle cost analysis.

An assumption to facilitate the estimation is that condition change between the states is following the linear progression. With the assumption, deterioration speeds of each interval can be characterized by speed parameters. Note that the parameter β in this chapter has different meaning in the Chapter 5.3. The concept is illustrated in the Figure 5.8.

A. Reinterpretation of the Markov chain by the localized regression model
Theoretically, ΔDI_t which is the quantity of deteriorated pavement condition during estimation unit t is obtainable by using a simple equation with estimated results from the Markov hazard model.

$$\Delta DI_t = \lambda_i t, \qquad (t = 1) \tag{5.68}$$

However, the method cannot be applied to annual basis estimation structure (*i.e.* t=1) as it is, because bias are happen at every state condition change i to i+*1*, or from i to $i + j$ which is affected by more than 2 speed parameters $\lambda_i, \ldots, \lambda_{i+j}$. For that reason, it should be reinterpreted by the localized regression developed by this paper. The concept is simply described in the Figure 5.7.

An assumption to facilitate the estimation is that condition change between the states is following the linear progression. With the assumption, deterioration speeds of each interval can be characterized by the β_i^k. The information of the $H(i^k)$ and corresponding years $\tau(i^k)$ were from the Markov hazard model. The $\tau(i^k+1)-\tau(i^k)$ becomes life expectancies of each state $i(i=0,\ldots,J-1)$. Note that the capital J means the last state which indicates absorbing state. The life expectancies are used for estimation of condition intervals for applying different β_i^k. The parameters can be found by Eq. 5.69.

$$\beta_i^k = \frac{1}{\lambda_i} \quad i.e. \quad \beta_i^k = \left[\frac{H(i^k+1)-H(i^k)}{\tau(i^k+1)-\tau(i^k)}\right], \quad (i=0,\ldots,J-1) \tag{5.69}$$

Therefore, the basic estimation function for condition at analysis year p follows;

$$H^k(p) = \sum_0^p \beta_i^k [p_i^k] \tag{5.70}$$

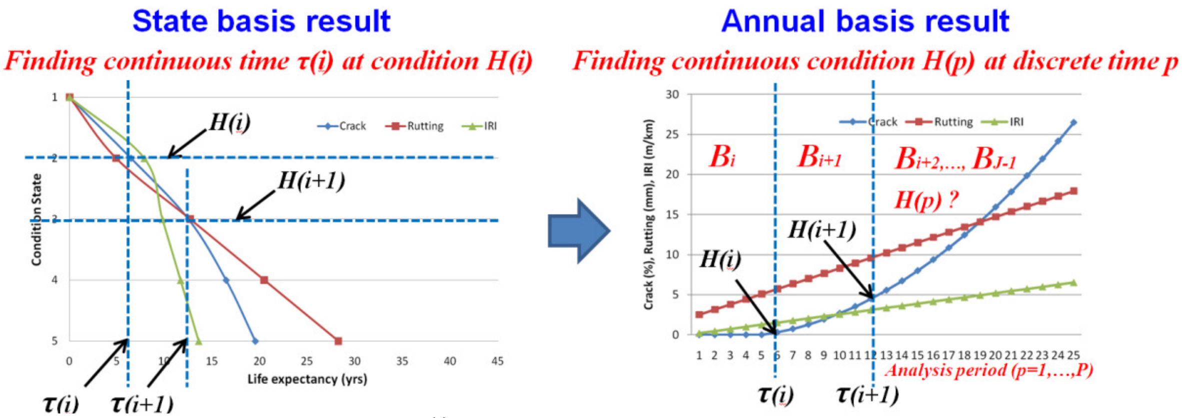
$$or \ H^k(p) = H^k(p-1) + \beta_i^k [p_i^k] \tag{5.71}$$

Where,

$H^k(p-1)$ = initial condition by maintenance work $(= H^k(p0))$

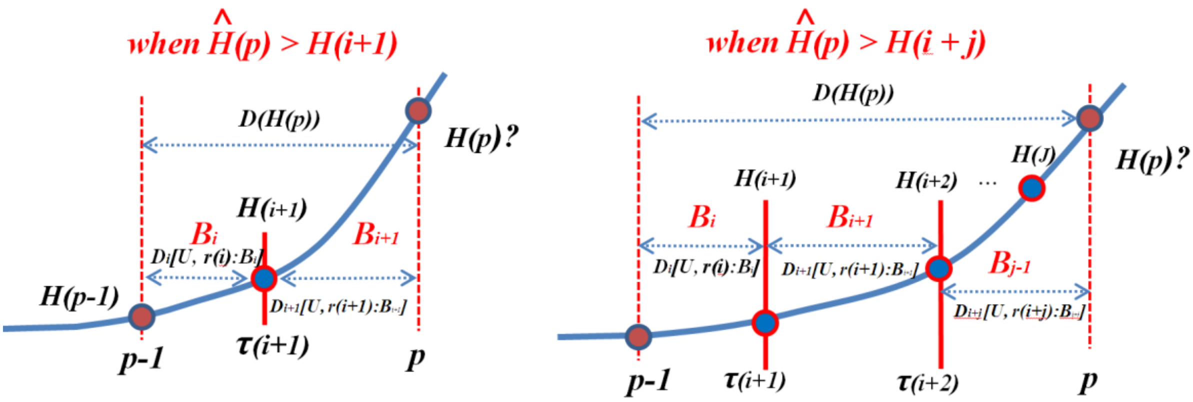
p_i^k = corresponding years with condition state of i of deterioration index k

As shown in the Figure 5.7, most of $H^k(p)$ are located between $\tau(i^k)$ and $\tau(i^k+1)$. However, cases that the estimated $\widehat{H}^k(p)$ over the $H(i^k+1)$ are happened at every $H(i^k+1)$. Sometimes it could be over the $H(i^k+j)$. Figure 5.8 is explaining the cases in detail.



Note: i = condition state $(i = 1,\ldots,J)$, $\tau(i)$ = condition point at condition state i, p = analysis period $(p=1,\ldots,P)$

Figure 5.7 A concept of a localized regression model by using Markov hazard model



Note: $D(H(p))$ = total deterioration between p and $p+1$, $D(i)$=deterioration affected by the β_i

Figure 5.8 Conditions affected by multi speed parameters (left: advancing 1 state, right: advancing j states)

If the $\widehat{H}^k(p)$ jumps only 1 state, the condition only affected by two speed parameters β_i^k and β_{i+1}^k. The total deterioration $D(H^k(p))$ equals to $[D(i^k) + D(i^k+1)]$. Thus, the Eq. 5.69 is substituted by Eqs. 5.72.

$$H^k(p) = H^k(p-1) + D(H^k(p)) \tag{5.72a}$$
$$D(H^k(p)) = D(i^k) + D(i^k+1) \tag{5.72b}$$
$$D(i^k) + D(i^k+1) = \beta_i^k r(i^k) + \beta_{i+1}^k r(i^k+1) \tag{5.72c}$$

The $D(i^k)$ is estimated by a function of estimation unit $U(=1)$, duration factor $r(i^k)$ and speed parameter β_i^k. The U and β_i^k are known. Thus, the $r(i^k)$ and $r(i^k+1)$ can be easily estimated by,

$$r(i^k) = \left[\frac{H(i^k+1) - H^k(p-1)}{\beta_i^k}\right] \tag{5.73a}$$
$$thus \quad r(i^k+1) = 1 - r(i^k) \tag{5.73b}$$

In case of jumping j states, the condition $H^k(p)$ is affected by $j+1$ speed parameters. Thus, it needs $r(i^k)$ as much as $j+1$. The series of $r(i^k+1) \ldots r\big(i^k+(j-1)\big)$ which are jumped states are given by,

$$r(i^k+1) \ldots r\big(i^k+(j-1)\big) = \left[\frac{H(i^k+2) - H^k(i^k+1)}{\beta_{i+1}^k}\right], \left[\frac{H(i^k+3) - H^k(i^k+2)}{\beta_{i+2}^k}\right] \ldots \left[\frac{H(i^k+j) - H^k(i^k+(j-1))}{\beta_{i+(j-1)}^k}\right] \tag{5.74}$$

And the duration $r(i^k+j)$ at the arrived state j is given by,

$$r(i^k+j) = 1 - [r(i^k) + r(i^k+1) \ldots r(i^k+j-1)] \tag{5.75a}$$
$$thus \quad r(i^k+j) = 1 - \textstyle\sum_i^{j-1} r(i^k) \tag{5.75b}$$

Finally, the $H^k(p)$ which is deteriorated more than 2 states can be simply estimated by the Eq. 5.76.

$$H^k(p) = H(i^k+j) + [\beta_{i+j}^k r(i^k+j)] \tag{5.76}$$

The Eqs. 5.71, 5.75 and 5.76 can be expressed by a discriminant,

$$H^k(p) = \begin{cases} H^k(p-1) + \beta_i^k[p_i^k], & \widehat{H}^k(p) \leq H(i^k+1) \\ H^k(p) = H^k(p-1) + D(H^k(p)), & \widehat{H}^k(p) > H(i^k+1) \\ H^k(p) = H(i^k+j) + [\beta_{i+j}^k r(i^k+j)], & \widehat{H}^k(p) > H(i^k+j) \end{cases} \tag{5.77}$$

Under the state basis model, pavement condition $H^k(p)$ cannot be deteriorated more than the absorbing state $H(J^k)$ due to the nature of the Markov transition probability. If road agency defines the $H(J^k)$ for rehabilitation level (*e.g.* overlay level), the Markov hazard model cannot give information about reconstruction which is suitable for much worse condition. In such case, the $H(J^k)$ is needed to be extended. The localized regression model also demands the speed parameter $\beta_{(J-1)+\infty}^k$ for worse conditions than $H(J^k)$. However, it was assumed $\beta_{(J-1)+\infty}^k = \beta_{J-1}^k$ with the definition of critical states $H^k(M)$ for crack (100%), rutting (100mm) and IRI (16m/km) respectively (*i.e.* $H^k(p) \leq H^k(M)$). In summary, the state basis result is converted into estimation functions which have different deterioration speed by the condition state. Examples of the function are showing in Figure 5.9.

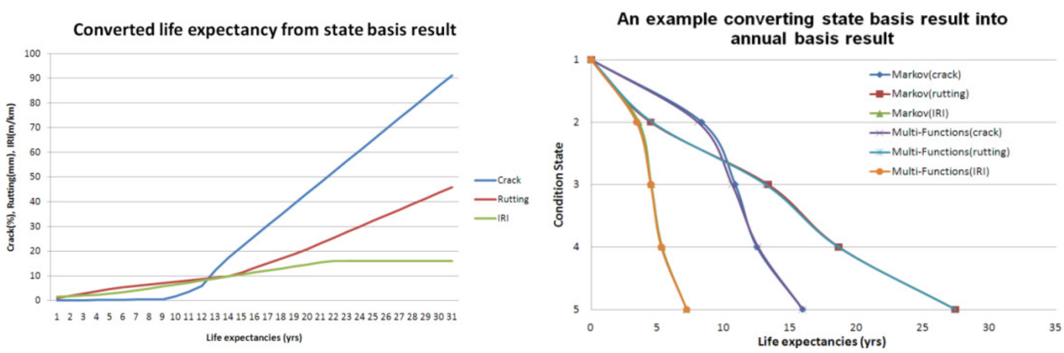


Figure 5.9 Examples on compatibilities between state basis result and annual basis result

5.4.2 Compatibility between Network and Section Basis Result

For easy comparison between section basis and network basis result, one of the two kind results should be changed into the other's type. Especially, the procedure converting network basis result into section basis result is essential for an application of the LCCA model in the Hybrid PMS. This chapter will address the both methods.

Basically, section basis information is from a representative regression models which are built by whole population of a network. Therefore the comparison can be easily available by drawing deterioration process be the regression model. In case of simple regression, it is enough to apply the time variable to the estimated linear regression model. For the case of the multiple regression model, average values of applied explanatory variables for the stochastic models may be reasonable, (even though, it has a limitation on exact presentation due to variance). Afterward, estimated benchmarked deterioration process characterized by the annual basis result has to be converted to state basis result (refer to Chapter 5.4.1.1). Then, direct comparison by using network level information is available.

The function that generates each section's deterioration processes from network basis result has an important role as a forecasting model in the LCCA modules. When user applies LCCA models by the Markov hazard model, preliminary steps are required;

A. Stochastic model builds the regression equations for estimating hazard rate θ_i of each condition state representing network.
B. Stochastic model calculates hazard rates of a network based on averaged explanatory variables x_i of a network
C. The hazard rates are converted into life expectancies of each condition state of a network.

As shown above procedures, the stochastic models just have network level information. Hence, additional procedures are required for producing each section's deterioration process by year. The work can be realized by simple procedures:

D. Set up the regression models estimated from the procedure "A" (network level model)
E. Substitute explanatory variables x_i of each section for the regression model
F. Estimate the hazard rates by condition state by using the regression model and explanatory variable of section
G. Estimate life expectancy of the condition state by using the hazard rate
H. Convert estimated state basis result into annual basis result (Refer to the Chapter 4.1.2)
I. Estimate deterioration speed of condition state $\beta(s_i)$ based on the result of the "H" step.
J. Define pavement condition of first year of simulation.
K. Run estimation function from the user specified condition(maybe inspection data to be started)
L. Complete deterioration process of sections for analysis period
M. LCCA model receives the results from the function.

5.5 Summary and Recommendations

Although the database system and PMS cycle management can support PMS activities during a cycle, it just treats "*Past*" and "*Present*" of PMS, the components cannot produce better solutions to enhance cost-effectiveness of their budget. Under the situation, they do not know whether or not their current management policy or specifications are optimized. The solution is introducing PMS analysis procedures. And its first step should be introduction of pavement deterioration forecasting (or estimation) model because it is a basement of all of PMS analysis.

Although the deterioration model is desired for everyone, its application is not for everyone. Since the pavement deterioration forecasting is totally depended upon the time-series pavement performance data and many explanatory variables, road agencies may be encountered many problems, unless they do not prepare suitable data contents from the initial stage of road construction. By the reason, deterioration models applied in many countries are usually different due to data condition or objectives. It implies that the Hybrid PMS should serve various deterioration model to give room for choice to everyone. To define general deterioration models, this paper was focusing their differences by following viewpoints;

- Data requirement
- Property of deterioration model
- Usage of result (Network level or Project level)

Data requirement is most critical factor for application of deterioration model. Even if someone develops very powerful model, it could be considered as useless one to others who cannot satisfy its data requirement. Thus, Hybrid PMS should have simple models that demands minimum data. Of course, advanced models should be settled for road agencies who are in a mature level.

The property of deterioration model can be classified into deterministic or stochastic model. Due to uncertainty in the pavement deterioration processes, usually stochastic models have been preferred than deterministic models in PMS sector. However, the deterministic model which developed by empirical or mechanistic approaches are also demanded for special cases for users who do not have enough capability to develop own model.

The usage of result could be distinguished by network level and project level. Network level application is usually for budget estimation or benchmarking approach on pavement deterioration process of network, while project level targets individual road section for specific purpose. The composition of deterioration model in the Hybrid PMS should cover both purposes. As a result, following model has been selected as member of deterioration model in the Hybrid PMS;

- Simplified linear regression
- Multiple regression
- Markov exponential hazard model
- Local mixture model

Since different properties of the deterioration models, their forecasting (or estimation) results cannot be compatible as it is. In addition, state basis results from stochastic models cannot be applied to LCCA model in the Hybrid PMS because the LCCA model demands annual basis input. As a solution, this paper suggested methodologies whereby make it compatible each other.

Note that the introduced four deterioration models or theories were not developed by this paper, but generally used in PMS sector. The most important concern of this chapter is not introducing various deterioration model, but how to compose deterioration models for the Hybrid PMS to satisfy various PMS situation and objectives.

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CHAPTER 6

Life Cycle Cost Analysis Model

6.1 General Introduction

Applying the principles of economic analysis to infrastructure projects occurs at two basic levels. First, the overall economic viability and timing of a project must be determined. This is most often carried out in comparison to and/or competition with other projects. Second, there is the requirement to achieve maximum economy for a project once it has been selected, programmed, and budgeted. Such within-project economic analysis is achieved by calculating the costs and benefits of the various alternatives that satisfy overall project requirements. In terms of economic analysis, the major difference between these two levels of infrastructure management is the amount of detail or information needed (Hudson *et al.*, 1997). To do the economic analysis, the life cycle cost analysis is an essence procedure.

The concept of LCCA is now widely applied to various management fields, especially in the infrastructure management. Basically, LCCA model for PMS estimates cost generated by operation of PMS by the viewpoint of agency, road user and socio-environmental effect. The concepts of LCC are mostly same but its definition particularly in contents of the user cost is usually different. In fact, there are many recommendations but there is no official standard which has been applied as an international standard. For that reason, the LCCA of the Hybrid PMS should be flexible and enough to satisfy various unknown users. The LCC contents of the Hybrid PMS has been determined by reviewing many previous researches and experiences. Since the LCC contents have been developed by independent modules, users can compose their original life cycle cost analysis model based on their PMS capabilities by aggregating contents from the Hybrid PMS. This is a main point of the hybrid concept.

In the Chapters 4.3.3 and 4.3.4, this paper has treated short-term economic analysis during a PMS cycle for practical PMS operation. The objective long-term economic analysis by LCCA is different from the former economic analysis in terms that the LCCA is for better future strategy applying estimation models. Properly, road agencies should have well-grounded sub-models for future description. This chapter will introduce LCCA models hired for the Hybrid PMS with fundamental knowledge and reviews of related researches to help understanding on basic concept of the LCCA in PMS

6.2 Customization Strategy in LCCA Model

The key points of customization strategy of LCCA model in the Hybrid PMS can be summarized as follows;

- ***Various LCC contents*:** The Hybrid PMS has various LCC contents as much as possible. This strategy widens user's choice for definition of user-specified LCC model.
- ***Modulation of LCC contents:*** By the modulation of each LCC contents, user can select LCC contents based on their interests and data limitation.
- ***Simplifying estimation method which is applicable by minimized data in PMS:*** Easy estimation method which demands fundamental data of pavement management field may facilitate easy application of life cycle cost analysis.
- ***Aggregation and disaggregation:*** The modulation turns into possibility of separation and combination of each estimation function of LCC contents. The separated function can be used as independence analysis module that helps user's current PMS model.

A key point in LCCA modeling is definition of LCC contents. There are many LCC contents which are affected by road investment level embodied by maintenance alternative. Application all the contents may be not for everyone because it demands many kinds of data and sophisticate estimation model. In the reality, the definition of LCC contents can be classified into two cases whether considering only agency cost or extending the scope to road users and socio-environmental cost. By the definition, the LCCA modeling becomes totally different. The Hybrid PMS needs to adopt the later to satisfy demands in most cases. It is a basic philosophy of this paper.

Although the Hybrid PMS includes many LCC contents, it must serve customization points to be applied in any situation. Someone think that it would be a very complex and huge model which is difficult (or impossible) to apply for their system. However, the problem can be solved by the plug-in system based on encapsulation strategy. In brief, road agencies can select required LCC contents based on definition of their LCC definition and data condition.

Definition of LCC estimation models is not simple task because variety of estimation models in terms of approach, theory, property of result, and data requirement is very huge. This paper has tried to adopt most general and sensible approach, but also to simplify or to apply assumptions for cases that have advantages in estimation way but have sophisticate structure. This is very important strategy in modeling since the level data requirement is nuclear in viability of application.

Lastly, the Hybrid PMS should consider practical application of road agencies. It could be differently applied by implementation scheme of road agencies. Full application is available, also it allows partial application as necessary. This is possible because modulation strategy of each LCC estimation function turns into separation and combination of the LCC contents. In brief, an extracted individual function can be used as independent analysis modules that helps user's current PMS model without any system modification.

Above considerations were applied as basic strategy in modeling of LCCA. However, it is expected that application of each agency may be encountered many problems because application of the LCCA model in the Hybrid PMS demands comprehensive understanding on overall structure from the pavement deterioration model to every detail of LCC estimation method.

6.3 Definition of Life Cycle Cost in PMS

6.3.1 LCC in PMS

The one of most important procedure for developing LCC model is definition of LCC contents. By this definition, scale of LCC would be changed. Sometimes, the definition could make different conclusion about the best alternative. For the definition, we firstly have to check "What is maximum and general definition?" and "What is indispensable and neglect-able contents?" In fact, there are many LCC contents that have been considered in pavement management field. Even if more contents may guarantee quality of the estimation result, such way usually requires too huge data that makes difficulties in data collection and application. In addition, it results too huge scale of LCC that reduce sensitivities of road agency cost. Under the huge LCC scale, usually economic analysis results say that more investment has higher economic indicators which are somewhat unrealistic in reality. And the indicators such as NPV (Net Present Value), IRR (Internal Return Rate) and B/C (Benefit Cost ratio) have very high value. For instance, the HDM-4 has very wide range of LCC, especially in VOC (Vehicle Operating Cost). This characteristic leads the analysis result into the 'User cost-oriented mode'. One research (Han *et al.,* 2007) has pointed that the ratio of user cost estimated by the HDM-4 has been occupied more than 99.5% from total life cycle cost. Of course, this couldn't be considered as a problem. In this case, however, the road agency cost loses discriminating power for determining best strategy that optimizes road agency cost. Such LCC model usually makes conclusion that keeping the best condition is the best strategy regardless of scale of agency cost (if user just check NPV only). This characteristic could be used for an abuse of analysis result. Therefore, some LCCAs include only agency cost, or LCC in a narrow meaning.

6.3.2 Comparison of Definitions of LCC Contents

This paper firstly has checked definition of LCC contents from previous researches. The Table 6.1 shows the comparison of definitions of LCC contents used for research or PMS software development.

Table 6.1 Comparison of definition of LCC contents for pavement management

References	Agency cost	User-cost	Socio-environmental cost (nonuser cost)	Residual cost (or salvage)
Hass *et al.* (1994)	Initial cost Maintenance cost	N/A	N/A	N/A
Hudson *et al.*(1997)	Initial cost Maintenance cost	Travel time cost VOC Accident cost Work-zone cost	Emission cost Noise cost Visual Neighborhood disruptions	Included (But, negative)
FHWA (1998) (RealCOST)	Initial cost Maintenance cost	Work-zone cost	N/A	Included
Bennett and Greenwood. (2003) (HDM-4 Ver.1.30)	Maintenance cost	Travel time cost VOC, Accident cost[2)]	Emission cost[2)]	N/A
Shahin (2005)	Initial cost Maintenance cost	N/A	N/A	N/A
MTBC (2005) (MicroBENCOST)	Initial cost Maintenance cost Administration cost	Travel time cost VOC, Accident cost	N/A	N/A
Do *et al.* (2006)	Maintenance cost	Travel time cost Vehicle operating cost	N/A	N/A
Uddin (2006)	Initial cost Maintenance cost Administration cost Cost of maintenance and protection of traffic Costs of borrowing[1)]	Travel time cost VOC Work-zone cost Accident cost	N/A	Included (But, negative)
MLTM (2009)	Initial cost Maintenance cost	Travel time cost VOC Accident cost	Emission cost Noise cost Greenhouse cost	N/A
Han *et al.* (2007)	Maintenance cost	Travel time cost VOC Work-zone cost	Emission cost Accident cost[3)]	N/A
Nam *et al.* (2009)	Maintenance cost	N/A	N/A	N/A

Note: 1) For projects not financed from allocated public funds or toll revenues
2) Included in the system, but changing into a monetary unit is not available.
3) Han et al.(2007) classified the accident cost as the socio-environmental cost (because social-losses are included in definition)

As shown in Table 6.1, the definition of LCC factor is similar also very different. In addition, there is too many differences not only detail contents belonged each factor but also estimation method. For that reason, definition of reasonable LCC contents and their estimation method should be treated as an important issue.

6.3.3 Definition of Agency Costs

Because agency costs are directly represented by the budget expenditure within a PMS cycle or analysis period, it is not so difficult to define. External or exogenous costs such as those associated with user cost during pavement operation, air pollution, and the like, may be combined with agency cost in a total economic analysis, and they may (or may not) affect agency decision making, but they do not appear in agency's budget. In practice, only agency cost is visible content from LCC contents by monetary term. Even if an alternative has the best economic result in terms of total LCC, the feasibility is concluded by the level of the agency cost. That is why the estimation result of agency cost has very important meaning than the other results, even though the ratio of the agency cost is usually smaller than the other LCC contents. From the Table 6.1, usual LCC contents of agency cost can be defined as,

- Initial cost
- Maintenance costs
- Inspection cost
- Administration cost

Among these contents, the maintenance cost is absolutely necessary. In case of the initial cost could be classified by an optional content based on user's objective. The initial cost is useful for evaluation for current asset value of the road section. However, the cost is used cost in the past. That is, initial cost and maintenance cost have different property each other. In addition, including initial cost could make a biased result that cheaper road section has much higher economic indices then expensive road. Above all, priority order of maintenance works should not be affected by degree of investment because future is the analysis objective.

Consideration of administration cost is not so usual concept in LCC simulation of PMS. Maybe, most LCCA models which are distributed to the world do not consider this cost inside of model. However, if someone want to treat total accounting which is extended to all kinds of budget expenditures, this could be a useful concept for road agency in reality. This could be called as the *'PMS operating cost'*. That is, maintenance budget is just one of categories among the various budget expenditures. If PMS software integrates all kinds of expenditures into the system, this could be much useful for building practical budget plan. By adjusting the other expenditure (or maintenance budget), they can make much flexible plan for various purposes, such as modifying inspection scheme, purchasing expensive inspection car, research and development project, employment conditions, strengthening maintenance level and so on. However, those kinds of budget are usually accounted for relatively small ratio compared with maintenance budget. Nevertheless, this concept could help realizing total management, and useful for regional level which manages small amount of road section. Therefore, the agency cost in a PMS cycle could be defined as follows;

- ***Maintenance costs:*** Re-construction, rehabilitation, repair, and preventive maintenance work
- ***PMS operating costs:*** Inspection, administration cost, equipment purchasing and maintenance/repair, labor, research and development project, etc.

Above definition might be good for practical operation of the PMS cycle. However, it is not suitable for PMS simulation, since the budget usages would be irregularly happen (except for the inspection cost). In addition, the cost is independent with pavement performance. For the reason, the Hybrid PMS defined the road agency cost as summation of maintenance cost and inspection cost.

6.3.4 Definition of User Costs

User costs involve the costs from users when they are occupying paved road sections. However, most agencies do not consider non-agency costs because these costs do not affect the road work funding, and these costs are difficult to quantify objectively. None the less, usually, the ratio of the user cost accounts for the highest part of total LCC. The general user costs are following contents:

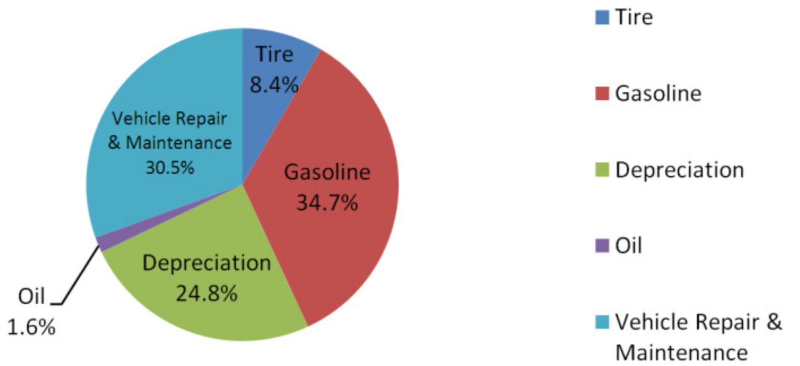
- Vehicle operating cost (VOC)
- Travel time cost
- Accident cost
- Work-zone cost (optional contents)

Among the four components shown above, the VOC and travel time cost for occupancy time on the road can be classified as essential factors that have to be included to the definition of user cost. These two contents should be hired as main contents of the user cost. However, the case including the accident cost and work-zone into the estimation objects is rarely found. Hence, the other two contents could be developed as optional contents by user's customization scheme. In general, estimation methodologies of VOC, travel time, accident and work-zone cost have been developed under similar concept and similar estimation methodology. The definition of the VOC associated with several sub-contents is also similar (see Table 6.2).

All of definitions of the VOC shown at the Table 6.2 are relatively similar. Only several researches or software have different definition about engine oil, depreciation and overhead cost. However, a general definition of the VOC contents can be said as the following,

- Fuel consumption
- Tire wear
- Engine oil consumption
- Vehicle Repair and Maintenance
- Depreciation of vehicle

To express the original meaning of the VOC, of course, including all contents shown above (or more contents) may be suitable. However, it usually makes over estimation of total LCC due to heavy user cost that disturbs reliable economic analysis. In addition, some contents have very small effect (like engine oil, depreciation, overhead cost etc.). A basic concept of the VOC model of the Hybrid PMS is considering the contents which are affected by pavement condition and physical condition of road section. By the concept, the fuel consumption, tire wear and engine oil consumption should be included into the VOC contents. Although the consumption of engine oil is affected by fuel consumption, the effect is very small to total VOC. Uddin and Torres-Verdin (1998) showed the ratio was 1.6% from the VOC by a case study of Mexico (Uddin, 2006). Accordingly, the engine oil consumption could be classified as an optional content.



Source: Uddin, 2006

Figure 6.1 Composition ratio of the VOC (A case: Mexico, $426 million in total)

Table 6.2 Comparison of definition of the VOC contents

PMS models or reference	Country (or software)	Fuel	Tires	Engine oil	Repair & Maintenance[1)]	Depreciation	Overheads
Winfrey (1963)	USA	X	X	X	X	X	-
de Weille (1966)	-	X	X	X	X	X	-
Bonney & Stevens (1967)	AFRICA	X	X	X	X	X	-
Claffey (1971)	USA	X	X	X	X	-	-
Daniels (1974)	AFRICA	X	X	-	X	X	-
Hide, *et al.* (1975)	AFRICA	X	X	-	X	X	-
AASHTO (1978)	USA	X	X	X	X	X	-
Zaniewski, *et al* (1982)	USA	X	X	-	X	X	-
Watanatada *et al.* (1987a)	Software *(HDM series)*	X	X	-	X	X	-
Bennett (1989)	NEWZELAND	X	X	-	X	X	-
NDLI (1995b)	HDM	X	X	X	-	-	-
FHWA (1998)	Software *(RealCOST)*	X	X	X	X	X	-
Bennett & Greenwood (2003)	Software (HDM series)	X	X	X	X	X	X
MTBC (2005)	Software *(MicroBENCOST)*	X	X	X	X	X	-
Goodman and Hastak (2006)	Software *(USER)*	X	X	X	X	X	-
Uddin and Torres-verdin (1998)	-	X	X	X	X	X	-
MLTM (2009)	Korea[2)]	X	X	X	X	X	

Source: (Revised) Bennett,1989

Note: 1) The content 'repair and maintenance' includes parts consumption, labor (crew wage).

2) An official legal standard defined by the Korean government

In case of the vehicle repair and maintenance cost could have relationship with pavement condition. However this content also could be classified as an optional content because advanced suspension technology have been developed, and the pavement condition of national highway or expressway of most countries is not so bad as the deterioration makes troubles or malfunctions of vehicle. Based on the above discussion, the VOC contents in the Hybrid PMS can be divided into essential and optional contents as follows;

- ***Essential contents:*** Fuel consumption, Tire wears
- ***Optional contents:*** Depreciation, engine oil consumption, vehicle repair and maintenance

Even though it was classified into essential and optional contents, all contents were included into the general version. But the contents can be customized by users' customization scheme.

6.3.5 Definition of Socio-environmental Costs

This is non-user cost or indirect cost occurred by construction and maintenance works. Definition of this cost may be very different by the types of object, such as water, land, soil, energy, air, noise, etc. Most of these costs are difficult to quantify objectively. The pavement management related socio-environmental cost may be soil contamination, noise, emission, and accident (this could be considered as not also user, but also social cost) and so on. But usually, most PMS models and researches have not considered these costs (or have included emission cost only).
Maybe someone would ask that *"Is there any relationship between global warming and pavement management?"* Basically, the pollutants are estimated by quantity of fuel consumption, and the quantities of each pollutant are estimated by a function of fuel efficiency (the vehicle speed). Since the vehicle speed is affected by the pavement condition, consequently, pavement condition also has relationship with vehicle emissions indirectly. Thus, the Hybrid PMS has included the emission cost as target of socio-environmental cost. Vehicles emit various chemical compounds as a direct result of the combustion process. The type and quantity of these emissions depends on a variety of factors including the tuning of the engine, fuel and driving conditions. When dealing with vehicle emissions, researchers focus primarily on the following substances (Bennett and Greenwood, 2003).

- Hydrocarbons (HC)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO2)
- Nitric Oxides (NOx)
- Sulphur Dioxide (SO2)
- Lead (Pb)
- Particulate matter (PM)

Heywood (1997) states that in the United States, vehicles are estimated to produce about 40-50% of the HC, 50% of the NOx and 80~90% of the CO emissions in urban areas. In addition, Patel (1996) estimates that around 40,000 deaths per year in India's major cities are caused by air pollution. The effect of these emissions both locally and globally is of growing concern, and thus it is imperative that in the evaluation of road operation options, the effect on vehicle emissions can be accurately modeled. Although not a primary concern of this research, the above emissions are reported to create or add to the environment problems in Table 6.3 (EPA, 1997). Recently, global warming is emerging as a very hot issue, particularly in carbon dioxide. In the Hybrid PMS, the carbon Dioxide, carbon monoxide and nitrogen oxides were classified as essential contents for emission cost. Of course, the others have been modeled. Users also can compose their original environmental cost model by aggregating the costs.

Table 6.3 Emission and their associated problems

Emission	Problems Caused by Pollutant
Hydrocarbons	Urban ozone (smog) and air toxics
Carbon Monoxide	Poisonous gas
Nitrogen Oxides	Urban ozone (smog) and acid rain
Carbon Dioxide	Global warming

Source: EPA (1997)

6.3.6 Definition of Salvage Value

The term, salvage or residual value, can be defined as, *"The remaining worth of reusable materials, or service life at the end of the analysis year."* Salvage value has often been included as a content of LCC by the type of object. This concept could have significant meaning for the case of buildings and roads which are constructed by BOT (Build-Operate-Transfer) project. Nevertheless, this value is usually considered as a negative value in pavement management field. Because, 1) Scale of the salvage value is usually very small compare with the total LCC in pavement field. 2) In addition, this cost becomes ignorable by the interest with long-term analysis period (usually 20-50 years). 3) One of characteristic of road is that the road is considered as a semi-permanent infrastructure once it is constructed as a public property. For that reason, there is no reason to estimate salvage value. 4) Above all, an assumption about life expectancy of pavement is required for estimation the salvage value. However, the assumption could be considered as unreasonable assumption by the forecasting or estimation method of pavement deterioration. For these reason, the salvage value is considered as negative contents in the Hybrid PMS even though the value is estimable. However, in case of (small) project level that applies small number of road section and short analysis period may require consideration of salvage value because the salvage value can make significant effect to economic indices that determine priority of alternatives.

6.3.7 Definition of Cost and Benefit

In fact, there is no benefit. All contents in the LCC are cost. For this reason, benefit of pavement management can be calculated by relative cost between alternatives. In a sense, a base alternative which is required for comparison with the other alternatives should be designated. It will be called as the "Base alternative". The base alternative could be the following schemes.

- No action
- Minimum action
- Keeping current action

Based on the characteristic of the base alternative, interpretation of the estimated result could be totally different. In case of the first option (no action), it may be useful for explanation of a benefit of PMS operation (or pavement maintenance). The second option can be applied to prove the best maintenance policy. The last one is good for comparison between current strategy and alternatives which shows benefits (or additional cost) of each alternative.

6.3.8 Summary of Definition of LCC Contents in the Hybrid PMS

Following the discussion in Chapters 6.3.1 ~ 6.3.6, defined LCC contents for the Hybrid PMS were classified as core and optional contents, and also core level, recommended level and advanced level (see Table 6.4).

Table 6.4 Definition and classification of the LCC contents for PMS analysis

Classification	Core level	Recommended level		Advanced level		
	Agency cost	User costs				Socio-environmental cost
		VOC	Travel time cost	Accident	Work zone	Emission cost
Essential	· Maintenance · Inspection	· Fuel cost · Tires cost	· Travel time on the road section	· Property Damage only		· CO, CO2, NOx
Optional	· Initial costs[1)] · PMS operation cost[1)]	· Depreciation · Vehicle repair & maintenance · Engine oil	N/A	· Injury · Fatal	· Additional travel time and the VOC due to work zone[1)]	· SO2,HC, PM, Pb

Note: 1) The contents are included in the definition, but are not included in the LCCA model

Based on the Table 6.4, total life cycle cost of an alternative can be expressed by the following equations,

$$LCC_i = AC_i + UC_i + EC_i \tag{6.1}$$

$$AC_i = \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{m=1}^{M}\frac{MC_p^{Sm}}{(1+r)^p} + \sum_{p=1}^{P}\sum_{s=1}^{S}\frac{IC_p^S}{(1+r)^p} \tag{6.2}$$

$$UC_i = \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{v=1}^{V}\left[\frac{Fuel_p^{Sv}}{(1+r)^p} + \frac{Tire_p^{Sv}}{(1+r)^p} + \frac{Oil_p^{Sv}}{(1+r)^p} + \frac{Dep_p^{Sv}}{(1+r)^p} + \frac{VRM_p^{Sv}}{(1+r)^p}\right] + \frac{TTC_p^{Sv}}{(1+r)^p} + \frac{Safe_p^{Sv}}{(1+r)^p} \tag{6.3}$$

$$EC_i = \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{v=1}^{V}\frac{CO_p^{Sv}}{(1+r)^p} + \frac{HC_p^{Sv}}{(1+r)^p} + \frac{CO2_p^{Sv}}{(1+r)^p} + \frac{NOx_p^{Sv}}{(1+r)^p} + \frac{SO2_p^{Sv}}{(1+r)^p} + \frac{Pb_p^{Sv}}{(1+r)^p} + \frac{PM_p^{Sv}}{(1+r)^p} \tag{6.4}$$

Where,
AC_i, UC_i, EC_i = road agency, road user and environmental cost under alternative i, respectively
MC_p^{Sm} = maintenance cost by a maintenance type m of analysis unit s in the year p $(m = 1, \dots, M; s = 1, \dots, S; p = 1, \dots, P)$
IC_p^S = inspection cost by an analysis unit s $(k = 1, \dots, K; s = 1, \dots, S)$
$Fuel_p^{Sv}, Tire_p^{Sv}, Oil_p^{Sv}, Dep_p^{Sv}, VRM_p^{Sv}, TTC_p^{Sv}, Safe_p^{Sv}$ = Fuel cost, tire cost, depreciation cost, engine oil cost, vehicle repair and maintenance cost, travel time cost and safety cost of a vehicle type v of analysis unit s in the year p $(v = 1, \dots, V; s = 1, \dots, S; p = 1, \dots, P)$
$CO_p^{Sv}, HC_p^{Sv}, CO2_p^{Sv}, NOx_p^{Sv}, SO2_p^{Sv}, Pb_p^{Sv}, PM_p^{Sv}$ = vehicle emission costs on carbon monoxide, hydrocarbons, carbon dioxide, nitric dioxide, sulphur dioxide, lead, and particulate matter of a vehicle type v of analysis unit s in the year p
r = interest

6.4 Cost Stream and Framework of LCC Model

6.4.1 LCC Stream with Pavement Condition

The LCCA model in the Hybrid PMS describes relationships pavement condition changed by maintenance strategy with LCC contents. To draw pavement deterioration history, deterioration process, maintenance criteria, work effect model are basically required. Based on this information, quantification of the LCC contents are available. The Figure 6.2a and Figure 6.2b shows simplified concept of LCC modeling of the Hybrid PMS.

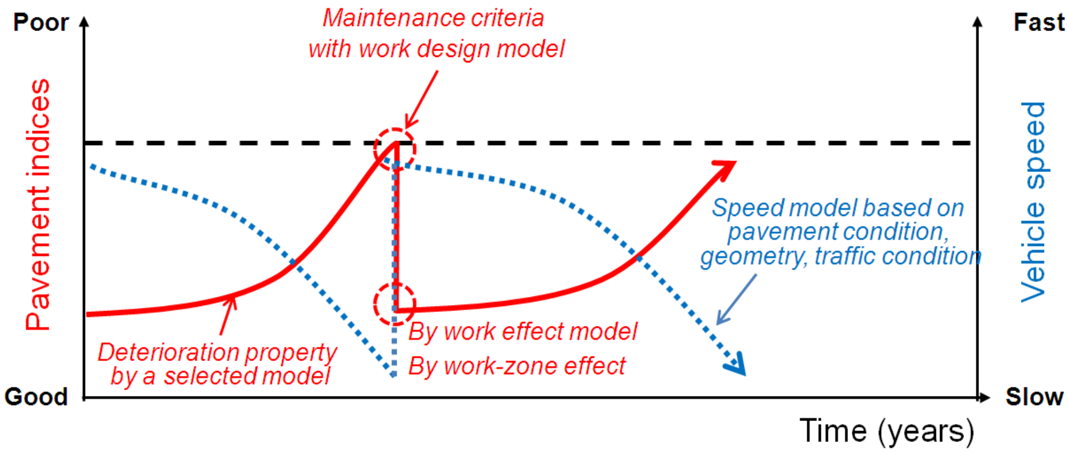


Figure 6.2a Concept of life cycle cost modeling (relationship pavement condition and vehicle speed)

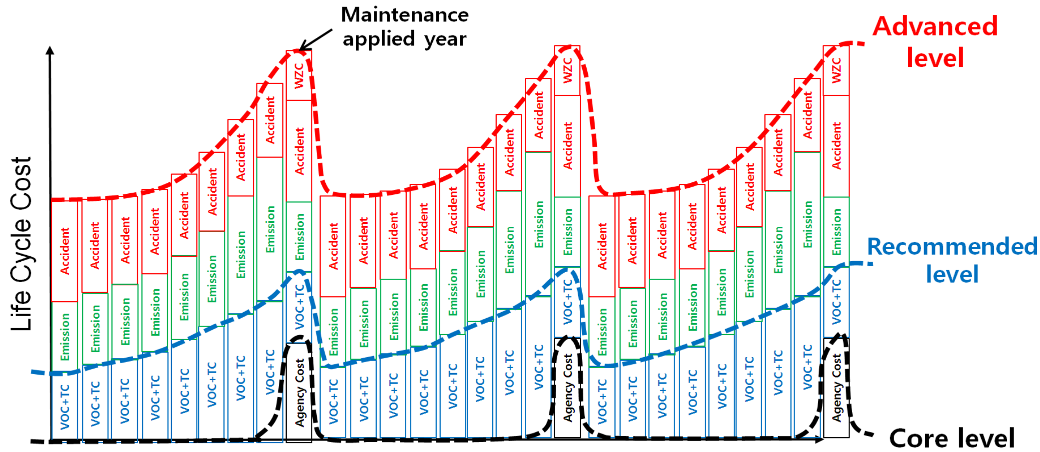


Figure 6.2b Concept of life cycle cost modeling (Cost stream)

As shown at the Figure 6.2, the LCC is changed by a function of deterioration speed, maintenance option, vehicle speed, unit costs, and physical road characteristics etc. The LCC in normal period which is not required for maintenance work are estimated by summation of the discounted costs of the vehicle operating cost, travel time cost, emission and accident. In case of maintenance conducted year, agency cost and work-zone effect are added. It is easily expected that many users do not have enough data to estimate some LCC contents. For example, to apply the advanced level, user must have much detail data, such as physical road condition (*e.g.* work-zone length) and accident properties by speed, distribution of vehicle volume by time unit, and vehicle engine characteristics associated with emission. For that reason, every estimation function of LCC contents is needed to be developed by a separated module. By the needs and data condition of users, the LCC definition can be changed. This is an important point of the hybrid concept in the LCC model.

6.4.2 Framework of LCCA Model

Overall framework of the LCCA model of the Hybrid PMS is illustrated in the Figure 6.3.

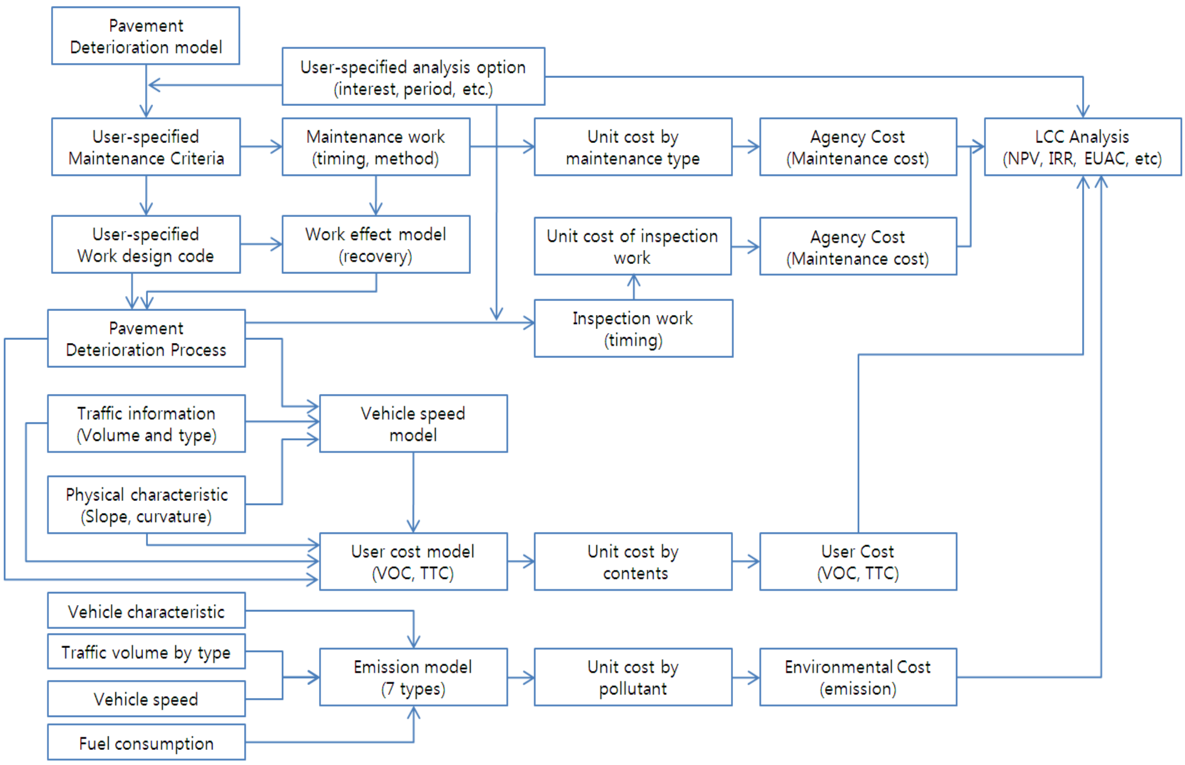


Figure 6.3 Framework of LCCA model of the Hybrid PMS

Basically, LCCA demands pavement deterioration model, pavement inventory data, and some application options and unit costs. Firstly, characteristic of pavement deterioration speed should be defined. With the simulation option (maintenance alternative) and work effect model, deterioration process during analysis period is estimated. In this procedure, maintenance and inspection work are determined. It results agency cost. By the supports of sub-models on vehicle speed and traffic volume, various road user and socio-environmental cost can be estimated. Finally, all costs are aggregated for economic analysis. Then, road agency can compare their alternatives by economic evaluation criteria. Note that the framework in the Figure 6.3 is full framework for advance level of LCCA. This could be customized by excluding some parts based on customization scheme of each road agency.

6.5 Estimation of Agency Costs

As discussed in the Chapter 6.3.3, the most important content among life cycle cost contents is the agency cost. Since agency costs are directly represented by the budget expenditure within a PMS cycle or analysis period, it is not so difficult to define. The total agency cost at the end of the analysis period is calculated by summation of initial cost, maintenance cost, PMS operational cost and salvage value of each section. General expression of agency cost is following equation.

$$TAC = \frac{IC}{(1+r)^p} + \left[\sum_{n=1}^{p} \frac{MC_i^n}{(1+r)^n}\right] + \left[\sum_{n=1}^{p} \frac{ISP_i^n}{(1+r)^n}\right] + C_{Adm}^n \tag{6.5}$$

Where,
TAC = total agency cost at the end of the analysis year
IC = initial cost
r = interest in percent (%)
p = analysis period (year), here, $p \in [1, \infty)$
n = an individual analysis year, thus $(n = 1, \ldots, p)$
MC_i^n = maintenance cost of i^{th} order which is applied in n^{th} year, satisfying $n \in (1, p)$ and $(i \leq p)$
ISP_i^n = inspection cost i^{th} order which is applied in n^{th} year
C_{Adm}^n = administrative cost of n^{th} year

6.5.1 Maintenance Costs

The Eq. 6.5 includes the initial cost, PMS operation cost into the total agency cost. However, these costs are negative cost in the Hybrid PMS. The general definition of the Hybrid PMS is $\left[\sum_{n=1}^{p} \frac{MC_i^n}{(1+r)^n}\right] + \left[\sum_{n=1}^{p} \frac{ISP_i^n}{(1+r)^n}\right]$. For much detail expression about maintenance cost and inspection cost shown in the Eq. 6.5. The equation should be detailed.

$$TAC_i = [MC_i^{entire} + MC_i^{part}] + IC_i + \alpha \tag{6.6}$$

For maintenance over rehabilitation: reconstruction, cutting-overlay, overlay and surface treatment

$$MC_i^{entire} = \sum_{y=1}^{Y} \sum_{s=1}^{S} [Lng_s \times W_s] \times UC_d \tag{6.7}$$

For partial maintenance: alligator crack, pothole and transverse thermal crack

For crack related maintenance cost,

$$MC_i^{part-C} = \sum_{y=1}^{Y} \sum_{s=1}^{S} \left[\frac{Lng_s \times W_s}{PC_s}\right] \times UC_d \tag{6.8}$$

For pothole related maintenance cost,

$$MC_i^{part-P} = \sum_{y=1}^{Y} \sum_{s=1}^{S} \left[\frac{Lng_s \times W_s}{NP_s * UAP}\right] \times UC_d \tag{6.9}$$

Where,
TAC_i = the total agency cost of an alternative i

MC_i^{entire} = the maintenance cost for the reconstruction, cutting-overlay, overlay and surface treatment
MC_i^{part-C} = the maintenance cost for crack related maintenance type (=crack seal, crack patching)
MC_i^{part-P} = the maintenance cost for pothole related maintenance type (=pothole patching)
IC_i = the inspection cost for an alternative i
α = the additional user specified contents for agency cost
Lng_s = the length of a section s in kilometer
W_s = the width of a section s in meter
UC_d = the unit cost of design code d
PC_s = the percentage of crack of a section s
NP_s = the number of potholes of a section s
UAP = the unit area of a pothole in square meter
NL_s = the number of lane of a section s
UC_{isp} = the unit cost of inspection in km/lane

6.5.2 Inspection Costs

The inspection cost is one of important parts of agency cost. Nevertheless, it has often been ignored in the LCCA procedure. This paper introduced the cost by a simple way. The method basically follows periodical inspection scheme, and additionally considers maintenance schedule determined by the deterioration process and maintenance alternatives in the simulation. After maintenance work over the rehabilitation level, the condition becomes reset (or nearly reset). If we assume or estimate the reset condition we do not need to inspect pavement condition at the year. And the work also resets elapsed time of inspection, denoted as "*AGE0*". Therefore, the inspection schedule during the analysis year can be differed by maintenance schedule. That is, deterioration speed also affects to the number of inspection. This concept will be used for making inspection schedule and cost estimation.

The required information for this procedure is as follows,

- Analysis year
- Inspection interval
- The number of lanes to be inspected
- Unit cost in (USD/lane/km)
- Interest (%)
- AGE0 at the start year
- Length of section (km)
- Maintenance history from estimated result (see the Chapter 13.4)

The function also can do economic analysis the same as maintenance cost analysis.

The inspection cost is estimated by a function of elapsed time from the last inspection, with last maintenance work which is over the rehabilitation type (reconstruction, cutting overlay and overlay) that reset pavement condition. The maintenance costs are differed by the type of maintenance and design of maintenance. This could be calculated by defining the unit cost by maintenance codes which were introduced in the Management function.

For inspection cost,

$$ISP_i = \left[\sum_{y=1}^{Y} \sum_{s=1}^{S} [Lng_s \times NL_s] \times UC_{isp}\right] \delta_s^y \qquad (6.10a)$$

$$\delta_s^y = \begin{cases} 1 & AGE0 \geq IISP \\ 0 & otherwise \end{cases} \qquad (6.10b)$$

Where,
δ_s^y = dummy parameter to check demand of inspection of section *s* in year *y*
$AGE0$ = An age indicator affected by elapse time of last inspection and last maintenance work over the rehabilitation level (overlay, reconstruction).
$IISP$ = user-specified inspection interval

6.6 Estimation of User Costs

User cost accounts for the highest part of the total life cycle cost. None the less, an importance of the user cost is negligent in practical maintenance because the cost is invisible money to road agency. However, road agency has to pay attention to the user cost because investment of agency cost is expressed in benefit of user cost. It is very sensitive to any investment decisions on transportation related infrastructure.

As discussed in the Chapter 6.3, the objects of modeling are vehicle operating costs, travel time cost and safety cost. To simplify model structure, the Hybrid PMS has followed empirical approaches.

6.6.1 Vehicle Operating Cost (VOC)

The issues on VOC have already been discussed in the Chapter 6.4.3. The objects of modeling are fuel cost, tire cost, engine oil cost, vehicle depreciation cost, and vehicle maintenance cost. Each model will be described with some significant reviews from previous models or researches.

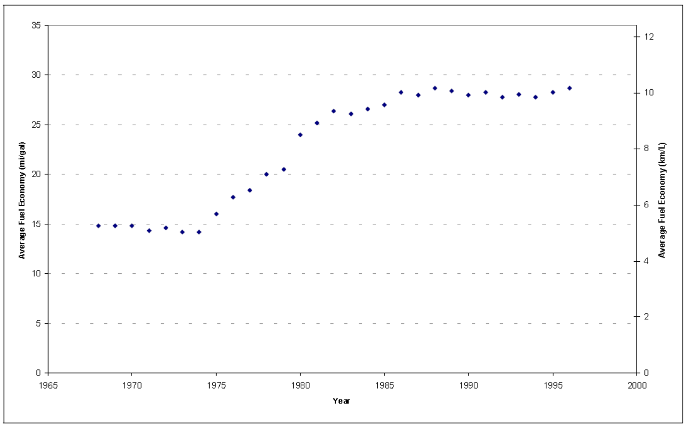
6.6.1.1 Fuel Cost

Fuel consumption is a significant component of the VOC, typically accounting for between 20~40 percent of the total VOC (HTC, 1999). It is influenced by properties of each vehicle type, traffic congestion, road condition and geometry characteristics and user's driving behavior. Fuel economy of passenger car has been a significant change over the 30 years, with an approximate improvement of nearly 200 percent. The majority of change occurred over a relatively short 10 year period during the oil crisis years.

Heaventich *et al.* (1991) indicate that although the average fuel economy has undergone dramatic improvement, the economy of the lowest 5 percent of passenger cars has undergone a relatively minor improvement over this same period (See the Figure 6.4). By referring the Figure 6.4, it is required that the fuel cost model should refer to the most recent research results.

A. Factors influencing fuel consumption
Virtually any change to the road, the traffic conditions, or the vehicle, will yield a change in the fuel consumption rate of the vehicle. Additionally, parameters which are not easily modeled such as driving style also have a significant influence. A change in any of the road attributes that effect the forces opposing motion, will in turn impact on the fuel consumption. The primary attributes relating to the road are;

- Gradient
- Roughness
- Texture
- Curvature



Source: Amann, 1997
Figure 6.4 Changes in Fuel Economy since 1968

Vehicle parameters that impact on the forces opposing motion also affect the amount of fuel consumed. Factors such as vehicle mass, frontal area and design, engine design and tires all play a significant role in the overall fuel consumed. Other factors, such as the style of driving also have a profound influence on the fuel consumption rate. For example, Elder (1983) found that at 80 km/h an eight per cent decrease in tire pressure led to a 2.1 per cent increase in fuel consumption. In India (Kadiyali *et al.,* 1981) it was found that at 80 km/h radial tires used 1.5 per cent less fuel than bias ply tires. The ambient conditions also play an important role, with the impact of wind strength and direction impacting on the forces against the vehicle. Armstrong (1983) determined that running engines below their operating temperatures consumed 40-60 per cent excess fuel. The maintenance of the vehicle, consisting of the tuning of the engine, condition of aerodynamic aids and the shape of loads on the back of trucks, although mainly beyond the realms of current modeling, all have a significant impact on the fuel consumed. However, when comparing one road investment alternative to another, these factors tend to be constant so are of lesser importance from a modeling perspective (Bennett and Greenwood, 2003).

B. Reviews of fuel consumption models

Research has been conducted into the fuel consumption of motor vehicles almost since they were first invented. In recent years a number of studies have been undertaken with the objective of quantifying the effects of speed, road geometry and surface condition on fuel consumption. Initially, researchers used coarse empirical data (*e.g.* de Weille, 1966), but this was then superseded by experimental studies that related the fuel consumption to specific operating condition and modeled it using an empirical approach. More recently, the fuel consumption has been modeled using mechanistic principles that relate the consumption to the forces opposing motion (Bennett and Greenwood, 2003). In general, the fuel consumption models are classified into empirical models and mechanistic models. The early empirical models related fuel consumption principally to vehicle speed. A number of studies found that the relationship between the specific fuel consumption (in L/1000 km) and vehicle speed was U-shaped. There are relatively high fuel consumption rates at both low and high speeds with the minimum fuel consumption arising at an "optimum" speed, generally around 40 - 60 km/h.

Table 6.5 Coefficients estimated for empirical fuel consumption model

Vehicle	Country	Fuel Model Coefficients						Other variables	Source
		a_0	a_1	a_2	a_3	a_4	a_5		
Passenger cars	India	10.3	1676	0.0133	1.39	-0.03	0.43		Chesher and Harrison (1987)
	India	21.85	504	0.0050	1.07	-0.37	0.47		IRC (1993)
	India	49.8	319	0.0035	0.94	-0.68	1.39		Chesher and Harrison (1987)
	Caribbean	24.3	969	0.0076	1.33	-0.63	-	+0.00286 $FALL^2$	Chesher & Harrison (1987)
	Kenya	53.4	499	0.0059	1.59	-0.85	-		Chesher & Harrison (1987)
Light Commercials	India	30.8	2258	0.0242	1.28	-0.56	0.86		Chesher & Harrison (1987)
	India	21.3	1615	0.0245	5.38	-0.83	1.09		IRC (1993)
	Caribbean	72.2	949	0.0048	2.34	-1.18	-	+0.0057$FALL^2$+1.12(GVW-2.11)RISE	Chesher & Harrison (1987)
	Kenya	74.7	1151	0.0131	2.91	-1.28	-		Chesher & Harrison (1987)
Heavy Bus	India	33.0	3905	0.0207	3.33	-1.78	0.86		IRC (1993)
	India	-12.4	3940	0.0581	0.79	-	2.00	+0.0061CKM	Chesher & Harrison (1987)
Truck	India	44.1	3905	0.0207	3.33	-1.78	0.86		IRC (1993)
	India	141.0	2969	0.0517	17.75	-5.40	2.50		IRC (1993)
	India	85.1	3905	0.0207	3.33	-1.78	0.86		Chesher & Harrison (1987)
	India	266.5	2571	0.0362	4.27	-2.74	4.72	-6.26 PW	Chesher & Harrison (1987)
	India	71.70	5670	0.0787	1.43	-	-	-9.20PW – 3.98 WIDTH	Chesher & Harrison (1987)
	Caribbean	29.2	2219	0.0203	5.93	-2.60	-	+0.85 (BVW-7.0)RISE+0.013 $FALL^2$	Chesher & Harrison (1987)
	Kenya	105.4	903	0.0143	4.36	-1.83	-	-3.22 PW	Chesher & Harrison (1987)

Source: Bennett and Greenwood, 2003

The reason behind this U-shape can be simply explained by considering the two extremes. At high speeds, the aerodynamic forces, which are related to the square of velocity, become dominant requiring large quantities of fuel to be consumed. At low speeds, which equate to low power requirements, the idle fuel consumption that powers the engine drag and accessories dominates. When the fuel consumption in mL/s is divided by the speed in m/s the U-shape arises. The common empirical formulation for fuel consumption is given by Eq. 6.11

$$FC = a_0 + \frac{a_1}{V} + a_2V^2 + a_3RISE + a_4FALL + a_5IRI \quad (6.11)$$

Where,
FC = fuel consumption in L/1000 km
V = vehicle speed in km/h
$RISE$ = rise of the road in m/km
$FALL$ = fall of the road in m/km
IRI = roughness in IRI m/km
$a_0 - a_5$ = constants (refer to the Table 6.5)

As shown in the Table 6.5, the degree of effect to fuel consumption is somewhat different between countries, and researches. By the average of the constants, fuel consumption by vehicle class and speed can be estimated (see Figure 6.5).

The mechanistic models predict that the fuel consumption of a vehicle is proportional to the forces acting on the vehicle. Thus, by quantifying the magnitude of the forces opposing motion one can establish the fuel consumption. Mechanistic models are an improvement over empirical models since they can allow for changes in the vehicle characteristics and are inherently more flexible when trying to apply the models to different conditions. One of comprehensive mechanistic fuel consumption models available is the ARFCOM model (Giggs, 1988) and its approach is summarized in the Figure 6.6.

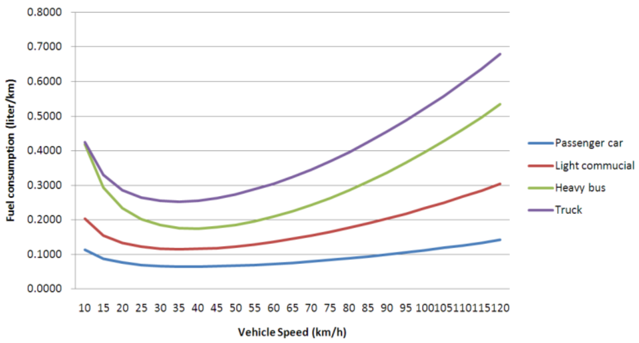
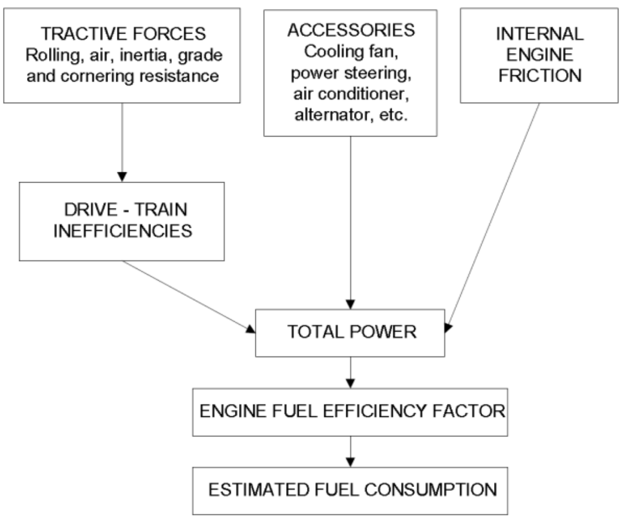


Figure 6.5 Fuel consumption by vehicle class and speed (averaged speed of Kenya, India, and Caribbean)



Source: Bennett and Greenwood, 2003
Figure 6.6 ARFCOM approach to modeling fuel consumption

This shows how the total power requirements are based on the tractive forces, the power required to run accessories, and internal engine friction. The fuel consumption is then taken as proportional to the total power requirements. This approach was selected as the basis for the HDM-4 fuel consumption model. The mechanistic approach can offer the greatest potential for meeting various research purposes. However, this approach may require many variables which are difficult to be secured. This could be a weakness of mechanistic model to users.

C. Suggestion of fuel consumption model

To be the most user friendly model, the model should be simple, and the data requirement also should be minimized. Hence, the empirical approach could be considered as a better alternative. The structure of the empirical model shown at the Eq. 6.11 may be reasonable because the data requirements in the model are very fundamental and essential data for PMS. However, the constant values in the Table 6.5 are quite different and very old which cannot represent current characteristic of vehicle types. For these reasons, it could not be used as a default model.

The simplest way may be the speed-based unit load method. Since the factors influencing fuel consumption shown in the Eq. 6.11 were already applied to speed model in the Hybrid PMS, maintenance activities can makes difference to quantification of fuel consumption. The basic model structure estimating fuel cost is expressed in the Eq. 6.12.

$$VOC_{Fuel} = \sum_{k=1}^{K} Fuel^k \times UC_{Fuel}^k \tag{6.12a}$$

Where,

$$Fuel^k = \left[a_1^k + \frac{a_2^k}{V^k} + a_3^k (V^k)^2 + a_4^k RISE + a_5^k FALL + a_6^k IRI\right] NV^k \tag{6.12b}$$

$$NV^k = AADT \times R^k \tag{6.12c}$$

The Eq. 12 can be rewritten with consideration of analysis section s, vehicle type k, and analysis period y,

$$VOC_{Fuel} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{k=1}^{K}\left[a_1^k + \frac{a_2^k}{V_y^{sk}} + a_3^k (V_y^{sk})^2 + a_4^k RISE^s + a_5^k FALL^s + a_6^k IRI_y^s\right] AADT_y^{sk} \times R_y^{sk} \times Leng^s \times UC_{Fuel}^k \tag{6.13}$$

Where,

VOC_{Fuel} = fuel cost for analysis period in USD

$Fuel^k$ = fuel consumption of a vehicle class k in liter ($k = 1, \ldots, K$)

UC_{Fuel}^k = unit cost of fuel of a vehicle class k in USD per liter

V_y^{sk} = journey speed of a vehicle class k of section s in analysis year y in km/h ($s = 1, \ldots, S; k = 1, \ldots, K; y = 1, \ldots, Y$)

NV^k = the number of vehicles of a vehicle class k

$AADT_y^s$ = annual average dairy traffic of section s in analysis year y

$Leng^s$ = section length in km

R_y^{sk} = vehicle class composition ratio of a vehicle class k of section s in analysis year y

$a_1 \sim a_6$ = model coefficients (refer to Table 6.6)

By using the coefficients in the Table 6.6, first part of the Eq. 6.12b, $a_1^k + \frac{a_2^k}{V^k} + a_3^k (V^k)^2 + a_4^k RISE + a_5^k FALL + a_6^k IRI$, fuel consumption in liter/km by vehicle class and speed can be estimated. The result is showing at the Table 6.7.

The basic fuel consumption model in the Hybrid PMS was compared with previous researches (shown at Figure 6.5.) in the Figure 6.7.

There are relatively high fuel consumption rates at both low and high speed with the minimum fuel consumption arising at an optimum speed, generally around 40-60km/h. This characteristic is similar with previous case studies in Kenya, India, and Caribbean. However, the current empirical study in Korea has the better fuel efficiency compared with the previous case studies which was performed around 20 years ago. This difference may be caused by advanced technologies for fuel efficiency. The total fuel cost is simply determined by multiplication between fuel consumption and unit cost of fuel. Note that the unit cost should be the price after deduction of tax. That is, the unit price for economic analysis should be the substantial price which is determined by a function of factory price and margin of gasoline station because economic analysis of pavement field treats the public goods. This relationship is explained in the Table 6.8.

Table 6.6 Model coefficients for estimation of fuel consumption by vehicle class (for Eq. 6.13)

	Passenger car	Small bus	Heavy bus	Small truck	Medium truck	Heavy truck
a_1	0.02882	0.03336	0.02476	0.01695	0.01695	0.06639
a_2	0.91	1.153	3.492	1.292	1.292	4.158
a_3	0.000003828	0.000004312	0.00001277	0.00001647	0.00001647	0.00002525
a_4	0.001264	0.0029775	0.0024833	0.0029775	0.006178	6.17833E-06
a_5	-0.000712	-0.0009625	-0.00178	-0.0009625	-0.00287	-0.00000287
a_6	0.0007633	0.000975	0.00124	0.000975	0.00269333	2.69333E-06

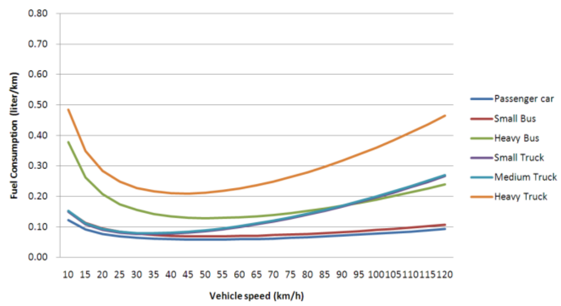
Source: $a_1 \sim a_3$ are referred from MLTM (2009)

$a_4 \sim a_6$ are averaged values from the Table 6.5 by converting unit. The Light Commercial Vehicle in the Table 6.5 has been allocated to small bus and small truck, and the truck has been allocated to medium and heavy truck by same model coefficients

Table 6.7 Fuel consumption by vehicle class and speed (liter/km) (A case: no slope, IRI=2.0m/km)

Speed(km/h)	Passenger car	Small Bus	Heavy Bus	Small Truck	Medium Truck	Heavy Truck
10	0.1217	0.1510	0.3777	0.1497	0.1532	0.4847
15	0.0919	0.1131	0.2629	0.1087	0.1122	0.3493
20	0.0774	0.0947	0.2069	0.0901	0.0935	0.2844
25	0.0691	0.0841	0.1749	0.0809	0.0843	0.2485
30	0.0641	0.0776	0.1551	0.0768	0.0802	0.2277
35	0.0610	0.0735	0.1427	0.0760	0.0794	0.2161
40	0.0592	0.0710	0.1350	0.0776	0.0810	0.2107
45	0.0583	0.0697	0.1307	0.0810	0.0844	0.2099
50	0.0581	0.0692	0.1290	0.0859	0.0894	0.2127
55	0.0585	0.0693	0.1294	0.0922	0.0956	0.2184
60	0.0593	0.0700	0.1314	0.0997	0.1032	0.2266
65	0.0605	0.0713	0.1349	0.1084	0.1118	0.2370
70	0.0621	0.0729	0.1397	0.1181	0.1215	0.2495
75	0.0640	0.0749	0.1456	0.1288	0.1322	0.2639
80	0.0662	0.0773	0.1526	0.1405	0.1439	0.2800
85	0.0687	0.0800	0.1606	0.1531	0.1565	0.2977
90	0.0715	0.0830	0.1695	0.1667	0.1701	0.3171
95	0.0745	0.0864	0.1792	0.1811	0.1846	0.3380
100	0.0777	0.0900	0.1899	0.1965	0.2000	0.3605
105	0.0812	0.0938	0.2013	0.2128	0.2162	0.3844
110	0.0849	0.0980	0.2135	0.2299	0.2334	0.4097
115	0.0889	0.1024	0.2265	0.2480	0.2514	0.4365
120	0.0931	0.1070	0.2402	0.2668	0.2703	0.4646

Note: No slope (rise =0, Fall=0) and IRI 2.00m/km



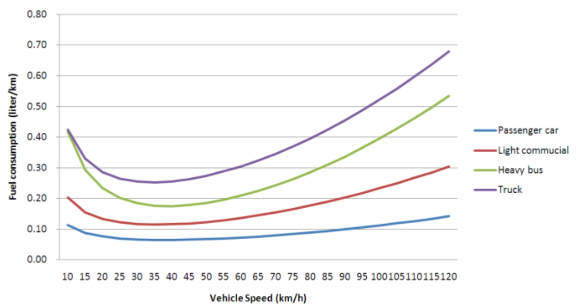


Figure 6.7a Fuel consumption model of Hybrid PMS (left)
Figure 6.7b Fuel consumption model of previous researches conducted in Kenya, India, Caribbean (right)

Table 6.8 Unit cost by fuel types (Case: Korea in 2007)

Classification	Gasoline	Diesel	Note
Factory price after deduction of tax (A)	633.13	669.42	
Factory price before deduction of tax (B)	1,515.81	1,314.31	
Wholesale price (C)	1,551.51	1,327.68	
Consumer's price (D)	1,632.54	1,435.46	
Substantial price (E)	749.86	790.57	A+(D-B)

Source: MLTM, 2009

6.6.1.2 Tire Consumption Cost

Tires are consumed continuously as vehicles drive. This tire consumption can be a major component of the total road user cost, particularly for heavy trucks because generally the heavier truck has more tire and faster wearing characteristic. For example, Opus-TRL (1999) report that in New Zealand tire costs constitute 18 percent of the total user costs for heavy trucks towing, compared to only five percent for passenger cars. In case of Brazil study, the tire costs were 23 percent of the total cost in rolling terrain (Watanatada *et al.,* 1987b)

A. Factors influencing tire consumption
The factors influencing tire consumption were defined by Nordström and Andersson (1995)

- ***Pavement condition:*** Tire consumption will increase with increasing roughness since that leads to increased vertical loading on the tires. The type of surface, its condition and its texture all play important roles in the tire consumption.
- ***Road alignment:*** Tire consumption increases significantly with the severity of road alignments, particularly with respect to horizontal curvature.
- ***Traffic conditions****:* Traffic interactions give rise to accelerations and decelerations which have a strong impact on tire consumption.
- ***Vehicle loading****:* The tire consumption is proportional to the vehicle loading and overloading. When coupled with poor road condition, this can lead to an increased frequency of carcass failures, especially on driven axles.
- ***Climate:*** The ambient temperature can have a significant impact on tire consumption, particularly in tropical countries where it can contribute to blowouts or stripping of tread.
- ***Tire properties:*** The type of tire (radial Vs. bias ply), if it is a new tire or a retread, the properties of the rubber compounds, and the inflation pressure all have an impact on the tire consumption rate.

B. Review of tire consumption modeling
There are two approaches which have been used to develop tire consumption models:

- ***Controlled experiments:*** These see the tire consumption measured on a small number of tires with a high degree of accuracy, or,
- ***Fleet surveys:*** The tire consumption of vehicle fleets is monitored. Since the precise operating conditions are not known, it is only practical to relate this tire consumption to aggregate descriptions of road condition.

There are advantages and disadvantages to each approach. While controlled experiments offer the potential for getting accurate measurements, they are difficult to conduct and by necessity only cover a small range of tires. They also do not generally give details on tire consumption under 'real life' conditions, although they are sometimes adjusted using additional data from fleet surveys. Fleet surveys have their own set of difficulties which Chesher and Harrison (1987) summarize as;

"… tyre data are difficult to collect because, at least in large organisations, tyres are moved from vehicle to vehicle. Further, tyre life varies greatly from tyre to tyre even under identical operating conditions. Tyre life also varies considerably according to load carried, position on the vehicle, speed of operation, driver behaviour and depends on company policy regarding standards of maintenance of tyres and vehicles and regarding frequency and standard of recap. Even with the relatively large samples obtained in India and Brazil it is difficult to extract information on the relationship between tyre consumption and highway

characteristics."

Thus, although they have the advantage of encapsulating the actual tire consumption under real life conditions, it is difficult to develop predictive models from the data insofar as the models may give unexpected results. For example, Papagiannakis (1999) analyzed tire data for truck fleets operating on smooth roads in North America. Even though the average roughness was only in the range of 1.4~1.9 IRI m/km, it was suggested that there was a significant (> 50 per cent) increase in tire wear over this range. Since the routes were comprised of interstate highways, these differences cannot be ascribed to speed differences and it is not clear why such changes would be observed at such low roughness when mechanistic theory suggests less of an impact.

Symonds (1996) investigated tire consumption using fleet data in Australia. Among their findings was that the variation in tire consumption for similar vehicles operating on the same route was greater than the tire consumption differences between routes—something also commonly encountered in maintenance and repair cost modeling.

One particular complication with fleet data is the widely differing tire lives found in service. For example, Daniels (1974) reports new passenger car lives in Africa ranging from 27,000 to 40,000 km. huge variations in life between vehicles was found in the India and Brazil user cost studies (Chesher and Harrison, 1987).

As described by Le Maître *et al.* (1998), there are marked variations in tire life between drivers and geographical areas. Tire life follows a lognormal distribution, with some drivers—representing extreme use—experiencing very short tire lives, while others with mild use having long lives. Le Maître *et al.* (1998) show that severity can be "interpreted by the differences in acceleration levels which each driver imposes on the vehicle" and that this can lead to a several fold difference in tire wear between different drivers.

C. Suggestion of a Tire consumption model for the Hybrid PMS

There are two types of models which have been developed for predicting tire consumption:

- *Mechanistic:* These relate the tire consumption to the fundamental equations of motion and are generally developed from controlled experiments.
- *Empirical:* These are more aggregate models, usually developed from fleet survey data.

Du Plessis and Schutte (1991) suggest that when modeling tire consumption *"empirical models seem to perform best, since they capture the tire policies implemented by operators which would be difficult, if not impossible, to model using purely theoretical purposes"*.

However, mechanistic models have the advantage of being able to cater for the full range of operating conditions encountered by vehicles in a consistent and theoretically robust manner. Nevertheless the mechanistic model usually requires many kinds of data such as, the model inside of the HDM-4. This could be an obstacle for vivid application. For that reason, the Hybrid PMS follows the empirical approach.

Irrespective of the type of model, it is essential that retreaded tires be explicitly considered. Retreaded tires generally cost less and may have different performance properties to new tires. The amount in use depends upon economic factors. In some countries they are common while in others rare. For example, Cenek *et al.* (1993) report that 20 per cent of N.Z. passenger car tire sales were retreads. A sample of buses had 57 new tires which were retreaded a total of 176 times making retreads 75 percent of the tires. However, this issue was ignored in the first version of the Hybrid PMS to give simple model.

In case of Korea, the MLTM (2009) suggests unit of tire consumption rate by vehicle class and speed as a legal guideline for integration of evaluation methods. The methodology was from de Weille (1966), but it was updated considering Korea situation in 1999. Their suggestion about tire consumption rate is showing at the Table 6.9 and the Figure 6.8.

The consumption rates in the Table 6.9 (and the Figure 6.8) can be formulated by an estimation function. By the analysis, polynomial type was available for formulating the data in the Table 6.9. The estimation functions by vehicle classes are presented in the Table 6.10.

Table 6.9 Tire consumption rate by vehicle class and speed (%/ 1,000km)

Speed (km/h)	Passenger car	Small bus	Heavy bus	Small truck	Medium truck	Heavy truck
10	0.7	0.6	1.6	0.6	1.2	1.9
20	1.3	1.1	2.6	1.1	1.9	3.3
30	2.0	1.8	3.8	1.8	2.7	5.0
40	2.9	2.5	5.3	2.5	3.7	7.1
50	3.7	3.2	7.1	3.1	4.9	9.3
60	4.7	4.0	9.2	4.0	6.1	12.3
70	5.8	5.0	11.6	5.0	7.4	15.4
80	7.0	6.1	14.8	6.1	9.2	19.6
90	8.5	7.4	18.5	7.4	11.0	24.7
100	10.1	8.8	22.9	8.8	13.2	20.3[1)]
110	12.3	10.7	27.8	10.7	15.6	37.2
120	14.6	13.0	33.1	13.0	-	-

Source: MLTM, 2009

Note: 1) An input error in the reference, this might be 30.3

Table 6.10 Estimation functions for tire consumption rate

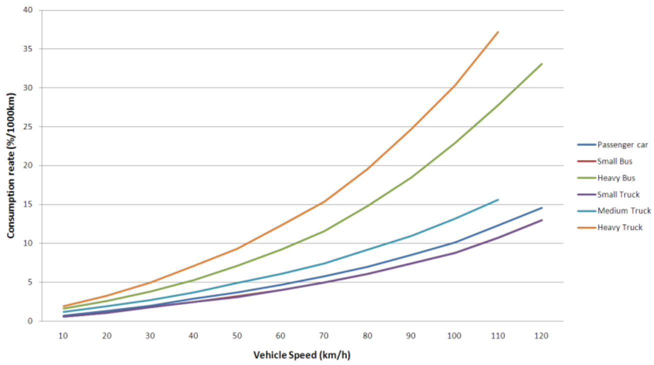
Vehicle class	Functions	R^2
Heavy truck	$y = 0.0176x^3 - 0.0224x^2 + 1.4585x + 0.4015$	0.9999
Heavy bus	$y = 0.009x^3 + 0.0556x^2 + 0.7329x + 0.8384$	0.9999
Medium truck	$y = 0.0039x^3 + 0.0227x^2 + 0.6506x + 0.4955$	0.9999
Passenger car	$y = 0.0059x^3 - 0.0337x^2 + 0.7875x - 0.1263$	0.9998
Small bus & truck	$y = 0.0061x^3 - 0.0426x^2 + 0.7263x - 0.1495$	0.9997

Source: (formulated from) MLTM (2009)

Table 6.11 Constants for tire consumption model

Vehicle Class	a_1	a_2	a_3	a_4
Heavy truck	0.0176	-0.0224	1.4585	0.4015
Heavy bus	0.009	0.0556	0.7329	0.8384
Medium truck	0.0039	0.0227	0.6506	0.4955
Passenger car	0.0059	-0.0337	0.7875	-0.1263
Small bus & truck	0.0061	-0.0426	0.7263	-0.1495

Source: (derived from) MLTM (2009)



Source: MLTM, 2009 (Graphed)

Figure 6.8 Tire consumption rate by vehicle class and speed

By substituting the constants into a_1, a_2, a_3 and a_4, an equation for estimating tire cost has been established. The tire consumption model in the Hybrid PMS is simply described in the Eq. 6.14,

$$VOC_{tire} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{k=1}^{K} \frac{AADT_y^{Sk} \times Ln^S \times \left[a_1^k\left(\frac{V_y^{Sk}}{10}\right)^3 + a_2^k\left(\frac{V_y^{Sk}}{10}\right)^2 + a_3^k\left(\frac{V_y^{Sk}}{10}\right) + a_4^k\right]}{100 \times 1000} \times UC_{tire}^k \qquad (6.14)$$

Where,

VOC_{tire} = total tire consumption cost

UC_{tire}^{k} = unit cost of a tire
Ln^{s} = section length in km
$a_1 \sim a_4$ = model constants (see the Table 6.11)

6.6.1.3 Engine Oil Cost

As discussed in the Chapter 6.3.4, engine oil consumption constitutes a relatively small component of total user cost (even VOC). This component could be excluded from the LCC, but it is required to have perfect meaning of user cost (or vehicle operating cost). Users of the Hybrid PMS can include also exclude this component by their customization scheme.

A. Review of engine oil consumption model
Engine oil consumption is explained through these two factors:

- Oil contamination
- Oil loss

Contamination may occur because of impurities resulting from the combustion process. It may also be due to external sources, such as dust on the road surface. This is a main reason that the manufacturer recommends changing engine oil, usually after travelling a set distance. In case of oil losses arise through faulty seals or by the combustion process wherein oil may leak past the pistons and be burned with the fuel (Bennett and Greenwood, 2003).

Claffey (1971) investigated engine oil consumption, and well describes the mechanism that speed had an impact on oil consumption as did the frequency of stop-go cycles.

"The magnitude of the oil consumed to replace contaminated oil depends in part on whether operation is at high sustained speed with engines properly warmed up (long trips), so that sludge is burned away, or at low speed on short trips with frequent stops when unburned combustion remnants are able to accumulate. Oil replacement because of contamination is also accelerated by operation on dusty roads when some dust particles get by filters to form an abrasive oil contaminant."

By referring above paragraph, it is expected that the oil consumption rates should be separately modeled for urban and free-flow traffic. For HDM-III, Watanatada *et al.* (1987a) proposed the following model for predicting oil consumption based on road condition:

$$OC = a_0 + a_1 IRI \tag{6.15}$$

Where,
OC = oil consumption in liter/1000km
IRI = international roughness index in m/km
a_0, a_1 = model coefficients (refer to Table 6.12)

Kadiyali (1991) in updating the CRRI (1982) costs adopted Eq. 6.16 which was from the original CRRI (1982) work. The Table 6.13 gives the parameters for use with this model. This equation was adopted by IRC (1993) for economic appraisals in India. This model added more parameters about geometry, width and roughness.

$$OC = a_0 + a_1 RF + a_2 \frac{RI}{W} \tag{6.16}$$

Where,
RF = rise and fall in m/km
W = pavement width in meter
$a_0, \sim a_2$ = model coefficients (See Table 6.13)

Schutte (1981) proposed a speed dependent oil model for South Africa based on the work of Claffey (1971). This model considered vehicle speed only (see Eq. 6.17)

$$OC = a_0 + a_1 V \tag{6.17}$$

Where,

V = vehicle speed in km/h

In case of Korea, the MLTM (2009) suggest a table for estimating the engine oil consumption by vehicle class and speed. The table was a calibrated result of de Weille (1966) by field surveys performed in 1999. Table 6.14 and Figure 6.9 are showing the details of the result.

Table 6.12 HDM-III oil model coefficients

Vehicle Class	a_0	a_1
Passenger car and Utilities	1.55	0.15
Light Trucks	2.20	0.15
Medium and Heavy Trucks	3.07	0.15
Articulated Trucks	5.15	0.15
Heavy Buses	3.07	0.15

Source: Watanatada et al., 1987a

Table 6.13 Indian oil consumption model parameters by vehicle class

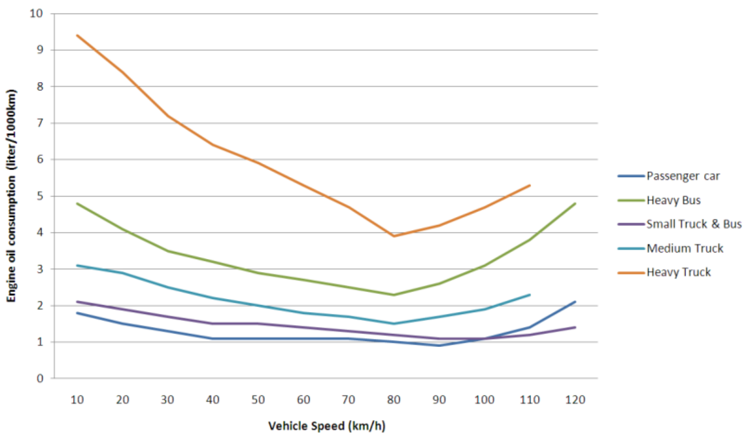
Vehicle Class	a_0	a_1	a_2
Motorcycles	0.39	0.00750	0.08
Passenger cars	1.94	0.03969	0.43
Light truck	1.00	0.02400	0.11
Medium and Heavy Trucks	2.48	0.06010	0.29
Heavy buses	3.66	0.01271	0.48

Source: Kadiyali et al., 1981

Table 6.14 Engine oil consumption rate by vehicle class and speed (Liter: 1,000km)

Speed (km/h)	Passenger car	Small Bus	Heavy Bus	Small Truck	Medium Truck	Heavy Truck
10	1.8	2.1	4.8	2.1	3.1	9.4
20	1.5	1.9	4.1	1.9	2.9	8.4
30	1.3	1.7	3.5	1.7	2.5	7.2
40	1.1	1.5	3.2	1.5	2.2	6.4
50	1.1	1.5	2.9	1.5	2.0	5.9
60	1.1	1.4	2.7	1.4	1.8	5.3
70	1.1	1.3	2.5	1.3	1.7	4.7
80	1.0	1.2	2.3	1.2	1.5	3.9
90	0.9	1.1	2.6	1.1	1.7	4.2
100	1.1	1.1	3.1	1.1	1.9	4.7
110	1.4	1.2	3.8	1.2	2.3	5.3
120	2.1	1.4	4.8	1.4	-	-

Source: MLTM, 2009



Source: MLTM ,2009 (Graphed)

Figure 6.9 Oil consumption rate by vehicle class and speed (in Korea)

The Table 6.14 showing the engine oil consumption rate can be modeled by polynomial functions.

$$OC = a_1\left(\frac{V}{10}\right)^5 + a_2\left(\frac{V}{10}\right)^4 + a_3\left(\frac{V}{10}\right)^3 + a_4\left(\frac{V}{10}\right)^2 + a_5\frac{V}{10} + a_6 \tag{6.18a}$$

The Eq. 6.18a can be rewritten with consideration of driving length in analysis section s and analysis period y,

$$VOC_{tire} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{k=1}^{K}\frac{AADT_y^{Sk}\times Leng^S\times\left[a_1^k\left(\frac{V_y^{Sk}}{10}\right)^5+a_2^k\left(\frac{V_y^{Sk}}{10}\right)^4+a_3^k\left(\frac{V_y^{Sk}}{10}\right)^3+a_4^k\left(\frac{V_y^{Sk}}{10}\right)^2+a_5^k\left(\frac{V_y^{Sk}}{10}\right)+a_6^k\right]}{1000}\times UC_{tire}^k \tag{6.18b}$$

The model coefficients for the Eq. 6.18b were derived from the Table 6.14. The coefficients are presented in the Table 6.15.

Pienaar (1984) investigated the effects of operating conditions on oil consumption experiments were conducted with a fleet of ten vehicles (Pienaar, 1984). It was found that oil loss was a function of engine speed and that it was proportional to the fuel consumption. The Table 6.16 gives the values of the oil loss as a fraction of the fuel consumption for the different vehicle class.

The HDM-4 oil consumption model was based on the work of the research by Pienaar (1984) which related oil consumption to operation and contamination. The operational losses are a function of fuel consumption, while the contamination is a function of the distance between oil changes and the oil capacity. The following is the model adopted for HDM-4 (Bennett and Greenwood, 2003);

$$OC = OC_{Cont} + OC_{Oper}\times Fuel \tag{6.19a}$$

Where,
OC = oil consumption in liter/1000km
OC_{Cont} = oil loss due to contamination in liter/1,000km
OC_{Oper} = oil loss due to operation in liter/1,000km
$Fuel$ = fuel consumption in liter/1,000km

Table 6.15 Model coefficients for tire consumption model

Vehicle class	Coefficients						R^2
	a_1	a_2	a_3	a_4	a_5	a_6	
Heavy truck	-0.000304487	0.010620629	-0.127964744	0.720177739	-2.678811189	11.53939394	0.9921
Heavy bus	-0.000210219	0.007498629	-0.093342503	0.551741396	-1.899305156	6.254545455	0.9965
Medium truck	6.41026E-05	-0.001835664	0.022814685	-0.117395105	-0.051200466	3.263636363	0.9918
Small truck & bus	2.45098E-05	-0.000301231	-0.002420129	0.055355735	-0.390102324	2.45	0.9872
Passenger car	9.04977E-05	-0.001775675	0.007246675	0.054757987	-0.522187029	2.2727	0.9917

Source: derived from MLTM (2009)

Table 6.16 Coefficients of engine oil consumption model

Vehicle class	Distance until change (km)	Engine oil capacity (L)	Rate of oil consumption (L/1000km)	Rate of oil loss (Liter[1)]/Liter[2)])
Passenger car	9290	4.1	0.44	0.0028
Light delivery vehicles	7300	4.9	0.67	0.0028
Medium trucks	9000	13.6	1.73	0.0021
Heavy trucks	10000	30.6	3.06	0.0021
Heavy buses	8000	19.6	2.43	0.0021

Source: Pienaar (1984)
Note:1) Engine oil consumption,
2) Fuel consumption

Table 6.17 Default HDM-4 oil consumption model parameters

Representative vehicle	Description	Distance between oil changes (km)	Engine oil capacity (Liter)	Rate of oil contamination (Liter/1000km)	Oil loss due to operation[1)] (Liter/Liter)
1	Motorcycle	5,000	2.0	0.40	0.0014
2	Small car	10,000	4.0	0.40	0.0028
3	Medium car	10,000	4.0	0.40	0.0028
4	Large car	10,000	4.0	0.40	0.0028
5	Light delivery Vehicle	7,500	5.0	0.67	0.0028
6	Light goods Vehicle	7,500	5.0	0.67	0.0028
7	Four wheel drive	7,500	5.0	0.67	0.0028
8	Light truck	9,000	14.0	1.56	0.0021
9	Medium truck	9,000	14.0	1.56	0.0021
10	Heavy truck	10,000	31.0	3.10	0.0021
11	Articulated truck	10,000	31.0	3.10	0.0021
12	Mini bus	7,500	5.0	0.67	0.0021
13	Light bus	8,000	14.0	1.75	0.0028
14	Medium bus	8,000	14.0	1.75	0.0021
15	Heavy bus	8,000	20.0	2.50	0.0021
16	Coach	8,000	20.0	2.50	0.0021

Source: Bennett (1996a)
Note: 1) OL_{Fuel} *in the Eq.6.20*

The loss due to contamination is determined as follows:

$$OC_{Cont} = \frac{OL_{cap}}{D_{chng}} \tag{6.19b}$$

Where,
OL_{cap} = engine oil capacity in liter
D_{chng} = distance between oil changes in 1000km

For practical application, the Eq.6.19a and the Eq. 6.19b can be reorganized by changing unit of each variable, and consideration driving distance and fuel consumption.

$$VOC_{oil} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{k=1}^{K}\left[\left(\frac{OL_{cap}^{k}}{CD^{k}}\right) \times Leng^{s} \times AADT_{y}^{sk}\right] + \left[OL_{Fuel} \times Fuel_{y}^{sk}\right] \times UC_{oil}^{k} \tag{6.20}$$

Where,
OL_y^{sk} = engine oil consumption of vehicle type *k* of section *s* in year y in liter
OL_{cap}^{k} = engine oil capacity of vehicle type *k* in liter
CD^k = distance between oil changes in kilometer
$Leng^s$ = length of section *s*
$AADT_y^{s_k k}$ = traffic volume of vehicle type *k* of section *s* in year y
OL_{Fuel} = oil loss per fuel consumption in liter (oil)/liter (fuel)
$Fuel_y^{sk}$= fuel consumption of vehicle type *k* of section *s* in year y in liter

B. Comparison of engine oil consumption models

To compare the reviewed approaches (the HDM-III, Kadiyali, HDM-4, and MLTM) several assumptions are required because required data of each model is different. The result of comparison is summarized in the Table 6. 18. Its estimation result and evaluation is addressed in the Table 6.19.

Table 6.18 Comparison of engine oil consumption model

Models	Estimation function	Applied variables	Applied assumptions for comparison[4)]
HDM-III (Watanatada *et al*., 1987a)	Road condition based: $OC = a_0 + a_1 IRI$	Roughness	·Case = passenger car ·IRI = 2.0m/km ·Slope = 0.0m/km ·Pavement width = 14m[1)] ·Vehicle speed = 80km/h ·Engine oil capacity = 4 liter[2)] ·Distance between oil change = 10,000km[2)] ·Fuel consumption rate = 0.662 liter/km[3)]
Kadiyali (Kadiyali, 1991)	Road condition + geometry based: $OC = a_0 + a_1 RF + a_2 \frac{RI}{W}$	Roughness, slope, pavement width	
MLTM (MLTM, 2009)	Vehicle speed dependent: $OC = a_1 \left(\frac{V}{10}\right)^5 + a_2 \left(\frac{V}{10}\right)^4 + a_3 \left(\frac{V}{10}\right)^3 + a_4 \left(\frac{V}{10}\right)^2 + a_5 \frac{V}{10} + a_6$	Vehicle speed	
HDM-4 (Bennett, 1996a)	Oil loss and contamination based: $OC = OC_{Cont} + OC_{Oper} \times Fuel$	Engine oil capacity, Distance between oil changes, Fuel consumption	

Note: 1) 4 lanes (1 lane = 3.5m)
2) Refer to the Table 6.17
3) Refer to the Table 6.7
4) Assumed conditions are the best conditions.

Table 6.19 Comparison of estimation result by each model (case: passenger car, 1000km)

Models	Engine oil consumption rate (liter/1000km)	Expected distance between oil changes (km)[1)]	Evaluation[2)]
HDM-III (Watanatada *et al*., 1987a)	1.8500	2162.2	-2837.84
Kadiyali (Kadiyali, 1991)	2.0014	1998.6	-3001.43
MLTM (MLTM, 2009)	1.0022	3991.2	-1008.78
HDM-4 (Pienaar, 1984)	0.5853	6833.4	1833.40

Note: 1) engine oil capacity was assumed as 4 liters
2) compared with assumed usual change cycle (5,000km)

C. Suggestion of engine oil consumption model for the Hybrid PMS

As shown in the Table 6.18, assumed conditions were almost best conditions. Under the situation each model has somewhat different consumption rate. When engine oil capacity is assumed around 4 liters, expected distance between oil changes of HDM-III and Kadiyali model is relatively short compared with the general understanding on life expectancy of engine oil (the general awareness is around 5,000km for a passenger car). Maybe both the MLTM and the HDM-4 model are applicable. However, HDM-4 result is much practical because 1) the applied assumptions were almost the best condition, but also 2) there is a tendency that many drivers delay their oil change cycles.

In term of data requirement, the HDM-III, MLTM, and Kadiyali could be easily applied. In the case of the HDM-4 model, by establishing the typical distances between oil changes as well as the average oil capacity the parameter, OC_{Cont}, can be readily quantified, or be assumed by referring the Table 6.17. Note that when we see the basic equation of HDM-4 model (see the Eq. 6.19) as it is, the oil consumption is affected by pavement condition because the fuel consumption is affected by the vehicle speed, and the vehicle speed is also affected by pavement condition reflected by level of road investment. In the Hybrid PMS, the two model, HDM-4 and MLTM model, have been modeled as basic components for users. That is, the Eq. 6.18b (for MLTM model) and the Eq. 6.20 (for HDM-4 model) are adopted as basic equations respectively.

6.6.1.4 Vehicle Maintenance and Repair Costs

A. Difficulties of modeling of vehicle maintenance and repair cost

The term, maintenance cost and repair cost (hereinafter vehicle maintenance costs) are comprised of two components: parts consumption and labor hours. Bennett and Greenwood (2003) noted that all the VOC components, vehicle maintenance costs are both difficult to measure empirically and to predict. This is because:

- The costs usually arise infrequently over the life of the vehicle, particularly for larger components;
- The maintenance practices of the owners/operators have a major impact on the costs. For example, Chesher and Harrison (1987) note that the variation in costs between operators was greater than that due to different road conditions;
- The maintenance costs for similar vehicles can vary significantly between manufacturers;
- Vehicles operating in harsh conditions may be of more robust construction and therefore have lower maintenance costs than standard vehicles and,
- Associating maintenance costs to operating conditions is difficult since vehicles tend to operate over a range of roads so the costs are averaged out.

Dunkerley (2003) highlights the difficulties of making completely portable relationships between countries. A heavy bus costs was USD 18,000 in India; USD 37,000 in Indonesia and USD116,000 in Africa. This cost differential has three implications on maintenance cost modeling (Dunkerley, 2003);

- Low priced vehicles lead to low cost spare parts as old vehicles are cannibalized
- Expensive vehicles mean that there is an industry for repairing and refurbishing existing vehicles rather than scrapping them, leading to a higher consumption of spares (and a discontinuity in the age-parts consumption relationship); and,
- The use of vehicle price in the denominator of the parts consumption relationships severely distorts the predictions.

Dunkerley (2003) also showed that the cost of a used engine was higher than a new engine in India. Namely, definition of car price is a critical point determining the scale of the vehicle maintenance cost because the cost is estimated by percentage of the vehicle price. This approach was adopted after the Kenya User cost study when it was found that parts cost were strongly correlated to replacement vehicle price. This has the advantage of making the models more transferable to different environments, although Chesher and Harrison (1987) note that;

"… this is to large extent a cosmetic operation since there is little reason to expect there to be a static relationship between vehicle prices and maintenance costs transferable across environments even under common highway conditions…"

B. Review of vehicle maintenance model
(a) Brazil Model (HDM-III)
The structure of the parts model is quite complicated. This model is based on the vehicle cumulative kilometer and pavement condition (IRI). The Brazil relationships have the following form (Watanatada *et al.*, 1987a):

$$PARTS = COSP \times CKM^{kp} \times exp(CSPIRI \times IRI) \qquad for\ IRI \leq IRIOSP \tag{6.21a}$$

$$PARTS = CKM^{kp}(a_0 + a_1 \times IRI) \qquad for\ IRI > IRIOSP \tag{6.21b}$$

$$a_0 = COSP \times exp(CSPIRI \times IRIOSP)\,(1 - CSPIRI \times IRIOSP) \tag{6.22}$$

$$a_1 = COSP \times CSPIRI \times exp\,(CSPIRI \times IRIOSP) \tag{6.23}$$

$$LH = COLH \times PARTS^{CLHPC} exp\,(CLHIRI \times IRI) \tag{6.24}$$

Where,
$PARTS$ = standardized parts consumption as a fraction of the replacement vehicle price per 1000 km
CKM = vehicle cumulative kilometer in km
IRI = roughness in IRI m/km
$IRIOSP$ = transitional roughness beyond which the relationship between parts consumption and roughness is linear
$COSP$ = parts model constant
$CSPIRI$ = parts model roughness coefficient
LH = number of labor hours per 1000 km
$COLH$ = labor model constant
$CLHIRI$ = labor model roughness coefficient

Watanatada *et al.* (1987a) served default model parameters. None the less, the review (Bennett, 1995) found that few studies calibrated the maintenance model. This is undoubtedly due to the difficulties in gathering sufficient data for model calibration.

Dhareshwar (1983) and Watanatada (1983) made to model parts consumptions mechanistically. The analysis postulated a simple model of the form;

$$PARTS = a_0 + a_1 SPE + a_2 PPE \quad (6.25)$$

Where,
a_0, a_1, a_2 = constants
SPE = suspension energy
PPE = propulsive energy

The model was modified to take into account vehicle age as;

$$PARTS = a_0 + (a_1 SPE + a_2 PPE) CKM^{a_3} \quad (6.26)$$

(b) India Research

Watanatada *et al.* (1987a) provided a set of maintenance relationships developed from data collected in the India User Cost Study. These models are different to those developed by the India RUC Study (CRRI, 1982) and include fewer variables. There were three different model forms in the Indian relationships for standardized parts costs, one for cars and utilities, one for buses and one for trucks. There are similarities between these relationships and those for Brazil but there are also important differences.

For cars and utilities, for example, there was no dependence on vehicle age and parts were simply an exponential function of roughness. For buses, parts consumption was the product of two functions, total travel raised to the power of 0.359 (broadly similar to Brazil) and an exponential function of roughness, curvature, gradient and road width. The relationship for trucks was similar to that for buses except that the exponential term also includes mass (Bennett and Greenwood, 2003). There are four different models for maintenance labor, one for cars, one for utilities, one for buses and one for trucks. The models have a similar form to Brazil. Labor hours are proportional to standardized parts cost raised to a power of around 0.5. In the case of buses and trucks, the labor hours are also multiplied by an exponential function of road roughness (Bennett and Greenwood 2003).

(c) USA Research

Winfrey (1969) presented maintenance costs based on the results of surveys. These were updated by Claffey (1971) using an approach which has been termed the constituent component approach.

A list of parts requiring non-routine maintenance was assembled along with the distance travelled before the maintenance was required. Weighting these by the cost of repairs one can establish an average cost. The Table 6.20 shows the results of this method for a "standard size" passenger car (Claffey, 1971). This suggests a cost of \$0.0072/km, or \$7.2 per 1000 km.

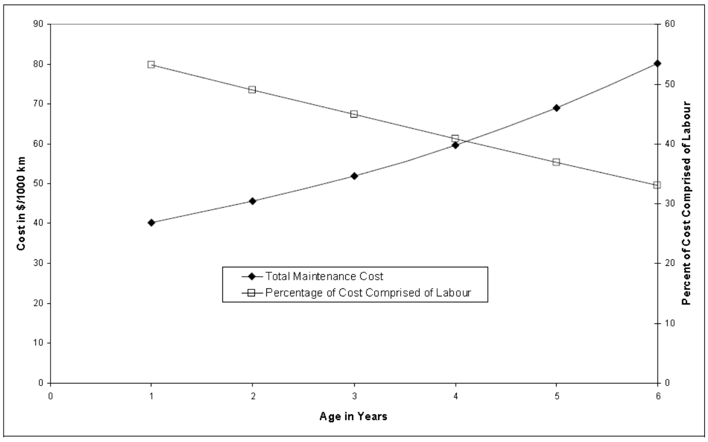
Papagiannakis (1999) gives the results of a study into heavy truck parts consumption. Figure 6.10 shows the effects of age on maintenance cost as well as the percentage of the cost due to labor.

It will be noted that there is a significant increase in the maintenance costs with age and at the same time the percentage of the costs due to labor decreases. This indicates, not unexpectedly, an increase in the number of parts replaced as the vehicle ages. One finding of this study which is at variance with other studies is that roughness effects manifest themselves on parts consumption even at low roughness (< 2 IRI m/km). This is possibly due to inaccuracies in estimating the roughness of the roads which the vehicles were operated on.

Table 6.20 Average maintenance cost using constituent component approach (passenger car)

Vehicle part	Distance Travelled Before Repairs ('000km)		Cost of repairs ($)		Average cost (cents/km)
	Range	Mean	Range	Mean	
Automatic transmission	86-165	106	100-255	178	0.17
Engine block	80-144	112	65-130	93	0.08
Shock absorbers	48-96	70	28-51	37	0.05
Brake system	64-123	86	40-58	41	0.05
Distributor	16-34	22	5-20	12	0.05
Exhaust	48-90	62	18-33	26	0.04
Carburettor	51-96	72	21-40	29	0.04
Universal	48-86	70	20-31	28	0.04
Rear axle	160-181	170	54-75	66	0.04
Generator	67-96	83	18-40	32	0.04
Water pump	54-88	69	18-30	24	0.03
Springs	64-160	109	28-46	40	0.04
Fuel pump	70-102	83	12-20	15	0.02
Oil pump	147-221	174	16-28	21	0.01
Radiator	106-154	122	10-25	16	0.01
Fan belt	64-109	82	3-6	4	0.00
Total					0.72

Source: Claffey (1971). (Revised for unit conversion from miles to kilometer)



Source: Bennett and Greenwood, 2003

Figure 6.10 Effect of age on cost and labor component

(d) South Africa Research

As a part of their considerable studies into VOC, the CSIR in South Africa developed models for parts consumption. The research can be grouped into two areas: that orientated at speed effects and that at roughness effects.

As described by du Plessis (1989), the speed effects cost research saw maintenance costs divided into routine and non-routine maintenance components. The sum of these two was the total maintenance costs. This total cost was then modified to account for operating conditions, principally speed. For cars, the routine costs were generally assumed to be those corresponding to the manufacturer's recommended maintenance policy. The non-routine costs were then either assumed to be a fixed percentage of the routine costs or calculated based on estimates of the distance life of various components on the vehicle. Initially, the speed effects were estimated based on a third order polynomial regression of the Winfrey (1969) costs. However, this was later superseded by an approach which divided the costs into the following categories;

- Those distances based and thus independent of speed;
- Those mainly influenced by time;
- Those mainly influenced by road speed;

- Those mainly influenced by engine speed; and,
- Those mainly influenced by stop/go and speed change cycles

Routine maintenance costs were distance-based. The time-based costs were converted to their present worth and divided by the utilization to obtain a per km cost. Since the utilization can be a function of speed, these were also to some degree influenced by speed. The costs directly influenced by road speed were assumed to be linearly proportional to speed. The engine speed costs were those due to the power requirements of the engine and were assumed to be proportional to fuel consumption. All brake and clutch repairs were assumed to be due to speed changes. The total costs were then predicted using a polynomial of the following form:

$$PCST = a_1 + a_2V + \frac{a_3}{V} + a_4V^2 \quad (6.27)$$

Where,
$PCST$ = maintenance cost in cents/km
a_1 to a_4 = model parameters

The key problem with applying this method is the sensitivity of the results to the assumed average speed of the vehicle. du Plessis (1989) shows that there are significantly different results if one assumes that the costs apply at a low urban speed instead of a higher rural speed. Such differences have not been validated in user studies.

To investigate roughness effect on part consumption, du Plessis and Meadows (1990) operated three identical rental cars over preselected routes, two with unsealed and one with a sealed surface for 40,000 km. Marked differences were observed in the maintenance costs on the unsealed versus sealed roads. It was found that there was damage both due to roughness and also the unsealed surface. The small sample size did not permit for a relationship between parts consumption and roughness to be developed, however, the authors noted that the costs were similar to what would arise with the Brazil model at that roughness.

du Plessis *et al.* (1989) used 12 months of cost records from a single bus operator running 740 vehicles on wide ranging conditions to develop relationships. This led to the development of the following model for predicting parts consumption:

$$PARTS = exp(-0.5254 + 0.6779 \times ln\,CKM + 0.3338 \times ln(13 \times IRI)) \times 10^3 \quad (6.28)$$

Finally, Findlayson and du Plessis (1991) studied five separate forestry operations which had cost data. This led to the development of the following model:

$$PARTS = exp(-3.0951 + 0.4514 \times ln\,CKM + 1.2935 \times ln(13 \times IRI)) \times 10^{3*} \quad (6.29)$$

* An error in the reference, maybe 10^{-3}

In case of labor model, the South African research led to the development of the following labor hours relationships (du Plessis and Schutte, 1991):

For buses,

$$LH = 0.763exp\,(0.0715 \times IRI)\left(\frac{PARTS}{NVPLT}\right)^{0.517} \quad (6.30)$$

For trucks,

$$LH = \max\left(3, -0.375 + 0.017\left(\frac{PARTS}{NVPLT}\right) + 0.182 \times IRI\right) \quad (6.31)$$

Where,
$NVPLT$ = replacement vehicle price, less tires

(e) New Zealand Research

The New Zealand vehicle operating cost model (Bennett, 1989) used the HDM Brazil relationships for spare parts calibrated for local use by the addition of a constant term—*i.e.* a translation calibration. The cost of maintenance labor was then calculated as the product of parts cost and the factor "55/45". Opus-Beca (1998) describes the results of a study into maintenance costs using various sources of data, mainly commercial fleet databases. It was found that:

- The mean parts costs for light vehicles were within 20 percent of those predicted by the HDM-III model at low roughness; medium trucks were 40 percent higher and heavy trucks 100 percent higher;

- The maintenance costs were constant over the first 3-4 years of vehicle life before increasing;
- The proportion of maintenance costs due to routine servicing as opposed to specific maintenance varied over the life of the vehicle. They decreased from 75 percent for new cars to less than 20 percent for cars seven years or older;
- Parts cost constituted 44-61 percent of the total maintenance costs, with this percentage not varying greatly with vehicle age;
- There was evidence of body type influencing maintenance costs: for example, tanker trucks were found to have 75 percent higher costs than bulk material costs;
- It was not possible to differentiate costs between urban and rural roads or by road condition. This was due to limitations in the data instead of indicating that these effects do not exist.

Cenek and Jamieson (1999) investigated roughness effects using vehicles equipped with accelerometers on the body and suspension. The result noted that at lower roughness the accelerations do not have much of an impact. This can be used to confirm the roughness level below which there is no impact on parts consumption.

It was also found that there were speed effects and it was proposed that a combination of speed and roughness—*i.e.* the roughness expressed as IRI m/h instead of IRI m/km—would be a better predictor of parts consumption. The results clearly show that the higher the speed, the greater the impact of roughness on body accelerations. This was something also suggested by Paterson and Watanatada (1985) who recommended that the average rectified velocity is a better determinant of speed than average rectified distance.

(f) Swedish Research

The VETO model was developed by the Swedish Road and Traffic Research Institute (VTI) (Hammarström and Karlsson, 1987). It contains two approaches to the calculation of spare parts and maintenance labor, one empirical and one mechanistic. The former relies on the HDM Brazil relationships while the latter employs a "wear index" for vehicle components. The mechanistic model is a detailed simulation of an idealized two-dimensional vehicle travelling over a surface with a specified profile. The model works on the basis that the wear and tear of components depends upon the product of the number of stress cycles they have been subjected to and the stress amplitude raised to the sixth power. The number of cycles is assumed to be constant per unit length of road (independent of roughness) while the stress amplitude for each component is proportional to the RMS value of the dynamic component of the wheel load.

(g) HDM-4 model (World Bank)

Owing to the absence of significant new data, the HDM-4 parts consumption model by necessity is largely based on the HDM-III model. It was developed to address the following perceived shortcomings in the HDM-III model:

- The need to limit the model predictions at low roughness levels;
- The desire for a simpler and more easily followed model structure;
- The refinement of the model parameters with regard to the effects of roughness on parts consumption; and,
- The ability to model different trade-offs between parts and labor.

This led to the following parts consumption model (Bennett, 1996b):

$$PARTS = [K0pc\{CKM^{kp}(a_0 + a_1 RI)\} + K1pc](1 + CPCON \times dFUEL_{avg}) \quad (6.32)$$

Where,

CKM = cumulative kilometer ($CKM = 0.5LIFE \times AKM$)

$CPCON$ = the congestion elasticity factor (default = 0.1)

$dFUEL_{avg}$ = the average additional fuel consumption due to congestion as a decimal

$K0pc$ = a rotational calibration factor (default = 1.0)

$K1pc$ = a translational calibration factor (default = 0.0)

a_0 to a_3 = model coefficients

Bennett (1996b) estimated parameter values for this model from the HDM-III model predictions. The exponential models were replaced by linear models which gave similar predictions in the range of 3-10 IRI m/km. Using a cumulative kilometer of 100,000 km for the distance travelled, the parameters a_0 and a_1 were established.

In case of HDM-4 labor hours model, as would be expected, there were large regional variations in the labor hours predictions which reflected the different maintenance practices and other factors such as the relative costs of parts versus labor. The desire for simplification, Bennett (1996b) proposed the following simple linear model for labor hour;

$$LH = K0lh[a_0 PC^{a_1}] + K1lh \tag{6.33}$$

Where,
LH = number of labor hours per 1000km
$K0lh$ = rotational calibration factor (default = 1)
$K1lh$ = translation calibration factor (default = 0)
a_0, and a_1 = model parameters

It is possible to eliminate the effects of roughness on parts consumption at low roughness. This is done using the following smoothing relationship has been adopted;

$$RI = max\ (IRI, min\ (IRI_0, a_0 + a_1 \times IRI^{-a_2}) \tag{6.34}$$

Where,
IRI_0 = limiting roughness for parts consumption in IRI m/km
a_0 to a_2 = model constants

The Eq.6.32 and Eq.6.33 can be simplified by excluding the congestion effect and calibration factor, for example;

$$PARTS = CKM^{kp}(a_0 + a_1 RI) \tag{6.35}$$

$$LH = a_0 PC^{a_1} \tag{6.36}$$

These simplified equations may have same or very similar results because the effect of road congestion is not so significant.

(h) Korea research (MLTM)
The Ministry of Land, Transportation and Maritime affair (MLTM) in Korea issued a guideline for road investment (MLTM, 2009). In this guideline, the MLTM suggested a table for vehicle maintenance cost estimation. The table gives values united by percentages of vehicle price by vehicle class and speed. This unit was based on the method suggested by de Weille (1966), and they performed calibration by field questionnaire survey. The result is showing in Table 6.21, and graphed in the Figure 6.11.

Table 6.21 Rate of vehicle repair and maintenance by vehicle class and speed (%[1]/ 1,000km)

Speed (km/h)	Passenger car	Small bus	Heavy bus	Small truck	Medium truck	Heavy truck
10	0.055	0.078	0.068	0.078	0.183	0.038
20	0.065	0.088	0.078	0.088	0.195	0.048
30	0.077	0.097	0.087	0.097	0.207	0.057
40	0.080	0.100	0.090	0.100	0.220	0.060
50	0.090	0.110	0.103	0.110	0.243	0.063
60	0.095	0.115	0.115	0.115	0.260	0.070
70	0.100	0.120	0.120	0.120	0.292	0.070
80	0.110	0.130	0.140	0.013[2]	0.320	0.080
90	0.113	0.143	0.153	0.143	0.355	0.093
100	0.120	0.154	0.163	0.154	0.380	0.103
110	0.113[3]	0.167	0.173	0.163	0.420	0.113
120	0.145	0.180	0.184	0.180	0.470	0.123

Source: MLTM, 2009
Note:1) percentage of vehicle price
2) An input error in the reference. This might be 0.130
3) An input error in the reference. This might be 0.133

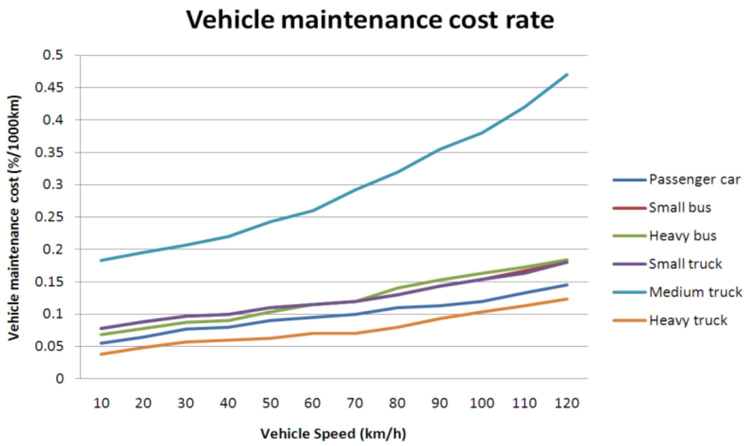


Figure 6.11 Vehicle maintenance cost rate (Case: Korea)

Table 6.22 Model parameters for vehicle maintenance cost (in Korea)

Vehicle class	a_1	a_2	a_3	a_4	R^2
Passenger car	0.00008	-0.0015	0.0152	0.0409	0.9964
Small truck & Bus	0.00006	-0.0008	0.0103	0.0695	0.9968
Medium truck	0.00001	0.0014	0.0061	0.1759	0.9988
Heavy truck	0.00006	-0.00009	0.0095	0.0315	0.9894
Heavy bus	-0.00005	0.0012	0.0026	0.0664	0.9955

The Table 6.21 also can be expressed by a three order of polynomial equation,

$$R_{VMCR} = a_1\left(\frac{V}{10}\right)^3 + a_2\left(\frac{V}{10}\right)^2 + a_3\left(\frac{V}{10}\right) + a_4 \tag{6.37}$$

Where,
R_{VMCR} = vehicle maintenance cost rate in percentage of vehicle price
V = vehicle speed in km/h
a_0 to a_3 = model coefficients (see Table 6.22)

The Eq.6.37 are rewritten in the Eq. 6.38.

$$VOC_{Veh\_Mntn} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{k=1}^{K}\left[\frac{\left\{a_1^k\left(\frac{V_y^{Sk}}{10}\right)^3 + a_2^k\left(\frac{V_y^{Sk}}{10}\right)^2 + a_3^k\left(\frac{V_y^{Sk}}{10}\right) + a_4^k\right\}\times\left(Leng^S \times AADT_y^{Sk}\right)}{1000\times100}\right]\times UC_{Mntn}^k \tag{6.38}$$

C. Summary and suggestion of vehicle maintenance cost model for the Hybrid PMS
From the review, main points for vehicle maintenance cost model are summarized as follows;

- Vehicle maintenance cost is summation of part consumption and labor hour.
- Main factor is vehicle age, pavement condition and vehicle speed.
- Under good pavement condition, there is no impact (or lower impact) on parts consumption.
- By aging of a vehicle, total vehicle maintenance cost rate is increasing, while the rate of labor cost becomes lower due to tendency that users change of parts instead of repair.
- Kinds of approach (mechanistic or empirical) and data requirement

Related researches reviewed in this paper are compared in the Table 6.23.

Table 6.23 Comparison of researches on vehicle maintenance cost

Research	Variables			Evaluation			
	Speed	Pavement condition	Vehicle aging	Vehicle class	Integrated approach	Percentage of vehicle price	Easy application
Brazil (HDM-III)	-	X	X	X	-	X	-
India	-	X	-	X	-	X	-
USA	-	X	-	-	X	-	X
South Africa	-	X	-	Δ[3)]	-	X	X
New Zealand	X	X	X	X	-	-	-
HDM-4	Δ[1)]	X	X	X	-	X	-
Simplified HDM-4	-	X	X	X	-	X	X
MLTM	X	Δ[2)]	-	X	X	X	X

Note: 1) HDM-4 model does not considers speed but congestion effect
2) Pavement condition could be indirectly affected to the vehicle maintenance cost, if the speed model considers pavement condition as a variable
3) South Africa model applied only bus and truck

From the above the points, the preconditions for better vehicle maintenance cost model are defined as follows;

- Speed dependent model
- Pavement condition based model
- Considering vehicle age
- Evaluated by vehicle class
- Evaluated by percentage of vehicle price
- Integrated approach on part consumption and labor hour
- Easy application

HDM-4 vehicle maintenance cost model is, of course, well-grounded model with the many case studies. Nevertheless, the MLTM model could be the better strategy satisfying the basic objective of the Hybrid PMS. The model just requires speed from the speed estimation model (will be explained in the Chapter 6.9.1). Since the speed model already considered an effect from pavement condition, the effect would make difference on vehicle maintenance cost. In addition, the MLTM model is the latest research results compared than the others. By the consideration of developing advanced technologies on durability of vehicle parts, the result may bring much trustable result.

6.6.1.5 Vehicle Depreciation Cost

The depreciation cost sometimes has often been excluded in the LCCA. However, this component may account for the highest ratio of vehicle operating cost. For that reason, user has to be careful for designing (or customizing) this model, and including this cost component into the LCC.

A. Reviews of vehicle depreciation model

Depreciation has both time and use related components. Ideally, the time related component should be treated as a standing cost while the distance related component is a running cost. Only the distance related component will be influenced by road investments, although if there is speed increases and additional utilization the allocation of the time related component will be affected (Bennett and Greenwood, 2003).

Halcrow Fox (1982) note that there is a relationship between the allocation of depreciation and utilization. Highly utilized vehicles will have short service lives and thus, higher distance based depreciation than vehicles with low utilization levels.

In most instances the depreciation has been allocated between time and use by assuming a percentage split. Some values reported in the literature are given in the Table 6.24 (Bennett and Greenwood, 2003).

Table 6.24 Reported allocations of time and distance depreciation components

Country	Percentage allocation of depreciation	
	Time (%)	Distance (%)
Australia	60	40
Denmark	0	100
Germany	50	50
N.Z. [1)]	70	30
N.Z. [2)]	85	15
U.K.	60	40
U.S.A. [3)]	Varies	Varies

Source: Bennett and Greenwood, (2003)
Note: 1) Passenger cars
2) Commercial vehicles and buses
3) Allocation is a function of utilization and speed

Daniels (1974) presented a technique for determining the time and use related components of depreciation. This technique was later applied by Butler (1984) to the U.S.A. It was based on the assumption that depreciation can be expressed as a function of a constant time component and a distance component which is linearly dependent on utilization.

The N.Z. values for depreciation (Bennett, 1989) are based on the predictions of a model that gave depreciation as a function of time and distance travelled. It was noted that there had been a change in the allocation over time with depreciation in 1988 being due more to time than it was in 1980.

Bennett (1996b) describes the development of the final models for capital cost modeling in HDM-4 using data from Thailand. It can be assumed that the residual value of the vehicle (RVPLT) is proportional to roughness: vehicles operated on rougher roads will have a lower residual value since they will have suffered more wear and tear. Bennett assumed that the residual values for all vehicles were 15 percent at a roughness of 5 IRI m/km; five percent at a roughness of 15 IRI m/km, and a minimum of two percent. Using a linear relationship was expressed as;

$$RVPLTPCT = max[a_0, a_1 - max(0, (RI - a_2))] \tag{6.39}$$

Where,
$RVPLTPCT$ =residual vehicle price in percent
a_0 = minimum residual value of the vehicle in percent (default = 2.0)
a_1 = maximum residual value of the vehicle in percent (default = 15.0)
a_2 = average roughness IRI below which the maximum value arises (default = 5)

The depreciation is calculated by using the Eq. 6.40;

$$DEP = 1000\frac{(1-0.01\,RVPLTPCT)}{LIFEKM} \tag{6.40}$$

Where,
DEP = depreciation cost as a fraction of the replacement vehicle, less tires
$LIFEKM$ = optimal lifetime utilization in km

The optimal life time utilization is calculated by;

$$LIFEKM = \frac{LIFEKM0 \times LIFEKMPCT}{100} \tag{6.41}$$

Where,
$LIFEKM0$ = average service life in km
$LIFEKMPCT$ = optimal lifetime kilometer as a percentage of baseline life

The average service life is calculated from the expression,

$$LIFEKM0 = AKM0 \times LIFE0 \tag{6.42}$$

Where,
$AKM0$ = average annual utilization in km
$LIFE0$ = average service life in years

The 0.01 in the Eq. 6.40 converts the residual value from a percentage to a fraction. The denominator of the Eq. 6.40 represents the lifetime utilization. The calculation of the depreciation cost is done using the Eq. 6.43;

$$DEPCST = DEP \times NVPLT \tag{6.43a}$$

$$NVPLT = NVP - N_{wheel} \times P_{wheel} \tag{6.43b}$$

Where,
$DEPCST$ = depreciation cost in cost/1000km
$NVPLT$ = replacement vehicle cost, less tires
NVP = replacement vehicle price
N_{wheel} = number of wheels on the vehicle
P_{wheel} = new tire price

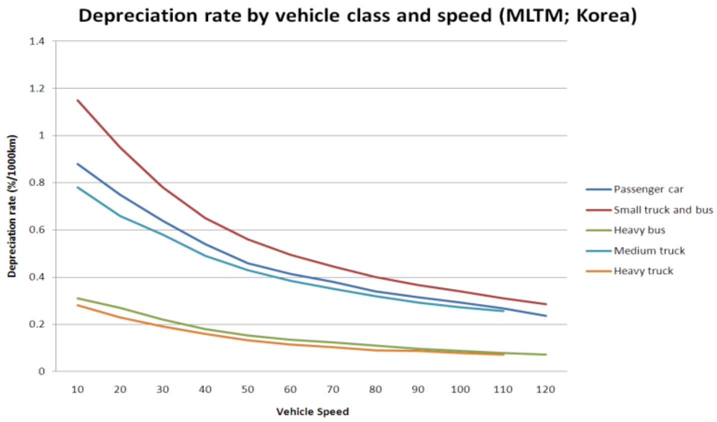
In brief summary, the model suggested by Bennett (1996b) is based on the residual values considering pavement condition. Afterward, the residual value is applied to estimating the depreciation cost as a fraction of the replacement vehicle by a function of utilization (annual driving distance) of vehicle price. Note that this method represents the depreciation cost by cash per 1000km, and excludes tire cost from the price of new vehicle.

The MLTM (2009) also suggested the depreciation rate on vehicle price by vehicle class and speed. This method expresses the depreciation cost by percentage of vehicle price. Table 6.25 gives the depreciation rate estimated by field questionnaire surveys.

Table 6.25 Depreciation rate by vehicle class and speed (%/ 1,000km)

Speed (km/h)	Passenger car	Small bus	Heavy bus	Small truck	Medium truck	Heavy truck
10	0.880	1.150	0.310	1.150	0.780	0.280
20	0.750	0.950	0.270	0.950	0.660	0.230
30	0.640	0.780	0.220	0.780	0.580	0.190
40	0.540	0.650	0.180	0.650	0.490	0.160
50	0.460	0.560	0.153	0.560	0.430	0.133
60	0.415	0.495	0.135	0.495	0.385	0.115
70	0.380	0.445	0.123	0.445	0.350	0.103
80	0.340	0.400	0.110	0.400	0.320	0.090
90	0.315	0.367	0.097	0.367	0.293	0.088
100	0.293	0.340	0.087	0.340	0.273	0.079
110	0.268	0.310	0.079	0.310	0.256	0.072
120	0.237	0.285	0.071	0.285	-	-

Source: MLTM, 2009
Note: percentage of vehicle price



Source: MLTM, 2009 (Graphed)
Figure 6.12 Depreciation rate by vehicle class and speed (Korea)

Table 6.26 Parameters for estimating depreciation rate of a vehicle (in Korea) (%[1)]/1,000km)

Vehicle class	a_0	a_1	a_2	a_3	R^2
Small truck and bus	-0.0009	0.0258	-0.2743	1.3986	0.9997
Passenger car	-0.0006	0.0165	-0.1852	1.0542	0.9994
Medium truck	-0.0004	0.0125	-0.149	0.9161	0.9995
Heavy bus	-0.0002	0.0061	-0.0695	0.3782	0.9978
Heavy truck	-0.0002	0.0061	-0.067	0.3412	-

Source: (Derived from) MLTM (2009)
Note: 1) Percentage of new vehicle price

The order of vehicle class having higher depreciation rate was small truck and bus, passenger car, medium truck, heavy bus and heavy truck (see the Figure 6.12). The values in the Table 6.25 follow also a three order polynomial equation. This can be expressed by a function of speed;

$$DEP = a_0\left(\frac{V}{10}\right)^3 + a_1\left(\frac{V}{10}\right)^2 + a_2\left(\frac{V}{10}\right) + a_3 \quad (6.44)$$

Where,
DEP = depreciation rate in percentage/1000km
V = vehicle speed in km/h
a_0 to a_3 = model constants (refer to the Table 6.26)

$$VOC_{Dep} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{k=1}^{K}\left[\frac{\left\{a_0^k\left(\frac{V_y^{Sk}}{10}\right)^3 + a_1^k\left(\frac{V_y^{Sk}}{10}\right)^2 + a_2^k\left(\frac{V_y^{Sk}}{10}\right) + a_3\right\}\times\left(Leng^S \times AADT_y^{Sk}\right)}{1000\times100}\right] \times UC_{Dep}^k \quad (6.45)$$

B. Suggestion of the vehicle depreciation model for the Hybrid PMS
The two models addressed in the previous chapter have different approach. The first one (Bennett, 1996b) results depreciation cost by functions of pavement condition, utilization, and vehicle cost. Last one is based on speed difference for depreciation rate. Since MLTM model requires a procedure converting the depreciation rate to price, estimation way of both models are same that apply $'DEPCST = DEPPCT \times NVP'$. One difference is that the Bennett model excludes tire cost from new vehicle cost in the last stage (see. the Eq. 6.43b).

However, there is a huge difference estimating depreciation rate of each vehicle class. In case of the Bennett model, it is basically influenced by an effect from pavement condition. By the definition of a_0, a_1, and a_2 in the Eq. 6.44, the depreciation rate can be completely changed, particularly in the parameter a_1 for maximum (the worst) condition. It implicates that the same pavement conditions could have different results by data characteristics, such as variance, and outlier. This will be discussed once again with a trial (see the Table 6.28b).

Basically, the Bennett model has advantage on considering pavement condition in the model. On the other hands, the MLTM model considers vehicle speed which was ignored in the Bennett model. Of course, the MLTM model also considers pavement condition indirectly into the speed model. However, the effect generated by the speed model may be relatively small. The model has advantage of the latest research result. However, it also has a limitation of empirical approach which requires calibration of estimation parameters. Data requirement of two models are compared in the Table 6.27. Based on the preconditions, two models were compared. The Table 6.29 gives the results.

Table 6.27 Comparison of data requirement of vehicle depreciation models

Data requirement	Bennett (1996b)	MLTM (2009)
Vehicle price	X	X
Tire price	X	-
Number of tire	X	-
Pavement condition	X	-
Utilization of each vehicle [1)]	X	-
Vehicle speed by class	-	X

Note: 1) annual driving distance and service life

Table 6.28a Precondition and assumptions for the vehicle depreciation cost - general

Requirement	Passenger car	Articulated truck	Note
Vehicle price ($)	10,000	110,000	A = Referred[1)]
Annual utilization (km)	23,000	86,000	B = Referred
Average life (year)	10	14	C = Referred
Optimal lifetime utilization (km)	230,000	1,204,000	D = B * C
Tire cost ($)	80	100	E = Referred
Number of tire	4	15	F = Referred
IRI (m/km)	4	4	G = Assumed
Speed (km/h)	8	8	H = Assumed
AADT of the vehicle class	15,000	300	I = Assumed
Section length (km)	3	3	J = Assumed
Total driving length (km)	45,000	900	K = I * J
Length unit per 1000km	45	0.9	L = K / 1000

Note: 1) referred to HDM-4 (ver. 1.30) default value in the program

Table 6.28b Precondition and assumptions for the vehicle depreciation cost – pavement (IRI: m/km)

Contents	Minimum	Maximum	Average	IRI	RVPLTPCT
IRI (Default-Bennett)	2.00	15.00	5.00	4.00	15
IRI (Korea)[1)]	1.50	4.89	2.95	4.00	3.84

Note: 1) The IRI data was from Korea's national highway (486 sections)

Table 6.29 Comparison results between the Bennett and the MLTM

Contents	Default				Korea			
	Bennett		MLTM		Bennett		MLTM	
	PC	H.T[1)]	PC	H.T	PC	H.T	PC	H.T
Vehicle price ($)	10000	110000	10000	110000	10000	110000	10000	110000
Vehicle price, less tire ($)	9680	108500	9680	108500	9680	108500	9680	108500
Depreciation rate (per 1000km)	0.003696	0.000706	0.003214	0.000932	0.004181	0.000799	0.003214	0.000932
Depreciation unit cost ($/1000km)	35.77	76.60	32.14	102.52	40.47	86.66	32.14	102.52
Depreciation cost for a section for a day ($)	1609.83	68.94	1446.30	92.27	1821.19	77.99	1446.30	92.27
Depreciation cost for a section for a year ($)	587586.5	25162.7	527899.5	33677.8	664733.2	28466.4	527899.5	33677.8

Note: 1) Heavy truck (referred to the articulated truck in the HDM-4)

Even though the Bennett model requires much data, it is expected that both models are not so difficult to apply to users in terms of data requirement because the data is usual for estimating life cycle cost of pavement field (except for utilization of each vehicle class).

To compare the models, a simple trial has performed for the case of passenger car and truck. The Table 6.28 shows applied preconditions and assumptions for the trial.

From the Table 6.29, the results can be summarized as follows;

- The depreciation rates from two model are similar
- The Bennett model makes different result under the same pavement condition
- Even though the depreciation rates are similar, the difference becomes very huge, because the unit cost is for a day, for a section, and for a vehicle class.

The depreciation rate was relatively similar. However the effect could be very huge. For example, the difference of total depreciation cost of only the passenger car (15,000 veh/day) in a section for a year was $136,833.67 when pavement condition data in Korea was applied (the default case was $59,687.02). This cost will be increased in a geometric progression by increasing the analysis period and target section. Because the depreciation cost with the vehicle maintenance cost accounts for the highest ratio of life cycle cost, the depreciation model should be carefully designed, and user should take into consider whether the cost is included into the life cycle cost or not.

It is somewhat difficult to determine which model is the better. The Bennett model has strengths on the microscopic approach that consider much detail information, particularly in pavement condition data, while the MLTM model is much easy to apply to user. To simplify the model, the Hybrid PMS will adopt the MLTM model which requires only vehicle's speed for the first general version of the Hybrid PMS. This could be altered to the Bennett model by user's customization scheme.

6.6.2 Travel Time Cost

Travel time cost model is an essential part of the user costs with the vehicle operating cost. Besides, the travel time is very important component in various economic appraisals of road projects. The travel time estimation has very different sides. Usually, the travel time under discrete flow (such as, inter-urban area having traffic jam and signaled traffic light) is very difficult to estimate. On the other hand, travel time estimation model for free-flow like expressway usually has relatively higher precision. In the Hybrid PMS, the travel time is estimated a most simple method with several assumptions as follows;

- Vehicles ride at uniformed (estimated) speed within a section (but each vehicle types have different speed).
- Vehicles ride at uniformed (estimated) speed during a year (but the annual speed is different during analysis period)
- No speed difference between lanes
- No variables making any negative or positive effect to speed change

The amount of time used, usually expressed the unit as h/1000km, is estimated from the predicted journey speed in km/h. This is multiplied by the unit cost of time to calculate the travel time cost.

6.6.2.1 Travel Time Cost Estimation Model

Simply, the cost is determined by a function of vehicle speed and section length. This can be formulated as a simple equation;

$$USER_{Travel\ Time} = \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{k=1}^{K}\left[\frac{Leng^{s}}{V_{y}^{sk}} \times (AADT_{y}^{sk} \times 365)\right] \times UC_{TT}^{k} \tag{6.46}$$
$$(k = 1, \dots, K; s = 1, \dots, S; Y = 1, \dots, Y)$$

Where,
$USER_{Travel\ Time}$ = estimated travel time cost in USD
$Leng^{s}$ = section length in km
V_{y}^{sk} = speed of vehicle class k of a section s in analysis year y in km/h
$AADT_{y}^{sk}$ = number of vehicle of class k of a section s in analysis year y
UC_{TT}^{k} = unit travel time cost for vehicle class k in USD/vehicle-hour

Since the effects from road characteristics (such as geometry, pavement condition and traffic condition) were considered in the speed model, the V_{y}^{sk} (in the Eq. 6.46) can be used as a speed factor which reflects pavement condition affected by level of road investment.

6.6.2.2 Consideration of Unit Costs

While the estimation of used travel time is simple, it is not so easy to establish a value of time. This is probably the most difficult data requirement in the travel time cost estimation because there are too many variables that determine time value of every individual. This chapter will treat typical definition in the pavement field. The typical specification of the time value is defined in the Table 6.30. The Hybrid PMS adopts concepts shown in the Table 6.30. If users want to follow above definition, they have to fill blanks in the Table 6.31.

Table 6.30 Ideal specification of the time value

Variables	Classification	Note
Purpose of travel	Business	Travel for business activities
	Leisure (or non-work)	Travel for leisure, visiting family, personal business, going to school, supermarket, etc.
Type of vehicle class	Passenger car	Driver + fellow riders[1)]
	Bus (small and heavy)	Driver + passenger[2)]
	Truck	Driver + fellow riders[1)]
Number of person in a car	Driver	Must be one person
	Passenger	Should be investigated
Regional characteristics	Inter-Urban	Should be investigated Taxi should be separately estimated
	Between Regions	Should be investigated

Note: 1) Assumed that the fellow riders have same time value with the passenger car driver
2) Assumed that the fellow rider have different time value with the bus driver

Table 6.31 Data requirement on time value unit for travel time cost estimation[1)]

Contents	Passenger car		Bus (small and heavy)[2)]			Truck	
	Driver and fellow riders		Driver	Fellow riders		Driver and fellow riders	
	Business	Non-business	Business	Business	Non-business	Business	Non-business
Ratio of trip purpose (%)	(A)	(a)					
Number of person (n/veh)	(B)	(b)					
Time value ($/person-hour)	(C)	(c)					

Note: 1) To consider regional characteristic (urban or region), one more table is required.
2) The unit cost set for bus should be separately classified into small bus and heave bus due to bus capacity

To simplify the type cost units, the Hybrid PMS adopts only one set of unit cost for regional application because the main target of the Hybrid PMS is national highway or expressway. This is, of course, can be customized for inter-urban road section by just modifying the unit costs in the simulation. In addition, the Hybrid PMS applies an integrated unit cost by vehicle classes. The concept can be formulated by an equation;

$$UC_{TT}^{k} = \sum_{p=1}^{P} NP_{p}^{k} \times UC_{TT_p}^{k} \qquad (p = 1, \dots, P; k = 1, \dots, 3) \tag{6.47}$$

Where,
UC_{TT}^{k} = unit travel time cost for vehicle class k in monetary terms/vehicle-hour (1= passenger car, 2=bus, 3=truck)
NP_{p}^{k} = the number of person of vehicle class k for the trip purpose p (1= business, 2= non-business) in person in monetary terms/person-hour
$UC_{TT_p}^{k}$ = unit travel time cost of vehicle class k for the trip purpose p

The Table 6.32 gives an example applying the Eq. 6.47 for a case of passenger car with the Table 6.31. The Table 6.33 introduces an example of unit cost applied for feasibility studies of road investment in Korea.

Table 6.32 Example of estimating integrated time value for a passenger car

Contents	Passenger car	
	Driver and fellow riders	
	Business	Non-business
Ratio of trip purpose (%)	(A)	(a)
Number of person (n/veh)	(B)	(b)
Time value ($/person-hour)	(C)	(c)
Time value by purpose and vehicle class ($/vehicle-hour)	(D)= (B*C)	(d)= (b*c)
Time vale by vehicle type ($/vehicle-hour)	Time value for a passenger car = (D)+(d)	

Table 6.33 Unit cost of travel time by vehicle class and purpose (Case: Korea in 2009) (Unit: USD)

Contents	Passenger car		Bus			Truck
	Business purpose	Non-business purpose	Driver	Business purpose	Non-business purpose	Driver
Trip purpose (%)	28.600	71.400	100.0	15.0	85.0	100.0
Average passengers per vehicle (n/veh)	0.445	1.112	1.000	1.497	8.483	1.000
Time value (person·hour)	14.343	5.293	12.014	14.343	2.546	10.506
Time value by trip purpose and vehicle class (veh·hour)	6.383	5.886	12.014	21.472	21.596	10.506
Time value by vehicle class (person·hour)	12.268		55.082			10.506

Source: MLTM, 2009

As noted above, the Hybrid PMS uses the integrated type of time value by the vehicle class. That is, user has to calculate (or assume) the integrated time unit cost before application. If user wants to analyze the travel time cost by the trip purpose, this will be readily available by user's customization.

6.6.3 Traffic Safety Cost

Accident cost or traffic safety has often been excluded from the target of analysis in pavement field due to its complexity and uncertainty. The frequency and degree of accidents are influenced by too many variables. Bennett and Greenwood (2003) noted that the growing realization of the substantial costs of road accidents (often over one percent of GNP) has renewed the desire to include possible accident saving along with reduction in vehicle operating costs and time savings in economic appraisals.

There is a general approach by a function of accident rate and hazard exposure (driving distance). This approach may (or may not) be reasonable to estimate absolute cost for accident cost. However, the estimation result cannot be different by road investment level. In brief, every alternative of pavement maintenance strategies has same accident cost. If a user has a purpose to estimate scale of the accident cost, this would be reasonable. However, in terms of economic appraisal, the road investment should influences to the accident frequency (rate) and severity by serving the better and safer road pavement condition. This chapter will introduce following two approaches on traffic safety modeling:

- Accident rate and hazard exposure (hereinafter, hazard exposure method)
- Pavement condition based approach

The two methods basically have similar flow that apply type of accident (*e.g.* Fatal, injury, property and etc.) and unit cost of the types. Difference is estimation method for number of accident. For economic analysis in PMS, the pavement condition based method is better. However, the hazard exposure method is the most general method including the other fields. Therefore, both models has been modeled in the Hybrid PMS for various application.

6.6.3.1 Accident Rate and Hazard Exposure Method

The most general method in estimation of accident costs is hazard exposure method by using averaged annual driving distance (by vehicle types), and accident rates (by a metrics of vehicle types and accident types). It is very easy to apply. However, the data requirements may require additional researches. Also the value should be periodically updated to exactly reflect reality. The basic equation of this method is;

$$R_{acc} = \frac{N_{acc}}{EXPO} \quad (6.48)$$

Where,
R_{acc} = accident rate in accidents in 100 million veh-km
N_{acc} = the number of accident within a year
$EXPO$ = exposure to accident in kilometer per year

The $EXPO$ in the Eq. 6.48 is usually expressed in 100 million veh-km. This can be calculated by the Eq. 6.49;

$$EXPO = \frac{AADT \times 365 \times Leng}{10^8} \tag{6.49}$$

Where,
$EXPO$ = accident exposure in a section (not including intersection)
$AADT$ = annual averaged dairy traffic in veh/day
$Leng$ = section length in km

The basic equations for modeling traffic accident cost are;

$$N_{acc} = EXPO \times R_{acc} \tag{6.50}$$

$$USER_{acc} = N_{acc} \times UC_{acc} \tag{6.51}$$

Where,
$USER_{acc}$ = user cost by accident in monetary terms
UC_{acc} = unit cost for accident in monetary terms
R_{acc} = accident rate by types

By the consideration of accident type, analysis year and sections, the equations above may be rewritten as follows;

$$USER_{acc} = \sum_{s=1}^{S} \sum_{y=1}^{Y} \sum_{k=1}^{K} \left[\frac{AADT_y^s \times 365 \times Leng^s}{10^8} \right] R_{acc}^k \times UC_{acc}^k \tag{6.52}$$
$$(k = 1, \ldots, 3 \,; y = 1, \ldots, Y \,; s = 1, \ldots, S)$$

Where,
s = sections
y = analysis year
k = type of accident (usually, $K = 3$, defined as fatal, injury, and property only)

The basic equation may or may not be same in most applications. However, the definition of the k is sometimes different. In case of the HDM-4 (Bennett and Greenwood, 2003), the k was defined to fatal, injury, damage only which is same with the Eq. 6.52, while the MLTM (2009) has wider range of accident including social-loss. Their definition about type of accident, and its unit costs are summarized in the Table 6.34. The method will be compared with the pavement condition based method in the Chapter 6.6.3.2.

Table 6.34 An example of types of accident and unit cost (Case: Korea) (Unit: 10,000 won/case or person)

Classification			Unit cost for human loss	Unit cost for property loss	Unit cost for social loss
Human related accident	Fatal	per case	-	101	-
		per person	37,827 (10,784[2)])	-	157
	Injuries[1)]	per case	-	101	-
		per person	369 (1,217[2)])	-	123
Property related accident	Car only	per case	-	97	13
	All properties	per case	-	107	13

Source: MLTM, 2009
Note: 1) Injuries includes 3 types by the degree (divided into severe injury, injury, slight injury)
2) Cost in the parenthesis is for mental cost (PGS: Pain, Grief, and Suffering)

6.6.3.2 Pavement Condition Based Method

Although pavement condition has effects to traffic safety, it has been often ignored in the modeling on economic analysis. Improving road safety through proper pavement engineering and maintenance is one of the major objectives of pavement management system. This effort and effect should be evaluated for better understanding on an importance of pavement maintenance.

This chapter will introduce a research (Chan *et al.*, 2009) which utilized the Tennessee Pavement Management System (TPMS) and Accident History Database (AHD) to investigate the relationship between accident frequency and pavement conditions. Focusing on asphalt pavements by twenty-one negative binomial regression models for various accident types were calibrated with different pavement distress and condition variables including deterioration indicators, Rut Depth (RD), International Roughness Index (IRI), and Present Serviceability Index (PSI). The following equation was used to basic model the relationship between pavement distress and accident rate;

$$E(A) = a \times AADT^{b} \times e^{cX} \quad (6.53)$$

Where,
$E(A)$ = number of pavement related accidents per year (n/0.1mile/year)
a,b, and c = regression coefficients
X = explanatory variable representing pavement distress

The Eq. 6.53 can be further expressed as Eq. 6.54a and Eq. 6.54b:

$$Ln[E(A)] = a + b + ln(AADT) + cX \quad or \quad (6.54a)$$

$$E(A) = e^{a+b+ln(AADT)+cX} \quad (6.54b)$$

As a result, Chan *et al.* (2009) suggested model parameters by the three deterioration indices (see Table 6.35).

About the results, Chan *et al.* (2009) noted that the modeling results indicate that the RD models did not perform well, except for accidents at night and accidents under rain weather conditions; whereas, IRI and PSI were always significant prediction variables in all types of accident models. Comparing the three groups of models' goodness-of-fit results, it is found that the PSI models had a better performance in crash frequency prediction than the RD models and IRI models.

Table 6.35 Summary of negative binomial models for traffic accident estimation

Conditions	Rut depth model			IRI model			PSI model		
	a (p value)	*b* (p value)	*c* (p value)	*a* (p value)	*b* (p value)	*c* (p value)	*a* (p value)	*b* (p value)	*c* (p value)
All conditions	-6.26	0.742	-1.015	-5.833	0.675	0.005	-4.07	0.655	-0.345
	0	0	-0.685	0	0	-0.005	0	0	0
Daylight	-5.789	0.666	0.341	-5.463	0.63	0.005	-3.639	0.584	-0.361
	0	0	-0.738	(0.000	0	0	0	0	0
Nighttime	-11.834	1.107	4.093	-11.13	1.021	0.006	-8.986	1.003	-0.435
	0	0	0	0	0	0	0	0	0
Good weather	-6.415	0.735	0.05	-6.14	0.681	0.004	-4.6	0.665	-0.304
	0	0	-0.96	0	0	0	0	0	0
Rain condition	-7.606	0.703	5.209	-6.931	0.681	0.004	-4.6	0.665	-0.604
	0	0	0	0	0	0	0	0	0
Peak hour	-6.807	0.721	0.244	-6.522	0.664	0.005	-4.778	0.645	-0.344
	0	0	-0.822	0	0	0	-0.001	0	0
Non-peak hour	-0.6043	0.723	1.857	-5.728	0.616	0.004	-4.192	0.657	-0.005
	0	0	-0.081	0	0	-0.001	0	0	0
Daylight & No adverse	-5.992	0.666	-0.42	-5.805	0.615	0.005	-4.524	0.655	-0.345
	0	0	-0.685	0	0	-0.005	0	0	0
Dark / No adverse	-11.837	1.036	5.994	-10.638	0.892	0.009	-7.431	0.684	-0.65
	0	0	0	0	0	0	0	0	0
Daylight w/ Rain	-6.262	0.532	4.641	-5.63	0.453	0.007	-3.314	0.433	-0.473
	0	-0.001	-0.002	-0.001	-0.007	0	-0.069	-0.01	0
Dark w/ Rain	-12.765	1.057	7.059	-11.633	0.941	0.007	-9.295	0.931	-0.5
	0	0	0	0	0	-0.001	0	0	0

Source: (Simplified) Chan et al., 2008

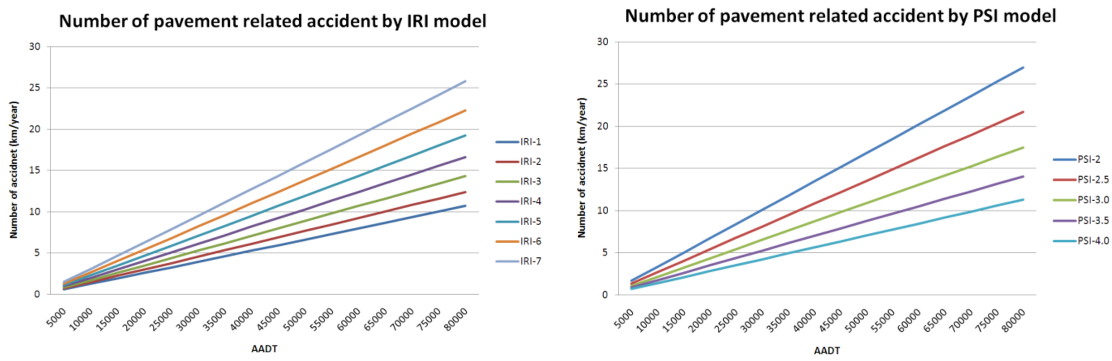


Figure 6.13 Comparison accident rates by using IRI (left) and PSI (right) model

Even though the PSI model yielded best fitness, the IRI model was also not so bad for estimation model. The PSI requires crack, rutting, and IRI to estimate, while the IRI model is available by IRI only. However, the Eq. 6.54 is following the inch-mile unit. To use IRI index as a variable, this should be changed into m/km unit. Hence, the Eq. 54b can be converted into Eq. 6.55;

$$E_{km}(A) = \frac{e^{a+b\times ln(AADT)+c\left(\frac{X}{0.040894}\right)}}{0.161} \tag{6.55}$$

Where,
$E_{km}(A)$ = number of pavement related accidents per year (n/km/year)
$Leng$ = section length in km
X = IRI in m/km or PSI index

For practical application,

$$USER_{acc} = \sum_{s=1}^{S}\sum_{y=1}^{Y}\sum_{k=1}^{K}\left[\frac{e^{a+b\times ln(AADT)+c\left(\frac{X}{0.040894}\right)}}{0.161}\right] \times Leng_s \times R_{acc}^k \times UC_{acc}^k \tag{6.56}$$

Where,
R_{acc}^k = accident rate by accident types k

Estimation results by the IRI & PSI model are compared by sensitivity analysis in the Figure 6.13.

The two models have very similar estimation results. This method is only for estimating number of accident, not for the accident type. For that reason, additional procedures to forecast the degree of accidents are required for estimating total accident cost. One limitation of this method is compatibilities with the other countries. Since the estimation models have been developed by accident data in U.S. Obviously, the behaviors related to traffic safety are different. The model parameters in the Table 6.35 are needed to be calibrated.

6.6.4 Work-zone Cost

Work-zone cost has not been included as a basic function of the Hybrid PMS due to heavy data requirement and small scale of the LCC. This could be classified as minor contents. This function may be useful for traffic flow researches than PMS. In PMS field, Lee *et al.* (2008) has applied the work-zone effect model to find optimal time-zone for maintenance work by economic analysis on traffic jam caused by work-zone. In case of FHWA (FHWA, 1998), they have defined the road user cost as additional costs occurred by work-zone only. However, the definition might be unusual definition (subjectively). Even though the work-zone effect is ignorable in PMS, this paper simply introduces concept and mechanism of work-zone for users who are in an advanced level of PMS.

6.6.4.1 Introduction

Every road maintenance work makes work-zone effect. In practice, we can often find many construction or maintenance sites on the road. When drivers encounter the work-zone site, they usually reduce their speed due to insufficient capacity reduced by lane closure. Usually, we called it as the bottle-neck phenomenon. Even if the road capacity is enough, driver may or may not reduce their speed for their safety, or they are forced to reduce speed by adjusted temporal speed limitation. Obviously, the work-zone effects loss of user cost in terms of travel time cost and vehicle operating cost. In addition, sometimes the effect becomes a reason of traffic accident. None the less, this effect is usually excluded from the object of analysis for LCC estimation because usually the cost from work-zone is relatively too small. On the contrary, data requirement is quiet heavy, such as detailed section information, work-zone length, hourly traffic distribution, work duration and time-zone etc. The work-zone effect has been defined as follows (TRB, 1994);

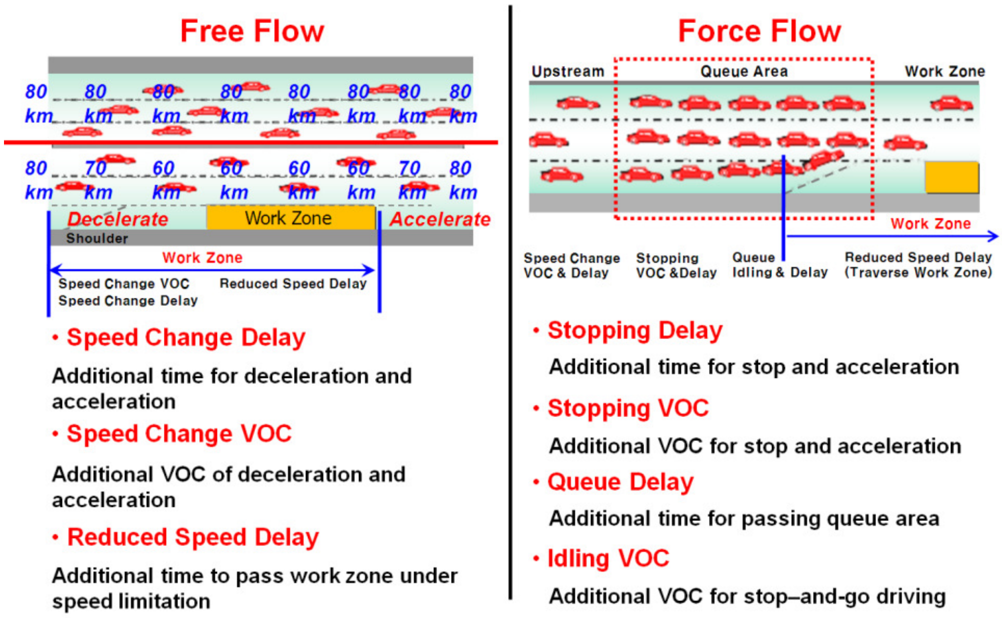
"Work Zone is an area of a highway where maintenance and construction operation impinge on the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the area"

There were many researches about the work-zone (FHWA, 1998; Greenwood, 2003; NDLI, 1995b; Bennett and Greenwood, 2003; Han *et al.,* 2007). It should be appreciated that under certain configurations of road works, deterministic solutions are available. While many of these deterministic models are not used in the current modeling logic, they are provided to aid the reader in understanding the theory of queuing delays.

6.6.4.2 Work-zone Theory

FHWA (1998) introduced a life cycle cost analysis model, the RealCost software. In the model, only work-zone cost is assigned to the user cost. This software hires both deterministic and probabilistic approaches (by Monte-carlo simulation). By referring the model, this paper introduces a mechanism of work-zone under the deterministic approach.

Before addressing user cost calculation procedures, it is helpful to conduct a conceptual analysis of a work zone operation. There are seven possible work zone user cost components that can occur; three are associated with a Base Case situation where traffic operates under Free-Flow conditions, and four are associated with a Queue situation where traffic operates under *Forced-Flow* conditions. The next section conceptually discusses potential user costs involved under Free-Flow and Forced-Flow (Level of Service F) conditions. The Figure 6.14 presents the cost components associated with both flows.



Source: (Re-organized) FHWA, 1998

Figure 6.14 Work-zone effect components under free and forced flow

At the free flow, the work zones restrict traffic flow either by reducing capacity or, as a minimum, by posting lower speed limits. The Figure 6.14 (left side) shows free-flow conditions at a work zone. All traffic that flows through the work zone must, at a minimum, slow while traveling through it and then accelerate back to normal operating speed. This is commonly referred to as a speed change and it results in three work zone-related User Cost components: speed change delay, speed change VOC, and reduced speed delay.

- ***Speed change delay*** is the additional time necessary to decelerate from the upstream approach speed to the work zone speed and then to accelerate back to the initial approach speed after traversing the work zone.
- ***Speed change VOC*** is the additional vehicle operating cost associated with decelerating from the upstream approach speed to the work zone speed and then accelerating back to the approach speed after leaving the work zone.
- ***Reduced speed delay*** is the additional time necessary to traverse the work zone at the lower posted speed; it depends on the upstream and work zone speed differential and length of the work zone.

If traffic demand remains below work zone capacity, added work zone user costs are limited to the above three components and the analysis is relatively simple. In most cases, delay times remain relatively low and represent more of a minor irritation and inconvenience than a serious problem.

At the forced flow (Level of Service F), when hourly traffic demand exceeds work zone capacity, traffic flow breaks down and a queue of vehicles develops, as the Figure 6.14 shows. It is important to note that the queue forms not in the work zone itself, but in the upstream approach to the work zone. Once a queue occurs, all approaching vehicles must not only slow down before proceeding through the work zone itself, but they also must stop at the upstream end of the queue and creep through the length of the physical queue under forced-flow conditions. As long as demand exceeds capacity, the length of the queue grows, exacerbating the problem. When demand eventually falls below capacity, or when capacity is increased above demand by removing the work zone restriction, vehicles then leave the queue faster than they arrive and the length of the queue shrinks and eventually dissipates. When capacity is reduced on high-traffic facilities, it is common for queues to develop in the morning peak traffic period, dissipate, and then redevelop in the afternoon peak traffic period. In exceptionally congested areas, queues may form early in the morning and continue throughout the day and into the evening hours. Queuing situations impose four work zone-related user costs that only apply to vehicles that encounter a physical queue.

- ***Stopping delay*** is the additional time necessary to come to a complete stop from the upstream approach speed (instead of just slowing to the work zone speed) and the additional time to accelerate back to the approach speed after traversing the work zone.
- ***Stopping VOC*** is the additional vehicle operating cost associated with stopping from the upstream approach speed and accelerating back up to the approach speed after traversing work zone.
- ***Queue delay*** is the additional time necessary to creep through the queue under forced-flow conditions.
- ***Idling VOC*** is the additional vehicle operating cost associated with *stop-and-go* driving in the queue. The idling cost rate multiplied by the additional time spent in the queue is an approximation of actual VOC associated with stop-and-go conditions. When a queue exists, stopping delay and VOC replace the free-flow speed change delay and VOC.

The conceptual analysis presented here is geared primarily to freeway conditions. Conceptual analysis of other facilities with at-grade intersections would also incur speed change, stopping, delay, and idling cost but at a much higher frequency, because of intersection-control devices and turning movements.

6.6.4.3 Computational Analysis and Data Requirement

Once the individual work zones have been identified, each is evaluated separately. This is the point at which individual user cost components are quantified and converted to dollar cost values. This section provides an approach for actually quantifying and costing the individual work zone user cost components encountered. The 12 overall steps involved are:

Table 6.36 Data requirements for estimating work-zone delay

Data Requirement		Note
Traffic flow	AADT (veh/day)	By each section data
	Vehicle composition (%)	By each section data
	AADT increment rate (%)	By data or assumption
	Directional hourly traffic distribution (%)	By each section data
Capacity	Number of lane	By each section data
	Speed limitation (km/h)	By law or recommendation
	Capacity on free flow (pcphpl)	By physical characteristic of road section
	Capacity on Queue (pcphpl)	By physical characteristic or the road section
	Capacity on Work zone (pcphpl)	By physical characteristic or the road section
	Maximum queue length (meter)	By physical characteristic or the road section
Work	Working time zone (hour/day)	By maintenance plan
	Working duration (day)	By maintenance plan
	Number of lane block	By maintenance plan
	Speed limitation	By speed law for construction site

- Project future year traffic demand.
- Calculate work zone directional hourly demand.
- Determine roadway capacity.
- Identify the user cost components.
- Quantify traffic affected by each component.
- Compute reduced speed delay.
- Select and assign VOC cost rates.
- Select and assign delay cost rates.
- Assign traffic to vehicle classes.
- Compute individual user costs components by vehicle class.
- Sum total work zone user costs.
- Address circuitry and crash costs.

Table 6.36 gives information for estimating work-zone delay. For estimating the cost additional information is required for travel time cost and vehicle operating cost.

6.7 Estimation of Socio-environmental Cost

In the Hybrid PMS, the socio-environmental cost has been limited as only emission cost. A part of safety cost could be classified by the social cost. However, this paper classified the safety cost as a part of the user cost for simplicity. This chapter will introduce an estimation method for 7 types of substance from vehicle emission. The method is basically follows the World Bank model (the HDM-4). However, some parts have been changed by consideration of data requirement and structure of the Hybrid PMS for much easy application.

Vehicle emits various harmful compounds that cause the urban smog, air toxics, acid rain, and global warming. The needs of evaluation of emissions from vehicles becomes an important issue even pavement management field. In fact, the emission is non-user cost or indirect cost occurred by construction and maintenance of infrastructures. These compounds from the vehicle are considered to not only form the majority of the emissions, but also form the most damaging to the natural environment and human health. When dealing with vehicle emission researchers focus primarily on the following substances;

- Hydrocarbons (HC)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO2)
- Nitric Oxides (NOx)
- Sulphur Dioxide (SO2)
- Lead (Pb)
- Particulate matter (PM)

This chapter will discuss about the methodologies estimating the above compounds, and suggests the way to convert the estimated compound into the cost.

6.7.1 Factors Influencing Vehicle Emissions

About the factors influencing emission, Bennett and Greenwood (2003) summarized the main factors as the following;

- Petrol versus diesel engines
- Hot versus cold emissions
- Evaporation
- Effect of legislation
- Two stroke engines

6.7.2 Reviews of Research History in Vehicle Emission

Predicting vehicle emissions has proved to be more difficult than that of fuel consumption owing to the greater variability in results. Many vehicle emissions can be expected to have a high degree of correlation with fuel consumption owing to fuel being one of the primary agents in the combustion process. In support of this approach, An *et al.* (1997) states;

"analysis indicates a strong correlation between fuel use and engine-out emissions under specific conditions".

The SNRA (1995) produced a range of parameters and statistics for a simple linear model between fuel consumption and the various emissions. SNRA (1995) state that;

"R^2 values could be considered high enough to accept a simple model describing exhaust emissions as linear functions of fuel consumption."

On the other hand, ETSU (1997) state that;

"The emissions of nitrogen oxides do not depend on fuel consumption, however, and are more directly linked to engine speed and temperature of combustion."

They then go on to state,

"The disadvantage of the fuel consumption model is that in several cases the emission of a specific pollutant is not physically dependent on the level of fuel consumed."

ETSU (1997) presented the following equation for predicting the vehicle speed dependent emissions;

$$EOE_i = a_1 + a_2 V + a_3 V^{a_4} + a_5 e^{a_6 V} \tag{6.57}$$

Where,
EOE_i = engine out emission in g/km for emission i
a_1 to a_6 = model parameters varying by emission type and vehicle
V = vehicle speed in km/h

Bennett and Greenwood (2003) noted about speed dependent model based on the Eq. 6.57;

…only one utilized the exponential term. Therefore, the model could well be simplified to exclude the final component. This simplified model form is similar to the early empirical fuel consumption models. Therefore, although the ETSU (1997) state that the emission of some pollutants are not related to fuel, the form of the predictive model tends to suggest that a moderate level of correlation would in fact exist—supporting the findings of other researchers.

In using any model it is necessary to consider the transportability of the results to differing vehicles and/or countries. To this end ETSU (1997) state;

"the data for deriving the empirical relationships between fuel consumption and pollutant emissions have been measured by laboratories in the developed world. It is not clear how suitable these relationships would be under different climatic conditions, with different vehicle types and levels of maintenance."

It is somewhat difficult to determine the best approach. From the next chapter, fuel dependent model and speed dependent model will be compared.

6.7.3 Description of Emission Models

6.7.3.1 Fuel Dependent Model

Based on the discussions in the Chapter 6.7.2, it could be concluded that the most appropriate emissions model was one which predicted most emissions as a function of fuel. The exception was Carbon Dioxide which would be modeled as a Carbon balance equation, wherein any Carbon not consumed by the other emissions, by default is emitted as the CO_2. The method of modeling each of the emissions is shown in the Table 6.37. The remainder of this chapter presents the various model forms and parameter values required to estimate the compounds of emission. The method in the Figure 6.15 was applied as a basic model of the HDM-4. The basic model form is;

$$TPE_i = EOE_i \times CPF_i \tag{6.58}$$

Where,
TPE_i = tailpipe emissions in g/km for emission i
EOE_i = engine out emission in g/km
CPF_i = catalyst pass fraction for emission i

Here, the engine out emission, EOE_i can be estimated by;

$$EOE_i = Fuel\left(\frac{g_{emission}}{g_{fuel}}\right)_i \tag{6.59a}$$

$$Fuel = \frac{IFC \times MF \times 1000}{V} \tag{6.59b}$$

Where,
$Fuel$ = fuel consumption in g/km
$\left(\frac{g_{emission}}{g_{fuel}}\right)_i$ = ratio of engine-out emissions per gram of fuel consumed for emission i
IFC = instantaneous fuel consumption in mL/s
MF = mass of fuel in g/mL
V = vehicle speed in m/s

Here, emission from fuel consumption can be estimated by regression analysis suggested by SNRA (1995);

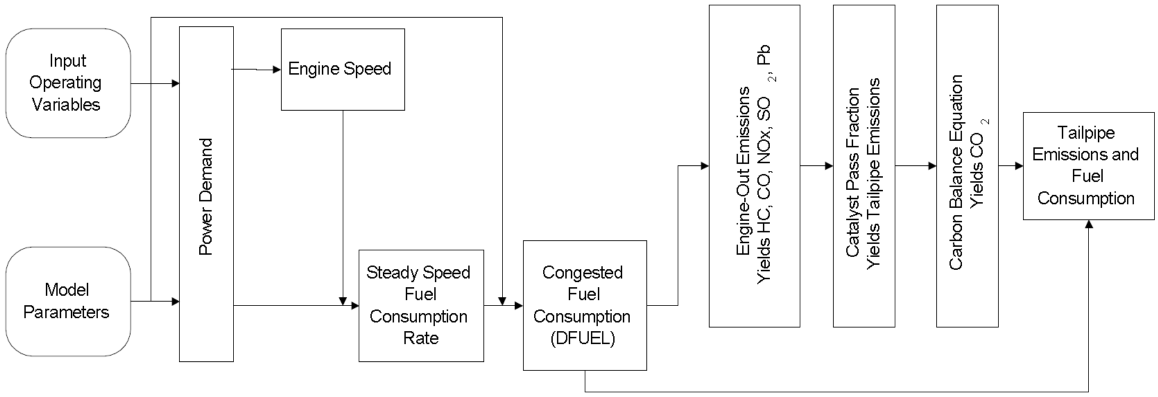
$$Emissions\ (g/s) = a_0 + a_1 \times IFC \tag{6.60}$$

The constants in the Eq.6.60 by the compounds are in the Table 6.38.

Table 6.37 Selection of estimation method by emission

Emission	Fuel consumption	Carbon Balance
Hydrocarbons (HC)	X	-
Carbon Monoxide (CO)	X	-
Nitrogen Oxides (NOx)	X	-
Particulates Matter (PM)	X	-
Carbon Dioxide (CO_2)	-	X
Sulphur Dioxide (SO_2)	X	-
Lead (Pb)	X	-

Source: Bennett and Greenwood, 2003



Source: Bennett and Greenwood, 2003

Figure 6.15 Emission model of the HDM-4

Table 6.38 Coefficients for vehicle emission from Swedish study (for the Eq. 6.60)

Vehicle type	Area	HC			CO			NOx			Particulates		
		a0	a1	R2	a0	a1	R2	a0	a1	R2	a0	a1	R2
Car	Rural	-0.000113	0.000436	0.877	-0.002	0.00512	0.655	-0.00182	0.0034	0.992			
	Urban	0.0000349	0.000357	0.622	-0.00206	0.00467	0.2	-0.0015	0.0024	0.58			
	Total	-0.000272	0.000394	0.847	-0.00291	0.00554	0.658	-0.00314	0.0040	0.895	-1.48x10-5	3.92x10-5	0.758
Light Duty	Rural	-0.00691	0.000866	0.949	-0.00886	0.0145	0.62	-0.000839	0.00251	0.835			
	Urban	0.00015	0.0002350	0.47	-0.00728	0.0126	0.687	-0.000269	0.00152	0.417			
	Total	-0.00533	0.00078	0.913	-0.00968	0.0148	0.713	-0.00166	0.00283	0.838	-2.16x10-5	6.85x10-5	0.56
Truck	Rural	0.0156	0.000808	0.14	0.0215	0.00623	0.83	0.0185	0.0185	0.886			
	Urban	0.0261	-0.000977	0.063	0.0454	0.00186	0.051	-0.0126	0.0332	0.961			
	Total	0.0233	-0.000785	0.038	0.0383	0.00275	0.106	0.0205	0.0187	0.842	-5.25x10-4	1.40x10-3	0.862
Artic-Truck	Rural	0.0106	0.00129	0.484	-0.00165	0.00921	0.982	0.0860	0.0178	0.974			
	Urban	0.0156	0.00208	0.592	0.0225	0.00573	0.365	0.034	0.0306	0.971			
	Total	0.0244	0.000345	0.189	0.00776	0.00814	0.838	0.1	0.0175	0.783	2.81x10-3	2.10x10-4	0.164

Source: SNRA, 1995

A. Carbon Monoxide (CO)

For the prediction of CO, it is assumed that a direct relationship exists between fuel consumption and the production of CO in the engine;

$$EOE_{CO} = a_{CO} Fuel \tag{6.61}$$

Where,

EOE_{CO} = engine-out CO emissions in g/km

a_{CO} = a constant ($=g_{CO}/g_{fuel}$)

B. Hydrocarbons (HC)

Hydrocarbons are believed to be generated from two sources within a combustion engine. The first is from the burning of the fuel, while the second is from incomplete combustion. Therefore, the model for the prediction of HC being emitted from the engine is as follows;

$$EOE_{HC} = a_{HC} Fuel + \frac{r_{HC}}{V} 1000 \tag{6.62}$$

Where,

EOE_{HC} = engine-out HC emissions in g/km

a_{HC} = a constant ($=g_{HC}/g_{fuel}$)

r_{HC} = a constant to account for incomplete combustion in g/s

C. Nitric Oxides (NO_X)

Nitric Oxides are possibly the emission that this least related directly to fuel consumption. As a result of this, the model used to relate NOx production as a function of fuel consumption is more complex that the others presented in this chapter. The model form proposed by An *et al.* (1997) is:

$$EOE_{NOx} = max\left[a_{NOx}\left(Fuel - \frac{FR_{NOx}}{V}1000\right), 0\right] \tag{6.63}$$

Where,
EOE_{NOx} = engine-out NOx emissions in g/km
a_{NOx} = a constant (=g_{NOx}/g_{fuel})
FR_{NOx} = fuel threshold below which NOx emissions are very low in g/s

D. Sulphur Dioxide (SO_2)

The ETSU (1997) present fuel dependent emission models for SO2 and Pb. The models presented are of the same form as Eq.6.64;

$$EOE_{SO_2} = 2a_{SO_2}Fuel \tag{6.64}$$

Where,
EOE_{SO_2} = engine-out SO_2 emissions in g/km
a_{SO_2} = a constant (=g_{SO_2}/g_{fuel})

A default value of a_{SO_2} is estimated by ETSU (1997) from a variety of countries fuel supplies as, 0.0005 for petrol vehicle and 0.005 for diesel vehicles.

E. Lead (Pb)

The quantity of the Pb produced is related directly to the quantity of lead present in the fuel, which in recent years has been dramatically decreased (or eliminated) in many countries due to health concerns. Estimation of the model coefficient was made by assuming that a proportion (default = 75 %) of the lead in the fuel is converted to lead emissions (ETSU, 1997). Based on this assumption, the following relationship was derived for predicting the Pb engine out emissions:

$$EOE_{Pb} = Prop_{Pb} \times a_{Pb} \times Fuel \tag{6.65}$$

Where,
EOE_{Pb} = engine-out Pb emissions in g/km
$Prop_{Pb}$ = proportion of lead emitted (default = 0.75)
a_{Pb} = a constant (=g_{P_b}/g_{fuel})

A default value of a_{Pb} was estimated by ETSU (1997) from a variety of countries fuel supplies as:

- 0.000537 for petrol vehicles; and,
- 0.00 for diesel vehicles (*i.e.* diesel fuel should contain no lead).

F. Particulate Matter (PM)

Particulate Matter has same format with the HC prediction (refer to Eq.6.62)

$$EOE_{PM} = a_{PM}Fuel + \frac{r_{PM}}{V}1000 \tag{6.66}$$

Where,
EOE_{PM} = engine-out HC emissions in g/km
a_{PM} = a constant (=g_{PM}/g_{fuel})
r_{PM} = a constant to account for incomplete combustion in g/s

G. Catalytic Converters

In the Eq.6.58, the catalytic converter has important role for estimating emission. Catalytic converters aim to reduce certain harmful emissions into chemical compounds that are less harmful to both human life and the environment. Significant changes have been made to the efficiency of the catalyst technology since the early oxidizing catalysts. An *et al*. (1997) present the following equation for the prediction of CPF, with the relevant constants;

$$CPF_i = 1 - \varepsilon_i \times exp\,[-b_i \times IFC \times MF] \tag{6.67}$$

Where,
CPF_i = catalyst pass fraction for emission i

ε_i = maximum catalyst efficiency for emission i
b_i = stoichiometric CPF coefficient

The addition of a deterioration component to the modeling of the *CPF* yields the following equation (SNRA, 1995);

$$CPF_i = 1 - \varepsilon_i \times exp[-b_i \times IFC \times MF]\, min\left[\left(1 + \frac{r_i}{100} AGE\right), MDF_i\right] \tag{6.68}$$

Where,
r_i = deterioration factor for emission i in %/year
AGE = vehicle age in years
MDF_i = maximum deterioration factor for emission i (default = 10)

But the age factor of vehicle, the right side of the Eq.6.68, "$min\left[\left(1 + \frac{r_i}{100} AGE\right), MDF_i\right]$", is one of calibration factor to consider aging condition of vehicle. But it is very unrealistic variable which cannot be applied in the practical application. Hence, the Hybrid PMS applied the basic model described in the Eq. 6.67.

H. Carbon balance

The estimation of CO2 production is undertaken by solving the carbon balance equation given below as Eq.6.69. This equation, extracted from ETSU (1997), yields the quantity of CO2 based on the overall Carbon consumed, less that extracted by other forms (Bennett and Greenwood, 2003).

$$TPE_{CO_2} = 44.011\left(\frac{FC}{12.011+1.008\, a_{CO_2}} - \frac{TPE_{CO}}{28.011} - \frac{TPE_{HC}}{13.018} - \frac{TPE_{PM}}{12.011}\right) \tag{6.69}$$

Where,
a_{CO_2} = a fuel dependent model parameter representing the ratio of hydrogen to carbon atoms in the fuel.

I. Summary

For the prediction of vehicle emissions, the basic equation is;

$$TPE_i = EOE_i \times CPF_i \tag{6.70a}$$

For estimation of quantity of each emission EOE_i;

$$EOE_{CO} = a_{CO} Fuel \tag{6.70b}$$

$$EOE_{HC} = a_{HC} Fuel + \frac{r_{HC}}{V} 1000 \tag{6.70c}$$

$$EOE_{NOx} = max\left[a_{NOx}\left(Fuel - \frac{FR_{NOx}}{V} 1000\right), 0\right] \tag{6.70d}$$

$$EOE_{SO_2} = 2a_{SO_2} Fuel \tag{6.70e}$$

$$EOE_{Pb} = Prop_{Pb} \times a_{Pb} \times Fuel \tag{6.70f}$$

$$EOE_{PM} = a_{PM} Fuel + \frac{r_{PM}}{V} 1000 \tag{6.70g}$$

The catalytic pass fraction including age (or deterioration) of vehicle is given by;

$$CPF_i = 1 - \varepsilon_i \times exp[-b_i \times IFC \times MF] \tag{6.70h}$$

The CO_2 is predicted based on the assumption of carbon balance utilizing the following relationship;

$$TPE_{CO_2} = 44.011\left(\frac{FC}{12.011+1.008\, a_{CO_2}} - \frac{TPE_{CO}}{28.011} - \frac{TPE_{HC}}{13.018} - \frac{TPE_{PM}}{12.011}\right) \tag{6.70i}$$

The parameter values for 16 default vehicle type for the above equations are given in Table 6.39. The mass of fuel (MF) may be taken as (Heywood, 1988)

- MassFuel of Petrol = 0.75 g/mL
- MassFuel of Diesel = 0.86 g/mL

Table 6.39a Default emission model parameter values for representative vehicle classes - A

Vehicle Types [1)]	Fuel type	HC		NOx		CO	SO2	Pb		PM		CO2
		aHC	rHC	aNOx	FRNOx	aCO	aSO2	Prop_Pb	aPb	aPM	bPM	aCO2
MC	P	0.06	0	0.02	0	0.2	0.0005	0.75	0	0.0001	0	1.8
PC-S	P	0.012	0	0.055	0.17	0.1	0.0005	0.75	0	0.0001	0	1.8
PC-M	P	0.012	0	0.055	0.17	0.1	0.0005	0.75	0	0.0001	0	1.8
PC-L	P	0.012	0	0.055	0.17	0.1	0.0005	0.75	0	0.0001	0	1.8
LDV	P	0.012	0	0.055	0.17	0.1	0.0005	0.75	0	0.0001	0	1.8
LGV	P	0.012	0	0.055	0.17	0.1	0.0005	0.75	0	0.0001	0	1.8
4WD	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
LT	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
MT	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
HT	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
AT	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
MNB	P	0.012	0	0.055	0.17	0.1	0.0005	0.75	0	0.0001	0	1.8
LB	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
MB	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
HB	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2
COACH	D	0.04	0	0.027	0	0.08	0.005	0.75	0	0.0032	0	2

Source: An et al., 1997 ; ETSU, 1997 ; SNRA, 1995
Note: Following the HDM-4 default vehicle classification (Bennett and Greenwood, 2003)

Table 6.39b Default emission model parameter values for representative vehicle classes - B

Vehicle Types [1)]	Fuel type	HC			NOx			CO			SO2			Pb			PM		
		εi	bi	ri	εi	bi	ri	εi	bi	ri	εi	bi	ri	εi	bi	ri	εi	bi	ri
MC	P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC-S	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
PC-M	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
PC-L	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
LDV	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
LGV	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
4WD	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
LT	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
MT	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
HT	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
AT	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
MiniBus	P	0.999	0.03	20	0.812	0	11	0.999	0.05	4.8	0	0	0	0	0	0	0	0	4.8
LB	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
MB	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
HB	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8
COACH	D	0.9	0	20	0.25	0	11	0.9	0	4.8	0	0	0	0	0	0	0.5	0	4.8

Source: An et al., 1997; Clean Cat, 2000 ; Discount Converter Ltd, 2000 ; Greenwood, 2003 ; Hammarstrom, 1999 ; SNRA, 1995
Note: HDM-4 default vehicle classification (Bennett and Greenwood, 2003)

Table 6.40 Emission rate estimated by the fuel dependent model (case: passenger car)

Speed (km/h)	CO	NOx	HC	PM	CO2	SO2	Pb
10	0.123217	0.307897	0.009329	0.00909773	289.3534	0.090977	0
20	0.088366	0.250835	0.006644	0.00548588	174.4396	0.054859	0
30	0.094423	0.271549	0.007048	0.0046662	148.3357	0.046662	0
40	0.10164	0.277559	0.007553	0.00421433	133.9379	0.042143	0
50	0.130948	0.318529	0.009689	0.00430455	136.7568	0.043046	0
60	0.167646	0.356583	0.012372	0.00446858	141.9115	0.044686	0
70	0.215737	0.397101	0.015898	0.00471473	149.6598	0.047147	0
80	0.257158	0.420523	0.018942	0.00483195	153.3162	0.04832	0
90	0.339132	0.473151	0.024985	0.00525593	166.6635	0.052559	0
100	0.433896	0.522493	0.031996	0.00566513	179.5172	0.056651	0

Note: Fuel consumption rate was referred to the Table 6.16 which was estimated by Korea national highway data

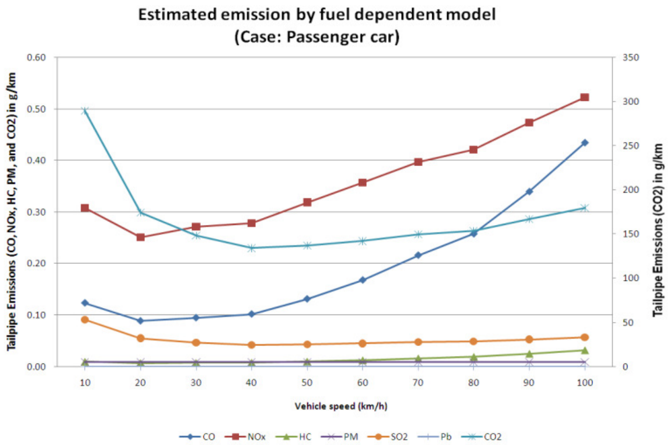


Figure 6.16 Emission rates by fuel dependent emission model

By using the equations and recommended parameters shown above, vehicle emission of a passenger car was estimated as an example. The fuel consumption rate was referred to the Table 6.7 which was estimated by using Korea national highway data. The Table 6.40 and The Figure 6.16 give the result of fuel dependent emission model as a mesoscopic approach.

Note that the emission model in the Hybrid PMS does not have to follow the complex estimation flow described in the Figure 6.15. Since the Hybrid PMS already have fuel consumption model, the result can be directly applied for emission model. It simplified data requirement and sophisticate estimation procedures.

6.7.3.2 Speed Dependent Model

Due to desire for simplicity, speed dependent emission models have been widely applied to many emission model as a macroscopic approach (NIER, 2007; ETSU, 1997; Bennett and Greenwood, 2003). Because the coefficients in the model are mostly derived by detail laboratory experiment, most results could guarantee its accuracy. Maybe the differences between the models or researches are occurred by definition of vehicle types.

Recently, the technologies for reducing air pollutants have been improved. Also, legislations about vehicle emission standard have been strengthening. Hence, the coefficient for vehicle emissions should be referred form recent result.

The MLTM (2009) suggested parameters for estimating each compound by referring research results performed by National Institute of Environmental Research (NIER, 2007) in Korea. However they treated five compounds excluding the Pb and SO2. The estimation functions by vehicle types and speed are showing at the Table 6.41.
By the functions in the Tables 6.41a ~ Table 6.41e, emissions rate per unit kilometer were estimated. Table 6.42 gives the results. As an example, the Figure 6.17 shows passenger car's emission by speed level.

Table 6.41a Estimation function for CO emission by vehicle class (speed dependent model)

Classification		Equations for coefficients
Passenger car		$65.759 \times V^{-1.1804}$
Bus	Small bus	$3.7386 \times V^{-0.5273}$
	Medium bus	$16.973 \times V^{-0.5273}$
	Heavy bus	*Public inner-city bus* = $23.761 \times V^{-0.5094}$ (*when* $V \leq 50$) *The others* = $44.229 \times V^{(-0.7411)}$
Truck	Small truck	$3.331 \times V^{-0.386}$
	Medium truck	$30.701 \times V^{-0.6688}$
	Heavy truck	$44.229 \times V^{(-0.7411)}$

Source: MLTM, 2009 referred from NIER, 2007
Note: speed range 1~100km/h, Passenger car = 1500~2000cc

Table 6.41b Estimation function for HC emission by vehicle class (speed dependent model)

Classification		Equations for coefficients
Passenger car		$23.975 \times V^{-1.5404}$
Bus	Small bus	$1.2912 \times V^{-0.778}$
	Medium bus	$5.5534 \times V^{-0.6478}$
	Heavy bus	*Public inner-city bus* = $8.1065\times\ V^{-0.6746}$ (*When* $V \le 50$) *The others* = $44.229 \times V^{(-0.7411)}$
Truck	Small truck	$0.7334 \times V^{-0.5169}$
	Medium truck	$10.161 \times V^{-0.6487}$
	Heavy truck	$8.471 \times V^{(-0.566)}$

Source: MLTM, 2009 referred from NIER, 2007
Note: speed range 1~100km/h, Passenger = 1500~2000cc

Table 6.41c Estimation function for NOx emission by vehicle class (speed dependent model)

Classification		Equations for coefficients
Passenger car		$7.4218 \times V^{-0.803}$
Bus	Small bus	*When* $V \le 35$ *then* $7.046 \times V^{-0.58}$ *Else if* $35 \le V \le 100$ *then* $0.0003\times V^2 - 0.0339 \times V + 1.7737$
	Medium bus	*When* $V \le 80$ *then* $30.015 \times V^{-0.6054}$ *Else if* $80 \le V \le 110$ *then* $0.0018\times V^2 - 0.2758 \times V + 12.502$
	Heavy bus	*Public inner-city bus* = $66.205\times\ V^{-0.4041}$ (*When* $V \le 50$) *The others* = $82.397\times V^{(-0.3783)}$
Truck	Small truck	*When* $V \le 35$ *then* $7.046 \times V^{-0.58}$ *Else if* $35 \le V \le 100$ *then* $0.0002\times V^2 - 0.0313 \times V + 1.8357$
	Medium truck	*When* $V \le 25$ *then* $44.224\times V^{-0.5514}$ *Else if* $25 \le V \le 100$ *then* $0.0009\times V^2 - 0.1533 \times V + 10.66$
	Heavy truck	$82.397\times V^{(-0.3783)}$

Source: MLTM, 2009 referred from NIER, 2007
Note: speed range 1~100km/h, Passenger car = 1500~2000cc

Table 6.41d Estimation function for PM emission by vehicle class (speed dependent model)

Classification		Equations for coefficients
Passenger car		*0*
Bus	Small bus	*When* $V \le 45$ *then* $0.6025\times V^{-0.4829}$ *Else if* $45 \le V \le 100$ *then* $0.0000009\times V^2 - 0.0006 \times V + 0.0643$
	Medium bus	*When* $V \le 45$ *then* $3.6875 \times V^{-0.7865}$ *Else if* $45 \le V \le 110$ *then* $0.00006\times V^2 - 0.0078 \times V + 0.4259$
	Heavy bus	*Public inner-city bus* = $3.875\times\ V^{-0.4259}$ (*When* $V \le 50$) *The others* = $5.9671\times V^{(-0.4199)}$
Truck	Small truck	$0.3646\times V^{-0.2444}$
	Medium truck	*When* $V \le 55$ *then* $2.962\times V^{-0.5834}$ *Else if* $55 \le V \le 110$ *then* $0.00006\times V^2 - 0.0105 \times V + 0.6703$
	Heavy truck	$5.9671\times V^{(-0.4199)}$

Source: MLTM, 2009 referred from NIER, 2007
Note: speed range 1~100km/h, Passenger car = 1500~2000cc

Table 6.41e Estimation function for CO_2 emission by vehicle class (speed dependent model)

Classification		Equations for coefficients
Passenger car		$1391.5 \times V^{(-0.5632)}$
Bus	Small bus	*When* $V \le 30$ *then,* $1389 \times V^{(-0.544)}$, *Else if* $30 < V \le 100$ *then* $0.0502 \times V^2 - 6.2772 \times V + 363.18$
	Medium bus	$0.1251 \times V^2 - 15.385 \times V + 646.05$
	Heavy bus	*Public inner-city bus* = $2426.4 \times\ V^{-0.3604}$ (*only* $V \le 50$) *The others* = $7710.2 \times V^{(-0.3898)}$
Truck	Small truck	*When* $V \le 35$ *then,* $1577.5 \times V^{(-0.5621)}$ *Else if* $35 < V \le 100$ *then* $0.0462 \times V^2 - 5.6452 \times V + 352.31$
	Medium truck	$0.1029 \times V^2 - 14.937 \times V + 798.9$
	Heavy truck	$7710.2 \times V^{(-0.3898)}$

Source: MLTM, 2009 referred from NIER, 2007
Note: speed range 1~100km/h, Passenger car = 1500~2000cc

Table 6.42 Emission rate by vehicle class and speed by speed dependent model (Unit: g/km)

Vehicle class	Speed (km/h)	CO	NOx	HC	PM	CO2
Passenger car	10	4.341	1.168	0.691	0	380.437
	20	1.915	0.67	0.237	0	257.48
	30	1.187	0.483	0.127	0	204.913
	40	0.845	0.384	0.082	0	174.262
	50	0.649	0.321	0.058	0	153.682
	60	0.524	0.277	0.044	0	138.685
	70	0.437	0.245	0.034	0	127.152
	80	0.373	0.22	0.028	0	117.94
	90	0.324	0.2	0.023	0	110.371
	100	0.287	0.184	0.02	0	104.012
Small bus	10	1.11	1.853	0.215	0.198	396.919
	20	0.77	1.24	0.126	0.142	272.234
	30	0.622	0.98	0.092	0.117	220.044
	40	0.534	0.898	0.073	0.101	192.412
	50	0.475	0.829	0.062	0.097	174.82
	60	0.432	0.82	0.053	0.104	167.268
	70	0.398	0.871	0.047	0.111	169.756
	80	0.371	0.982	0.043	0.118	182.284
	90	0.349	1.153	0.039	0.126	204.852
	100	0.33	1.384	0.036	0.133	237.46
Medium bus	10	4.06	7.446	1.25	0.603	504.71
	20	2.641	4.894	0.798	0.35	388.39
	30	2.054	3.829	0.613	0.254	297.09
	40	1.718	3.217	0.509	0.203	230.81
	50	1.496	2.81	0.441	0.186	189.55
	60	1.336	2.517	0.391	0.174	173.31
	70	1.214	2.293	0.354	0.174	182.09
	80	1.118	2.114	0.325	0.186	215.89
	90	1.039	2.265	0.301	0.21	274.71
	100	0.973	2.927	0.281	0.246	358.55
Heavy bus	10	7.353	26.109	1.715	1.333	1058.187
	20	5.166	19.731	1.074	0.966	824.273
	30	4.202	16.749	0.817	0.801	712.21
	40	3.629	14.911	0.673	0.701	642.066
	50	3.239	13.625	0.579	0.632	592.453
small truck	10	1.37	2.539	0.223	0.208	432.384
	20	1.048	1.558	0.156	0.175	292.86
	30	0.896	1.171	0.126	0.159	233.174
	40	0.802	0.904	0.109	0.148	200.422
	50	0.736	0.771	0.097	0.14	185.55
	60	0.686	0.678	0.088	0.134	179.918
	70	0.646	0.625	0.082	0.129	183.526
	80	0.614	0.612	0.076	0.125	196.374
	90	0.586	0.639	0.072	0.121	218.462
	100	0.563	0.706	0.068	0.118	249.79
Medium truck	10	6.582	12.424	2.282	0.773	659.82
	20	4.14	8.478	1.455	0.516	541.32
	30	3.157	6.871	1.119	0.407	443.4
	40	2.604	5.968	0.928	0.344	366.06
	50	2.243	5.245	0.803	0.302	309.3
	60	1.986	4.702	0.714	0.256	273.12
	70	1.791	4.339	0.646	0.229	257.52
	80	1.638	4.156	0.592	0.214	262.5
	90	1.514	4.153	0.549	0.211	288.06
	100	1.411	4.33	0.512	0.22	334.2
Heavy truck	10	8.028	34.484	2.301	2.269	3142.43
	20	4.803	26.53	1.554	1.696	2398.414
	30	3.556	22.757	1.236	1.431	2047.782
	40	2.874	20.41	1.05	1.268	1830.554
	50	2.436	18.758	0.925	1.154	1678.059
	60	2.128	17.508	0.835	1.069	1562.94
	70	1.898	16.516	0.765	1.002	1471.792
	80	1.719	15.703	0.709	0.948	1397.144
	90	1.575	15.018	0.663	0.902	1334.449
	100	1.457	14.431	0.625	0.863	1280.754

Source: (Derived from) MLTM, 2009

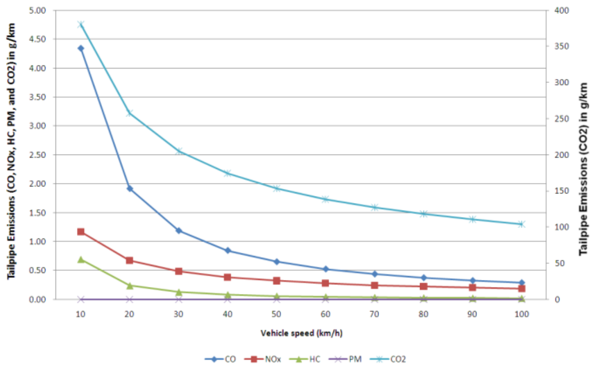


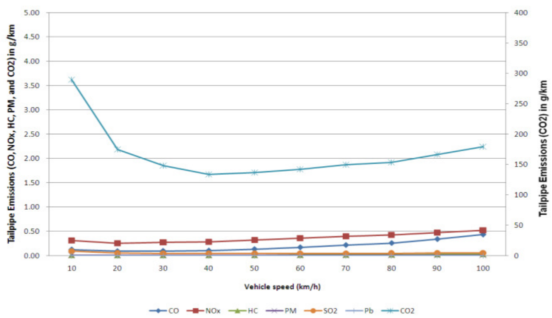
Figure 6.17 Emission rate of passenger by speed dependent emission model

6.7.3.3 Comparison of Fuel Dependent and Speed Dependent Model

This chapter compares results estimated by the two models. The Figure 6.18 shows the graphs drew by applying same axis scales. For comparison of the results, the changing trends and quantity of emission by speed change should be confirmed. As shown in the Figure 6.18, basically two models have different philosophy; Speed dependent model was modeled to estimate the faster speed emits less compounds. On the other hands, fuel dependent model has various trends by speed change. The Table 6.43 compares the trends.

About the relationship between speed and emission, The U.S. EPA (1997) showed that the NOx and CO emission rates have concave shape by speed change. Based on the information, fuel dependent model may have much reasonable characteristic. About the quantity of emission, even though the two models have different estimation trends, they have similar result except for the CO. If two models are applied in economic analysis, the speed dependent model makes benefits in proportion to level of investment of road maintenance, while the result of fuel dependent model is depended upon the original speed level of each section. In other to say, the higher level of maintenance strategy could make negative effect, if the vehicle speed of a section is located in the right side of the optimal point in the graph.

The established theory (or general view) in fuel efficiency is that there is an optimal speed (or interval) which is considered around 40km/h ~ 60km/h. By referring the theory, the fuel dependence model has been adopted as a basic emission model in the Hybrid PMS.



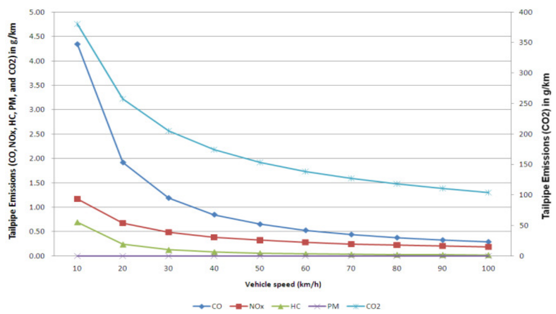


Figure 6.18a Emission rate by the fuel dependent model (case: passenger car) (left)
Figure 6.18b Emission rate by the speed dependent model (case: passenger car) (right)

Table 6.43 Comparison of emission models on estimation trends by speed change

Emission from vehicles	Fuel dependent model	Speed dependent
CO	Concave	Descend
NOx	Concave	Descend
HC	Ascend	Descend
PM	Flat	Descend
CO2	Concave	Descend
SO2	Concave	N/A
Pb	Zero	N/A

6.8 Economic Analysis

Economic analysis treats the cost stream of alternatives to investigate the economic viability of different strategy or technical standards during analysis period. The estimated costs and benefits can be expressed by various economic decision criteria that show cost-effectiveness of alternatives. The economic analysis in PMS could be said as a procedure estimating and comparing the economic decision criteria of alternatives. On the other hands, finding hide meaning behinds each LCC contents in reality is also very important, because this could be differently interpreted by views of road agencies who are in a different situation. This chapter introduces definition of cost and benefit in PMS analysis, economic decision criteria and near-optimization method under budget constraint.

6.8.1 Definition Cost and Benefit

Main categories of costs and benefits in the Hybrid PMS are:

- Agency cost
- Road user cost
- Environmental cost

These can be explained by customization schemes. Table 6.44 gives much detail information about definition, contents and its importance which can be standards of customization.

The costs and benefits of each alternative should be expressed by monetary terms. This can be done by assigning the 'Base alternative' which is an object of comparison with an alternative i. As simply explained in the Chapter 6.3.7, the base alternative can be 1) without project (no action) 2) with minimum project, or 3) keeping current project by purposes of analysis. By equations,

Table 6.44 Summary of LCC contents classified by importance

Type	Definition	Contents		Importance		
Agency Costs	Incurred by road agency for pavement management	Maintenance work		Essential		
		Inspection work			Recommended	
		Equipment			Recommended	
		R&D				Optional
		Operation cost				Optional
User costs	Incurred by road users when they are on the road.	VOC	Fuel	Essential		
			Tire		Recommended	
			Engine oil			Optional
			Maintenance		Recommended	
			Depreciation			Optional
		Travel time cost		Essential		
		Accident cost			Recommended	
Environmental cost	Incurred by vehicle emission	CO		Essential		
		NOx		Essential		
		HC			Recommended	
		PM			Recommended	
		CO2		Essential		
		SO2			Recommended	
		Pb				Optional

$$NB_i = Cost_i + Benefit_i \tag{6.71a}$$

$$Cost_i = AC_i - AC_{base} \tag{6.71b}$$

$$Benefit_i = (UC_i + EC_i) - (UC_{base} + EC_{base}) \tag{6.71c}$$

Where,
NB_i = relative net benefit of an alternative i
$Cost_i$ = relative agency cost of an alternative i
$Benefit_i$ = relative benefit of an alternative i from user cost and environmental effect
AC_i = discounted agency cost of an alternative i
AC_{base} = discounted agency cost of a base alternative
UC_i = discounted user cost of an alternative i
EC_i = discounted environmental cost of an alternative i
UC_{base} = discounted user cost of a base alternative
EC_{base} = discounted environmental cost of a base alternative

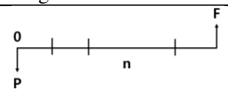
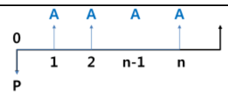
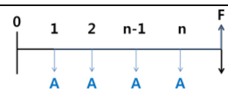
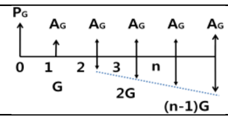
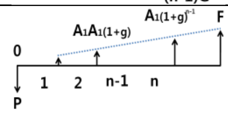
6.8.2 Economic Indicators and Discount Rate

The following economic indicators are computed from the cost streams by the user-specified discount rate. The indicators hired in the Hybrid PMS are;

- Net Present Value (NPV)
- Equivalent Uniform Annual Cost (EUAC)
- Internal Rate of Return (IRR)
- Benefit/Cost ratio (NPV/Cost ratio)

A. Net Present Value (NPV)
The present value formula is a core for expressing time value of money (budget or asset). Various formulas can be derived from this formula. The common formulas for equivalency calculations are summarized in the Table 6.45 (Blank and Tarquin, 2002)

Table 6.45 Common formulas for equivalency calculation

Type	Find/Given	Factor Notation	Relation	Sample Cash Flow Diagram
Single amount	*F/P* Compound amount	$(F/P,r,n) = (1+r)^n$	$F = P(F/P,r,n)$	
	P/F Present worth	$(P/F,r,n) = \frac{1}{(1+r)^n}$	$P = F(P/F,r,n)$	
Uniform series	*P/A* Present worth	$(P/A,r,n) = \frac{(1+r)^n - 1}{r(1+r)^n}$	$P = A(P/A,r,n)$	
	A/P Capital recovery	$(A/P,r,n) = \frac{r(1+r)^n}{(1+r)^n - 1}$	$A = P(A/P,r,n)$	
	F/A Compound amount	$(F/A,r,n) = \frac{(1+r)^n - 1}{r}$	$F = A(F/A,r,n)$	
	A/F Sinking fund	$(A/F,r,n) = \frac{r}{(1+r)^n - 1}$	$A = F(A/F,r,n)$	
Arithmetic gradient	*PG/G* Present worth	$(P/G,i,n) = \frac{(1+r)^n - in - 1}{r^2(1+r)^n - 1}$	$P_G = G(P/G,r,n)$	
	AG/G Uniform series	$(P/G,r,n) = \frac{1}{r} - \frac{n}{(1+r)^n - 1}$	$A_G = G(A/G,r,n)$	
Geometric gradient	*PG/A1 and g* Present worth	$P_g = \begin{cases} \frac{A_1\left[1 - \left(\frac{1+g}{1+r}\right)^n\right]}{r-g} \\ A_1 \frac{n}{1+r} \end{cases}$	$g \neq r$ $g = r$	

Source: Blank and Tarquin, 2002
Note: r = *interest rate*
n = *number of interest period*
P = *present sum of money*
F = *future sum of money at the end of* n *periods*
A = *amount of each end-of-period payment or receipt in a uniform series of* n *period (the entire series equivalent to* P *or* F *with interest rate* i

As shown in the Table 6.45, there are many expression ways of the present value. The Net Present Value (NPV) of investment option alternative i, relative to base alternative is the sum of the discounted annual net benefits or costs, is calculated from the relationship;

$$NPV_{i-base} = \sum_{y=0}^{Y} \frac{NB_{y(i-base)}}{[1+r]^y} \tag{6.72}$$

Where,
$NB_{y(i-base)}$ = net benefit of alternative i relative to base alternative in year y
r = discount rate (%)
y = analysis year ($y = 0,1,2,\dots,Y$)

B. Equivalent Uniform Annual Cost (EUAC)
Equivalent uniform annual cost, known as capital recovery cost, represents the NPV of all discounted cost and benefits of an alternative as if they were to occur uniformly throughout the analysis period. The EUAC is a particularly useful indicator when budgets are established on an annual basis. The preferred method of determining the EUAC is first to determine the NPV, and then use the following formula to convert it to the EUAC (FHWA, 1998). The basic equation is:

$$EUAC_i = NPV_i \frac{r(1+r)^n}{(1+r)^n-1} \tag{6.73}$$

To express detail meaning of the Eq.6.73, the net present value of alternative i, NPV_i, can be substituted by NPV_{i-base}. That is, the basic formula of the EUAC means the uniformed annual benefit (or additional cost) including road agency, road user, and environmental cost relative to the base alternative. To give much meaningful information to road agency, the NPV_i in the Eq.6.73 can be substituted by $COST_{i-base}$ or AC_i:

$$EUAC_{NPV\_AC_i} = COST_{i-base} \frac{r(1+r)^n}{(1+r)^n-1} \tag{6.74a}$$

$$or \quad EUAC_{AC_i} = AC_i \frac{r(1+r)^n}{(1+r)^n-1} \tag{6.74b}$$

In brief, the $EUAC_{NPV\_AC_i}$ means uniformed annual benefit of agency cost relative to base alternative. In case of the $EUAC_{AC_i}$, this means uniformed annual agency cost of alternative i during analysis period. This may be much useful information to agency.

C. Internal Rate of Return (IRR)
Internal rate of return (IRR), which is the interest rate for computation that equates the present worth of benefits with the present worth of costs (Goodman and Hastak, 2006). Simply, the IRR is the discount rate at which makes the NPV to zero. The Formula is;

$$NPV = \sum_{y=0}^{Y} \frac{NB_{y(i-base)}}{[1+r^0]^y} = 0 \tag{6.75}$$

The equation is solved for the r^0. This could be available by the method of trial and error to determine the zero by adjustment of discount rates with NPV f opposite signs. The IRR gives no indication of the size of the costs or benefits of an alternative. It acts as a guide to the profitability of the investment. Namely, the higher is the better. If the computed IRR is larger than the planning discount rate, then the investment is economically justified (Odoki and Kerali, 2000).

The determination of the internal rate of return is often referred to as the discounted cash flow method in the analysis of private ventures. The discounted cash flow analysis is used by the World Bank, the United Nations Development Program, and increasingly, by many United States government agencies. The internal rate of return computation has several characteristics noted by Goodman and Hastak (2006);

- An interest rate does not have to be stated in advance, in order to proceed with the calculation.
- The rate of return may be compared with the acceptable rate(s) of return for economic sectors (or types of projects) established at a high policy level by the international bank or the country involved.
- If a project is financed by funds on hand, or borrowed at a subsidized rate, the internal rate of

return will permit the ranking of projects.

- The internal rate of return is not, however, considered by many economists to be a fully correct method of evaluating projects. It is theoretically correct only where projects are independent of one another and are compared on by one to a target rate of return.
- Moreover, the ranking given by the internal rate of return is not entirely insensitive to the discount rate.
- There is also the problem of cost allocation for a multipurpose project.
- Other difficulties may arise in the calculations when benefit and cost streams are unusual.

D. Benefit cost ratio (BCR)

The benefit cost ratio is one of most popular indicators with the IRR used for publicly sponsored infrastructure projects. The benefit cost ratio (BCR) of alternative i, relative to base alternative, is the ratio can be simply calculated by;

$$BCR_{i-Base} = \frac{NPV_{i-Base}}{AC_i} + 1 \tag{6.76}$$

Where,

BCR_{i-Base} = benefit cost ratio of alternative i

NPV_{i-Base} = relative net present value of alternative i with base alternative

AC_i = absolute agency cost of an alternative i

The BCR also has several characteristics as follows;

- The BCR could eliminate the bias of NPV towards larger project options but, like the IRR, they give no indication of the size of the costs or benefits involved (Odoki and Kerali, 2000).
- The BCR may be quite sensitive to the interest rate selected for discounting (Goodman and Hastak, 2006).
- Another disadvantage is the possible confusion over whether maintenance cost reductions should be in the numerator or the denominator, and whether cost reductions are “Benefits” or “Negative cost” (Hudson *et al.,* 1997)

6.8.3 Analysis Sequence

To give simple explanation, the pseudo code that represents the overall sequence logic is given under below;

```
START;

    Define alternative and input data;
    Loop for each alternative;
        Loop for each section;
            Loop for each analysis year;
                Calculate traffic information (volume and composition);
                Estimate deterioration indices;
                Estimate work effect and agency cost;
                Estimate agency cost;
                Estimate vehicle speed;
                Estimate user costs (VOC, TC, AC);
                Estimate environmental costs;
                Save the results
            End loop;
        End loop;
    End loop;

    Loop for each pair of option to be compared (for economic analysis);
        Loop for each analysis year;
            Loop for each section;
                Calculate un-discounted net benefits;
```

Calculate discounted net benefits;
End loop;
Calculate total un-discounted net benefits of all sections;
Calculate total discounted net benefits of all sections;
End loop;
Calculate economic indicators (NPV, IRR, BCR, and EUAC);
End Loop;
Perform budget optimization;
Output results;
END;

The analysis sequence logic for life cycle cost explained above was illustrated in the Figure 6.19:

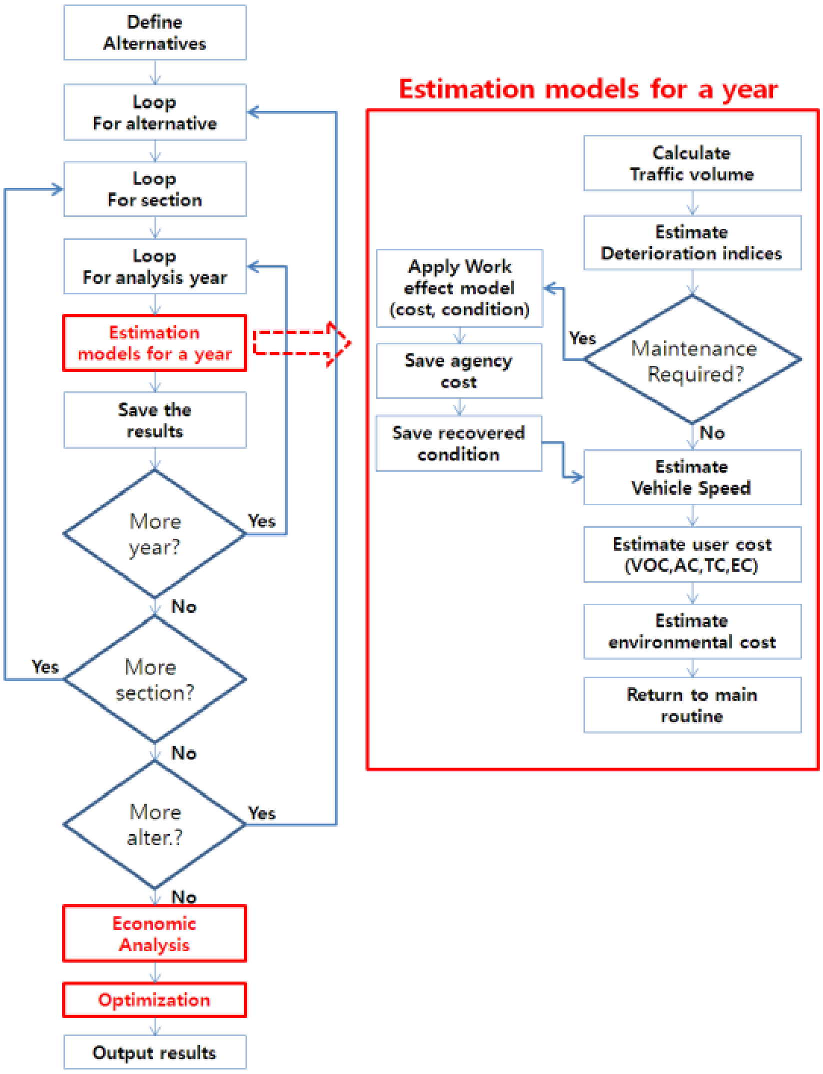


Figure 6.19 A flowchart of life cycle cost analysis sequence logic

6.8.4 Typical Economic Analysis Results of the Hybrid PMS

By using the LCCA model in the Hybrid PMS, many kinds of information can be extracted. Since all of results were estimated by vehicle type, section, individual year, network and alternative, it is very flexible for additional researches by users' application. General information from the LCCA model in the Hybrid PMS is listed in the Table 6.46. A typical example of economic analysis results comparing user-specified alternative are shown at the Table 6.47 ~ Table 6.51.

Table 6.46 Summary of typical results from the Hybrid PMS

Categories	Kinds of results	Note
Pavement condition	Pavement deterioration speed	By deterioration indices from forecasting models
	Deterioration history	With maintenance history
	Averaged annual network condition	
	Averaged network condition during analysis period	by deterioration indices
PMS works	Maintenance and inspection history	
	The number of conducted inspection and maintenance	by maintenance types
	Budget requirement	
Road user effects	Fuel consumption rate and cost	Aggregated by vehicle operating cost
	Tires wear rate and cost	
	Engine oil consumption rate and cost	
	Vehicle depreciation rate and cost	
	Vehicle maintenance rate and cost	
	Total travel time and cost	By vehicle class: passenger car, bus and truck
	The number of accidents by severity	Severity: Death, injury and property damage only
	Accident cost by severity type	
Environmental effect	Emission rate by 7 types of substance	HC, CO, CO2, NOx, SO2, Pb, and PM
	Total emission cost	
Economic evaluation	Cost streams during analysis year in network level	Summarized by discounted or undiscounted cost
	Detail of LCC of alternative *i*	
	Cost and benefit analysis between alternatives	
	Economic decision criteria of alternative *i*	NPV, NPV/Cost ratio, IRR, and EUAC
Traffic information	Traffic volume (load) information during analysis period	By statistic method
	Vehicle speeds	By free and journey speed

Note: Basic analysis units of the result were vehicle type, section, and individual year, network, and alternatives.

Table 6.47 An example of annual cost stream in network level of alternative *i*

YEAR	Analysis year	Agency Cost		User cost							Environmental cost	Total Transport Cost
				Vehicle Operating Cost					Travel time cost	Accident cost		
		Maintenance cost	Inspection Cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost				
2001	1	-	-	552,956	43,307	5,741	69,284	107,416	554,425,919	12,823,782	38,585,912	606,614,316
2002	2	-	-	544,291	42,586	5,656	68,211	106,006	546,895,470	12,594,714	37,967,430	598,224,363
.	.	.	.	.	.	.	.	.	.	.	.	
2040	40	1,896	2,550	70,421	5,380	733	8,752	13,976	71,623,769	1,881,189	4,896,165	78,504,831

Table 6.48 An example of total transport cost of alternative *i*

Alternative	Base Altern ative	Agency Cost		User cost							Total Environmental cost	Total Transport Cost	EUAC in Agency cost	EUAC in Total Transport Cost
				Vehicle Operating Cost					Travel time cost	Accident cost				
		Maintenance cost	Inspection Cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost						
Alternative i	NO	7,170,511	171,728	9,634,022	744,146	100,175.3	1,201,615	1,895,668	9,748,326,718	241,158,197	670,883,967	10,681,286,748	457,571	665,661,458
.	.	.	.	.	.	.	.	.	.	.	.		.	.
Alternative *j*	YES	3,827,052	175,719	9,633,544	742,370	100,174.6	1,200,429	1,899,038	9,760,667,081	244,953,062	670,647,175	10,693,845,646	249,454	666,444,133

Table 6.49 An example of cost and benefit analysis between alternatives

Alternative	Base alternative	(COST) Increase in Road Agency Cost		(Benefit) Saving in Road User Cost							Savings in Environmental cost	Total benefit (Relative benefit)
		Increase in Maintenance cost	Increase in Inspection Cost	Savings in Fuel cost	Savings in Tire cost	Savings in Engine oil	Savings in Vehicle maintenance	Savings in Vehicle depreciation	Savings in Travel time cost	Savings in Accident cost		
Alternative i	NO	3,343,459	-3,991	-478	-1,776	-1	-1,186	3,370	12,340,363	3,794,865	-236,791	12,558,898
. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
Alternative *j*	YES	0	0	0	0	0	0	0	0	0	0	0

Table 6.50 An example of economic decision criteria between alternatives

Alternative	Base alternative	Economic indices		Equivalent Uniformed Annual Cost			
		NPV/COST ratio	IRR	Agency cost	Total cost	Difference in Agency cost	Difference in Total Transport Cost
Alternative i	NO	3.7607	276%	138,379	665,596,399	-96,462	1,235,640
. .	. .	. .	. .	. .	. .	. .	. .
Alternative *j*	YES	0		41,917	666,832,039	0	0

Table 6.51 An example of pavement performance analysis; Average pavement condition during analysis period in network level

Alternative	Base alternative	Deterioration indices		
		Crack	Rutting	IRI
Alternative-preventive	NO	1.6164	8.3408	2.0134
Alternative-Typical	NO	2.3609	9.0909	2.1362
Alternative-retarded	YES	2.4749	10.1897	2.3142

6.8.5 Accounting Functions

Accounting is essential function to prove the power of budget that improves physical condition of pavement, as well as cost-effectiveness. The terminologies, economic analysis and accounting, are seem to be similar but there is a small difference in terms of a practical PMS plan. The economic analysis which treats cost and benefit stream is used to compare the economic viability among different alternatives. Economic analysis can also be used to investigate the technical standards and strategies to be followed by a particular investment decision. These functions were realized by the 'LCCA function' in the Hybrid PMS. Strictly speaking, accounting is also included in the boundary of economic analysis. However, the accounting has two more important terms, budget limitation and optimization. That is, the objective of accounting function is to find an answer *"Which pavement maintenance strategy is the most reasonable in order to maximize economic benefit under budget constraint by a viewpoint of marginal cost-effectiveness?"* Also it can be applied to estimate the scale of budget requirement to satisfy user-specified objective functions.

6.8.5.1 Near-optimization Methods in PMS

General optimization method in PMS could be divided into five levels;

- ***Core level (Work scheduling for a PMS cycle):*** Estimating next year's (A PMS cycle's) budget requirement and making work schedules. It treats real situations not for the simulation. For the reason, forecasting function is not required in this level.

- ***General level - I (Near optimization for maximizing NPV):*** Finding the best alternative that shows the highest NPV under budget constraint

- ***General level - II (Near optimization for maximizing condition recovery)*** **:**Finding the best alternative that shows the highest condition recovery under budget constraint

- ***Advanced level - I (Network-based near optimization approach that maximizes NPV):*** Many subdivided alternatives are applied for finding the best alternative in terms of maintenance timing and method (design)

- ***Advanced level - II (Section-based near optimization approach that maximizes NPV):*** Optimization by specific priority rule to maximize the objective function under a concept of section-based simulation of user specified alternatives based on forecasting result(s)

The core, general-I, general-II and advanced-I level follows network-based approach, while the advanced level - II is section-based approach. The formers have only one alternative as a solution. In case of the section-based approach, each section could have different best alternative based on the properties of pavement deterioration and LCC environments. Simply, the best alternative of the advance level is a set composed by combination of the best alternatives for each section.

6.8.5.2 Maximizing Objective Functions

A. Maximizing net present value

This option is target to maximize economic benefit under budget available. As an index for determination of the priority, *'NPV/cost ratio'* is applied which is formulated in the Eq. 6.77.

$$EI_{NPVj} = \left[\frac{NPV_j - NPV_i}{C_j - C_i}\right] \tag{6.77}$$

Where ,

EI_{NPVj} = efficiency index on economic efficiency of alternative *j*

NPV_j = net present value of user specified alternative *j*

NPV_i = net present value of base alternative *i*

C_j = cost for alternative *j*

C_i = cost for alternative *i*

B. Maximize of condition recovery of network

This option is target to minimize value of deterioration index of entire network. As an index for determination of the priority, *'[Condition recovery of k × Length] / cost ratio'* is applied instead of 'NPV/cost ratio' (See Eq. 6.78).

$$EI_j^k = \left[\frac{\Delta CI_j^k - \Delta CI_i^k}{C_j - C_i}\right] \tag{6.78}$$

In detail,

$$EI_j^k = \frac{\sum_{s=1}^{S}[\{(bCI_j^{sk} - aCI_j^{sk}) \times Ln^s\}\delta_j^s] - \sum_{s=1}^{S}[\{(bCI_i^{sk} - aCI_i^{sk}) \times Ln^s\}\delta_i^s]}{C_j - C_i} \tag{6.79}$$

Here,

$$\delta_{i\ or\ j}^s = \begin{cases} 1 & when \text{ maintenance work is conducted in section } s \text{ under alternative } i \text{ or } j \\ 0 & otherwise \end{cases} \tag{6.80}$$

Where,

EI_j^k = An efficient index on condition recovery of user-specified deterioration index *k* by alternative *j*

ΔCI_j^k = Total amount of condition recovery of user-specified deterioration index *k* by alternative *j*

ΔCI_i^k = Total amount of condition recovery of user-specified deterioration index *k* by base alternative *i*

$bCI_{i\ or\ j}^{sk}$ = Before maintenance condition of deterioration index *k* in section s by alternative *j*

aCI_j^{sk} = After maintenance condition of deterioration index *k* in section *s* by alternative *j* or base alternative

Ln^s = Length of section *s* in kilometer

$\delta_{i\ or\ j}^s$ = A dummy variable to check whether maintenance work was conducted or not.

6.8.5.3 Procedure of the Near-optimization

The analysis flow widely divided into network basis or section basis. It is based on the *"What-if"* analysis. For that reason, this paper uses the term, "Near-optimization", not "optimization". A flowchart describing accounting function is illustrated in the Figure 6.20.

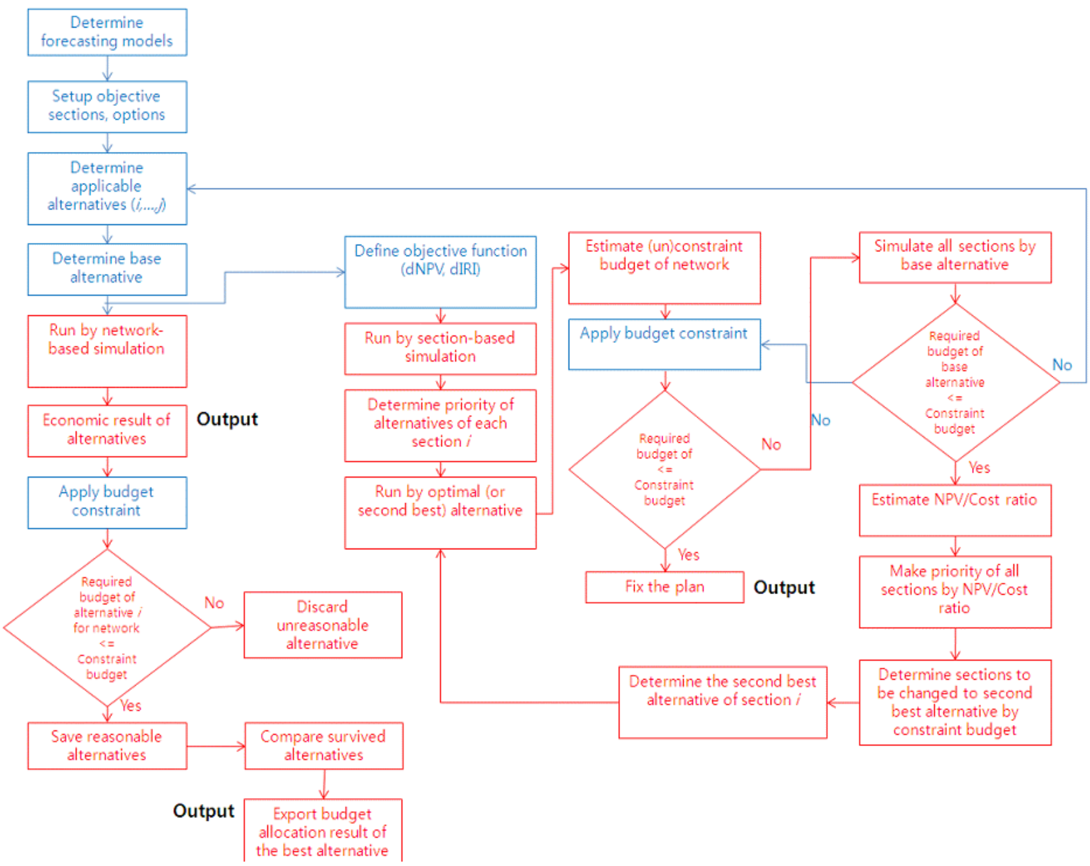


Figure 6.20 System architecture of the accounting functions in the Hybrid PMS

6.8.6 Data Requirements for Application

This chapter summarize data requirement for each LCC contents. As noted in every chapter, this paper tried to minimize data requirement for easy application. The Table 6.52 shows summary of the data requirement.

Table 6.52 Summary of data requirement for life cycle cost analysis components

Categories	LCC contents	Required data	Note	Unit	Data set
Agency cost	Maintenance	Section length	For calculating area	Km	A
		Number of lanes	For calculating area	n	A
		Width of lanes	For calculating area	Meter	A
		Deterioration indices	For matching with maintenance criteria		A (and B)
		Unit costs for maintenance	By the type of maintenance	$ / m^2 (km)	A
	Inspection	Elapse time	from last inspection or maintenance	year	A
		Unit costs for inspection	By monetary terms	$ / lane/km	A
Speed model	N/A	Speed limit	Legal speed	Km/h	B
		Slope	Rise + Fall	m/km	B
		Curvature	Horizontal curvature	Deg./km	B
		Pavement condition	IRI	m/km	A
		Number of lanes	For calculating capacity (pcphpl)	N	A
		Width of lanes	For calculating capacity (pcphpl)	Meter	A
		Traffic volume by types	By traffic volume generator	Veh/day	Estimated
		PCSE by vehicle type	Passenger Car Space Equivalent	coefficient	D
Traffic volume generation model	N/A	Traffic volume	AADT	Veh./day	B
		Vehicle composition ratio	By user-defined vehicle types	%	C
		Increment rate of AADT by traffic volume level	Estimated by historical AADT data	%	D
		Standard deviations of increment rate by AADT level	Estimated by historical AADT data	%	D
VOC	Fuel	Vehicle speed	By the speed model	Km/h	Estimated
		Slope	Rise + Fall	m/km	B
		Pavement condition	IRI	m/km	A,B
		Traffic volume	By traffic volume generator	Veh/day	Estimated
		Unit costs by fuel types	By diesel and patrol	$	D
		Section length	For calculating driving distance	Km	A
	Tire	Vehicle speed	By the speed model	Km/h	Estimated
		Traffic volume by types	By traffic volume generator	Veh./day	Estimated
		Unit costs for tire	Tire cost by vehicle types	$	D
		Section length	For calculating driving distance	Km	A
	Engine oil	Vehicle speed (speed-based model)	By the speed model	Km/h	Estimated
		Fuel consumption (fuel-based model)	By fuel consumption model	L/1000km	Estimated
		Engine capacity (optional) (fuel-based model)	By vehicle types	Liter	D
		Engine oil change cycle (optional) (fuel-based model)	By vehicle types	1000km	D
		Traffic volume by types	By traffic volume generator	Veh./day	Estimated
		Unit cost for engine oil	By vehicle types	$	D
		Section length	For calculating driving distance	Km	A
	Vehicle maintenance	Vehicle speed	By the speed model	Km/h	Estimated
		Traffic volume by types	By traffic volume generator	Veh./day	Estimated
		Vehicle prices	By vehicle types	$	D
		Section length	For calculating driving distance	Km	A
	Vehicle depreciation	Vehicle speed	By the speed model	Km/h	Estimated
		Traffic volume by types	By traffic volume generator	Veh./day	Estimated
		Vehicle price	By vehicle types	$	D
		Section length	For calculating driving distance	Km	A
Travel time cost	Travel time	Vehicle speed	By the speed model	Km/h	Estimated
		Section length	For calculating driving distance	Km	A
		Traffic volume by types	By traffic volume generator	Veh./day	Estimated
		Time value by vehicle class	By vehicle type (PC, bus, truck) By business and non-business	$ /hour	D
		Number of passenger by vehicle type	By vehicle type (PC, bus, truck)	n	D
Accident cost	Accident	Pavement conditions	Crack, Rutting, IRI for calculation of PSI (or IRI)	%, mm, m/km	A

		Traffic volume by types	By traffic volume generator	Veh./day	Estimated
		Accident rate	By accident types	%	D
		Unit cost for accident	By accident types	$	D
		Section length	For calculating driving distance	Km	A
Environmental cost	Emission	Fuel consumption (for fuel-based model)	By fuel consumption model	liter	Estimated
		Unit costs for each pollutants	Unit cost for each pollutants	$/ton	D
		Vehicle speed (for speed-based model)	By the speed model	Km/h	Estimated
Basic information (or options)	N/A	Identification of analysis unit	Homogeneous unit or maintenance unit, or inspection unit	User specified	
		Vehicle classification	Number of types and class, Integration of similar types		
		Interest	Discount rate for road investment		
		Analysis period	By purposes		
		Currency	Exchange rate per USD is recommended		
		Maintenance criteria	For generating alternatives		
		Inspection interval	For generating alternatives		

Note: Model coefficients in the sub-models were not considered as data contents

In the Table 6.52, most of the LCC model requires relatively fundamental data in PMS, such as traffic volume, road length, traffic volume and etc. This information would be useful for designing database content and tables.

6.8.7 Application Procedures

To apply the LCCA model of the Hybrid PMS, users firstly have to understand the overall procedure for application. The procedures are illustrated in the Figure 6.21.

The procedure explained in the Figure 6.21 can be simply divided into pavement deterioration forecasting phase, and LCCA phase.

For the forecasting phase, users have to follow these procedures;

- Selecting forecasting model(s)
- Extracting data for selected deterioration forecasting from the database
- Establishing forecasting functions (Crack, rutting, IRI)
- Applying maintenance standard (effects)

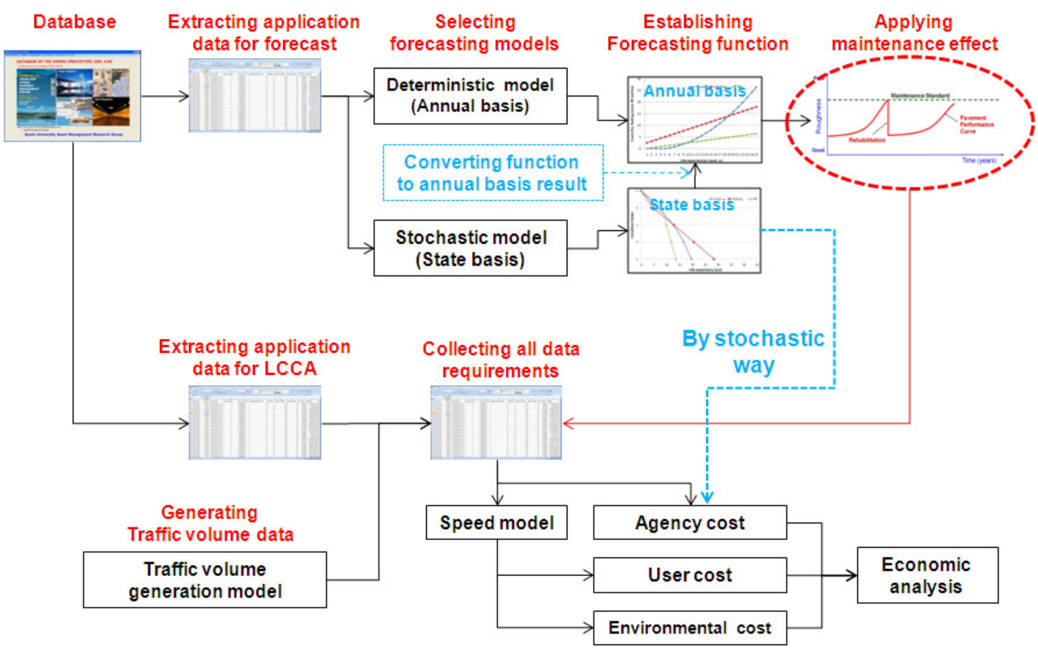


Figure 6.21 Application procedures for life cycle cost analysis in the Hybrid PMS

In case of the LCCA procedure;

- Defining LCC contents and detail simulation options for LCCA
- Extracting data for LCCA from the database
- Generating traffic volume data
- Receiving pavement deterioration process from the deterioration forecasting results
- Applying LCCA models
- Doing economic analysis

As shown in the Figure 6.21, the LCCA is impossible without (annual basis) pavement deterioration forecasting result. If users want to use stochastic models to full LCCA function, they have to apply additional function converting state basis result into annual basis result. Until this chapter, explanation of two sub-models on vehicle speed and traffic volume generation has been missed. It is because the two models are not direct factors for LCC content. It will be treated in the next chapter (Chapter 6.9).

6.9 Sub-models for LCCA

In most chapters, readers may feel that the vehicle speed and vehicle volume during analysis period does very important roles, especially in estimating user and environmental cost. This paper suggests the two sub-models on vehicle speed estimation and traffic volume generation which is revised to be easily applied in PMS analysis.

6.9.1 Speed Estimation Model

The vehicle speed affects to most of LCC contents directly or indirectly. The vehicle speed modeling especially in discrete traffic flow requires very deep understanding on mechanism among vehicle under different road situation. In case of traffic management field, much sophisticate modeling in microscopic level may be demanded. However, macroscopic approach may be enough for the pavement field. Due to desire for simplicity in application, most general theories have been applied for the modeling with simple modification. This chapter will introduce from fundamental knowledge on vehicle speed to suggestion of speed model for pavement field.

6.9.1.1 Definition of the Speeds

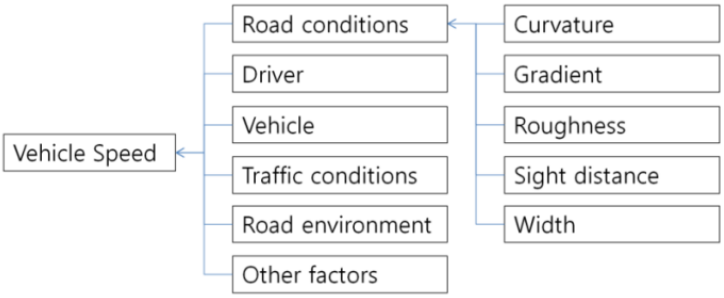
There are several terms that show different characteristics of vehicle's speed. The terms are defined as follows (Bennett and Greenwood 2003, modified),

- ***Spot speeds*** are measured at a point on the road. These are often called time speeds
- ***Journey speeds*** are speeds over a section of road. These are often called space speeds
- ***Free speeds*** are the speed vehicles travel when unaffected by other traffic, but affected by road characteristics and speed limitation with an enforcement factor
- ***Operating speeds*** are speeds adopted when affected by other traffic and road alignment but at lower flow levels.
- ***Congested speeds*** are speeds adopted when affected by other traffic and road alignment at high flow levels (that is, speed under congested conditions)
- ***Desire speeds*** are ideal speed determined by user's willingness without any negative road variables, but affected by only speed limitation.(but, the speed could be over the speed limitation)

For PMS analysis, the journey speed should be an object of estimation. By the above definitions, we can easily realize that the journey speed demands modeling on the free speed, plus consideration of traffic flow.

6.9.1.2 Factors Influencing Vehicle Speed

There are so many factors influencing vehicle speed on the road. The Figure 6.22 shows general groups that influence vehicle speed.



Source: Bennett and Greenwood, 2003

Figure 6.22 Factors influencing vehicle speeds

In the Figure 6.22, only 6 broad categories are shown. But there are many individual factors in every category. For example, Oppenlander (1966) in a review of 160 items in the literature listed over 50 specific factors that influence speeds. From the many researches, it was found that the variable affecting vehicle speed which may or may not have impact depending upon local conditions. The Table 6.53 compares the results from four multivariate analyses of speed related factors.

The individual studies considered more factors than listed in the Table 6.53. This table only shows the common factors tested in all studies. It shows that very few factors were significant in more than one study. Besides, the result from various studies are often contradicted each other. This is for the reason that local characteristics of each country are very different. It means that the speed model must have a calibration factor based on local observation. Even though there are so many factors influencing vehicle speed, the Hybrid PMS considers only limited factors within a range of road related factors for simplifying data requirement.

- Speed limitation
- Physical road condition
- Geometry condition
- Pavement condition
- Traffic condition

Table 6.53 Comparison of multivariate analysis results on influencing factor to vehicle speed

Factors	Wortman (1965)	O'Flaherty and coombe (1971a, b, c)	Galin (1981)	Barnes (1988)
Country	USA	Britain	Australia	N.Z.
Type of speed	Spot	Journey	Journey	Spot
Number of Factors Investigated	38	66	48	14
Minimum sight distance	X	Δ	-	-
Roadside establishments	X	Δ	X	-
Combination trucks	X	Δ	-	-
Horizontal curvature	Δ	X	-	-
Two or more passengers	Δ	X	Δ	Δ
Bunching	-	X	X	-
Driver age	-	-	X	X
Driver sex	Δ	Δ	X	Δ
Vehicle age	-	-	X	X
Vehicle engine size	-	-	X	X
Weather (dry versus wet)	Δ	Δ	X	-
Car ownership	-	-	Δ	Δ
Trip purpose	-	-	Δ	Δ
Trip distance	-	-	X	X

Source: Bennett and Greenwood, 2003

Note: X = Significant effect on speed in multivariate analysis

Δ = No significant effect on speed in multivariate analysis

- = Not tested in multivariate analysis

There is an assumption to avoid being a complex model which requires much detail information about road facilities and characteristic of vehicle flow; a vehicle type has same journey speed, desired speed and traffic flow influenced speed within a same condition. The information may be required for traffic flow simulation describing much detail stream with functions of many kinds of variables within a road section. In general, such detail information is not so usual for pavement management fields, especially in economic analysis.

6.9.1.3 Suggestion of Speed Model

The vehicle speed estimation model in the Hybrid PMS considers three kinds of speeds.

- *Desire speeds* are ideal speed determined by user's willingness without any negative road variables, but affected by only speed limitation.
- *Free speeds* are the speed vehicles travel when unaffected by other traffic, but affected by road characteristics and speed limitation with an enforcement factor
- *Traffic flow speed* influenced by a function of road capacity and traffic volume.

The three speeds shown above have a close relationship in the model. Desire speed is determined by speed limit with an enforcement factor of each vehicle class. Based upon this speed, negative factors to speed, such as slope, curvature, pavement condition, and road widths (positive effect) are considered for estimation of the free speed. Then, negative effect caused by traffic volume was considered. Finally, the lower becomes the operation speed of a vehicle class of a section. This explanation is formulated in Eq.6.81 and Eq.6.82.

$$V_{Journey} = V_{Free} - V_{Traffic} \qquad (6.81)$$

Where,
$V_{Journey}$ = journey speed in a section in km/h
V_{Free} = speed affected by physical road characteristics (slope, curvature), speed limitation, and over-speed behavior by vehicle class, in km/h
$V_{Traffic}$ = decrement of speed influenced by traffic volume in km/h

Where,

$$\text{If slope} \geq 0 \text{ then } V_{Free} = V_{desire} + a_1 S_R + a_3 Curve + a_4 Pave - a_5 Width, \qquad (6.82a)$$

$$\text{Otherwise } V_{Free} = V_{desire} + a_2 S_F + a_3 Curve + a_4 Pave - a_5 Width \qquad (6.82b)$$

Then,

$$If\ V_{Free} \geq V_{permit}\ then\ V_{permit} \Longrightarrow V_{Free}\ Otherwise\ V_{Free} = V_{Free}$$

$$If\ Width > 5, then\ a_5 = 0\ Otherwise\ a_5 = a_5$$

Where,
V_{desire} = are ideal speed determined by user's willingness without any negative road variables, but affected by only speed limitation which can be determined by $[V_{Limit} * a_6]$, in km/h
V_{Permit} = speed limitation considering enforcement factor, which can be determined by $[V_{Limit} * a_7]$
S_R = rise in m/km
S_F = fall in m/km
$Curve$ = horizontal curvature in degrees/km
$Pave$ = roughness in IRI m/km
$Width$ = pavement width in meter
$a_1 - a_5$ = regression coefficients (refer to Table. 6.54)
a_6 = a coefficient representing over-speed characteristics of each vehicle class

Required assumptions to be simple are;

- Each vehicle type has different speed
- A vehicle type have same speed in a section
- A vehicle type drives at uniform speed in a section
- No difference between driving lanes
- The AADT is uniformly scattered to 24 hours

A. Estimation of the free speed

The main task to estimate free speed is determining coefficients that make negative effects to free speed. There were many researches applying multivariate model by vehicle class. Table 6.54 summarizes the coefficients which are used in Eq. 6.53. The coefficients in the Table 6.54 presented the different effects to free speed measured in many studies. In fact, there is little agreement among the studies, particularly in the coefficient for the road width. Whereas some researchers have found that it is only on narrow pavements that width effects become pronounced (Hide *et al.,* 1975), others apply a width effect even to high standard roads such as are found in Germany (McLean, 1991) and Sweden (Brodin and Carlsson, 1986). It is also important to note that several researchers were not able to find a significant width effect (Troutbeck, 1976) and not only is the magnitude of the effect of width on speed opens to interpretation, but even its very existence.

McLean (1989) goes on to suggest that width effects will be manifested on narrow pavements through a modification to the driver's desired speeds. As the width of the pavement decreases, the likelihood of being affected by a vehicle travelling in the opposite direction increases. Thus, the driver would reduce their desired speed. This thesis is supported by the finding from Abaynayaka *et al.*,(1974), Hide *et al.*, (1975), Morosiuk and Abaynayaka (1982) who found that it was only when the pavement width was below 5.0m that speeds were affected by width. By referring these research results, the Hybrid PMS assumed that the a_5 becomes negative factor when road width is narrower than 5 meters. However, it is expected that the coefficient would be a negative factor in most cases because most sections are wider than 5 meters.

By referring the coefficients in the Table 6.54, the Hybrid PMS suggested a default range and default value of each vehicle class in the Table 6.55.

The coefficients were tested by using the Korea national highway data. The results are summarized in Figure 6.23 and Table 6.56.

Table 6.54 Summary of coefficients for the free speed estimation

	Description	Study	Reference	PC[1)]	LCV[2)]	CV[3)]	Bus[4)]
a_1	Uphill	Kenya	Hide *et al.* (1975)	-0.372	-0.418	-0.519	-0.526
		Caribbean	Morosiuk & Abayanayaka (1982)	-0.078	-0.085	-0.222	-
		India	CRRI (1982)	-0.178	-	-0.175	-0.277
a_2	Downhill	Kenya	Hide *et al.* (1975)	-0.076	-0.050	0.030	0.067
		Caribbean	Morosiuk & Abayanayaka (1982)	-0.067	-0.067	-0.122	-
		India	CRRI (1982)	-0.155	-	-0.037	-0.159
a_3	Curvature	Kenya	Hide *et al.* (1975)	-0.111	-0.074	-0.058	-0.066
		Caribbean	Morosiuk & Abayanayaka (1982)	-0.027	-0.022	-0.017	-
		India	CRRI (1982)	-0.009	-	-0.014	-0.011
a_4	Pavement condition	Kenya	Watanatada (1981)	-0.64	-	-	-
		Brazil	GEIPOT (1982)	-2.00	-	-	-
		Caribbean	Morosiuk & Abayanayaka (1982)	-0.62	-0.47[5)]	-0.76[5)]	-
		India	CRRI (1982)	-2.57	-	-1.25[5)]	-1.71[5)]
a_5	Pave-width	India	CRRI (1982)	1.82	-	-0.88	-1.35
		Australia	Leong (1968)	0.98	-	-	-
		Britain	Ford (1977)	7.07	-	-	-
		Canada	van Aerde and Yagar (1981)	5.67	-	-	-
		Caribbean	Morosiuk & Abayanayaka (1982)	8.10	-	-	-
		Germany	Lamm et al. (1986)	5.00	-	-	-
		Jamaica	Bunce and Tressidder (1967)	4.32	-	-	-
		Kenya	Abaynayake et al. (1974)	5.45	-	-	-
		Kenya	Hide *et al.* (1975)	7.10	-	-	-
		South Africa	NITRR (1983)	2.20	-	-	-
		Sweden	VTI (1990)	0.70	-	-	-
a_6	Over-speed	Assumption	The Hybrid PMS default	1.10	1.05	1.00	1.00
a_7	Enforcement	Assumption	The Hybrid PMS default	1.00	1.00	1.00	1.00

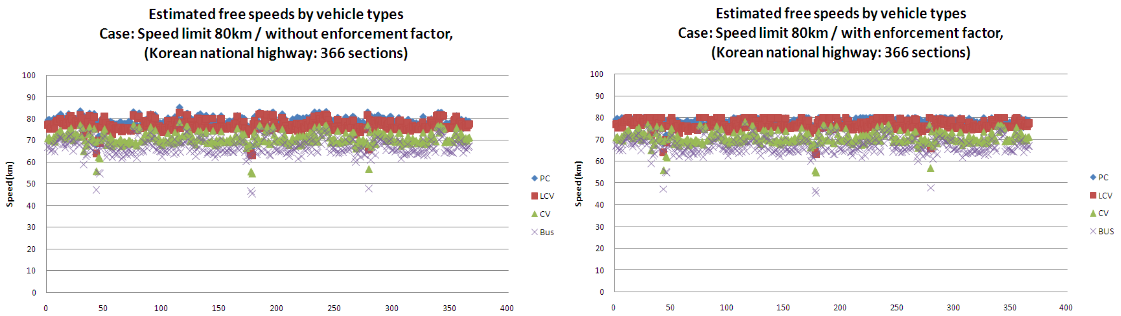
Note: 1) Passenger Car,
2) Light Commercial Vehicle
3) Medium and Heavy Commercial Vehicle
4) Heavy Bus
5) Estimated by the relationship between coefficients

Table 6.55 Default ranges and values of each model parameter for free speed estimation

Model parameters	Default range		Default			
	Max	Min	PC	LCV	CV	Bus
a_1 (Rise)	-0.526	-0.078	-0.209	-0.252	-0.305	-0.402
a_2 (Fall)	-0.159	0.067	-0.099	-0.059	-0.043	-0.046
a_3 (Curvature)	-0.111	-0.009	-0.049	-0.048	-0.030	-0.039
a_4 (Pavement)	-2.570	-0.470	-1.458	-0.470	-1.005	-1.710
a_5 (Pave width)	8.100	0.700	4.401	-	0.880	1.350
a_6 (Over-speed)	0.900	1.200	1.100	1.050	1.000	1.000
a_7 (Enforcement)	1.100	1.000	1.000			

Table 6.56 Estimated free speeds by vehicle classes

Index	PC	LCV	CV	BUS
Average	78.32214	76.68044	70.785562	66.779992
Minimum	66.84987	62.93866	54.610823	45.49063
Maximum	80	80	78.194647	77.04846
Difference	13.15013	17.06135	23.583823	31.55783
Standard deviation	1.882207	2.318488	2.9781654	3.975311



Note: speed limit = 80km/h, enforcement factor = 1.0

Figure 6.23 Estimated free speeds by vehicle classes (Korea national highway, 366 sections)

As discussed above, it is a little bit difficult to define a default value that satisfies every country's speed characteristics. Note that even if the Hybrid PMS defines a default value of each coefficient, it is recommended to develop models based on local observations.

B. Estimation of the traffic influenced speed

There are several alternatives estimating the traffic influence speed. To simplify the model, this paper suggests a simplest method which is modifying a basic formulation of the Highway Capacity Manual (TRB, 2000). The original equation is,

$$ATS = FFS - 0.0125q_p - f_{np} \qquad (6.83)$$

Where,

ATS = average travel speed in km/h

FFS = free-flow speed km/h

q_p = analysis flow rate

f_{np} = adjustment factor for no-passing zones

The equation may be rewritten as,

$$V_{Traffic} = V_{free} - \left[0.0125 * \frac{\sum_{t=1}^{24}\sum_{k=1}^{K} AADT*D_f*R_t*P^k*PCSE^k}{Leng*PHF*f_g*f_{HV}}\right] - f_{np} \qquad (6.84)$$

Where,

$V_{Traffic}$ = decrement of speed influenced by traffic volume, in km/h

$AADT$ = annual average dairy traffic in veh/day
Ln = number of lanes (one-way)
D_f = adjustment factor for directional distribution of traffic
R_t = hourly traffic volume ratio of time t from the AADT, here, $(t = 1, \ldots, 24)$, $\sum_{t=1}^{24} R_t = 1.00$
P^k = composition ratio of a vehicle type k, $(k = 1, \ldots, K)$, *i.e.* $\sum_{k=1}^{K} P^k = 1.00$
$PCSE^k$ = passenger car space equivalencies of a vehicle type k
$Leng$ = number of lane
PHF = peak hour factor (default = 0.90) (Barry, 2004)
f_g = grade adjustment factor
f_{HV} = heavy vehicle adjustment factor

The ATS in Eq. 6.83 representing the average traffic speed in a section can be substituted for the V_{free} addressed in the previous chapter. In case of the q_p, the analysis flow, needs a complex calculation procedure that converts the AADT into the hourly traffic flow with consideration of the directional adjustment factor, hourly traffic ratio, vehicle composition, and passenger car space equivalencies of a vehicle, and peak hour factor, and so on. The constant, 0.0125, in the Eq. 6.84 makes negative effect to average traffic speed by a vehicle.

Most traffic condition influenced speed estimation models are hour-basis and lane-basis methodology (*e.g.* TRB, 1992, 2000; Bennett and Greenwood 2003; FHWA, 1998). However, most PMSs usually have only AADT and vehicle composition data. To apply the model shown at the Eq. 6.84, road agency must have much detail information on hourly traffic distribution of all sections. Although the data is good for research purpose (*e.g.* work-zone effect), it requires huge amount of effort and budget. For that reason, the Hybrid PMS suggests a simplified model structure (see Eq. 6.85).

$$V_{Traffic} = V_{free} - \left[0.0125 * \frac{\sum_{k=1}^{K} AADT * P^k * PCSE^k}{24 * Ln * PHF}\right] \quad (6.85)$$

The suggested model basically assumes uniform distribution of traffic volume during 24 hours, and also same directional distribution of traffic (*i.e.* 50% / 50%). Of course, it is non-sense in reality. But the effect to travel time cost may be same because every vehicle reduce same amount vehicle speed. In case of the adjustment factor f_{np} for no-passing zones, was excluded from the Eq. 6.84 by referring a recent research result (Kuttinen *et al.*, 2005).

The estimated journey speed applies the PCSE unit as an equivalency factor for estimating the analysis flow rate. There are two types of equivalency factors in use, and it is important to understand the difference between the two units. It is defined as the following (Bennett and Greenwood, 2003),

- ***Passenger Car Equivalencies (PCE):*** These are also called passenger car units (PCU) have been commonly used in capacity studies, such as with the HCM (Highway Capacity Manual). These represent the number of additional passenger cars which, if added to the traffic stream, would have the same impeding effect as the vehicle of interest – usually a truck, The PCE is based on two considerations; 1) the area occupied by the vehicle, and 2) its impact on the traffic stream through its performance.

- ***Passenger Car Space Equivalencies (PCSE):*** These are only based on the area occupied by the vehicle and not on its performance impact on the traffic stream.

Hoban *et al.* (1994) recommended default PCSE values by vehicle class. The PCSE values were established based on the assumption that each vehicle has a typical length as well as typical leading and following headways. The basic values only accounted for the longitudinal space occupied by vehicles. Additionally, larger vehicles tend to impact adjacent lanes, with the “adjacent lane” effect being greater for larger vehicles and for narrower roads (Hoban *et al.,* 1994). This led to the final PCSE values varying by width as shown in the Table 6.57.

This methodology could be used for calibration of the PCSE values based on characteristics of vehicle length and average speed of each vehicle type. The suggested model for the journey speed was also empirically tested by using the Korea national highway data, (see Figure 6.24 and Table 6.58).

Table 6.57 Default PCSE values by vehicle class

Vehicle class	Average length (m)	Time Headway (s)	Space Headway (m)	Total Space (m)	Basic PCSE	Recommended Values(Includes 'Basic' plus adjacent lane effect		
						Two or Four lanes	Narrow two lanes	One-lane
Car	4.0	1.6	32	36.0	1.0	1.0	1.0	1.0
Pickup	4.5	1.8	36	40.5	1.1	1.0	1.0	1.0
Heavy bus	14.0	2.2	44	58.0	1.6	1.8	2.0	2.2
Light truck	5.0	2.0	40	45.0	1.3	1.3	1.4	1.5
Medium truck	7.0	2.2	44	51.0	1.4	1.5	1.6	1.8
Heavy truck	9.0	2.4	48	57.0	1.6	1.8	2.0	2.4
Truck & Trailer	15.0	2.5	50	65.0	1.8	2.2	2.6	3.0

Notes: 1) Basic data from Hoban et al. (1994)
2) Time headway calculated from space headway using 72 km/h speed
3) Truck and Trailer average length increased to 15 from 11 given in Hoban et al. (1994) based on difference between total space and space headway

Table 6.58 Estimated journey speeds by vehicle classes

Index	PC	LCV	CV	BUS
Average	75.92856	74.28686	68.39199	64.38642
Minimum	65.06769	62.75326	54.25992	45.19545
Maximum	79.87347	79.75903	77.65837	76.51218
Difference	14.80577	17.00577	23.39844	31.31673
Standard deviation	2.788985	3.087202	3.64584	4.486778

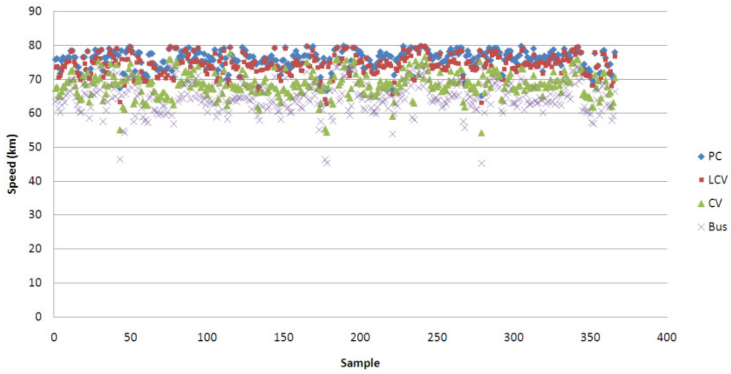


Figure 6.24 Estimated journey speeds (case: 4 lanes, 80km speed limit, and enforcement factor 1.0)

Even though this model applied the uniform distribution of hourly traffic volume, it is expected that over and under estimated results make an offset effect. The maximum difference of the average speed among the vehicle classes is around 10 km/h. From the experiences in Korea national highway, the results in the Table 6.58 were fairly reasonable.

6.9.2 Traffic Volume Generation Model

Traffic volume is very sensitive to overall life cycle cost analysis, especially in deterioration speed and road user cost. Nevertheless, many researchers have often applied it by simple assumption. Following the scale of the traffic volume, the LCCA result can be easily fabricated for securing ample budget, or proving feasibility of projects. About the problems, this paper suggests traffic volume generation models based on statistical method. By applying the methods, road agency can do much objective LCCA. This chapter will introduce two kinds of models which can be used for different purposes. In addition, the traditional methods also will be reviewed.

6.9.2.1 Reviews of the General Methods

A. Uniform method

This method allocates a uniformed value by referring first year's AADT to all of analysis years. By a equation;

$$AADT_y^{sk} = \overline{AADT}_o^{sk} \quad (6.86)$$

$$(k = 1, \dots, K; y = 1, \dots, Y; s = 1, \dots, S)$$

Where,

$AADT_y^{sk}$ = AADT of vehicle type *k*, of section *s*, in analysis year y,

$\overline{AADT}_o^{sk}$ = AADT in first analysis years (*i.e.* measured AADT)

Its concept means that the latest traffic condition will be continued during the analysis year. Although this method is simple, it has strength on easy application. This method is often preferred to avoid arguments over or under estimation of the LCC. This strength is very important especially in project level of analysis.

B. Compound interest method

This is the most typical method applying increment rate by compound interest method. By a equation;

$$AADT_y^{sk} = AADT_{y-1}^{sk} + \left[AADT_{y-1}^{sk} \times r^k\right] \quad (6.87)$$

Or, by the compound interest method,

$$AADT_i^{sk} = \overline{AADT}_o^{sk}[1 + r^k]^y \quad (6.88)$$

Where,

r^k = changing rate of vehicle type k.

Although many case studies have often applying this method based on the specific interest suggested by national standard or research results, road agencies has to be careful for over estimation. In general, an analysis period in the pavement field is usually 20~40 years (or more). Hence, this method could have a tendency to overestimate traffic volume (even beyond capacity of a section). One of solutions is assigning different interest to user specified traffic levels or periods. However, it also requires additional researches for definition of the traffic level and periods.

C. Changing AADT in figure

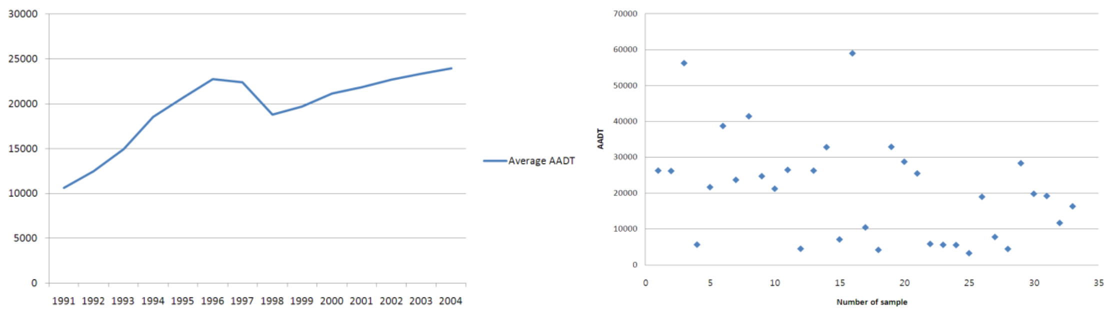
To avoid the problem of the compound interest method, applying AADT in figure could be an alternative.

$$AADT_y^{sk} = AADT_{y-1}^{sk} \pm AADT_{adj}^{k} \quad (6.89)$$

Here, the $AADT_{adj}^{k}$ is absolute values to increase or decrease AADT in previous year. However, this method may be unusual for practical application because determination of $AADT_{adj}^{k}$ is also difficult. Besides, change of traffic volume is not usually expressed by absolute value.

D. Applying estimation function

Another alternative could be applying estimation functions such as polynomial, exponential, logarithm function based on time-series traffic volume data. If the estimation model has a high accuracy, this method might be the best alternative among the deterministic way. However, the method also has a limitation on uncertainty in future trends. For example, Korea had been fall into economic crisis from 1998~2000. At the period, the traffic volume was sharply decreased (See Figure 6.25).



Data source: TMS, 2006

Note: 33 samples sections were randomly extracted by the level of traffic volume from the Korea national highway

Figure 6.25 Average AADT of Korea national highway (left) and dispersion (right)

Since the traffic volume is affected by many kinds of direct or indirect variables, the estimation function should hire explanatory variables. However, it also requires additional estimation procedure on the explanatory variables. With many complex and additional steps, the reliability would be doing down.

6.9.2.2 Suggestion of Traffic Volume Generation Models

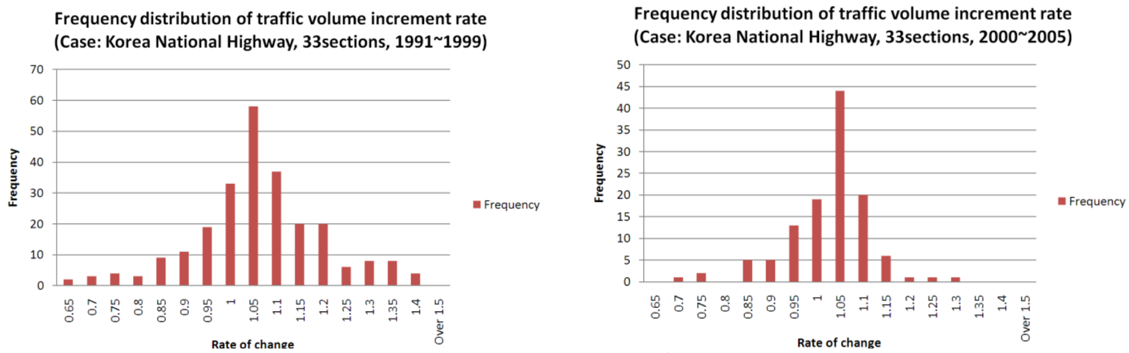
A. Generation increment rate following localized normal distribution

This paper introduces a simple method based upon uncertainty of traffic volume increment or decrement trend. Usually, most researches assigned the traffic volume by incremental trend. However, the traffic volume also can e decreased. Also the trend can be changed by every individual year. The Figure 6.26 and Figure 6.27 show the fact by using Korea national highway data by dividing two period, 1990s and 2000s.

From the Figures 6.26 and 6.27, we can find several important features;

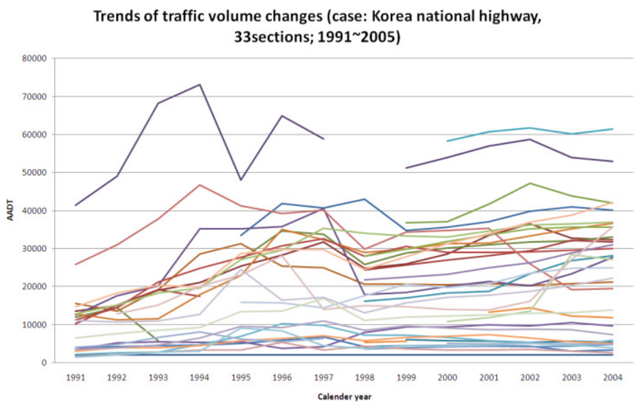
- The increment rate of traffic volume could be differed by the time (or economic situation *etc.*)
- The traffic volume could be increased but also decreased (under the 1.00)
- The increment rate data (approximately) follows the normal distribution.
- Traffic volume changing process was almost random.
- Dispersion of AADT and increment rate could be differed by road section groups(*e.g.* level of AADT)

As noted above, if the data is assumed to follow the normal distribution, $X \sim N(\mu, \sigma^2)$, the annual increment rate can be easily generated by referring to average μ and variance σ^2 of time-series traffic data. The normal distribution $X \sim N(\mu, \sigma^2)$, can be converted into a linear equation as follows;



Data source: TMS, 2006

Figure 6.26 Frequency distribution of traffic volume increment rate of the Korea national highway in 1990s (left) and 2000s (right)



Data source: TMS, 2006

Figure 6.27 Annual traffic volume changing processes in Korea national highway (1991~2005)

$$X \sim N(\mu, \sigma^2) \rightarrow Y = \mu + \sigma X \sim N(\mu, \sigma^2) \tag{6.90}$$

To generate random number X which is following $N(0, 1^2)$, the Box Muller algorithm can be applied. The Box Muller algorithm takes two independent standard uniform random variables $U_1, U_2 \sim Unif(0,1)$. And the U_1, U_2 produces independent standard normals X_1, X_2 by the Eqs. 6.91a and 6.91b.

$$X_1 = \sqrt{-2 \ln U_1} \times \cos(2\pi U_2) \tag{6.91a}$$

$$X_2 = \sqrt{-2 \ln U_1} \times \sin(2\pi U_2) \tag{6.91b}$$

Then, the independent standard normals substitutes the Eq. 6.90 with the μ and σ. It would be nice to get a standard normal from a standard uniform by inverting the distribution function. However, calculation procedure on cosine and sine is a little bit complex. To solve this problem, Maraglia and Bray (1964) suggest the Polar method. The algorithm follows these steps,

- ***Step 1*:** Generate $U_1, U_2 \sim Unif(0,1)$
- ***Step 2:*** Calculate V_1, V_2 and their summation S by Eq. 6.92.

$$\begin{cases} V_1 = 2U_1 - 1 \\ V_2 = 2U_2 - 1 \\ S = V_1^2 + V_2^2 \end{cases} \tag{6.92}$$

- ***Step 3:*** If the $S > 1$, return to the Step 1. Otherwise, go to Step 4.
- ***Step 4:*** Calculate X_1 and X_2 by using the Eqs. 6.93a and 6.93b

$$X_1 = \sqrt{\frac{-2 \ln S}{S}} \times V_1 \tag{6.93a}$$

$$X_2 = \sqrt{\frac{-2 \ln S}{S}} \times V_2 \tag{6.93b}$$

- ***Step 5:*** Substitute X_1 and X_2 for $Y(r_y^s) = \mu + \sigma X \sim N(\mu, \sigma^2)$

If necessary, truncated normal distribution can be applied. The standard to cut tails of distribution can be assigned by user-specified value or some statistical values. For example, confidence interval determined by a function of confidence level $Z_{\alpha/2}$, average μ , and number of sample n would be reasonable.

- **(optional) *Step 6*:** Estimate confidence interval Lim_l^T and Lim_l^B of each traffic volume level. Here, the confidence interval is estimated by;

$$Lim_l^T = \mu + Z_{\alpha/2}\sqrt{\frac{\sigma^2}{n}} \text{ ,and } Lim_l^B = \mu - Z_{\alpha/2}\sqrt{\frac{\sigma^2}{n}} \tag{6.94}$$

- ***(optional) Step 7:*** Delete tails (samples) by referring the Lim_l^T and Lim_l^B, and regenerate X_1 and X_1 when the sample satisfies the interval. Or substitute Lim_l^T and Lim_l^B for the samples to avoid repeated calculation
- ***Step 8*:** Apply the $Y(r_y^s)$ for AADT estimation by using the Eq. 6.95.

$$AADT_y^s = AADT_{y-1}^s \times r_y^s \tag{6.95}$$

By the Eq. 6.95, we can generate annual AADT of all road sections during the analysis period. However, there is high a possibility that road group classified by specific variables, such as level of AADT, road classification (*e.g.* highway, regional way, and inter-urban), or number of lane. The groups could have different μ and σ^2. It means that increment rate of each road group should be differently generated by referring their data characteristics by μ and σ^2. If the AADT level is applied for road group classification, the generation method should be modeled by a dynamic method by a function of AADT level. This could be realized by the Eq. 6.96 that applies r_{yl}^s that adds AADT group l $(l = 1, \dots, L)$ which may (or may not) have different normal distribution types $r_{yl}^s \sim N(\mu_l, \sigma_l^2)$. By the consideration above point, the Eq. 6.951 is reorganized in Eqs. 6.96a and 6.96b.

$$AADT_y^s = AADT_{y-1}^s \times r_{yl}^s \;\; (or \;\; AADT_y^s = AADT_0^s \times r_{yl}^s) \quad (6.96a)$$
$$(y = 1, \ldots, Y; s = 1, \ldots, S; l = 1, \ldots, L)$$
$$Here, \begin{cases} r_{yl}^s \sim N(\mu_l, \sigma_l^2) \\ V_y^s \in l \end{cases} \quad (6.96b)$$

As shown at Eq.6.96a and Eq.6.96b, the model could generates traffic volume increment or decrement rate by different normal distribution in dynamic way based on the condition of the $AADT_{y-1}^s$. That is, the final distribution shape is interfered by various normal distributions having different properties depended upon classified road groups $l\,(l = 1, \ldots, L)$. In addition the $AADT_{y-1}^s$ can be substituted by $AADT_0^s$ which is first year's AADT to give much stable AADT. If the $AADT_0^s$ is applied, it becomes static way.

In practical use, consideration of heterogeneity of road groups, and truncation of both tails (at least a tail on the right side) are mandatory because unrealistic traffic volume data could be generated by accumulation of high level of increment rate. To avoid this problem, there are several solutions. The first one is that application of road capacity which can be estimated by physical road characteristics, such as number of lane, width of lane, shoulder and so on. Theoretically, the V_y^s cannot over the road capacity C_u^s. For that reason, we need an additional procedure checking the outliers. This can be simply expressed by;

$$AADT_y^s = MIN[(C_u^s \times 24), \widehat{AADT}_y^s] \quad (6.97)$$

If necessary, the lower limitation of AADT C_b^s also can be applied by combination with the Eq.6.97,

$$AADT_y^s = MAX[(C_b^s \times 24), MIN\{(C_u^s \times 24), \widehat{AADT}_y^s\}] \quad (6.98)$$

The hat [^] in the Eq.6.97 and Eq.6.98 means estimated but also temporal AADT before checking the boundary. Note that the both standards C_u^s and C_b^s could be substituted by user specified boundary U_u^s and U_b^s. In reality, it is better to apply the U_u^s and U_b^s because usually the AADT cannot reach the road capacity. The explained method generates increment rates based on normal distribution $X \sim N(\mu, \sigma^2)$. However, there is a possibility that the data distribution of a country could be much close to other distribution type which follow continues probability distribution. However, it is believed that most data would follow the normal distribution.

Trends of the generated traffic volume by trials satisfied the properties listed in the previous paragraphs. Description of reality is important, however, much important strength is mitigating subjective judgment for LCCA. By repeated application of this method, we could find probabilistic interval of LCC based on traffic volume.

B. Generation increment rate following triangular-trapezoidal-shaped distribution

This paper developed a simple traffic volume generation method having trapezoidal-shaped distribution that can adjust shape of distribution based on two random factors U_1 and U_2 with two boundary factors ε_l^T and ε_l^B. The basic formulation is showing in the Eq.6.99a and Eq.6.99b.

$$\widehat{AADT}_y^s = \widehat{AADT}_{y-1}^s + [\widehat{AADT}_{y-1}^s \times r_{yl}^s] \quad (6.99a)$$
$$r_{yl}^s = [\varepsilon_l^T \times U_1] + [-\varepsilon_l^B \times U_2] \quad (6.99b)$$

By integration of the Eq.6.99a and Eq.6.99b, it becomes Eq.6.99a with conditions in Eq.6.99b;

$$\widehat{AADT}_y^s = \widehat{AADT}_{y-1}^s + \left[\widehat{AADT}_{y-1}^s \times \{\varepsilon_l^T \times U_1\}\right] + \left[AADT_{y-1}^s \times \{-\varepsilon_l^B \times U_2\}\right] \quad (6.100a)$$
$$(y = 1, \ldots, Y\,; s = 1, \ldots, S\,; l = 1, \ldots, L)$$
$$Here, \begin{cases} U_1, U_2 \sim Unif(0,1) \\ \widehat{AADT}_y^s \in l \end{cases} \quad (6.100b)$$

Where, ε_l^T and ε_l^B are standards for making boundary of increment or decrement rate of user-specified traffic volume level groups $(l = 1, \ldots, L)$. By the adjusting of ε_l^T and ε_l^B, degree of increment and decrement can be flexibly adjusted. For instance, developing countries which are in an fast economic growth, the countries may have higher ε_l^T. If a user allocates zero for the ε_l^B, the model generates only increment trend. On the other hands, developed countries which has maximum traffic volume level could have higher ε_l^B than ε_l^T.

In case that the ε_l^T and ε_l^B have same value, the algorithm generates random number following triangular distribution, $Tri(-\varepsilon_l^B, 0, \varepsilon_l^T)$. The range of ε_l^T and ε_l^B determines interval of the distribution. By the adjusting the two values, the shape of distribution also can be adjusted. If one parameter has higher value than the other, the algorithm makes trapezoidal-shaped distribution looks like a compound of triangular distribution and uniform distribution. The properties of the distribution are normalized in the Eq.6.101 and Eq. 6.102.

If the $\varepsilon_l^T = \varepsilon_l^B$,

$$r_{yl}^s \sim Tri(-\varepsilon_l^B, 0, \varepsilon_l^T) \tag{6.101}$$

Otherwise, (that is $\varepsilon_l^T \neq \varepsilon_l^B$*)*

$$r_{yl}^s \sim TZ\left(-\varepsilon_l^B + \frac{\varepsilon_l^B + \varepsilon_l^T}{2}, \varepsilon_l^B, -\varepsilon_l^B + \frac{\varepsilon_l^T}{2}, \varepsilon_l^T, -\varepsilon_l^B + \varepsilon_l^T\right) \tag{6.102}$$

Where, the components in the parenthesis describe a shape of trapezoid of traffic volume level l by order of middle point of distribution, start and end point of total distribution, start and end point of uniform distribution. One of benefits is that user can easily define boundary of distribution by the ε_l^T and ε_l^B.

In this algorithm, the r_{yl}^s which is determined by a function of relationship between U_1, U_2 and ε_l^T, ε_l^B (with traffic volume level l has an important role for data generation. Besides, the $\widehat{AADT}_{y-1}^s$ which is previous year's traffic volume also has very important role because it is starting point of data generation. As shown in the Eq.6.100, the $\widehat{AADT}_{y-1}^s$ is varied in every year. Moreover, the $\widehat{AADT}_{y-1}^s$ makes dynamic changes of user-specified traffic volume level groups l during analysis period. Probabilistically, higher r_{yl}^s can be continuously assigned to a section. In such case, unrealistic traffic volume data (perceived by analyzer's subjective intuition) could be generated. To prevent this, the $AADT_0^s$ can be substituted for the $\widehat{AADT}_{i-1}^s$ in the Eq.6.100. By the application of $AADT_0^s$ instead of the $\widehat{AADT}_{y-1}^s$, the algorithm may generates much stable data.

The Figures 6.28 ~ Figure 6.29 show simple examples showing characteristic of triangular-trapezoidal-shaped distribution by adjusting the ε_l^T and ε_l^B. Note that the sample scale for testing characteristic of the distribution was 20,000 respectively.

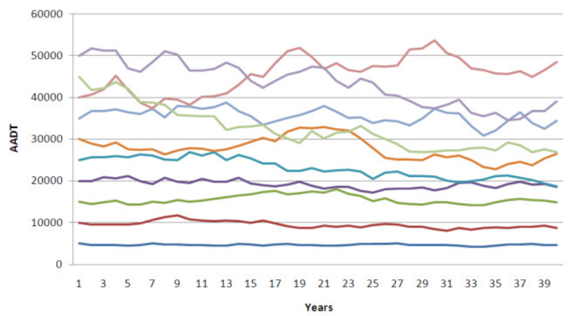


Figure 6.28a Lower variance
(Case: ε_l^T=0.1, ε_l^B=0.1)

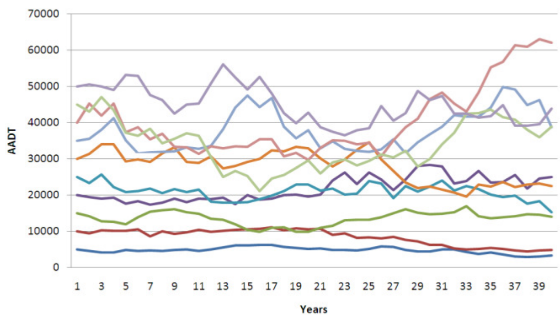


Figure 6.28b Higher variance
(Case: ε_l^T=0.2, ε_l^B=0.2)

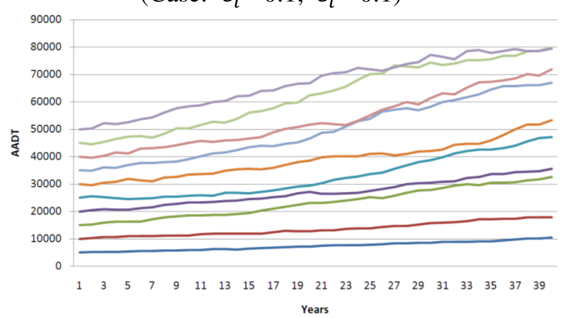


Figure 6.28c Increasing trend
(Case: ε_l^T=0.05, ε_l^B=0.02)

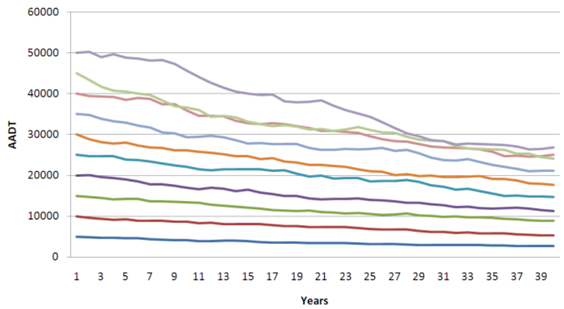


Figure 6.28d Decreasing trend
(Case: ε_l^T=0.05, ε_l^B=0.02)

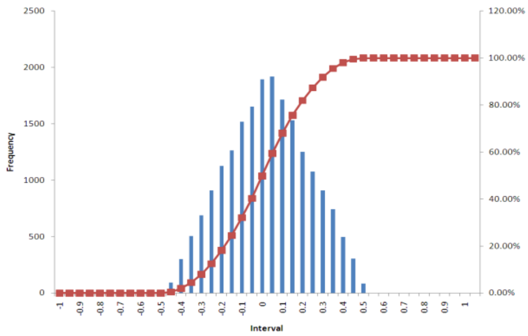


Figure 6.29a A case for $\varepsilon_l^T = \varepsilon_l^B$ (triangular)
(Case: ε_l^T=0.5, ε_l^B=0.5)

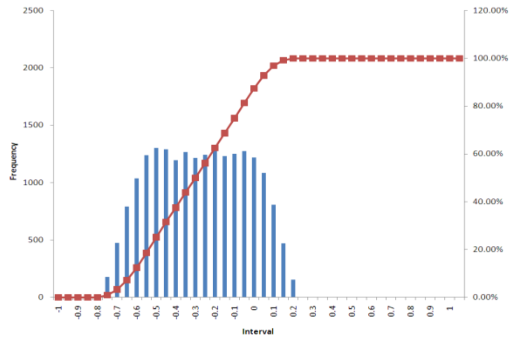


Figure 6.29b A case for high difference (trapezoidal)
(Case: ε_l^T=0.2, ε_l^B=0.8)

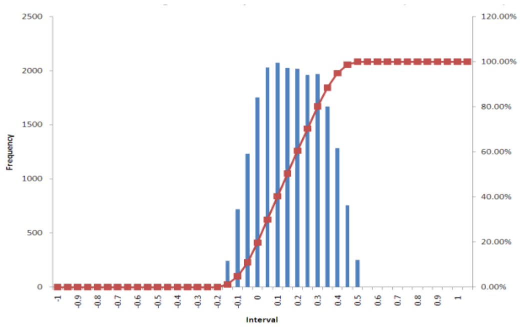


Figure 6.29c A case for an increasing trend
(Case: ε_l^T=0.5, ε_l^B=0.2)

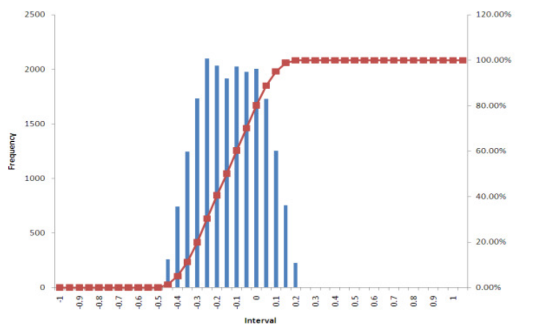


Figure 6.29d A case for a decreasing trend
(Case: ε_l^{IC}=0.2, ε_l^{DC}=0.5)

Note: The sample scale to test characteristic of distribution was 20,000 respectively.

6.10 Representative Vehicle Types

Most countries are now collecting the data as a national policy because the traffic information is very useful for many fields, particularly in the transportation sector. The traffic information is generally characterized by the AADT (or ADT). And the AADT is determined by summation of traffic volumes of each representative vehicle. In brief, road agencies must have a standard on representative vehicles for data collection, as well as PMS analysis. As noted in the Chapter 6.9, the traffic volume can make significant effect to LCCA results. However, road agencies have to realize that the definition of representative vehicle also can handle the LCCA results. Since the traffic loads and unit costs are defined by each vehicle types, the definition affects to deterioration speed and LCC scale.

Definition of the representative vehicles may cause so many arguments because most countries have very different characteristics on vehicles types reflecting their situations. Properly, they are now collecting vehicle volume under different classification. This difference has been caused by the different viewpoints from the different fields. For example, traffic field usually lets their focuses to effect on traffic flow, while the pavement field considers vehicle load characteristic as much important factor for vehicle classification. Unfortunately, the traffic volume information is usually collected by transportation sector, the classification often are not matched with demands of pavement field. As a result of the reason, we can easily find cases that one country have multi-standards for vehicle classification. Maybe someone think it is easy to define by in-house effort. However, the works is never easy because property data of each vehicle also should be a set. In case of the HDM-4 model, 160 data is dedicated for definition of property of each vehicle type.

This chapter will discuss about 1) current situations on definition of representative vehicles of the world (or models), and 2) suggesting how to define the standard for pavement management field. Even though this procedure is not officially included in the LCCA procedures in the Hybrid PMS, road agencies should carefully check their definition before application. It could affect to their overall PMS structure from inspection, database, to economic analysis. If compatibility on vehicle classification among the countries is established, the benefit may be very huge beyond our expectation.

6.10.1 Reviews of Definition of Representative Vehicles

There are many kinds of vehicle definitions from around world (or PMS model). Table 6.59 introduces several cases. In case of Table 6.60 gives more cases adopted in different studies or countries which are compared by a standard (Bennett, 1995)

Table 6.59 Summary of definitions of representative vehicles

References	Number of types	Description	Vehicle Class	Main factors
FHWA (U.S) (FHWA, 2001)	13	· Motorcycles · Passenger Cars · 2 Axles, 4-Tire Single Units, Pickup or Van · Buses · 2 Axles, 6-Tire Single Units · 3 Axles, Single Unit · 4 or More Axles, Single Unit · 3 to 4 Axles, Single Trailer · 5 Axles, Single Trailer · 6 or More Axles, Single Trailer · 5 or Less Axles, Multi-Trailers · 6 Axles, Multi-Trailers · 7 or More Axles, Multi-Trailers	· Motorcycle · Passenger Car · Single unit trucks · Single combination trucks · multi-trailer trucks	· Number of axles · Number of unit · Number of tires · Type of vehicle
RealCOST (U.S) (FHWA, 1998)	3	· Passenger cars and other 2-axle, 4-tired passenger vehicles (classification types 1-3) · Single-unit trucks, 2-axle, 4-tired or more commercial trucks (classification types 4-7) · Combination-unit trucks (classification types 8-13)	· Passenger car · Single unit truck · Combination truck	· Number of axles · Number of tires · Number of unit · Type of vehicle
HERs (U.S)	7	· Passenger car A- small · Passenger car B- medium · Truck-single unit A- 4tire · Truck-single unit B- 6tire · Truck-single unit C- 3~4axle · Combination truck A- 4axle · Combination truck B- 5axle	· Passenger car · Single unit truck · Combination truck	· Number of axles · Number of tires · Number of unit · Type of vehicle
MLTM (2009) (Korea)	6	· Passenger car · Small bus · Heavy bus · Small truck · Medium truck · Heavy truck	· Passenger car · Bus · Truck	· Shape and Size · Type of vehicle
KICT (2008) (Korea)	12	· Passenger car · Heavy bus · Small truck A - 1~2.5ton (2axle) · Small truck B - 2.5ton~ (2axle) · Medium truck A - 3axle · Medium truck B - 4axle · Medium truck C - 5axle · Heavy truck A - Semi trailer (4axle, 2unit) · Heavy truck B - Full trailer (4axle, 2unit) · Heavy truck C - Semi trailer (5axle) · Heavy truck D – Full trailer (5axle, 2unit) · Heavy truck E – Semi trailer (6axle, 2unit)	· Passenger car · Bus · Small truck · Medium truck · Heavy truck (Trailer)	· Gross weight · Number of axles · Number of unit · Type of vehicle
HDM-4 (World Bank) (Bennett and Greenwood, 2003)	16	· Motorcycle · Passenger car - small · Passenger car - medium · Passenger car - large · Light delivery vehicle – panel van, utility or pickup truck · Light goods vehicle · Four wheel drive – landrover/jeep · Light truck - <3.5ton · Medium truck - >3.5ton · Heavy Truck – Multi-axle rigid truck · Articulated Truck · Mini-bus – panel van (usually 4tire) · Light bus (<3.5ton) · Medium bus (3.5~8.0ton) · Heavy Bus (Multi-axle or large tow-axle bus) · Couch (Large bus designed for long distance travel)	· Motorcycle · Passenger car · Bus · Utility · Truck	· Gross weight · Number of axles · Number of unit · Number of tire · Type of vehicle

HDM-III (World Bank) (Bennett and Greenwood, 2003)	10	· Passenger car - small · Passenger car - medium · Passenger car - large · Utility · Heavy bus · Medium Truck - Petrol · Medium Truck - Diesel · Heavy truck – 2axle · Heavy truck – 3axle · Articulated truck	· Passenger car · Utility · Bus · Truck · Articulated truck	· Vehicle size · Type of fuel · Number of axles · Type of vehicle
MicroBENCOST (Canada) (MTBC, 2005)	4	· Small pass · Medium/Large pass · Pickup/Van · Bus	· Small vehicle · Medium/Large vehicle · Utility vehicle · Bus	· Vehicle size · Type of vehicle
Kobayashi *et al.*,2008 (Japan)	2	· Small car · Heavy car	· Small car · Heavy car	· Vehicle size
MLIT (2008) (Japan)	4	· Passenger car – normal vehicle · Passenger car - bus · Truck – small type · Truck – normal type	· Passenger car · Truck	· Vehicle size · Type of vehicle
ASFA (2008) (France)	4	· Light Vehicles · Intermediate vehicles · HGV (Heavy Goods Vehicle) or bus with two axles · HGV or bus with three or more axles · 5. Motorcycle	· Passenger car · HGV/Bus · Motorcycle	· Overall height · Gross vehicle weight · Number of axles · Type of vehicle

Table 6.60 Summary of representative vehicles applied in different studies

Country	MC	PC			LDV	LGV	LT	MT	HT	AT	LB	MB	HB	Types
		S	M	L										
Australia		X	X	X	X		X	X	X	X			X	9
Bangladesh		X			X			X					X	4
Barbados		X	X		X	X		X	X				X	7
Botswana		X			X	X		X	X	X	X		X	8
Burundi		X			X	X		X	X	X	X			7
Canada		X	X	X	X		X	X	X	X			X	9
Ethiopia		X			X	X		X	X	X	X		X	8
Guatemala			X		X				X	X		X	X	6
Hungary		X					X	X	X	X			X	6
India		X	X					X	X				X	5
Indonesia	X	X			X		X	X	X		X		X	8
Jordan				X				X					X	3
Lesotho		X			X			X	X		X	X	X	7
Malaysia		X					X	X	X	X			X	6
Myanmar		X			X		X	X	X		X		X	7
Nepal			X		X			X					X	4
Nigeria		X				X		X	X				X	5
New Zealand		X	X		X	X	X	X	X	X			X	9
P.R.China		X					X	X	X	X	X		X	7
PNG		X			X		X	X	X	X				6
Romania		X					X	X	X	X			X	6
Russia		X					X	X	X	X			X	5
Tanzania		X			X			X	X				X	5
Thailand		X					X	X	X		X		X	6
Trinidad		X			X		X	X	X		X	X		7
Uganda		X			X			X		X			X	5
South Africa		X			X			X	X				X	5
Sri Lanka	X	X			X		X	X	X	X		X	X	9

Source: (Revised) Bennett, 1995

The Table 6.59 and the Table 6.60 prove that every country or model is applying different number of representative vehicles, details, and even main factors used for definition. However, we can find the general standards for the vehicle classification as follows;

- Vehicle shape and size
- Number of unit (Single or articulated)
- Number of axles
- Number of tires
- Vehicle class (Passenger car, bus, and truck)
- Gross weight

Above contents could be main factors for vehicle classification in PMS.

6.10.2 Definition of Representative Vehicles

Even though some countries or researches have applied a lot of types, the road agencies do not have to follow the standard as it is. It is much important to consider characteristics of vehicle composition of each country. For a simple example, around 80~90% of road traffic are occupied by motorcycle in Vietnam. Properly, a vehicle type should be allocated for it. If a country has various trucks, it is required to subdivide classification for trucks.

Since it is difficult to model all kinds of vehicle types on the road, the vehicles should be resort as representative vehicles for calculating vehicle operating costs and estimating pavement deterioration forecast. The characteristic of representative vehicles covers all vehicles within a certain class. The key questions related to vehicle type and class can be summarized as follows,

- There are dozens of vehicle type on the road. How many representative vehicles are reasonable?
- In a same vehicle type, there are also many kinds of vehicles having different characteristic. How to define property of the vehicle type?
- What kinds of property data are required for each vehicle?

About the possible approaches used in describing representative vehicles, there are two approaches. The first one is to develop a "composite" vehicle. This is a hypothetical vehicle whose characteristics are representative of all vehicles in a given class. The second approach is to select an actual vehicle as the representative vehicle. There are advantages and disadvantages to each approach. While the composite vehicle approach yields a vehicle whose characteristics are representative of the entire fleet, it relies upon having detailed data available for all vehicle characteristics which, in practice, are difficult to obtain. Even though the characteristics of an actual vehicle may not be completely representative for the entire class, it is generally much easier to obtain these data. In practice, most analysts adopt vehicle characteristics based on individual vehicles (Bennett, 1995).

After definition of vehicle types, detail characteristics of the vehicle should be defined. This could be divided into physical characteristics and LCC related unit costs. In the pavement field, vehicle load characteristic characterized by the ESALF makes significant effects to deterioration process. It links to load level that determines pavement deterioration speed. In case of the unit costs, it changes LCC scale. Minimum property data of vehicle fleet for pavement management field (including pavement deterioration model and life cycle cost analysis) are suggested as follows;

About physical characteristic of vehicle,

- ESALF (Equivalent Single Axle Load Factor) - essential
- Number of tires, axles, units and gross weight - optional
- PCSE (Passenger Car Space Equivalent) - optional

For life cycle cost analysis,

- Fuel types and the unit cost
- Tire, car, oil price
- Average number of passengers by vehicle types
- Time value by vehicle types
- Etc. (Additional information by definition of the LCC contents)

Note that level of demand of the vehicle fleet information is depended upon the approach of life cycle cost analysis. For example, the mechanistic approach requires rich data representing each vehicle type. On the other hand, the empirical approach usually requires several key data, just vehicle volume and unit cost. Hence, road agencies have to consider the requirement of their application way.

One of important issue is whether the motorcycle is included into the classification or not. The motorcycle is a significant component of the total vehicle fleet in many developing countries, especially in East-south Asia. In some countries, it is impossible to explain traffic flow without consideration of the motorcycle. In fact, the effect from the motorcycle could be neglected to pavement deterioration modeling. In brief, it does not affect to agency cost. However, it has huge effects to road user cost. Since most of PMS models do not consider the motorbike in the classification (see the Table 6.58 and Table 6.59), the countries who are in such traffic condition may have to develop customized PMS model.

In case of the Hybrid PMS, the definition by the HDM-4 model was referred as default classification. Of course, it was essential for supporting HDM-4 model as a strategy of the Hybrid PMS. Except for the reason, the definition serves very subdivided and flexible classification so that the user can reorganize their classification by referring the standards. In addition, the definition gives very detailed vehicle property data including 160 factors developed by many research projects. It is recommended to follow the standard by finding most similar vehicle types which have most similar properties. Of course, most important factors listed in previous paragraph should be calibrated (or domesticated). In brief summary of this chapter, this paper suggest reorganizing current vehicle fleet by referring HDM-4 classification with calibration procedure of core factors related with load characteristic and their LCC approach.

6.11 Summary and Recommendations

This chapter addressed details of Life Cycle Cost Analysis (LCCA) which is a principle of economic analysis to PMS. It can cover various research purposes occurred at finding overall economic viability of a project (or alternative), and optimizing the project in economic viewpoints. The results of the LCCA are usually applied for examination and improvement current management policy (not for practical maintenance work directly). Although the LCCA model could be an option to PMS development, it is a core element to advance management efficiency of road agency. This paper strongly advocates settling LCCA model into the PMS.

To develop rich and flexible LCCA model to appease road agencies as much as possible, this paper has focused following customization points not only for development but also application;

- Definition of LCC contents
- Modulation of sub-models
- Simplification of estimation method
- Flexible application way for various purpose
- Reflecting road investment level

A key point in LCCA modeling was definition of LCC contents. There are many LCC contents which are affected by road investment level embodied by maintenance alternative. Application all the contents may be not for everyone because it demands many kinds of data and sophisticate estimation model. In the reality, the definition of LCC contents can be classified into two cases whether considering only agency cost or extending the scope to road users and socio-environmental cost. By the definition, the LCCA modeling becomes totally different. The Hybrid PMS needs to adopt the later to satisfy demands in most cases because it is a basic philosophy of this paper. Although the Hybrid PMS includes many LCC contents, it must serve customization points to be applied in any situation. Someone think that it would be a very complex and huge model which is difficult (or impossible) to apply for their system. However, the problem can be solved by the plug-in system based on encapsulation strategy. In brief, road agencies can select required LCC contents based on definition of their LCC definition and data condition. Definition of LCC estimation models is not simple task because variety of estimation models in terms of approach, theory, property of result, and data requirement is very huge. This paper has tried to adopt most general and sensible approach, but also to simplify or to apply assumptions for cases that have advantages in estimation way but have sophisticate structure. This is very important strategy in modeling since the level data requirement is nuclear in viability of application. Lastly, the Hybrid PMS should consider practical application of road agencies. It could be differently applied by implementation scheme of road agencies. Full application is available, also it allows partial application as necessary. This is possible because modulation strategy of each LCC estimation function turns into separation and combination of the LCC contents. In brief, an extracted individual function can be used as independent analysis modules that helps user's current PMS model without any system modification.

Under the basic strategy, LCCA model in the Hybrid PMS has following sub-models under annual basis deterministic approach;

- Inspection cost
- Maintenance cost
- Fuel cost
- Tire cost
- Engine oil cost
- Vehicle maintenance cost
- Vehicle depreciation cost
- Travel time costs
- Road safety costs (accident cost)
- Emission costs (7 types of compound)
- Network condition analysis
- Cost streams analysis
- Economic analysis by decision criteria
- Traffic volume generation
- Vehicle speed estimation model

Most parts of this chapter dedicated for descriptions of development procedure. It is difficult to summarize in short. Even though, this paper tried to follow general approaches, and to simplify estimation methods, it is expected that application of each agency may be encountered many problems because application of the LCCA model in the Hybrid PMS demands comprehensive understanding on overall structure from the pavement deterioration model to every detail of LCC estimation method.

Perhaps, self-development of every individual model would be very difficult task. Also application of full LCC contents is not simple issue because it demands calibrations of the model coefficient. It is expected that the partial application would be mainstream of usage of the LCCA model. Of course, reliable application with customization and calibration procedure is recommended. However, it is believed that road agencies can use the default models which demand very general data in PMS. In such case, the detail value and costs would be meaningless, but it could be useful in prioritizing alternatives to find best alternative, or comparison with analysis results from other LCCA models.

This chapter could be considered as criteria for programming phase in LCCA. This is much important meaning of this chapter than showing detail of the LCCA model.

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CHAPTER 7

Empirical Applications of Hybrid PMS to Heterogeneous PMS Situations

7. 1 General Introduction

Since the Hybrid PMS is a total system that has rich function and system component, it can be applied for various PMS analyses. In addition, it can produce very detail results at every analysis sequence. In fact, it is difficult to show all of details of the applications and their detail in a paper. For that reason, this chapter will focus following contents;

- Customization points in application
- Establishment of PMS development plans
- Typical application of Hybrid PMS in LCCA

As general information, this chapter started with issues on customization points in terms of system, function, and programming. This information may be useful when road agencies check their situation and establish their future development plan.

For case studies on establishing development plan, Korea, Japan and Vietnam which have different PMS history, current PMS environments, and desire level of PMS capabilities have been selected. The customization schemes of the pilot countries are established by experiences and data resources from their countries. Of course, real-application by collaboration with each road agency is the best way. However, it takes time to draw well-grounded blueprint because it should consider so many internal and external factors linked with their PMS.

In case of the typical application of the Hybrid PMS, this paper applied a typical LCCA procedure composed by pavement deterioration forecasting, performance analysis under current management policy, cost estimation, and economic analysis. It was divided two cases by different type of deterioration models (deterministic and stochastic model). As a data resource, a part of Vietnamese data in 2004 and artificial data from database of the Hybrid PMS were applied. Note that the two cases cannot be compared since they applied different data, procedure and standard.

7. 2 Customization (Application) Points

To establish customization scheme, the first procedure should be having a clear grasp of the characteristics of each country's PMS, and defining desire level of their PMS. Road agencies must have sufficient time for this procedure because it is very difficult to change PMS structure once it is established. The paper classified the points into 3 categories; system level, functional level, and programming level

7.2.1 Considerations in System Level

This is considerations for system level that determine overall structure and components. In this level, road agencies have to think about the roles of PMS in current and future. The roles of PMS can be divided into three categories as follows;

- ***Data management*:** data collection and accumulation, error processing, statistic, and so on
- ***Management of PMS cycle*:** maintenance and inspection scheduling, maintenance design, budget estimation for a PMS cycle, and reporting

- ***PMS analysis***: Long-term pavement performance analysis, economic analysis (*i.e.* LCCA), budget optimizations, accounting and so on.

Based on the above contents, user can define current and desired level of management efficiency by referring the standard suggested by this paper (see the Chapter 2). From the differences between current and desired PMS, user could realize what should be additionally considered. Afterward, feasibilities of their implementation or improvement strategy for the desire level have to be checked in terms of data conditions, system components, and budget requirement. Finally, application way of the Hybrid PMS (full introduction, partial application, or as external model) also should be determined. If road agencies demands special functions which is not included in the general version of the Hybrid PMS, it should be developed for themselves.

7.2.2 Considerations in Functional Level

From the system level, users may roughly draw overall system framework of desired PMS. In the functional level, much detail things about the each function should be determined.

- ***Details of system components:*** Definition of physical components which realize the PMS functions
- ***Details of each functions*****:** Definition of the methodology of each sub-model
- ***Data requirement:*** Useless data, additionally required data based on the definition of the functions
- ***Heterogeneous factors:*** Special demands for their heterogeneous situations. For example, application of specific PMS analysis tool (HDM-4), and climate factors in Vietnam must be included into their consideration.

By different viewpoints,

- ***Data requirement*****:** Supporting entire PMS models defined by customization schemes. For the definition, pre-defined data sets by PMS capability levels can be applied by customization. In addition, definition of each data contents should be checked.
- ***Database system*****:** Type of database system (*e.g.* text-based, or visualized). Kinds of database function (*e.g.* supporting ready-made software now in use) should be defined.
- ***Management Cycle*****:** Adding useful procedures or simplifying useless procedures by referring suggested PMS cycle of the Hybrid PMS (see the Figure 5.1 and Table 5.1)
- ***Forecasting model*****:** Type of deterioration models considering actual usages and their data condition (*e.g.* stochastic or deterministic)
- ***Economic analysis*****:** Definition of scope of LCCA, economic indicators, and optimization procedures

7.2.3 Considerations in Programming Level

In programming level, road agencies have to check adoptability of the Hybrid PMS for their desired PMS in detail. In this level, all of definitions, estimation methods, even user interfaces can be customized based on definition of desired PMS and actual users' taste. However, it is recommended to keeping the definition of data properties (*e.g.* unit, deterioration indices), and input & output of each sub-model in the Hybrid PMS for compatibilities with others' PMSs.

7.3 Establishment of PMS Development Plans

This chapter presents simple case studies on establishing PMS development plans at the system level. Selected pilot countries Korea, Japan and Vietnam have different PMS histories (past), current PMS situations (present), and desired levels of PMS capability (future). The development schemes in this paper have been subjectively established by field experience, information on current situations, and data conditions from each country. However, the cases presented in this paper cannot be considered representative of each country.

7.3.1 Brief Descriptions of Pilot Countries

7.3.1.1 Korean PMS (National Highway: KICT)

Korea is a semi-developed country in Asia. The gross area is relatively or absolutely small, but they have good enough road network. Now, Korean government is operating PMSs for national highway, expressway and airport runway. However, the PMS are not well distributed to local governments. Among the PMSs, the national highway which is managed by KICT (Korea Institute of Construction Technology) is determined as a main object. (Recently, the expressway was transferred to the semi-private sector). Recently, Korean government has been recognized the importance of public asset management. They are very keen to improve cost-effectiveness of their limited budget by advanced management strategy.

Their first step for PMS has been started since 1986. At the first time, they have been relied on foreign technology imported from France. In 1997, inspection car (ARAN) was imported to automate inspection works, and to improve reliability of inspection data. However, they did not have any economic analysis process until 2000. For 15 years, they just had maintaining their road sections by the “worst-first” concept with “expert system” under budget limitation. Their first trial for economic analysis was introducing ready-made software, the HDM-4. They have invested enormous efforts for reliable application. Nevertheless, it did not take so much time to realize limitations of HDM-4 in terms of practical application, but also reliability of the HDM-4 model as itself. Now they are applying a part of HDM-4 model only for prioritizing maintenance works. Recently, they are very keen to improve their PMS structure, such as development of GIS-based integrated database, advanced inspection car and economic analysis tools. Their current PMS capability level is in a transition period from the “General level” to the “Recommended level”.

Most of PMS activities have systemically been progressed by self-developed standards and procedures, even though they do not have pavement deterioration forecasting model and LCCA procedures. Their consideration is toward only for operation of the PMS cycle with database. The Korean PMS could be classified as the typical *“Stage C: Database dependent level”* One of special things is they are now applying a ready-made software for prioritizing maintenance works. But their database does not have data extract functions supporting their external model or internal PMS activities. This will be a customization point in functional level. Their application scheme was as assumed as “As external models” for introducing LCCA procedures with some minor modifications of their current PMS (*e.g.* an additional function for supporting HDM-4, data error processing).

7.3.1.2 Vietnamese PMS (National Highway: VRA)

Vietnam, a developing country in Southeast Asia, so far has no expressway (under construction). Therefore, the national highway plays an important role in road transportation. Recently, demands of road infrastructures are expanded in fast speed along with high level of economic growth, So far, condition of road infrastructures in Vietnam is not enough to cover domestic demands. For that reason, interest of Vietnamese government is toward expanding road network than maintenance activities. However, they recently start to have interests in PMS.

PMS in Vietnam has a relatively short history, having been used only since 2001. During the past 10 years, the HDM-4 model has been applied with road inspections—in 2001, 2004 and 2007. Since the HDM-4 application was legalized several years ago, PMS has been focused exclusively on the use of this model. In fact, Vietnamese PMS is in chaos due to the inadequate implementation of ready-made software. In a strict sense, the Vietnamese system, which mandates only data collection and the application of HDM-4 for budget estimation, is somewhat removed from true PMS. HDM-4 is an analytical tool only for LCCA, not for practical pavement management, which requires database and PMS cycle management functions. In reality, maintenance work in Vietnam has been progressing only relative to the expert systems employed by individual local PMS managers. Even though Vietnamese PMS has a wide range of data contents to support HDM-4 application, data resources are not well applied to practical pavement management. Worst of all, the inspection data from 2001, 2004 and 2007 cannot be linked as a time-series dataset. Although they have rich data contents their data level cannot be considered as “Advanced level”. Vietnam’s is a typical story of failure caused by the lack of a sustainable PMS development strategy, and officials must now return to the first step of drawing up a blueprint for the future. Above all, road agencies have to change their mind that the HDM-4 and RoSy SYSTEMs are external models which is not internal models as it is.

By the brief reviews, current Vietnamese PMS capabilities could be classified as the *“Stage B: Expert system dependent level-B”* which has only incomplete or limited data. Their desire level was assumed to “Recommended level” which is considered as a most cost-effective alternative. Because, Vietnamese PMS is in a beginning stage, the application way was assumed to the “Full application”.

7.3.1.3 Japanese PMS (Local Roads: Mie Prefecture)

Japan is a developed country with adequate road and railway networks, and with a self-governing system where many different PMS models are used by individual administrative units. It is therefore difficult to identify a general PMS model representative of Japan. However, one Japanese trend is to pursue simplicity, effectiveness, and self-development. As a typical model, this paper has selected a PMS used in Mie prefecture. The number of data contents was less than for the other two countries, but the PMS capacity level was higher. It was available under a self-development strategy conducive to “Tailor made-sized” models. However, such a domesticated or customized system has the weakness that it is often not compatible with the systems of other countries. For example, the Japanese system has domestic standards not matched with international trends, such as the use of the MCI (Maintenance Control Index (PWRI, 1981)) as the representative pavement condition index (Kobayashi *et al.,* 2008). Though such country-specific standards work well for pavement management within Japan, it is necessary to follow international trends in PMS sectors for compatibility with other PMS models.

The desired level of Japan has been assumed as the feedback/improvement level based on modeling level-A, as there are already self-developed models satisfying PMS conditions and objectives in Japan. For system improvement, tasks include the redefinition of data contents and the elaboration of current pavement deterioration forecasting models from the deterministic to the stochastic type. As special considerations, enhancing geometric information and linking with bridge and tunnel management systems are recommended because most road sections in Mie prefecture are in mountainous regions with many bridges and tunnels.

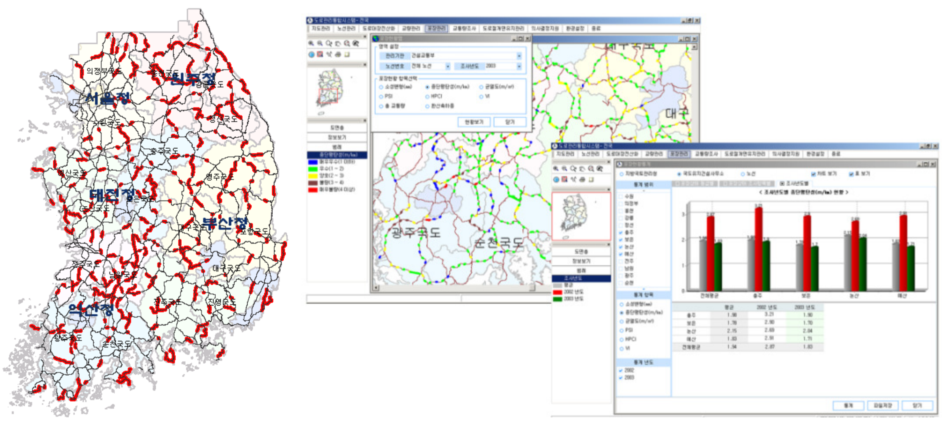


Figure 7.1 Visualized database system of Korean PMS

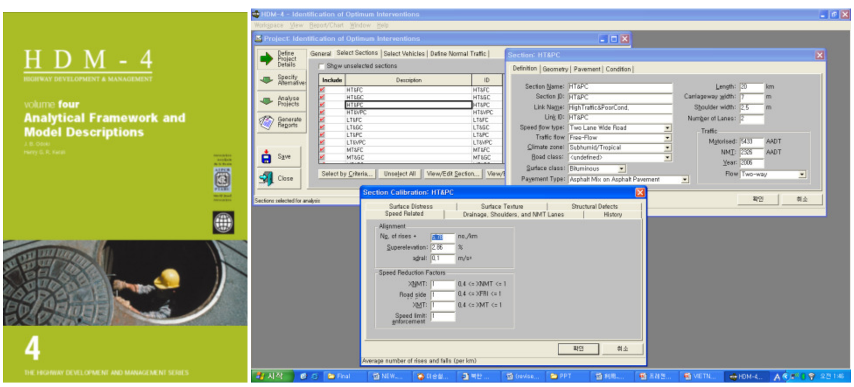


Figure 7.2 A manual and interface of the HDM-4 applied for Vietnamese PMS

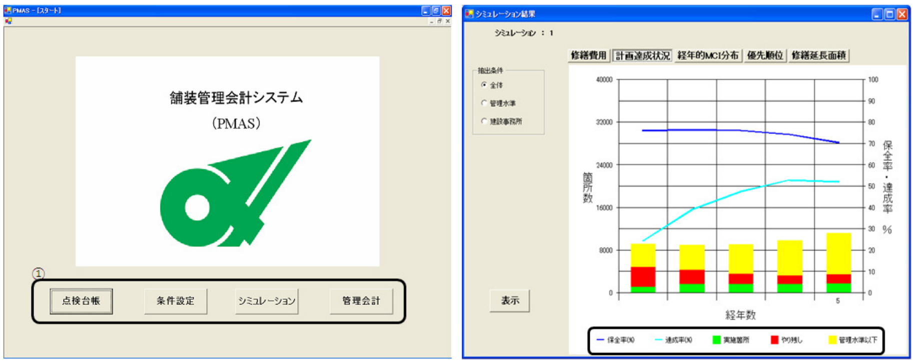


Figure 7.3 Interface of Pavement Management Accounting System (PMAS) of Mie prefecture

7.3.2 Establishment of Customization Schemes

Based on reviews in the Chapter 7.3.1, the current PMS situations and improvement plans of the three countries are simply summarized in Table 7.1.

Table 7.1 A brief summary of the PMS development (improvement) plans of Korea, Vietnam and Japan

Contents		Korea	Vietnam	Japan
Manager		KICT[1]	VRA[2]	Mie prefecture
Management objects		National Highway	National Highway	Local roads
Network Level		National network	National network	Regional network
Main issue		Management	Construction	Management
Current PMS condition	Data condition	Recommended level	Advanced level but minimum level (due to incompleteness of data)	Recommended level
	Database	Visualized database	Text-based database (By RoSy Base)	Text-based database
	PMS cycle	Self-defined cycle	Expert systems by local managers	Self-defined cycle
	Pavement deterioration model	N/A	Mechanistic-Empirical model (Un-calibrated HDM-4) (Odoki and Karali, 2000)	Simple regression
	Life cycle cost analysis	N/A, but partial application of HDM-4 for prioritization of maintenance works	Partial application of HDM-4 for estimating agency cost for every fiscal year	Road agency cost, simplified road user cost (VOC + travel time cost)
	Budget optimization	N/A	N/A	Accounting function
	Components of internal PMS	Database + Excel-based programs	RoSy Systems and HDM-4	PMAS(Kobayashi *et al.*,2008)
	External models	HDM-4 (PIARC, 2000), and RealCOST (FHWA, 1995)		N/A
Evaluation of current PMS capability level		Stage C: Database dependent level	Stage B: Expert system dependent level	Stage D: Modeling level – A
Desired PMS capability level		Stage E: Modeling level – B	First step = Stage C: Database dependent level Final = Stage D: Modeling level A	Stage F: Feedback / Improvement level
Main tasks for improvement		Introduction of advanced LCCA into current PMS	(For first step) Establishment of overall PMS development plan	･Revising data contents ･Elaboration of the current deterioration model
Sub-tasks for current PMS		･Development of LCC model ･Revising data contents ･Redesign of database function	･Self-evaluation of their PMS ･Fixing long-term development plan ･Definition of data requirement ･Rehabilitation of current PMS data ･Development of database	･Redefinition of data by international standard ･Adding (or changing) deterioration forecasting model by stochastic type
Special considerations		･Adding data extraction functions for HDM-4 and LCCA application into current database ･Linking with traffic monitoring system	･Integrating the other road facilities (*e.g.* guardrail, manholes, speed poles etc.) ･Enhancing data tables with information on climate factors and drainage systems	･Enhancing geometric information into current data ･Link with bridge and tunnel management system

Note: 1) KICT (Korea Institute of Construction Technology)
2) VRA (Vietnam Road Administration)

This paper has evaluated the current PMS capability level of each country at the database dependent level (Korea), the expert system dependent level-B (Vietnam), and modeling level-A (Japan) respectively. As the desired PMS capability level, modeling level-B has been designated for the Korean PMS because national guidelines (MLTM, 2009) require the inclusion of a wide range of LCC contents. In the case of Vietnam, modeling level-A was assumed as the desired level. To reach this level, Vietnamese PMS should rehabilitate the overall structure and review every detail from the beginning. However, the Vietnamese capability level cannot jump to the desired level instantaneously but should go through stage C until enough pavement inventory data is accumulated. Integrating other road infrastructure into one system is strongly recommended, since the VRA has the duty of managing all road facilities simultaneously. In addition, it is recommended that as a special consideration, data tables be enhanced with information on climate factors and drainage systems because Vietnam is a vertically long country with varying climate conditions. The desired level of Japan has been assumed as the feedback/improvement level based on Modeling level-A, as there are already self-developed models satisfying PMS conditions and objectives in Japan. For system improvement, tasks include the redefinition of data contents and the elaboration of current pavement deterioration forecasting models from the deterministic to the stochastic type. As special considerations, enhancing geometric information and linking with bridge and tunnel management systems are recommended because most road sections in Mie prefecture are in mountainous regions with many bridges and tunnels.

Perhaps anyone can easily devise a basic PMS development plan by considering the current and desired level of PMS. However, development plans would be imperfect and meaningless unless they take into account the heterogeneous situations of individual road agencies. Ready-made software cannot incorporate such important factors into the system. For this reason, self-development is essential for sustainable PMS development.

7. 4 Demonstration of Typical Application of the Hybrid PMS

This chapter demonstrates typical LCCA procedures by using the Hybrid PMS As analysis targets, a part of Vietnamese data in 2004, and artificial data from the database of the Hybrid PMS have been used. Difference of two applications was only type of deterioration model which results different type of forecasting result. Note that this is just a simple trial to show application way of suggested models with many assumptions. Thus, the result cannot represent any country or any case. This chapter will give condensed explanations due to level of description.

7.4.1 Application Procedures

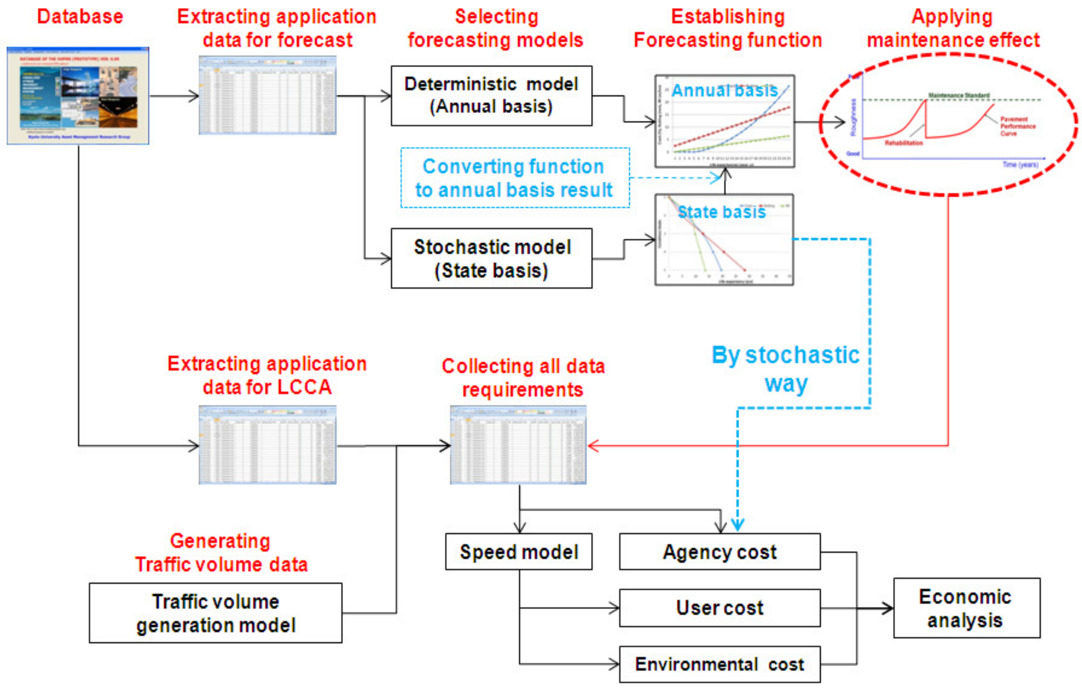
The application of LCCA model demands somewhat complex procedure. In fact, LCCA in pavement fields requires wide knowledge on pavement engineering, economics, mathematics, statistics, and even field experiences. Based on knowledge level of users, the level of application could be differed.

The application procedures can be simply divided into two phases; 1) pavement deterioration forecasting and 2) LCCA. Based on the application scheme, users should extract required data from the database corresponding with application scope. For the forecasting phase, users have to follow these procedures;

- Selecting forecasting model(s)
- Extracting data for selected deterioration forecasting from the database
- Establishing forecasting functions (Crack, rutting, IRI)
- Applying maintenance standard (effects)

In case of the LCCA procedure;

- Defining LCC contents and detail simulation options for LCCA
- Extracting data for LCCA from the database
- Generating traffic volume data
- Receiving pavement deterioration process from the deterioration forecasting results
- Estimating each LCC contents
- Applying the results for economic analysis



Note: duplicated with Figure 6.21

Figure 7.4 Application procedures for life cycle cost analysis in the Hybrid PMS

As shown in the Figure 7.4, the LCCA of the Hybrid PMS is impossible without (annual basis) pavement deterioration forecasting result. The stochastic models that result state-based result can estimate only road agency cost in the Hybrid PMS, Thus, if a user want to apply the stochastic results to full LCCA model, an additional function converting state basis result into annual basis result should be applied.

7.4.2 Simulation Planning

Simulations for demonstration have been conducted by two ways to show main deference caused by application of a type of deterioration forecasting models. In addition, the target sections were also different. That is, the result cannot be compared. The simulation planning and detail options are summarized in the Table 7.2 and Table 7.3.

Table 7.2 Summary of simulation schemes

Contents	Case study A : Actual data by stochastic model	Case study B : Artificial data by deterministic model
Target sections	50 sections : from Vietnamese pavement data in 2004	50 sections : from artificially generated data from the database of the Hybrid PMS
Simulation purpose	Finding better maintenance timing	Finding better maintenance timing
Forecasting model	Markov hazard model (with result converting function)	Multiple and simple regression
Application standard	Referring Korean standards (with many assumptions)	Referring Korean standards (with many assumptions)
Main results	・Scale of each LCC contents ・Basic economic analysis ・Comparison of alternatives ・Averaged network condition	・Scale of each LCC contents ・Basic economic analysis ・Comparison of alternatives ・Averaged network condition

Table 7.3 Description of simulation options

Classification	Contents	Description	For trials
General	Simulation scope	Kinds of results from the simulation model	Full LCC contents & economic analysis
	Analysis period	Usually 20-40 years or more	40 year
	Grouping strategy	Grouping road sections having similar properties (*e.g. regional classification, road class, vehicle load, pavement material etc.*)	For case – A:No classification (*Randomly extracted*) For case – B:Regional classification
	Target sections	Number of sections Kinds of sections	・ 2,200 sections for deterioration model ・ 50 sections for LCCA
Forecasting model	Type of forecasting model	Deterministic or stochastic model	Case A: Simple or multiple regression Case B: Markov hazard model
	Explanatory variable	The most significant variables affecting to deterioration speed	Traffic load, pavement strength, and surface material
Vehicle info.	Definition of the representative vehicles	Vehicle classification for composing AADT (*Recommended to following national standard, then re-organize, if necessary*)	7 types (referring KICT definition)
	Characteristic of the representative vehicles	Properties information of each vehicle, especially in traffic load, unit costs for LCC contents	Following KICT definitions
Traffic volume info.	Generation of future traffic volume	Definition of AADT during analysis period	Mixed truncated normal distribution model (referring Korea national highway data)
	Vehicle composition rate	Composition ratio of the AADT	Referring Korea national highway data
LCCA	LCC contents	Agency cost, road user cost, socio-environmental cost (*Based upon user's objectives, and data requirement*)	All contents in the Hybrid PMS
	Estimation method and options	Estimation models of each LCC contents, and detail options for applications	Defaults of the Hybrid PMS
Alternatives (Maintenance activities and effects)	Maintenance methods	Define the kinds of maintenance work for composing simulation alternative *(e.g. reconstruction, cutting overlay, overlay, surface treatment)*	・ Crack seal and patching ・ Overlay 50mm ・ Reconstruction
	Maintenance timing	Define the maintenance timing for composing simulation alternative *(e.g. Overlay 50mm = rutting 25mm or IRI 4.0m/km, Overlay 100mm= rutting 25mm or IRI 4.0m/km, with Traffic load > MESAL 1.0)*	3 alternatives; ・ Preventive type ・ Typical type ・ Retarded type
	Maintenance effect	Definition of condition recovery by maintenance types (User-specified condition or derived condition by maintenance effect model)	User-specified; Crack=0%, Rutting=5mm, IRI=1.5m/km
Economic analysis	Economic indices	Economic decision criteria for decision making	NPV, NPV/Cost, IRR, and EUAC
	Interest	Standard of interest for road investment	5.5% (Korean standard;MLTM,2009)
	Unit costs by maintenance types	Unit cost per square meter or kilometer based unit by maintenance type. Essential for calculation of agency cost.	Referring to Korean case *(KICT standard in 2005)*
	Unit costs of user costs	Unit cost of each LCC content. Essential for calculation of user cost (*fuel, time value, etc.*)	Referring MLTM definitions (MLTM, 2009)
	Unit cost of socio-environmental effect	Unit cost of each emission type, (sometimes) safety cost	Referring MLTM definitions (MLTM, 2009)
	Currency	Base currency of simulation. Default is USD but this can be converted into vernacular unit.	KRW 1,192/USD (at 09.01,2010)

Note: For application of the stochastic model, it is recommended to apply more than 1.000 samples.
2,200 sections are applied for establishing forecasting function in this simulation

The Table 7.3 is describing many simulations options by categories. However, contents may be more than the contents. For the trials, mostly Korean standard (KICT) were mainly applied because the guidebook published by government relatively is relatively well defining detail options (*e.g.* interest rate, unit costs). Of course, some contents were defined by this paper from experiences on many LCCA simulations.

7.4.3 Details of Simulations

7.4.3.1 Characteristics of Target Sections

Table 7.4 Characteristics of target sections (case: from artificial data for case study B)

Network	Num. of extracted sections	Climate	Road type	Unit length	Number of lane	Traffic load level	Material	Speed limit (km/h)	Construction year (Elapse time)
East	10	Sub-tropical cool	5 types[1)]	Random; 0.07~ 4.84km AVG: 2.5km	4	High	HMA[2)]	80	2000 (1year)
West	10	Temperate freeze	5 types		4	Middle	HMA	80	2000 (1year)
South	10	Tropical	5 types		4	High	HMA	80	2000 (1year)
North	10	Sub-tropical cool	5 types		4	Low	HMA	80	2000 (1year)
Highway	10	Sub-tropical cool	Normal	Random; 7.37~23.23 AVG: 13.01km	8	Middle	HMA	100	2000 (1year)

Note: 1)5 road types: normal, bridge, tunnel, uphill and downhill
2) HMA: Hot Mixed Asphalt

Since the Vietnamese data was randomly extracted from the data table, there was no grouping rule. On the contrary, the artificial data was extracted from the five networks having different properties on climate, road class and traffic load. Based on the grouping strategy, much meaningful analysis is available. Since the artificial data has been designed to have different deterioration speed by level of those explanatory variables, each network may have different characteristic on LCCA results. Such strategies on PMS analysis are very important. The Table 7.4 introduces a brief summary of the extracted sections from the artificial database.

7.4.3.2 Traffic Related Information

Most vehicle related information was referred from Korea national highway standard and TMS data (in 2005). Main contents are definition of vehicle type and traffic volume during analysis period.

A. Definition of vehicle type and properties

In case of Korea, there were different types of vehicle classification by organizations or institutes. The difference, in most case, is caused by different demand. For example, a highway company is collecting traffic volume data by 11 types for toll-pricing. While the national highway, 12 types are now used for official standard for ITS (intelligent Transport System) by TMS (Traffic Monitoring System). On the other hands, the PMS is applying simplified 7 types by converting 12 types from the TMS. The main information of the 7 types are summarizing in the Table 7.5. Among the information, ESALF and unit costs are most important data in PMS.

Table 7.5 Vehicle classification by physical and operational properties (Partial information)

Vehicle type	HDM-4 type	Vehicle class	Description	PCSE	Num. of wheels	Num. of axles	Operating weight	ESALF
Car	1	1	Small passenger cars	1.00	4	2	1.06	0.00
Light Bus	12	4	Light bus *(approximately < 3.5 tons)*	1.40	4	2	2.50	0.04
Heavy Bus	14	4	Multi-axle or large two-axle bus	1.60	10	3	10.00	0.80
Light Truck	7	3	Small two-axle rigid truck *(approx. < 3.5 tons)*	1.30	4	2	2.70	0.12
Medium Truck	8	3	Medium two-axle rigid truck *(> 3.5 tons)*	1.40	6	2	7.50	1.25
Heavy Truck	9	3	Multi-axle rigid truck	1.60	10	3	13.00	2.88
Trailer	10	3	Articulated truck or truck with drawbar trailer	1.80	18	5	28.00	4.63

Resource: Unofficial data resource used for HDM-4 application by KICT (Korea Institute of Construction Technology) in 2005

B. Traffic volume generation

Traffic volume generation will be following the mixed truncated normal distribution (see Chapter 6.9.2). The method demands several standards and data characteristic information. For the information, this paper has referred data in Korea national highway. The information presented in the Table 7.6.

As shown in the Table 7.6, 5 types of normal distribution were applied for data generation by traffic volume level. Properly, the histogram of total frequency distribution does not follow normal distribution. To check increment trends, both standards of the starting point $AADT_{i-1}^{s}$ and $AADT_{0}^{s}$ were applied (see Figure 7.5). By the trial, it was confirmed that it is necessary to apply multiple types of (normal) distribution to consider heterogeneity of traffic volume level. Besides, making boundary condition guarantees much stable data generation. The Figures 7.5 shows histograms of frequency distribution of traffic increment rate and estimated time series AADT data during analysis period by the cases applying $AADT_{i-1}^{s}$ and $AADT_{0}^{s}$.

As shown at the Figures 7.5 and Table 7.7, the two distributions obviously has different shape by the application way of V_{i-1}^{s}, V_{0}^{s}. However, it is difficult to determine which one is better because the traffic volume in every individual year is determined by a function of increment rate and V_{i-1}^{s} or V_{0}^{s}. It is needed to check AADT transition process during the analysis year. It is compared in the Figure 7.5.

Table 7.6 Information for traffic volume generation (for mixed truncated normal distribution method)

Group (l)	AADT Interval (standards of l)	Num. of sample	Average	Standard deviation	Confidence interval[1)]	
					Lower limit	Upper limit
1.Lowest	~5000	58	1.17	0.33	1.08	1.25
2.Low	~10000	56	1.00	0.19	0.95	1.05
3.Medium	~30000	146	1.10	0.21	1.07	1.14
4.High	~50000	66	1.01	0.14	0.97	1.04
5.Highest	50000~	12	0.98	0.11	0.91	0.94

Data resource: Extracted from unofficial data for HDM-4 application by KICT (Korea Institute of Construction Technology) in 2005
Note: 1) confidence level was 95%, that is, $Z_{a/2} = 1.96$

Table 7.7 Number of samples ranked in each traffic volume level l by V_{i-1}^{s} and V_{0}^{s}

AADT level groups (l)	V_{i-1}^{s}	V_{0}^{s}
1	8	40
2	684	360
3	120	709
4	1454	854
5	34	37
Summation (50 sec.×40 yrs)	2000	2000

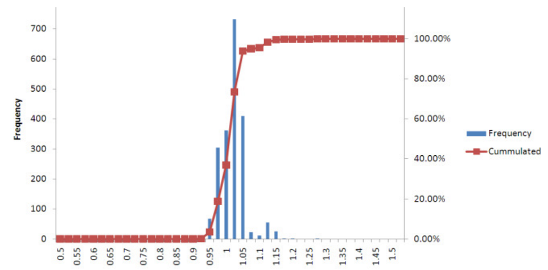


Figure 7.5a Frequency distribution by $AADT_{i-1}^{s}$

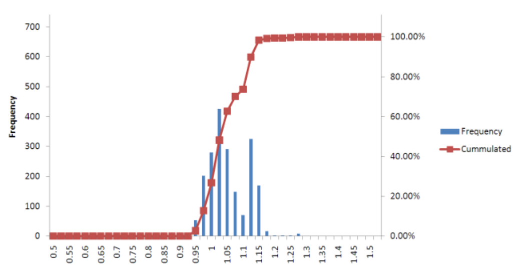


Figure 7.5b Frequency distribution by $AADT_{0}^{s}$

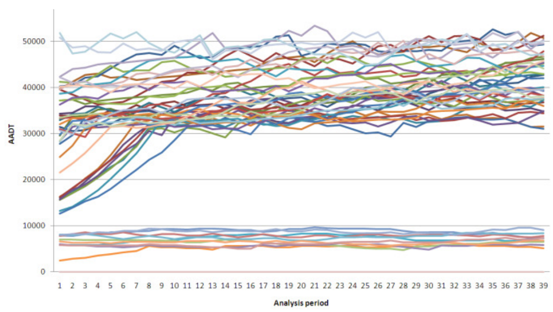


Figure 7.6a AADT trend by applying V_{i-1}^{s}

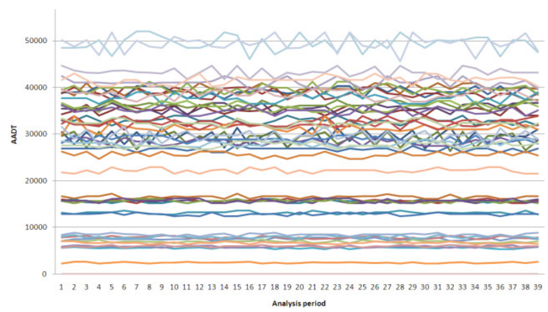


Figure 7.6b AADT trend by applying V_{0}^{s}

In the Figure 7.6a, it was confirmed that traffic volume level group 3 which applies V_{i3}^{s} makes high increment rate. It means that once estimated traffic volume are belonged to the group 3, the V_{i3}^{s} send the traffic volume level to the higher level which applies the V_{i4}^{s}. However, the other intervals $V_{i1\&2\&4\&5}^{s}$ have relatively stable conditions. It is expected that the traffic volume level group 3 (10,000~30,000) of the Korea national highway has higher average on traffic volume increment rate, lower and upper bound (see Table 7.6). Of course, the group 1 has much higher value. Nevertheless, it cannot make significant effects due to low AADT. In case of the V_{0}^{s} (see Figure 7.5b), we can see that each section is trying to keep their first year's AADT condition. This characteristic is understandable because the first year's AADT (measured value) is naturally determined by considering all kinds of basic characteristics of the road. That is, the AADT V_{0}^{s} may (or may not) be the most likely value. If the V_{i3}^{s} has a little bit stable value, two graphs in the Figure 7.6 may have similar trends. Theoretically, applying the V_{i-1}^{s} might be much reasonable. However, applying the V_{0}^{s} is better for practical viewpoint.

Applied method is a way based on statistical method that prevents making artificial increment or decrement trends by users. Maybe this characteristic is good for preventing fabrication of analysis result. On the other hands, it also has a weakness for flexibility. Sometimes user may want to control AADT level for research purposes. In this case, triangular-trapezoidal shape generation model is recommended.

7.4.3.3 Application of Pavement Deterioration Forecasting Model

A. Multiple regression

As pavement deterioration models, Markov hazard model for case study – A, and single & multiple regression model for case study – B were applied respectively. The multiple regression model was chosen as an example to find the most significant variables affecting deterioration process. Since the multiple regression model is a type of deterministic models that estimates spot condition considering user-specified independence variables, it is not suitable for time series estimation due to types of independence variable. To apply multiple regression for the time-series estimation, the independence variables should be time-dependent variable, such as elapsed time, cumulated traffic volume (or MESAL), etc. Also we should think about population to find unknown parameters (β_i) for formulating estimation function. Because the target of LCCA was just 50 sections, it could generate biased result due to shortage of sample scale. For the problems, all sections (2,200 sections) were applied for establishment of estimation function. The estimation function was assumed to represent the 50 sections. The purpose of this procedure is to establish estimation model of crack, rutting and IRI which are most usual deterioration indices in PMS. One more consideration is maintenance effects because the estimation models cannot consider maintenance effect. As noted in the Table 7.3, it applied user-specified reset condition instead of application of maintenance effect model for simplicity of explanation. An example of estimation results of IRI by the multiple regression model is summarized in the Table 7.18. Note that the results didn't follow typical methods to find the best variables set, such as forward selection, backward elimination or step wise regression.

The Tables 7.8 say that the selected variables, MESAL, SN and SURF_MARTL which characterize traffic load level, pavement strength and effect of advanced technology, were very significant for formulating the model. However, coefficients of determination (see the column shows "adjusted R-square" values), were relatively low (around 0.4) in statistical judgment. It is often cases in reality, while this implies that artificially generated pavement deterioration data is well reflecting reality.

To check deterioration characteristics, maintenance effect should be excluded from the simulation. With holding the SN and SURF_MATRL as constant based on the first year's condition (because there is no maintenance work that changes pavement strength and surface material), the generated traffic volume data explained in the Chapter 7.4.3.2 has been applied for determining annual accumulated traffic load, the MESAL. The estimation result is introduced in the Figure 7.7.

Dispersion of estimated deterioration speed was relatively huge. However, those characteristics are very usual in pavement deterioration. In subjective opinion, the deterioration speeds of artificially generated deterioration data were relatively slow. Even though somewhat higher typical maintenance criteria are applied (approximately crack 10%, rutting 20mm, IRI 3.0m/km), life expectancies until reaching the maintenance criteria were 39, 32, and 32 years respectively.

Table 7.8 Estimation function of IRI by multiple regression

Regression equation:	Y(IRI) = 1.34 + 0.17 MESAL -0.05 SN -0.03 SURF_MATRL				
Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F value	P-value
Regression	3.913526086	3	1.304508695	484.663078	4.1383E-242
Error	5.964537842	2216	0.002691578		
Total	9.878063928	2219			
R-sq	0.396183515		Determinant	0.973565922	
R-Sq(adj)	0.396183515		DW	1.587598577	
Parameter Estimates					
Predictor	Estimates	Std. Error	t value	P-value	VIFs
Constant	1.344465418	0.033326926	40.34171672	2.7233E-267	
MESAL	0.166025769	0.00481189	34.50323257	3.5845E-209	1.0001215
SN	-0.046908933	0.007022103	-6.680182528	3.00828E-11	1.027144602
SURF_MATRL	-0.034834345	0.002232579	-15.60273878	3.74314E-52	1.02702782

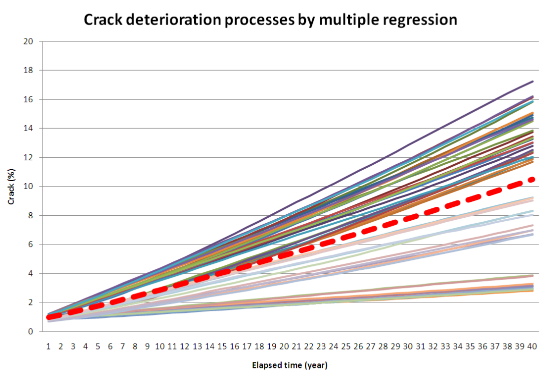


Figure 7.7a Estimation results of crack

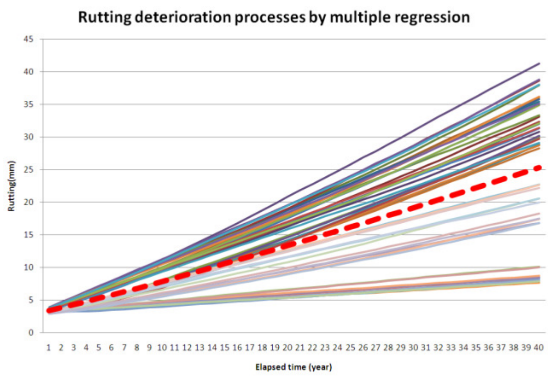


Figure 7.7b Estimation result of rutting

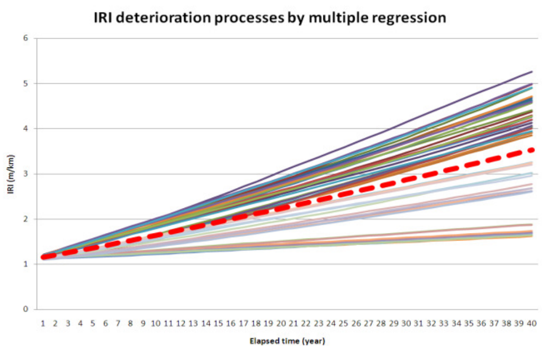


Figure 7.7c Estimation results of IRI

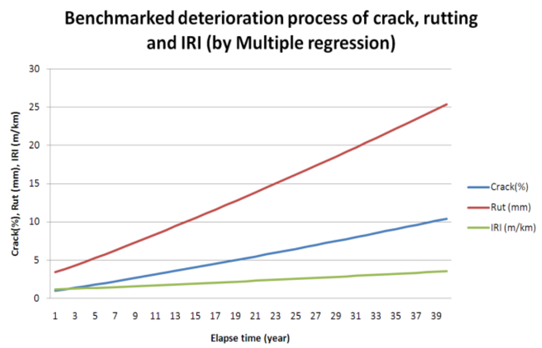


Figure 7.7d Benchmarked processes by indices

B. Pavement deterioration forecasting model – Markov exponential hazard model

The Markov hazard model has been applied to Vietnamese data in 2004. As typical results, estimation models of hazard rates θ_i^k by each user-specified condition states and explanatory variables, and Markov transition probabilities matrix can be resulted. By using the θ_i^k, life expectancies of each state can be calculated. The accumulated life expectancy becomes total duration to specific condition (usually maintenance criteria has often been applied). While the Markov transition probability can be used for budget estimation under probabilistic approach. For much easy and exact application, understanding theories on Markov chain, and hazard model is strongly recommended. It is explain in the Chapter 5.3.3. For application of the Markov hazard model, firstly, rating standard should be established. Applied standard for Vietnamese case are showing at the Table 7.9. The results are in the Table 7.10 and Figure 7.8.

Table 7.9 A rating standard for application of Markov hazard model

Rating	Crack (%)	Rutting (mm)	IRI (m/km)	Note
1	0	1	1.5	Reset condition
2	0.5	5	2.5	Moderate level
3	5	10	3	Preventive maintenance required
4	15	20	3.5	Overlay required
5	30	40	5	Reconstruction required

Table 7.10 Estimated life expectancies of each rating in year

State	Crack (Accumulated year)	Rutting (Accumulated year)	IRI (Accumulated year)
1 to 2	8.3135 (8.3135)	4.4617 (4.4617)	3.5769 (3.5769)
2 to 3	2.526 (10.8395)	8.8541 (13.3158)	0.9422 (4.5191)
3 to 4	1.6197 (12.4592)	5.3132 (18.629)	0.8182 (5.3373)
4 to 5	3.452 (15.9112)	8.7783 (27.4073)	1.8497 (7.187)

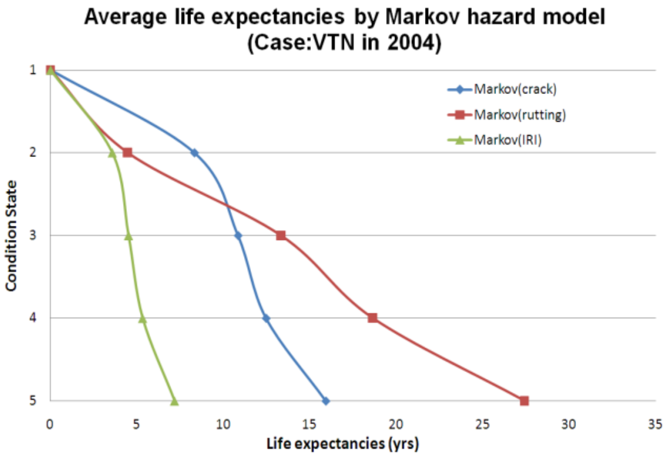
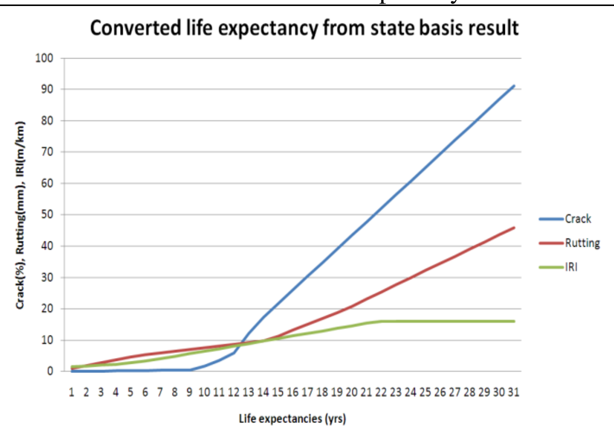


Figure 7.8 Average life expectancies of deterioration indices by Markov exponential hazard model (case: Vietnamese data in 2004)

Table 7.11 Estimated deterioration speed by localized linear regression converted from state basis result



Year	crack	rutting	IRI
0	0	1	1.5
1	0.0601	1.8965	1.7796
2	0.1203	2.7930	2.0591
3	0.1804	3.6896	2.3387
. . .	. . .	. . .	. . .
16	30.3859	15.0519	12.1468
17	34.7312	16.9341	12.9578
18	39.0765	18.8162	13.7687
19	43.4218	20.8453	14.5797
20	47.7671	23.1236	15.3906

Note: The maximum boundaries of each deterioration index were crack = 100%, rutting= 100mm and IRI=16m/km

As shown in the Table 7.10 and Figure 7.8, expression of life expectancies was based on user-specified rating standard. However, the Hybrid PMS demands year-basis result. It is able to be changed by localized linear regression method by each state suggested in the Chapter 5.4.1.2. Note that converted estimation function is not for the "life expectancy" any more, but this is a function for "deterioration speed" which extends limitation of forecasting pavement condition beyond the user specified standard of last rating. It implies that the estimation function of last state β_{J-1} is continued from C_{J-1}^{d} to the infinity (∞]. For that reason, it needs for another absorbing condition (*i.e.* maximum level of deterioration) for localized regression method. For the values, crack = 100%, rutting= 100mm and IRI=16m/km have been applied. The result from the state basis result to annual basis result is showing in the Table 7.11.

7.4.3.4 Estimation of Deterioration History and Maintenance Cost

A. Determination of deterioration history during analysis period

The explained pavement deterioration models were just for forecasting pavement condition without maintenance effect. The terms, "deterioration process" and "deterioration history", should be understood as different meaning. The deterioration history is determined by combination between deterioration process and maintenance alternative which characterized by maintenance method and timing (criteria). It is core procedure of life cycle cost analysis.

As a main deterioration model for case study B (using artificial data), this paper used the simple regression model instead of multiple regression because one of important independence variable, the elapsed time, it was left out of significant variables group due to poor fitness (*t-value* = 0.41, *P-value* =0.6794, *F-value* = 0.1738). Instead of the variables, accumulated traffic load which was revealed as the most significant explanatory variable was used as main explanatory variable. The results of simple regression for IRI estimation are summarized in the Table 7.12.

Note that the constants in the Table 7.12 should be substituted for the previous year's condition $C_{0\ or\ y-1}^{k}$ in dynamic way (here, k = deterioration indices). With the estimation function, maintenance alternatives should be defined. For this trial, three types of maintenance strategies were applied. The information is summarized in the Table 7.13.

The first and second alternative in the Table 7.13 have same maintenance methods, but their maintenance criteria is different. It is good for analysis on maintenance timing. On the contrary, the alternative III applied only reconstruction when the pavement condition is deteriorated beyond general level of maintenance criteria. By the combination of maintenance method and timing, road agencies can derive meaningful information for better maintenance strategy. Note that the maintenance criteria of each alternative have a little bit higher (or faster) standards in practical viewpoint. It is to cover characteristic that artificially generated target sections has slow deterioration speed.

With the alternative, there is one more consideration for drawing deterioration history. It is definition of the maintenance effects related with reset condition after the maintenance by each maintenance type. It was followed by specified conditions. The reset conditions shown at the Table 7.14 were assumed by field experiences in Korea. By the combination of the deterioration process, maintenance alternatives and recovery condition, deterioration history has been determined. As an example, the Figure 7.9 compares difference of deterioration histories of a section by alternative A (Preventive type) and B (General type).

The Figure 7.10 was from the case study B which is applying linear process. In case of the Markov hazard model which was re-organized by localized liner regression models for Vietnamese case, each deterioration index has different deterioration curves (see Figure 7.9). By the comparison of the Figure 7.9 and Figure 7.10, deterioration speed in case study A (Vietnam) was much faster than case study B (*i.e.* artificial data). Based on the information on maintenance type and timing, analysis of maintenance cost during analysis period is available. Examples are showing at the Table 7.17 ~ 7.20.

Table 7.12 Example of application of simple regression for IRI

Regression equation	Y(IRI) = 1.1 + 0.24 MESAL				
Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	P-value
Regression	0.141633037	1	0.141633037	35.11633966	3.25298E-07
Error	0.193596083	48	0.004033252		
Total	0.33522912	49			
s	0.063507887		Determinant	1	
R-Sq(adj)	0.422496224		DW	1.409230793	
Parameter Estimates					
Predictor	Coef. Est.	Std. Error	t value	P-value	
Constant	1.097779184	0.019184976	57.22077385	7.89966E-46	
MESAL	0.240209553	0.040535511	5.925904121	3.25298E-07	

Table 7.13 Alternatives of maintenance strategy for trials

Maintenance strategy	Routine level	Repair level	Rehabilitation level	Reconstruction level
Alternative I (Preventive level)	Crack seal & Crack patching: *When crack > 3%*	N/A	Overlay 50mm: *When rutting > 20mm Or IRI 3.0m/km*	N/A
Alternative II (General level)	Crack seal & Crack patching: *When crack > 5%*	N/A	Overlay 50mm: *When rutting > 25mm Or IRI 3.5m/km*	N/A
Alternative III (Retarded level)	N/A	N/A	N/A	Reconstruction; *When crack: 15% Or rutting > 35mm Or IRI 4.0m/km*

Note: Applied maintenance criteria are assumptions that cannot represent any country and any research results

Table 7.14 Work effect and unit cost by maintenance (assumed)

Initial condition	Crack (%)	Rutting (mm)	IRI (m/km)	Unit cost[1] (USD/m^2)
Crack seal & patching	0	No effect	No effect	14.24
Overlay 50mm	0	5	1.5	6.89
Reconstruction	0	3	1	12.86[2]

Note: 1) Unit costs were referred to an unofficial standard of KICT
2) Re-construction unit cost was based on ratio between overlay 50mm and reconstruction of HDM-4 model's definition

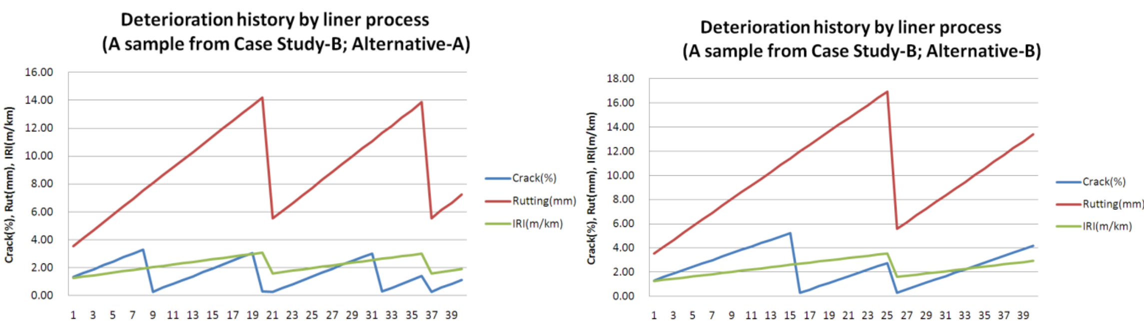


Figure 7.9 Deterioration history between preventive (left) and general (right) maintenance criteria

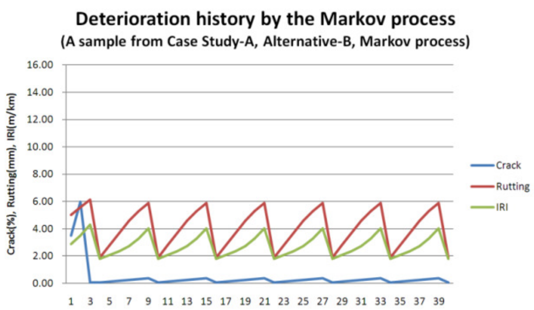


Figure 7.10 Deterioration histories by the Markov hazard model (by localized regression models)

Table 7.15 Example of maintenance cost for a section (Case study-B, Alternative-A)

SECT_ID	YEAR	Analysis year	Routine level	Rehab. level	Annual cost (Un-discounted)	Annual cost (Discounted)	Accumulated (Un-discount)	Accumulated (Discount)
EN1H1S1	2001	1	-	-	-	-	-	-
EN1H1S1	2002	2	-	-	-	-	-	-
EN1H1S1	2003	3	-	-	-	-	-	-
EN1H1S1	2004	4	-	-	-	-	-	-
EN1H1S1	2005	5	-	-	-	-	-	-
EN1H1S1	2006	6	-	-	-	-	-	-
EN1H1S1	2007	7	-	-	-	-	-	-
EN1H1S1	2008	8	Crack seal & patching	-	8,578	5,590	8,578	5,590
EN1H1S1	2009	9	-	-	-	-	8,578	5,590
EN1H1S1	2010	10	-	-	-	-	8,578	5,590
EN1H1S1	2011	11	-	-	-	-	8,578	5,590
EN1H1S1	2012	12	-	-	-	-	8,578	5,590
EN1H1S1	2013	13	-	-	-	-	8,578	5,590
EN1H1S1	2014	14	-	-	-	-	8,578	5,590
EN1H1S1	2015	15	-	-	-	-	8,578	5,590
EN1H1S1	2016	16	-	-	-	-	8,578	5,590
EN1H1S1	2017	17	-	-	-	-	8,578	5,590
EN1H1S1	2018	18	-	-	-	-	8,578	5,590
EN1H1S1	2019	19	Crack seal & patching	-	7,941	2,871	16,519	8,461
EN1H1S1	2020	20	-	Overlay 50mm	125,961	43,170	142,480	51,631
EN1H1S1	2021	21	-	-	-	-	142,480	51,631
EN1H1S1	2022	22	-	-	-	-	142,480	51,631
EN1H1S1	2023	23	-	-	-	-	142,480	51,631
EN1H1S1	2024	24	-	-	-	-	142,480	51,631
EN1H1S1	2025	25	-	-	-	-	142,480	51,631
EN1H1S1	2026	26	-	-	-	-	142,480	51,631
EN1H1S1	2027	27	-	-	-	-	142,480	51,631
EN1H1S1	2028	28	-	-	-	-	142,480	51,631
EN1H1S1	2029	29	-	-	-	-	142,480	51,631
EN1H1S1	2030	30	-	-	-	-	142,480	51,631
EN1H1S1	2031	31	Crack seal & patching	-	7,862	1,495	150,343	53,127
EN1H1S1	2032	32	-	-	-	-	150,343	53,127
EN1H1S1	2033	33	-	-	-	-	150,343	53,127
EN1H1S1	2034	34	-	-	-	-	150,343	53,127
EN1H1S1	2035	35	-	-	-	-	150,343	53,127
EN1H1S1	2036	36	-	Overlay 50mm	125,961	18,329	276,304	71,456
EN1H1S1	2037	37	-	-	-	-	276,304	71,456
EN1H1S1	2038	38	-	-	-	-	276,304	71,456
EN1H1S1	2039	39	-	-	-	-	276,304	71,456
EN1H1S1	2040	40	-	-	-	-	276,304	71,456

Table 7.16 Maintenance information aggregated by year (Case study-B, Alternative-A)

YEAR	Analysis year	Annual budget demand (Un-discounted)	Accumulated budget demand (Un-Discounted)	Annual budget demand (Discounted)	Accumulated budget demand (Discounted)
2001	1	-	-	-	-
2002	2	-	-	-	-
2003	3	-	-	-	-
2004	4	-	-	-	-
2005	5	11,274	11,274	8,626	8,626
2006	6	13,367	24,641	9,694	18,320
2007	7	21,826	46,467	15,004	33,324
2008	8	23,967	70,433	15,617	48,941
2009	9	12,165	82,598	7,514	56,454
2010	10	40,023	122,622	23,431	79,885
2011	11	44,810	167,432	24,866	104,751
2012	12	133,840	301,272	70,398	175,148
2013	13	34,535	335,807	17,218	192,366
2014	14	15,423	351,230	7,288	199,655
2015	15	305,447	656,677	136,820	336,474
2016	16	121,763	778,440	51,698	388,173
2017	17	131,969	910,410	53,111	441,283
2018	18	207,815	1,118,225	79,275	520,558
2019	19	218,564	1,336,789	79,028	599,586

2020	20	260,971	1,597,761	89,442	689,029
2021	21	58,480	1,656,241	18,998	708,027
2022	22	127,851	1,784,092	39,369	747,395
2023	23	95,432	1,879,524	27,854	775,249
2024	24	126,326	2,005,851	34,949	810,198
2025	25	1,164,094	3,169,944	305,265	1,115,463
2026	26	5,619	3,175,564	1,397	1,116,860
2027	27	145,587	3,321,150	34,301	1,151,161
2028	28	298,588	3,619,739	66,681	1,217,842
2029	29	667,266	4,287,005	141,246	1,359,088
2030	30	1,492,541	5,779,546	299,469	1,658,558
2031	31	107,848	5,887,393	20,511	1,679,069
2032	32	417,682	6,305,075	75,295	1,754,364
2033	33	126,204	6,431,279	21,565	1,775,928
2034	34	193,981	6,625,260	31,418	1,807,346
2035	35	23,709	6,648,969	3,640	1,810,986
2036	36	329,577	6,978,547	47,959	1,858,945
2037	37	769,756	7,748,303	106,173	1,965,117
2038	38	415,915	8,164,218	54,376	2,019,494
2039	39	231,449	8,395,667	28,682	2,048,176
2040	40	4,611	8,400,278	542	2,048,717

Table 7.17 Summary of maintenance cost by alternative (Case study-B, Alternative-A)

Simulation Report	Standard and estimated result
The number of sections	50
Analysis period	40
Interest (%)	5.50
Applied maintenance criteria	- Crack seal & patching at crack 3%, - Overlay 50mm at Rutting 15mm Or IRI 2.5m/km
Number of performed crack seal & patching	111
Number of performed overlay 50mm	54
Maintenance cost in USD (Discounted)	2,048,717
Equivalent Uniform Annual Cost (EUAC) (USD/year)	127,677

B. Determination of inspection schedules and cost

As a function of user-specified inspection interval and maintenance schedule, the inspection cost is differed. By applying the Eq. 6.10a and Eq. 6.10b in Chapter 6.5.2, the inspection cost can be estimated. An example is summarized in the Table. 7.18 and Table 7.19.

Table 7.18 Inspection information aggregated by section (Case study-B, Alternative-A)

SECT_ID	The number of inspection	Length of section	Total inspection length	Inspection cost (Un-discounted)	Inspection cost (Discounted)	Accumulated cost (Un-discounted)	Accumulated cost (Discounted)
EN1H1S1	7	4.57	64.01	6,401	4,506	6,401	4,506
EN1H1S2	7	3.05	42.65	4,265	2,986	10,665	7,492
EN3H1S1	9	0.19	3.39	339	226	11,005	7,718
EN3H1S2	7	1.85	25.96	2,596	1,818	13,601	9,536
EN3H2S2	9	0.89	15.93	1,593	1,071	15,194	10,607
EN3H2S3	7	2.19	30.61	3,061	2,164	18,255	12,771
EN3H2S5	6	0.45	5.36	536	394	18,791	13,165
EN3H3S1	8	0.93	14.88	1,488	1,021	20,279	14,185
EN3H5S5	8	3.93	62.83	6,283	4,140	26,562	18,325
EN3H6S1	8	1.04	16.70	1,670	1,146	28,231	19,471
NN1H1S1	9	1.12	20.18	2,018	1,382	30,250	20,853
NN1H1S2	9	0.31	5.62	562	382	30,812	21,236
NN3H1S1	9	2.20	39.69	3,969	2,673	34,781	23,909
NN3H1S2	9	2.19	39.35	3,935	2,647	38,716	26,556
NN3H2S2	9	3.79	68.27	6,827	4,621	45,542	31,177
NN3H2S3	9	4.62	83.11	8,311	5,693	53,854	36,869
NN3H2S5	9	2.77	49.79	4,979	3,410	58,833	40,280
NN3H3S1	9	0.07	1.34	134	92	58,967	40,371
NN3H5S5	9	2.50	44.93	4,493	3,012	63,459	43,383
NN3H6S1	9	0.79	14.29	1,429	977	64,888	44,361
SN1H1S1	8	1.11	17.76	1,776	1,210	66,664	45,570
SN1H1S2	6	3.80	45.64	4,564	3,155	71,228	48,725
SN1H2S2	8	4.48	71.72	7,172	4,873	78,399	53,598
SN1H2S3	8	3.26	52.19	5,219	3,485	83,619	57,083

SN1H5S3	8	3.21	51.34	5,134	3,511	88,753	60,594
SN1H5S4	7	1.83	25.60	2,560	1,793	91,313	62,387
SN1H5S5	8	4.25	68.01	6,801	4,640	98,114	67,027
SN1H6S1	8	1.70	27.18	2,718	1,885	100,832	68,911
SN1H8S5	9	0.36	6.49	649	437	101,481	69,348
WN9H1S1	10	4.66	93.26	9,326	6,190	110,807	75,538
WN9H1S2	10	1.63	32.53	3,253	2,159	114,060	77,697
WN11H1S1	10	3.03	60.68	6,068	4,028	120,128	81,724
WN11H1S2	10	4.84	96.82	9,682	6,426	129,810	88,150
WN11H2S2	10	4.02	80.30	8,030	5,330	137,840	93,480
WN11H2S3	10	4.29	85.71	8,571	5,689	146,411	99,169
WN11H2S5	10	3.96	79.23	7,923	5,259	154,335	104,428
WN11H3S1	10	3.93	78.64	7,864	5,220	162,199	109,647
WN11H5S5	10	0.36	7.16	716	475	162,915	110,122
WN11H6S1	10	3.52	70.49	7,049	4,678	169,964	114,801
HN1H1S1	9	10.96	197.25	19,725	13,352	189,689	12,153
HN1H1S2	9	16.57	298.22	29,822	20,068	219,512	14,221
HN1H1S3	9	9.74	175.38	17,538	11,899	237,049	160,120
HN1H1S4	9	23.23	418.15	41,815	28,733	278,864	188,853
HN1H1S5	9	15.61	280.97	28,097	19,064	306,961	207,917
HN1H2S1	9	7.38	132.82	13,282	9,081	320,244	216,997
HN1H2S2	9	19.42	349.56	34,956	23,718	355,200	240,715
HN1H2S3	8	11.06	176.95	17,695	12,446	372,895	253,161
HN1H2S4	8	8.26	132.15	13,215	9,072	386,110	262,233
HN1H2S5	8	9.52	152.32	15,232	10,591	401,342	272,824
HN1H3S1	8	11.37	181.93	18,193	12,590	419,535	285,414

Table 7.19 Summary of inspection cost by alternative (Case study-B, Alternative-A)

Simulation Report	Standard and estimated result
Number of section	50
Analysis period	40
Interest	5.5
Applied inspection interval(year)	4
The number of inspection lanes to be inspected	2
Inspection unit cost (USD/km/lane)	100
Total length (km)	240.81
Total inspection time (n/analysis period)	431
Total inspection length(km/analysis period)	4195.35
Total inspection cost (discounted)	285,414
Equivalent Uniform Annual Cost (EUAC) (USD/year)	17,787

7.4.3.5 Estimation of Vehicle Speeds

The pavement condition of every individual year y of section s influences vehicle speed. Properly, speed estimation is available after estimation of pavement history of each section. As noted in many previous chapters, the vehicle speed does important roles in the LCCA model. Many sub-models are linked to the speed changes. Basically, estimation unit is year y, section s, lane l and types of vehicle $V_y^{sk}(k = 1, \dots, 7\,; s = 1, \dots, 50\,; y = 1, \dots, 40)$. Detail model description has been delivered in the Chapter 6.9.1. Required data are summarized under below,

- Estimated traffic volume per lane by each vehicle type (veh/lane)
- Carriageway width (m)
- Slope in Rise(+), Fall(-), and curvature in degree/km
- Speed limit (km/h)
- The number of lane
- Roughness in IRI (m/km)
- Model coefficients (see Table.6.55)
- PSCE coefficients (see Table. 6.57)
- Enforcement factor (default=1.10)

To apply the speed estimation model explained in the Chapter 6.9.1, representative vehicles in Korea should be re-classified by referring the vehicle class in the Table 6.55. The Table 7.20 introduces the result. In fact, assumption is indispensable for re-classification procedure unless each country do not have domesticated model for speed estimation. The estimated free and journey speeds are summarized in the Table 7.21.

Table 7.20 Re-classification of vehicle type by vehicle class

Vehicle type (KICT, Korea)	Vehicle class (based on definition of estimation coefficient)
Passenger car	Passenger car
Heavy bus	Bus
Heavy truck	Commercial vehicle
Light bus	Light Commercial vehicle
Light truck	Light Commercial vehicle
Medium truck	Commercial vehicle
Trailer	Commercial vehicle

Table 7.21a Estimated free and journey speeds by vehicle types from the case study – A

Representative vehicles	Speed types	Minimum	Maximum	Average	Standard deviation
Passenger car	Free	35.45	70.98	60.70	9.09
	Journey	32.98	69.03	58.28	9.27
Heavy bus	Free	9.40	64.26	50.27	11.87
	Journey	6.93	62.31	47.84	12.07
Heavy truck	Free	22.76	66.13	54.69	10.10
	Journey	20.29	64.18	52.26	10.30
Light bus	Free	32.45	69.30	59.29	9.35
	Journey	29.84	67.35	56.87	9.55
Light truck	Free	32.45	69.30	59.29	9.35
	Journey	29.84	67.35	56.87	9.55
Medium truck	Free	32.45	69.30	59.29	9.35
	Journey	29.84	67.35	56.87	9.55
Trailer	Free	22.76	66.13	54.69	10.10
	Journey	20.29	64.18	52.26	10.30

Table 7.21b Estimated free and journey speeds by vehicle types from the case study – B

Representative vehicles	Speed types	Minimum	Maximum	Average	Standard deviation
Passenger car	Free	75.90	85.58	80.54	1.84
	Journey	70.62	84.31	77.14	2.97
Heavy bus	Free	62.76	77.45	69.92	3.81
	Journey	57.47	76.18	66.52	4.64
Heavy truck	Free	67.94	78.4	72.92	2.79
	Journey	62.57	77.12	69.52	3.68
Light bus	Free	74.54	82.73	78.30	2.18
	Journey	69.26	81.46	74.90	3.07
Light truck	Free	74.54	82.73	78.30	2.18
	Journey	69.26	81.46	74.90	3.07
Medium truck	Free	74.54	82.73	78.30	2.18
	Journey	69.26	81.46	74.90	3.07
Trailer	Free	67.94	78.40	72.92	2.79
	Journey	62.57	77.12	69.52	3.68

As shown in the Table 7.21, the average speed of case study A (Vietnam) was lower than the case study B around 20km. This is because Vietnamese road sections have worse physical road condition in terms of curvature, roughness, and slope, even though the average AADT per lane was less than the case study B (3,840 veh/lane VS. 5,434 veh/lane). In addition, speed deviations among the sections were bigger than case study B. The difference was caused by lower deviation of physical conditions and traffic volume in the case study B. In case of speed deviation by vehicle types, the maximum was around 8~10km. From the experiences in Vietnam and Korea, the speed estimation model of the Hybrid PMS was fairly reasonable to describe their situation, especially in deviation between min-max speeds.

7.4.3.6 Application of User and Socio-environmental Models

The user and socio-environmental cost can be automatically estimated when road agencies satisfies following data requirement in the Table 7.22.

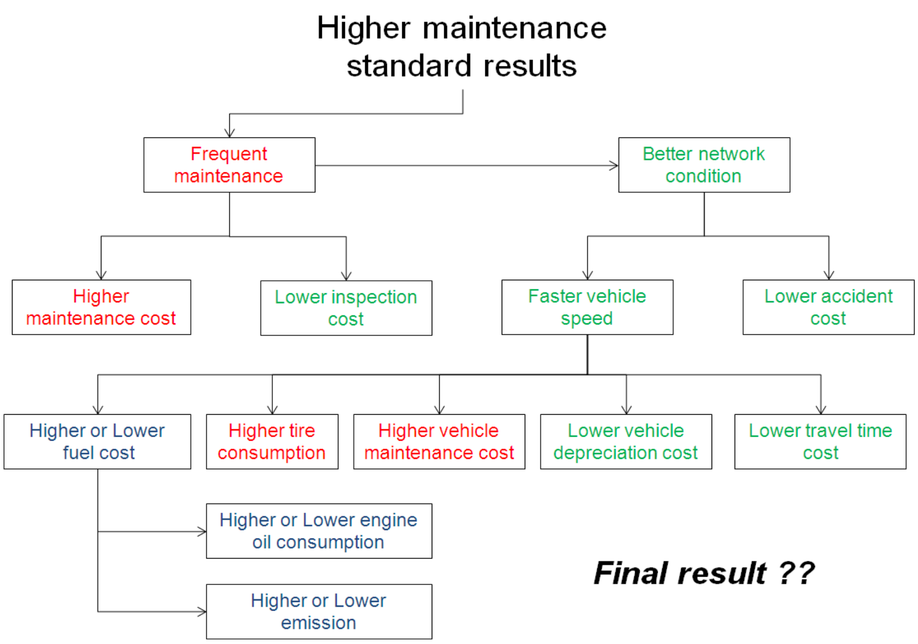
Some data requirements should be imported from other sub-models. Gray columns in the Table 7.22 are indicating the contents. It is simply explained under below;

- ***Pavement history***: by basic deterioration speed, maintenance alternative and recovery condition
- ***Fuel consumption***: by vehicle speed, physical road characteristic and pavement condition
- ***Traffic volume***: by statistical characteristic of AADT increment rate and first year's AADT
- ***Vehicle Speed:*** by physical and operational road characteristics and traffic volume

Since all of sub-models (LCC contents) in the Hybrid PMS were designed to show difference by road investment, it could be a good analytical tool to show the power of budget. The better (or higher) maintenance standard makes following effects in the Hybrid PMS (see Figure 7.11.)

Table 7.22 Summary of data requirements for user and socio-environmental costs

	Section length	Pavement condition	Fuel ($Fuel_y^{Sk}$)	AADT ($AADT_y^{Sk}$)	Speed (V_y^{Sk})	Unit costs	Model coefficient	Interest Currency	Note
Fuel	X	X	X	X	X	X	X	X	
Tire	X			X	X	X	X	X	
Oil model-A	X			X	X	X	X	X	Speed Dependent
Oil model-B	X		X	X	X	X	X	X	Fuel Dependent
Maintenance	X			X	X	X	X	X	
Depreciation	X			X	X	X	X	X	
Travel time	X			X	X	X	X	X	
Accident - A	X	X		X		X	X	X	Pavement condition dependent
Accident - B	X			X		X	X	X	Level of hazard exposure
Emission -A	X		X	X	X	X	X	X	Fuel dependent
Emission -B	X			X	X	X	X	X	Speed dependent



Note: red text = negative effect, green=positive effect, and blue = depended upon the speed level

Figure 7.11 Effects of maintenance standard in the life cycle cost

As shown in the Figure 7.11, a center of the LCCA is the "Speed model" which is affected by pavement condition. Based on the vehicle speed, trends of the fuel cost, engine oil cost and emission cost can be changed because the function of fuel consumption model has concave shape that has an optimal point (speed). When we check overall relationship among the LCC contents shown in the Figure 7.11, it is difficult to anticipate whether the higher maintenance standard makes positive or negative effect to total transport cost particularly in the fuel cost, engine oil and emission cost. We can easily anticipate that higher level of road condition could be not always the best alternative in terms of road user and socio-environmental cost. A part of estimation results will be simply demonstrated in the next chapter.

Basically, the Hybrid PMS has default model parameters for each sub-model of road user and environmental cost. That is, the road agencies who do not have enough data can use the default models with some assumptions. Although the users do not need to apply the full LCCA model, it is recommended to apply it as a sub-model to help their decision making.

7.4.3.7 Application of Economic Analysis

By the estimation procedures for total life cycle cost, many intermediate results showing differences by level of road investment have been estimated. However, this part will introduce only typical economic analysis results in PMS that compare user-specified alternatives. Maybe the comparison could be done in many ways by interest of road agencies. In this paper, economic analysis of the two case studies has done by different concept by definition of the base alternative which is an object of comparison. The base alternative in the case study A was the "Alternative – typical". If we assume that the VRA are now applying the alternative, a purpose of economic analysis becomes checking feasibility about changing current maintenance strategy. In case of the case study B, it was the "Alternative – retarded" applying minimum or worst maintenance strategy which requires minimum budget requirement. This is the most typical way to show (relative) benefit of alternatives in economic analysis. The economic analysis results of both case studies are demonstrates in the following tables (see Table 7.23 ~ 7.30).

Table 7.23 Economic analysis table for an alternative (Case Study-A, Alternative-A (Preventive type), 40 years, interest 5.5%) (Unit: USD)

YEAR	Analysis year	Agency cost		User cost							Environmental cost	Total Transport Cost
				Vehicle Operating Cost					Travel time cost	Accident cost		
		Maintenance cost	Inspection cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost				
2001	1	486,846	18,004	67,774	2,807	844	7,660	51,735	142,356,251	3,436,085	4,607,076	151,035,081
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
2039	39	229,696	863	9,018	366	112	1,011	6,922	19,051,877	486,712	612,431	20,399,009
2040	40	396,988	1,474	8,599	349	107	963	6,588	18,137,850	461,710	583,759	19,598,386
Total		22,133,810	88,498	1,164,001	47,590	14,469	130,859	891,577	2,454,179,947	61,208,051	79,069,174	2,618,927,976
EUAC		1,379,387	5,515	72,541	2,966	902	8,155	55,563	152,945,337	3,814,507	4,927,618	163,212,491

Table 7.24 Comparison of alternatives in NPV (Case Study-A, 40 years, interest 5.5%) (Unit: USD)

Alternative	Base alternative	Agency Cost		User cost							Environmental cost	Total Transport Cost	EUAC in Agency cost	EUAC in Total Transport Cost
				Vehicle Operating Cost					Travel time cost	Accident cost				
		Maintenance cost	Inspection Cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost						
Alternative-preventive	NO	22,133,810	88,498	1,164,001	47,590	14,468.8	130,859	891,577	2,454,179,947	61,208,051	79,069,174	2,618,927,976	1,384,902	163,212,491
Alternative-Typical	YES	18,075,896	85,108	1,165,494	47,312	14,471.9	130,620	894,486	2,462,870,534	63,064,357	79,143,043	2,625,491,323	1,131,800	163,621,521
Alternative-retarded	NO	14,675,271	80,073	1,164,429	47,523	14,469.7	130,798	892,367	2,456,586,174	61,918,146	79,093,508	2,614,602,759	919,558	162,942,942

Table 7.25 Comparison of alternatives in costs and benefits (Case Study-A, 40 years, interest 5.5%) (Unit: USD)

Alternative	Base alternative	(COST) Increase in Road Agency Cost		(Benefit) Saving in Road User Cost							Savings in Environmental cost	Total benefit (Relative benefit)
		Maintenance cost	Inspection Cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost	Travel time cost	Accident cost		
Alternative-preventive	NO	4,057,914	3,390	1,493	-278	3	-239	2,908	8,690,587	1,856,306	73,869	6,563,347
Alternative-Typical	YES	0	0	0	0	0	0	0	0	0	0	0
Alternative-retarded	NO	-3,400,625	-5,035	1,065	-210	2	-178	2,119	6,284,360	1,146,211	49,536	10,888,564

Table 7.26 Comparison of alternatives in economic indices (Case Study-A, 40 years, interest 5.5%) (Unit: USD)

Alternative	Base alternative	Economic indices		Equivalent Uniformed Annual Cost			
		NPV/COST ratio	IRR	Agency cost	Total cost	Difference in Agency cost	Difference in Total Transport Cost
Alternative-preventive	NO	1.6161	62%	138,379	665,596,399	50,053	1,235,640
Alternative-Typical	YES	-	-	88,326	666,117,896	0	0
Alternative-retarded	NO	No solution	No solution	41,917	666,832,039	-46,409	714,142

Table 7.27 Economic analysis table for an alternative (Case Study-B, Alternative-A (Preventive type), 40 years, interest 5.5%) (Unit: USD)

YEAR	Analysis year	Agency cost		User cost							Environmental cost	Total Transport Cost
				Vehicle Operating Cost					Travel time cost	Accident cost		
		Maintenance cost	Inspection cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost				
2001	1	-	-	552,956	43,307	5,741	69,284	107,416	554,425,919	12,823,782	38,585,912	606,614,316
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
2039	39	100,387	945	74,712	5,720	777	9,292	14,802	75,868,165	1,991,454	5,195,667	83,190,218
2040	40	1,896	2,550	70,421	5,380	733	8,752	13,976	71,623,769	1,881,189	4,896,165	78,503,477
Total		7,170,511	171,728	9,634,022	744,146	100,175	1,201,615	1,895,668	9,748,326,718	241,158,197	670,883,967	10,676,164,955
EUAC		446,869	10,702	600,396	46,375	6,243	74,885	118,139	607,519,068	15,029,062	41,809,719	665,661,458

Table 7.28 Comparison of alternatives in NPV (Case Study-B, 40 years, interest 5.5%) (Unit: USD)

Alternative	Base alternative	Agency Cost		User cost							Environmental cost	Total Transport Cost	EUAC in Agency cost	EUAC in Total Transport Cost
				Vehicle Operating Cost					Travel time cost	Accident cost				
		Maintenance cost	Inspection Cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost						
Alternative-preventive	NO	7,170,511	171,728	9,634,022	744,146	100,175.3	1,201,615	1,895,668	9,748,326,718	241,158,197	670,883,967	10,681,286,748	138,379	665,342,266
Alternative-Typical	NO	4,351,750	173,934	9,633,646	743,078	100,174.7	1,200,904	1,897,654	9,755,433,721	243,377,993	670,734,330	10,687,647,184	88,326	665,864,126
Alternative-retarded	YES	1,558,889	175,719	9,633,335	742,549	100,174.1	1,200,556	1,898,578	9,758,501,714	244,490,006	670,651,160	10,688,952,680	108,101	1,558,889

Table 7.29 Comparison of alternatives in costs and benefits (Case Study-B, 40 years, interest 5.5%) (Unit: USD)

Alternative	Base alternative	(COST) Increase in Road Agency Cost		(Benefit) Saving in Road User Cost							Savings in Environmental cost	Total benefit (Relative benefit)
		Maintenance cost	Inspection Cost	Fuel cost	Tire cost	Engine oil	Vehicle maintenance cost	Vehicle depreciation cost	Travel time cost	Accident cost		
Alternative-preventive	NO	5,611,623	-3,991	-687	-1,597	-1	-1,058	2,910	10,174,995	3,331,808	-232,806	7,665,932
Alternative-Typical	NO	2,792,862	-1,785	-311	-528	-1	-348	924	3,067,993	1,112,013	-83,170	1,305,496
Alternative-retarded	YES	0	0	0	0	0	0	0	0	0	0	0

Table 7.30 Comparison of alternatives in economic indices (Case Study-B, 40 years, interest 5.5%) (Unit: USD)

Alternative	Base alternative	Economic indices		Equivalent Uniformed Annual Cost			
		NPV/COST ratio	IRR	Agency cost	Total cost	Difference in Agency cost	Difference in Total Transport Cost
Alternative-preventive	NO	1.3671	37%	138,379	665,596,399	96,462	1,235,640
Alternative-Typical	NO	0.4677	No solution	88,326	666,117,896	46,409	714,142
Alternative-retarded	YES	-	-	41,917	666,832,039	0	0

The decision making for the best alternative can be different by viewpoint of road agencies. As standards, agency cost level, total transport cost (total LCC) level and economic decision criteria should be considered at the same time. With the standards, current PMS situations especially in budget constraint would affect to the decision making procedure as an important criteria. In case of the case study A, the decision making is very easy. The alternative C applying reconstruction only at deteriorated condition has the lowest agency cost, as well as total transport cost. However, economic analysis results of the case study B are a little bit complex. First, the retarded type was best alternative for saving agency cost. However, saving in total transport cost, as well as economic decision criteria said that the preventive maintenance strategy could have the highest cost-effectiveness. Based on the result, road agencies can insist budget adjustment to do the preventive maintenance type. The final decision could be determined by budget situation and viewpoints of the decision makers because the user and socio-environmental cost is invisible cost which cannot be easily understandable to decision makers. Changing network condition by budget levels may be much persuasive information to them. The best thing is making a pair the two contents to show much powerful effect of budget. Note that the budget allocation should be "*reasonable*" budget which is not "*enough*" budget for net benefit of total budget of a country.

7.4.3.8 Performance Analysis by Investment Levels

This chapter will introduce simplified performance analysis by investment levels by using the case studies. As general methods, we can check averaged network condition, deterioration history of network by the investment levels.

A. Average network condition, investment and deterioration speed

The average network conditions during analysis period are summarized in the Table. 7.31. The higher (expensive) standards properly have the better conditions. By the comparison between two case studies, we confirmed that the pavement condition level can be differed by deterioration speed even though same maintenance standard had been applied. As revealed in previous chapter, deterioration speed of the case study A was much faster than artificial data. Nevertheless, the average network condition of the case study A is much better. This is, because, the road sections which have slow deterioration speed have been remained at worse pavement condition for longer time. In brief, total duration staying at bad condition was longer than case study A. Since the frequent maintenance works, however, maintenance cost of case study A was around three times of case study B even though the physical road characteristic, especially in number of lane (linked to carriageway width; maintenance area), was half level. It implies that if the case study B has same deterioration speed with case study B, it becomes sextuple as high as current budget requirement level. On the contrary, average IRI condition in case study B was better. It was from low deterioration speed of IRI of sections in the case study B.

In the simulation, main reason of maintenance works was deterioration of rutting or crack. It implies that the maintenance works had been conducted even the IRI condition was in a good condition. For the better maintenance strategy, road agencies have to consider balance of deterioration speeds among the condition indices. For example, most reasons of maintenances in the case study were the IRI. If Vietnamese road agency improves (only) performance level of IRI by engineering method (e.g. advanced pavement material or design method), their pavement condition and budget condition would be remarkably improved. As described in this paragraph, the issues on network condition with budget requirement are not so simple, because the two issues are interfered with the deterioration speed.

Table 7.31 Averaged pavement condition by maintenance alternatives during analysis period (40years)

Alternatives	Crack (%)		Rutting (mm)		IRI (m/km)	
	Case study A	Cast study B	Case study A	Cast study B	Case study A	Cast study B
Alternative-Preventive	0.34	1.62	3.81	8.34	2.44	2.01
Alternative-Typical	0.63	2.36	4.18	9.09	2.69	2.14
Alternative-Retarded	1.57	2.48	4.93	10.19	3.32	2.31

B. Network conditions and cost streams by maintenance alternative
This chapter simply demonstrates time-series information on budget stream and network condition during the analysis period. The pavement condition by deterioration indices are graphed in the Figure 7.12.

The basic deterioration trends between case study A and B is different. The case study A was started from the real conditions (*i.e.* deteriorated condition) in 2004. On the other hand, all sections in the case study B were started from almost new condition. Since there was no maintenance work during the period in straight line, the angle of inclination can be interpreted as deterioration speed of each deterioration index. In addition, the start point of noised parts means that maintenance works have been started. One of strange thing in the case study A was that many sections have same deterioration conditions in 2004 (in raw data). Such section groups have a high probability to have almost same deterioration histories throughout the analysis period. For that reason, the averaged deterioration histories in the Figure 7.12 seem to a section. Usually, averaged pavement condition has noise like with the tails of the case study B. Surely, the phenomenon is not from the Hybrid PMS but from the data properties. With the time-series deterioration history, annual budget requirement (maintenance cost + inspection cost) could be compared. Note that the case study A and B are not objects of comparison, but alternatives in a case study should be. The graphs are demonstrated in the Figure 7.13. For much easy comparison, accumulated budget are showing at the Figure 7.14.

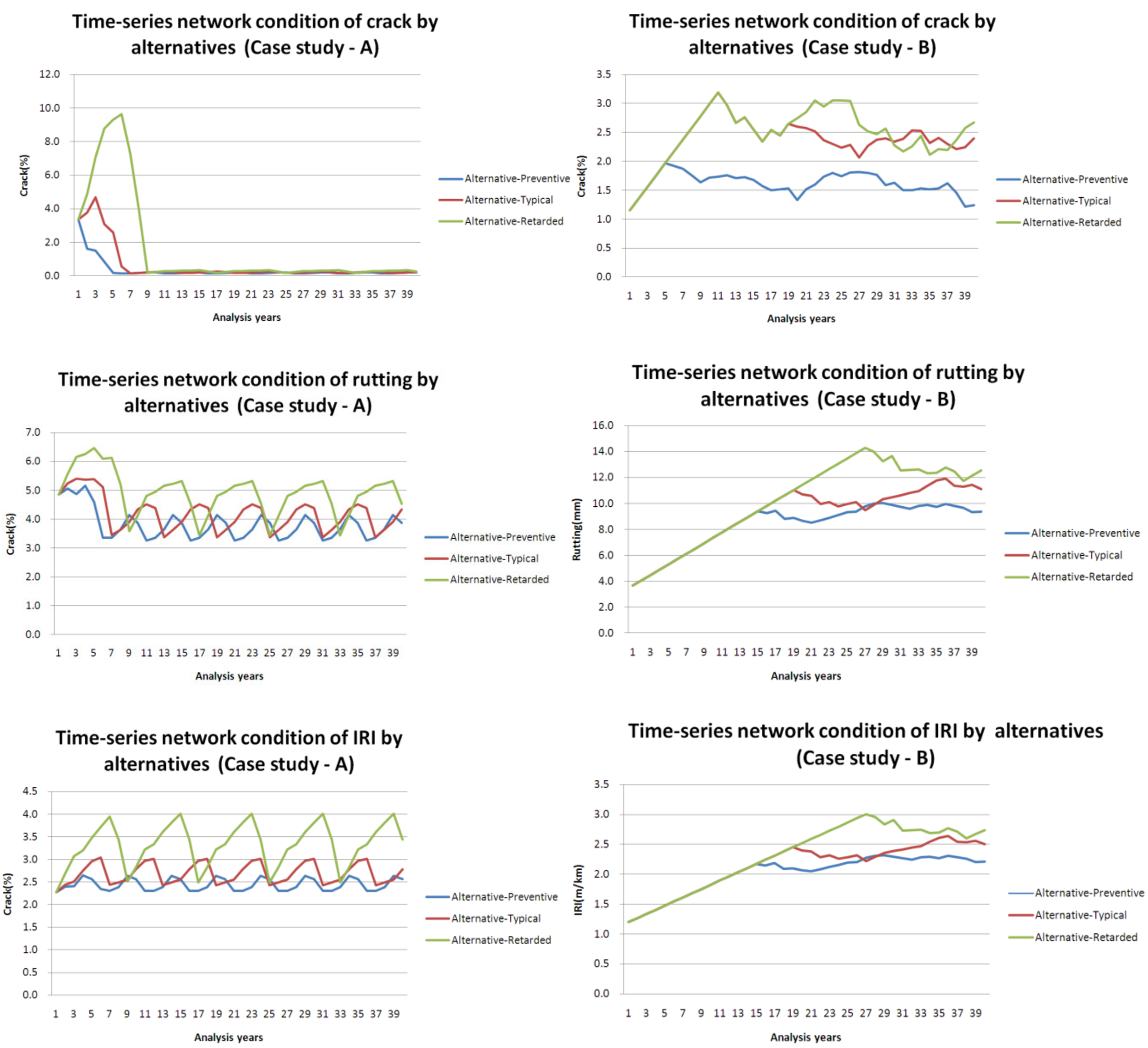


Figure 7.12 Time-series deterioration history of network by condition indices and case studies

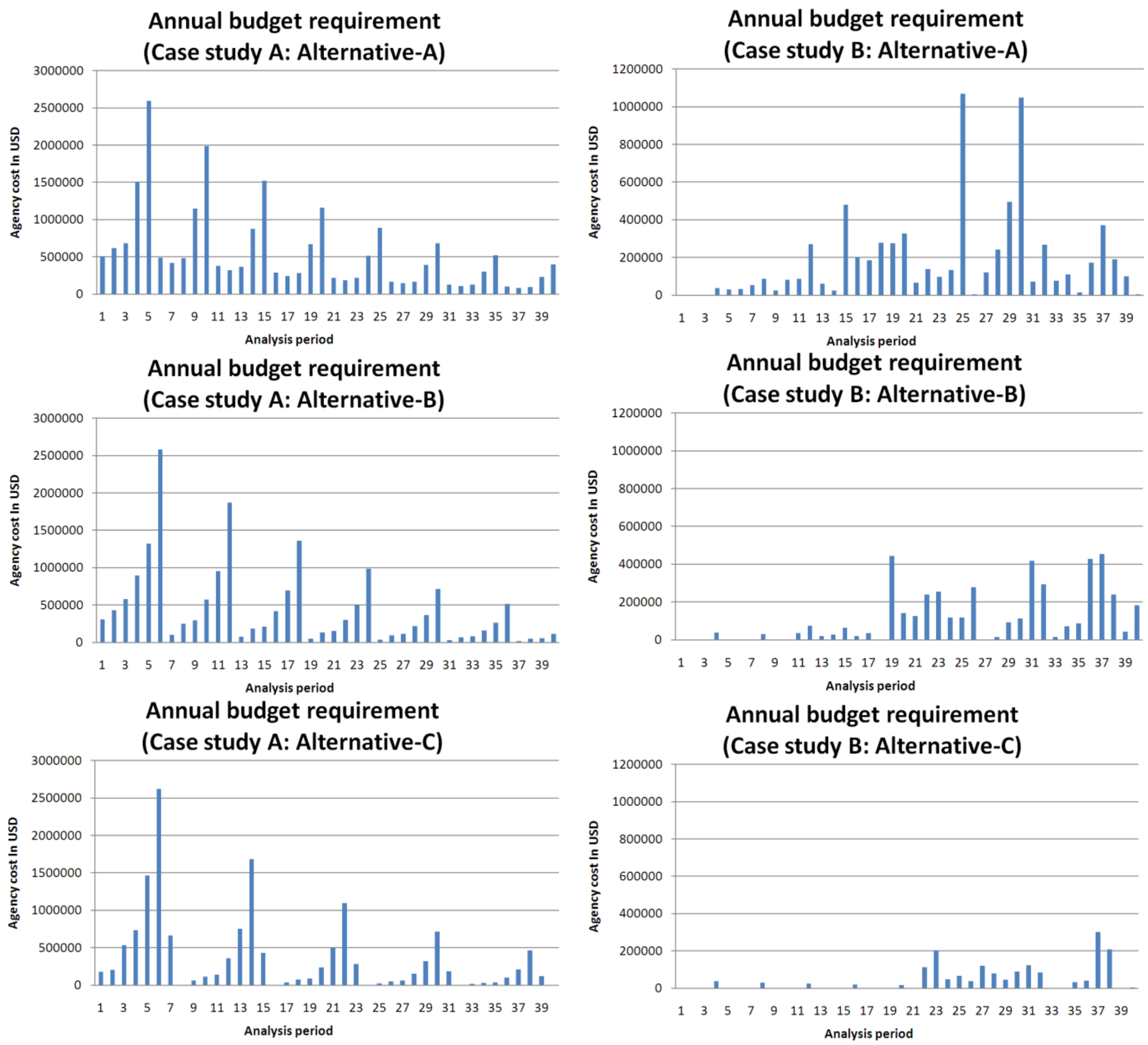


Figure 7.13 Annual agency cost during analysis period (inspection cost included)

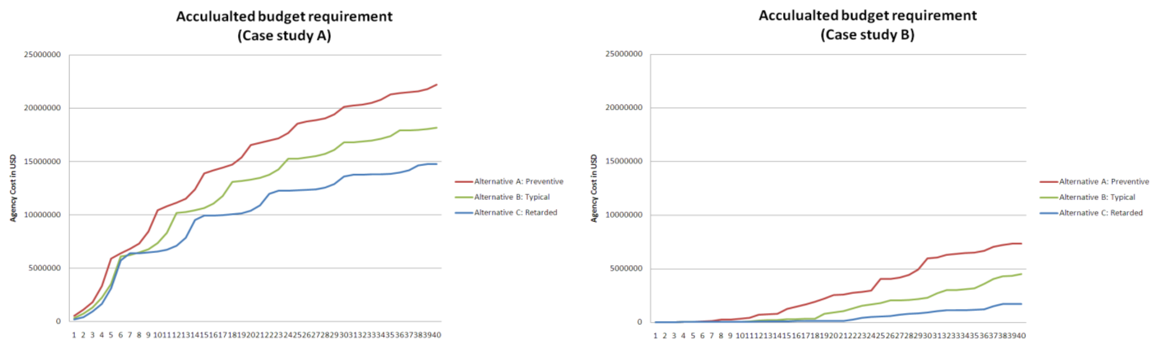


Figure 7.14 Accumulated budget requirements by alternatives (left: Case study A, right; Case study B)

7.5 Summary and Recommendations

Since the Hybrid PMS is a total system that has rich function and system component, it can be applied for various PMS analyses. However, it was difficult to show all the details in a paper. For that reason, this chapter have mainly introduced following contents;

- Customization points in application
- Establishment of PMS development plans
- Typical application of Hybrid PMS in LCCA

As general information, this chapter started with issues on customization points in terms of system, function, and programming. This information may be useful when road agencies check their situation and establish their future development plan.

For case studies on establishing PMS development plan, Korea, Japan and Vietnam which have different PMS history, current PMS environments, and desire level of PMS capabilities have been selected. The customization schemes of the pilot countries are established by experiences and data resources from their countries. By the review, this paper has evaluated the current PMS capability level of each country at the database dependent level (Korea), the expert system dependent level-B (Vietnam), and modeling level-A (Japan) respectively. As the desired PMS capability level, modeling level-B has been designated for the Korean PMS. With the processes, we realized that importance of long-term PMS development plan, and being of criteria.

In case of the typical application of the Hybrid PMS, this paper applied a typical LCCA procedure composed by pavement deterioration forecasting, performance analysis under current management policy, cost estimation, and economic analysis. It was divided two cases by different type of deterioration models (deterministic and stochastic model). As a data resource, a part of Vietnamese data in 2004 and artificial data from database of the Hybrid PMS were applied. Even though this paper introduced a case study as a general application way, its application could be expected based on application schemes. If general version cannot cover the schemes of road agencies, it is recommended to develop it as new function. It could be a new element of the Hybrid PMS in the future, then everybody can share the benefits.

Important meanings of this chapter are confirming feasibility of the LCCA model, the artificial pavement inventory data as an open recourse, and criteria for establishing development plan of PMS model. In addition, the general application way in LCCA could be considered as criteria for application of PMS analysis.

Bibliographies

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CHAPTER 8

Conclusions

8.1 A Brief Summary

Chapter 1
At the chapter 1, current situation in PMS development and application has been briefly reviewed. As a result, this paper has focused on "Heterogeneous PMS situation" and "Insufficient capacity" in PMS development" that make road agencies have difficulties on development and improvement of their PMS. To help sustainable development of PMS model, this paper defined research motivation as follows;

- Successful introduction of PMS model
- Sustainable improvement of PMS model
- Cultivating self-reliance whereby everybody develops their own PMS model
- Establishing compatibility among the PMS models

Due to the unreality of the best (self-development), and second-best alternative (ready-made software), this paper suggested development of Hybrid PMS with criteria of PMS as a third-best alternative. The third-best alternative should mitigate heterogeneity among the PMS models while the heterogeneity of PMS situation should be allowed as it is. It is somewhat contradictory. This was a main challenge of this paper.

Chapter 2
At the chapter 2, development and customization strategy which is the most important part of this paper have been discussed. As basic properties of the Hybrid PMS, this paper has defined following contents for much flexible and easy customization and application;

- Rich contents
- Free software
- Open-source software
- Easy and flexible customization
- Compatibility with current PMS model

To realize the properties, this paper has suggested a multidimensional approach;

- Macroscopic approach for criteria of planning phase
- Mesoscopic approach for criteria of implementation phase
- Microscopic approach for criteria of programming phase

This part should be highlighted since every element of the Hybrid PMS followed the above strategies.

Chapter 3
At the chapter 3, issues on development of database which is the most fundamental system component have been discussed. Since customization of ready-made database is fairly difficult task, this chapter mainly introduced development way of the database instead of introducing developed database.

As one more important research content, development of artificial pavement inventory data as an open-source has been addressed. The reasons why such researches are required is that no (permitted) PMS inventory data for the Hybrid PMS, and to serve open-source PMS inventory data for various purposes. To reflect reality as much as possible, this paper was focusing following characteristics in PMS;

- Uncertainty of the deterioration processes
- Relationship between deterioration speed and its explanatory variable
- Definition of data contents (general dataset + HDM-4 application)

- Different roles of data in inspection, maintenance, and analysis
- Demands of time-series data

To consider listed characteristics, this paper generated a pavement inventory dataset having multiple road agencies and networks under different characteristics in terms of geometry, climate, pavement design, traffic condition, and road class. In brief, the paper assumed a PMS data under a virtual country for data generation. Besides, a pavement condition generation model satisfying pavement deterioration characteristics both uncertainty and relationship between deterioration speed and its explanatory variable was suggested. The data generation processes explained in this chapter would be a good reference that shows how to compose their data tables.

The developed database for the Hybrid PMS also applied the concept of plug-in system based on encapsulation strategy. The system framework guarantees easiest application and modification in functional level. As a viewpoint of total system, there is no main interface that integrates the sub-models because the sub-models of the Hybrid PMS were developed as independent modulus. For that reason, the database system will play a role of a main interface of the Hybrid PMS.

Chapter 4
This chapter addressed PMS cycle management functions as criteria for PMS operation. The reasons why the functions are required can be found in these reasons;

- Facilitating dairy, monthly and annual PMS activities of PMS manager by automated system
- Reducing human errors caused by many related person who are engaged in different fields
- Standardization of PMS cycle as criteria for PMS operation

For developing management function, this paper introduced a tactical level of management cycle classified by three phases; *“PLAN, DO, and SEE”* which reflect annual activities of PMS manager during a cycle.

The management functions have deep relationship with update of database. Since the database of the PMS has a different property with general database that annual historical data should be saved without any modification, it must have a role for data update as an independent module. In addition, some functions (*e.g.* error processing or work effect estimation) are required for complex calculation procedures that cannot be done by the database due to a nature of system. That is, the management functions should be paired with the database. The paired functions could be considered as minimum requirements for PMS operation. Besides, it is believed that the management function would be most frequently applied function in the Hybrid PMS.

Chapter 5
At the chapter 5, pavement deterioration forecasting model which is an essential function of PMS analysis procedures. Because of difficulties in application due to a lack of data, and satisfying various purposes, the Hybrid PMS hired multiple deterioration model inside. To define general deterioration models, this paper considered following points;

- Data requirement
- Property of deterioration model
- Usage of result (Network level or Project level)

With the consideration, following models or theories are selected;

- Simplified linear regression
- Multiple regression
- Markov exponential hazard model
- Local mixture model

Since different properties of the deterioration models, their forecasting (or estimation) results cannot be compatible as it is. In addition, state basis results from stochastic models cannot be applied to LCCA model in the Hybrid PMS because the LCCA model demands annual basis input. As a solution, this paper suggested methodologies whereby make it compatible each other. Note that the introduced four deterioration models or theories were not developed by this paper, but generally used in PMS sector. The most important concern of this chapter is not introducing various deterioration model, but how to compose deterioration models for the Hybrid PMS to satisfy various PMS situation and objectives.

Chapter 6
At the chapter 6, LCCA which is a principle of economic analysis to PMS have been discussed. To develop rich and flexible LCCA model to appease road agencies as much as possible, this paper has focused following customization points not only for development but also application;

- Definition of LCC contents
- Modulation of LCC contents
- Simplified estimation method
- Flexible application way

Due to desire for simplification, this paper has tried to adopt most general and sensible approach, but also to simplify or to apply assumptions for cases that have advantages in estimation way but have sophisticate structure. Under the basic strategy, LCCA model in the Hybrid PMS has following sub-models under annual basis deterministic approach;

- Inspection and maintenance cost
- Vehicle operating cost (Fuel, tire, engine oil, vehicle maintenance and depreciation cost)
- Travel time costs
- Road safety costs (accident cost)
- Emission costs (7 types of compound)
- Network condition analysis
- Economic analysis (by cost streams, economic decision criteria)
- Traffic volume generation
- Vehicle speed estimation

It could be differently applied by implementation scheme of road agencies. Full application is available, also it allows partial application as necessary. This is possible because modulation strategy of each LCC estimation function turns into separation and combination of the LCC contents. In brief, an extracted individual function can be used as independent analysis modules that helps user's current PMS model without any system modification. Nevertheless, it is expected that many agencies may be encountered many problems because application of the LCCA model demands comprehensive understanding on overall structure from the pavement deterioration model to every detail of LCC estimation method. Also it demands calibrations of the model coefficient. It is expected that the partial application would be mainstream of usage of the LCCA model. However, it is believed that road agencies can use the default models which demand very general data in PMS. In such case, the detail value and costs would be meaningless, but it could be useful in prioritizing alternatives to find best alternative, or comparison with analysis results from other LCCA models. This chapter could be considered as criteria for development of LCCA model. This is much important meaning of this chapter than showing detail of the LCCA model.

Chapter 7
Since the Hybrid PMS is a total system that has rich function and system component, it can be applied for various PMS analyses. However, it was difficult to show all the details in a paper. For that reason, following contents have mainly introduced;

- Customization points in application
- Establishment of PMS development plans
- Typical application of Hybrid PMS in LCCA

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In case of the typical application of the Hybrid PMS, this paper demonstrated a typical LCCA procedure composed by pavement deterioration forecasting, performance analysis under current management policy, cost estimation, and economic analysis. It was divided two cases by different type of deterioration models (deterministic and stochastic model). As a data resource, a part of Vietnamese data in 2004 and artificial data from database of the Hybrid PMS were applied. Even though this paper introduced a case study as a general application way, its application could be expected based on application schemes. If general version cannot cover the schemes of road agencies, it is recommended to develop it as new function. It could be a new element of the Hybrid PMS in the future, then everybody can share the benefits.

Important meanings of this chapter are confirming feasibility of the LCCA model, the artificial pavement inventory data as an open recourse, and criteria for establishing development plan of PMS model. In addition, general application way in LCCA could be considered as criteria for application of PMS analysis.

8.2 Conclusions

This paper dedicated to suggest open-source Hybrid PMS model with criteria for PMS development as a third-best alternative to help successful and sustainable development of PMS. Main conclusions are summarized as follows;

1. There is *"Essential heterogeneity"* in PMS. For that reason, self-development of customized PMS model would be the best alternative for PMS sustainable PMS development. However, there are many obstacles in the reality due to *"Insufficient capacity in PMS development"*. Also application of ready-made software to everyone also has a critical limitation that road agencies cannot have suitable PMSs matching with their situation and interest. Therefore, we need third-best alternative which mitigates the two major problems in PMS development at the same time.

2. As the third-best alternative, this paper suggested open-source Hybrid PMS based on criteria of PMS development. The Hybrid PMS has rich PMS functions under flexible system architecture. It guarantees easy application and sustainable development by various application ways. It would be helpful for first introduction, self-examination, improvement of PMS model, especially in developing countries who do not have enough capability to do self-development.

3. To develop the Hybrid PMS, this paper established development and customization strategies divided into microscopic (planning phase), mesoscopic (for implementation phase), and microscopic approach (for programming phase). These strategies are highlights of this paper which is basic strategies for development, while it is important information for successful application of the criteria and the Hybrid PMS to road agencies.

4. The criteria of PMS development which were applied for the macroscopic approach mainly treated standardization of PMS models in system and functional level. It can be core information for drawing blueprint for desired PMS. At mesoscopic approach, this paper devised "Plug-in system" with "Encapsulation strategy" to design flexible system architecture. The strategy is a nuclear to realize the self-development by users. In case of microscopic approach, this paper imbued an important property "Open-source system" whereby road agency can develop their own customized PMS model.

5. As details of the microscopic approach, this paper suggested detail methods of general PMS functions composed by database, PMS cycle management function, pavement deterioration forecasting model and life cycle cost analysis model. It tried to follow general and recommended method. Besides, every model prepares many customization points to give a room for choice.

6. The criteria for PMS development, artificial pavement inventory data, and LCCA model in the Hybrid PMS are empirically tested by using cases in Korea, Vietnam and Japan.

7. One concern is giving easy understanding on details of model and even philosophy of the Hybrid PMS to users. As described in the paper, there are so many essential issues that have to be understood for successful application. It would be not easy. Developing manuals, websites and

summarized papers would be helpful to give better understanding.

8. One limitation is that all definitions are still unilaterally developed models and standards. However, the criteria will likely be improved by the continuous feedback of many road agencies in various PMS situations. Finally, the idea of creating standard criteria brings us closer to bilateral, or multilateral, criteria and the Hybrid PMS that could be considered an international standard for PMS development. This is ultimate goal of this paper.

9. Although the Hybrid PMS can support development of PMS model, the self-development is still the ideal solution that must be pursued by every road agency. The criteria for development of PMS model are for everyone. However, (full) application of the Hybrid PMS model is recommended only to road agencies who are in a beginning stage of PMS development.

APPENDIX

- **Appendix A – Data Definitions by PMS capabilities Level (For the Chapters 2 and 3)**
- **Appendix B – Standards for Generation of Artificial Pavement Deterioration Data (For the Chapter 3)**
- **Appendix C – Derivations of Markov exponential hazard Models (For the Chapter 5)**

Appendix A: Data Definitions by PMS Capabilities Level

Table A.1 Summary of data contents

Data set	Number of columns	By categories								By tables		
		ID	Physical & operational characteristics	Design variables	Maintenance & inspection history	Explanatory variables	Pavement condition data	Vehicle fleet	Subsidiary	Network	Vehicle fleet	Subsidiary
Dataset A	31	5	5	1	4	0	5	0	11	22	0	9
Dataset B	78(+47)	5	16	9	16	3	12	0	17	63	0	15
Dataset C	110(+32)	5	16	10	16	24	13	7	19	87	7	16
Dataset D	219(+109)	5	16	10	16	24	13	91	44	87	91	41

Table A.2 Definition of data contents

No	contents	Core	Categories[1)]	Description	Default	Note(contents in Navigator)	Data set[2)]	Table name	HDM[3)]
1	SECT_ID	1	1	Identification code for section (e.g. S01, S02)	SECT01		1	NETWORK	1
2	SECT_NAME	0	1	Description of section	MY_SECT		1	NETWORK	1
3	LINK_ID	0	1	Identification code for link that section belongs to (e.g. N1)	LINK01		1	NETWORK	1
4	LINK_NAME	0	1	Description of link that section belongs to (e.g. National road N.9))	MY_LINK		1	NETWORK	1
5	AGENCY_ID	1	1	Agency ID who manages the section	AGENCY01		1	NETWORK	0
6	LOCATION	1	2	Location information of a section (e,g, Address;Origin-Destination)	My location		1	NETWORK	0
7	LENGTH	1	2	Length of section in Km (L)	1		1	NETWORK	1
8	CWAY_WIDTH	1	2	Width of carriageway in meter	14		1	NETWORK	1
9	NUM_LANES	1	2	Number of lanes (NLANES)	4		1	NETWORK	1
10	ROAD_TYPE	1	2	Classification of road way by normal section, bridge, tunnel	0	0=normal, 1=bridge, 2=tunnel	1	NETWORK	0
11	SURF_CLASS	1	3	Surface class (bituminous, unsealed or concrete)	0	0 = Bituminous, 1 = Unsealed, 2 = Concrete	1	NETWORK	1
12	LAST_REHAB	1	4	Year of last rehabilitation (used in calculation of AGE indicators)	2000		1	NETWORK	1

13	LAST_INSPECTION	1	4	Year of last inspection	2009		1	NETWORK	0
14	AGE0_INSPECTION	0	4	Elapsed time from last inspection	1		1	NETWORK	0
15	AGE3_REHAB	0	4	Elapsed time from last rehabilitation type	10		1	NETWORK	0
16	COND_YEAR	1	6	Year for which following condition measures apply	2009		1	NETWORK	1
17	ROUGHNESS	1	6	Roughness in IRI m/km	1		1	NETWORK	1
18	CRACKS_TOT	1	6	Total area of cracking as % of total carriageway area (ACRA)	0		1	NETWORK	1
19	PHOLE_NUM	1	6	Number of pothole units (0.1m²) per Km (no./km) (NPT)	0		1	NETWORK	1
20	RUT_DEPTH	1	6	Mean rut depth in mm (RDM)	2		1	NETWORK	1
21	YEAR	1	8	Budget (Fiscal) year	2010		1	NETWORK	0
22	CURRENCY	0	8	Exchange rate per USD	1		1	SUBSIDIARY	0
23	UC_INSPECTION	1	8	Unit cost of inspection ($/km/lane)	100		1	SUBSIDIARY	0
24	UC_RECON	1	8	Unit cost of reconstruction ($/square meter)	12.86		1	SUBSIDIARY	0
25	UC_CUTTING	1	8	Unit cost of cutting method of pavement surface ($/square meter)	8		1	SUBSIDIARY	0
26	UC_REHAB_OL	1	8	Unit cost of overlay ($/square meter)	6.89		1	SUBSIDIARY	0
27	UC_REPAIR_ST	1	8	Unit cost of repair (Surface treatment) ($/square meter)	4		1	SUBSIDIARY	0
28	UC_ROUTINE_PAT	1	8	Unit cost of routine maintenance work (Patch) ($/square meter)	14.24		1	SUBSIDIARY	0
29	UC_ROUTINE_CS	1	8	Unit cost of routine maintenance work (Crack seal) ($/square meter)	14.24		1	SUBSIDIARY	0
30	INSP_INTERVAL	1	8	Inspection interval (year)	4		1	SUBSIDIARY	0
31	NOTE	0	8	Memo of special situation	N/A		1	NETWORK	0
32	TRAF_FLOW	0	2	Name of Traffic Flow Pattern selected for this section	Commuter	Commuter, inter-urban, Free-flow, seasonal	2	NETWORK	1
33	ROAD_CLASS	0	2	Name of road class selected for this section	Secondary or Main	Primary or Trunk, Secondary or Main, Tertiary or Local	2	NETWORK	1
34	SHLD_WIDTH	0	2	Average width of shoulders in meter	3		2	NETWORK	1
35	DIRECTION	1	2	Direction of traffic on section	two-way	One-way downhill, one-way uphill, two-way	2	NETWORK	1
36	RF	1	2	The average absolute rise plus fall of the road in m/km (RF)	1		2	NETWORK	1
37	CURVATURE	1	2	Average horizontal curvature of the road (deg/km) (C)	3		2	NETWORK	1
38	SPEED_LIM	1	2	Posted speed limit on section in km/hr (PLIMIT)	80		2	NETWORK	1
39	CRD_START_X	0	2	Coordination data of origin point of section unit (X axis)	To be inspected		2	NETWORK	0
40	CRD_START_Y	0	2	Coordination data of origin point of section unit (Y axis)	To be inspected		2	NETWORK	0
41	CRD_END_X	0	2	Coordination data of destination point of section unit (X axis)	To be inspected		2	NETWORK	0
42	CRD_END_Y	0	2	Coordination data of destination point of section unit (Y axis)	To be inspected		2	NETWORK	0
43	PAVE_TYPE	1	3	Pavement type characterizing overall condition of pavement	3	0 = AMGB, 1 = AMAB, 2 = AMAP, 3 = AMSB, 4 = STBG, 5 = STAB, 6 = STAP, 7 = STSB	2	NETWORK	1

44	SURF_MATRL	1	3	Surface material	0	0 = AC (Asphalt Concrete), 1 = HRA (Hot Rolled Asphalt), 2 = PMA (Polymer Modified Asphalt), 3 = RAC (Rubberised Asphalt Concrete), 4 = CM (Cold Mix / Soft Bituminous Mix), 5 = PA (Porous Asphalt), 6 = SMA (Stone Mastic), 7 = SBSD (Single Bituminous Surface Dressing), 8 = DBSD (Double Bituminous Surface Dressing), 9 = CAPE (Cape Seal), 10 = SL (Slurry Seal), 11 = PM (Penetration Macadam)	2	NETWORK	1
45	HSNEW	1	3	Thickness of most recent surfacing, in mm (HSNEW)	100		2	NETWORK	1
46	HSOLD	1	3	Total thickness of underlying previous surface layers, in mm (HSOLD)	0		2	NETWORK	1
47	HBASE	1	3	Thickness of base layer in original pavement in mm (for stabilized base only) (HBASE)	200		2	NETWORK	1
48	CBR	1	3	Sub grade California Bearing Ratio (CBR)	8		2	NETWORK	1
49	HSUBBASE	1	3	Height of sub base in mm (used to calculate SNP)	200		2	NETWORK	1
50	HANTI_FREEZE	0	3	Thickness of anti-freeze layer in mm	0		2	NETWORK	0
51	LAST_CONST	1	4	Year of latest reconstruction / new construction activity (used in calculation of AGE indicators)	2000		2	NETWORK	1
52	LAST_SURF	0	4	Last surfacing year (used in calculation of AGE indicators)	2000		2	NETWORK	1
53	LAST_PRVNT	0	4	Year of last preventive treatment (used in calculation of AGE indicators)	2000		2	NETWORK	1
54	AGE1_PRVNT	0	4	Elapsed time from last preventive maintenance type	10		2	NETWORK	0
55	AGE2_SURF	0	4	Elapsed time from last surface treatment type	10		2	NETWORK	0
56	AGE4_CONST	0	4	Elapsed time from last (re)construction type	10		2	NETWORK	0
57	SCHEDULED_MNTN	1	4	Scheduled maintenance work	0	0=no work, 1=reconstruction, 2=cutting overlay, 3=overlay, 4=surface treatment, 5=patching, 6=crack seal	2	NETWORK	1
58	CONDUCTED_MNTN	1	4	Conducted maintenance work	0	0=no work, 1=reconstruction, 2=cutting overlay, 3=overlay, 4=surface treatment, 5=patching, 6=crack seal	2	NETWORK	2
59	BUDGET_USED_MNTN	1	4	Used budget for maintenance activities	N/A		2	NETWORK	3
60	SCHEDULED_INSP	1	4	Scheduled inspection work	0	0=no work, 1=normal inspection, 2=special inspection(FWD, Core, GWR)	2	NETWORK	4
61	CONDUCTED_INSP	1	4	Conducted inspection work	0	0=no work, 1=normal inspection, 2=special inspection(FWD, Core, GWR)	2	NETWORK	5
62	BUDGET_USED_INSP	1	4	Used budget for inspection	N/A		2	NETWORK	6

63	TMS_CODE		5	Traffic management system code (traffic volumn code)	N/A		2	NETWORK	7
64	MT_AADT	1	5	Annual Average Daily Traffic for motorized transport (veh/day in both directions) (AADT)	20000		2	NETWORK	1
65	AADT_YEAR	1	5	Year in which above AADTs were recorded	2010		2	NETWORK	1
66	EDGEBREAK	0	6	Broken edge in m2/km (VEB)	0		2	NETWORK	1
67	TEXT_DEPTH	0	6	Texture depth in mm (TD)	0.7		2	NETWORK	1
68	SKIDRESIST	0	6	Skid resistance (measured at 50 km/h) (SFC50)	0.5		2	NETWORK	1
69	PSI	0	6	Pavement Serviceability Index (0~5)	4.5		2	NETWORK	0
70	CRACKS_THER	0	6	Percentage of transverse thermal crack area of maintenance unit(%)	0		2	NETWORK	0
71	CRACKS_ALLGTR	0	6	Percentage of Alligator crack area of maintenance unit (section)(%)	0		2	NETWORK	0
72	AREA_PATCHED	1	6	Percentage of patched area of maintenance unit (section) (%)	0		2	NETWORK	0
73	MNTN_CRITERIA_RECON	0	8	A maintenance criteria for reconstruction	My criteria		2	SUBSIDIARY	0
74	MNTN_CRITERIA_CUTOL	0	8	A maintenance criteria for cutting-overlay	My criteria		2	SUBSIDIARY	0
75	MNTN_CRITERIA_OL	0	8	A maintenance criteria for overlay	My criteria		2	SUBSIDIARY	0
76	MNTN_CRITERIA_ST	0	8	A maintenance criteria for surface treatment	My criteria		2	SUBSIDIARY	0
77	MNTN_CRITERIA_PAT	0	8	A maintenance criteria for patching	My criteria		2	SUBSIDIARY	0
78	MNTN_CRITERIA_CS	0	8	A maintenance criteria for crack seal	My criteria		2	SUBSIDIARY	0
79	SN	1	3	Structural number for pavement	4.7		3	NETWORK	1
80	CLIM_ZONE	1	5	Name of climate zone selected for this section	Sub-humid/tropical	Arid/Tropical, Humid/Tropical, Semi-Arid/Tropical, Sub-humid/Tropical, Sub-tropical-hot/Semi-arid, Tropical Arid, Tropical Humid, Tropical Semi-arid, Tropical Sub-humid	3	NETWORK	1
81	MESAL	1	5	Million Equivalent Single Axle Loads of section	0.16		3	NETWORK	0
82	AADT_LEVEL	0	5	User defined AADT level of section	Middle	Low, Middle, High	3	NETWORK	0
83	LOAD_LEVEL	0	5	User defined traffic load level of section	Middle	Low, Middle, High	3	NETWORK	0
84	RATIO_HV	0	5	Proportion of Heavy vehicle (differed by each user)	0.1		3	NETWORK	0
85	VEH_VOLUME_TYPE1	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
86	VEH_VOLUME_TYPE2	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
87	VEH_VOLUME_TYPE3	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
88	VEH_VOLUME_TYPE4	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
89	VEH_VOLUME_TYPE5	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
90	VEH_VOLUME_TYPE6	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
91	VEH_VOLUME_TYPE7	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
92	VEH_VOLUME_TYPE8	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
93	VEH_VOLUME_TYPE9	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
94	VEH_VOLUME_TYPE10	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
95	VEH_VOLUME_TYPE11	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
96	VEH_VOLUME_TYPE12	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
97	VEH_VOLUME_TYPE13	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
98	VEH_VOLUME_TYPE14	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0

99	VEH_VOLUME_TYPE15	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
100	VEH_VOLUME_TYPE16	1	5	Traffic volume of vehicle type i in AADT	N/A		3	NETWORK	0
101	DRAIN_COND	0	6	Drain condition	1	0 = Excellent, 1 = Good, 2 = Fair, 3 = Poor, 4 = Very poor	3	NETWORK	1
102	YEAR_VEH_INFO	1	7	Year of vehicle fleet data	N/A		3	VEHICLE	0
103	VEH_NAME	1	7	User specified name for vehicle type	Passenger car		3	VEHICLE	1
104	BASE_TYPE	0	7	HDM-4 base vehicle type upon which this vehicle type was derived.	2	0=motorcycle, 1=small car, 2=medium car, 3= large car, 4=light delivery, 5= light goods, 6=four wheel drive, 7=light truck, 8=medium truck, 9=heavy truck, 10= articulated truck, 11=mini bus, 12=light bus, 13=medium bus, 14=heavybus, 15=couch	3	VEHICLE	1
105	CLASS	1	7	Vehicle class to which vehicle belongs (referring to HDM-4 standard)	1	0=motorcycle, 1=passenger car, 2=utilities, 3=trucks, 4=buses	3	VEHICLE	1
106	INFO	0	7	Long-hand description of vehicle	4 wheel 2 axles		3	VEHICLE	1
107	VEH_AVG_COMP_RATE	1	7	Averaged vehicle composition rate in percentage	0.6		3	VEHICLE	0
108	ESAL	1	7	Number of equivalent standard axles	0.0001		3	VEHICLE	1
109	NOTORIOUS	0	8	Notorious section (having fast maintenance speed) or not	0 (normal)		3	NETWORK	0
110	INTEREST	1	8	Interest for road investment	5.5		3	SUBSIDIARY	0
111	PCSE	1	7	Passenger Car Space Equivalent factor	1		4	VEHICLE	1
112	NUM_WHEELS	0	7	The number of wheels per vehicle	4		4	VEHICLE	1
113	NUM_AXLES	0	7	The number of axles per vehicle	2		4	VEHICLE	1
114	EN_FUELTYP	1	7	Type of fuel (petrol or diesel).	0	0=petrol, 1=diesel	3	VEHICLE	1
115	EUC_VEH	1	7	Economic cost of new vehicle	5400		4	VEHICLE	1
116	EUC_TYRE	1	7	Economic cost of a replacement tyre	54.7		4	VEHICLE	1
117	EUC_FUEL	1	7	Economic cost of fuel per liter (Gasoline or Diesel)	0.63		4	VEHICLE	1
118	EUC_OIL	1	7	Economic cost of lubricants per litre	0.81		4	VEHICLE	1
119	EUC_WORK	1	7	Economic cost of passenger working time per hour	14.343		4	VEHICLE	1
120	EUC_NONWRK	1	7	Economic cost of passenger non-working time per hour	5.293		4	VEHICLE	1
121	EUC_TIME_VEH	1	7	Economic cost of travel time per hour by vehicle type	12.268		4	VEHICLE	0
122	S_DECREMENT	1	7	Speed decrement factor per PCSE	0.125		4	VEHICLE	0
123	SPEED_A1	1	7	A model coefficient for journey speed estimation model	-0.209333333		4	VEHICLE	0
124	SPEED_A2	1	7	A model coefficient for journey speed estimation model	-0.099333333		4	VEHICLE	0
125	SPEED_A3	1	7	A model coefficient for journey speed estimation model	-0.049		4	VEHICLE	0
126	SPEED_A4	1	7	A model coefficient for journey speed estimation model	-1.4575		4	VEHICLE	0
127	SPEED_A5	1	7	A model coefficient for journey speed estimation model	4.400909091		4	VEHICLE	0
128	SPEED_A6	1	7	A model coefficient for journey speed estimation model	1.1		4	VEHICLE	0
129	SPEED_A7	1	7	A model coefficient for journey speed estimation model	1.1		4	VEHICLE	0
130	FUEL_A1	1	7	A model coefficient for fuel consumption estimation model	0.02882		4	VEHICLE	0
131	FUEL_A2	1	7	A model coefficient for fuel consumption estimation model	0.91		4	VEHICLE	0
132	FUEL_A3	1	7	A model coefficient for fuel consumption estimation model	0.000003828		4	VEHICLE	0

133	FUEL_A4	1	7	A model coefficient for fuel consumption estimation model	0.001264		4	VEHICLE	0
134	FUEL_A5	1	7	A model coefficient for fuel consumption estimation model	-0.000712		4	VEHICLE	0
135	FUEL_A6	1	7	A model coefficient for fuel consumption estimation model	0.0007633		4	VEHICLE	0
136	TIRE_A1	1	7	A model coefficient for tire wear estimation model	0.0059		4	VEHICLE	0
137	TIRE_A2	1	7	A model coefficient for tire wear estimation model	-0.0337		4	VEHICLE	0
138	TIRE_A3	1	7	A model coefficient for tire wear estimation model	0.7875		4	VEHICLE	0
139	TIRE_A4	1	7	A model coefficient for tire wear estimation model	-0.1263		4	VEHICLE	0
140	OIL_A1	0	7	A model coefficient for engine oil consumption model	9.04977E-05		4	VEHICLE	0
141	OIL_A2	0	7	A model coefficient for engine oil consumption model	-0.001775675		4	VEHICLE	0
142	OIL_A3	0	7	A model coefficient for engine oil consumption model	0.007246675		4	VEHICLE	0
143	OIL_A4	0	7	A model coefficient for engine oil consumption model	0.054757987		4	VEHICLE	0
144	OIL_A5	0	7	A model coefficient for engine oil consumption model	-0.522187029		4	VEHICLE	0
145	OIL_A6	0	7	A model coefficient for engine oil consumption model	2.2727		4	VEHICLE	0
146	DISTANCE_OIL_CHANGE	1	7	Engine oil change cycle in km	10000		4	VEHICLE	0
147	OIL_CAPACITY	1	7	Engine oil capacity in liter	4		4	VEHICLE	0
148	OIL_CONT	1	7	Rate of oil contamination in liter/1000km	0.4		4	VEHICLE	1
149	OIL_OPER	1	7	Engine oil loss per fuel consumption in liter/liter	0.0028		4	VEHICLE	1
150	VEH_MNTN_A1	1	7	A model coefficient for vehicle maintenance cost estimation model	0.00008		4	VEHICLE	0
151	VEH_MNTN_A2	1	7	A model coefficient for vehicle maintenance cost estimation model	-0.0015		4	VEHICLE	0
152	VEH_MNTN_A3	1	7	A model coefficient for vehicle maintenance cost estimation model	0.0152		4	VEHICLE	0
153	VEH_MNTN_A4	1	7	A model coefficient for vehicle maintenance cost estimation model	0.0409		4	VEHICLE	0
154	VEH_DEP_A1	1	7	A model coefficient for vehicle depreciation cost estimation model	-0.0006		4	VEHICLE	0
155	VEH_DEP_A2	1	7	A model coefficient for vehicle depreciation cost estimation model	0.0165		4	VEHICLE	0
156	VEH_DEP_A3	1	7	A model coefficient for vehicle depreciation cost estimation model	-0.1852		4	VEHICLE	0
157	VEH_DEP_A4	1	7	A model coefficient for vehicle depreciation cost estimation model	1.0542		4	VEHICLE	0
158	NUM_PASSENGER_WORK	1	7	Number of passengers for business purpose per vehicle	0.445		4	VEHICLE	0
159	NUM_PASSENGER_NONWRK	1	7	Number of passengers for non-business purpose per vehicle	1.112		4	VEHICLE	0
160	PERCENT_TRIP_WORK	1	7	Percentage of business trip purpose	28.6		4	VEHICLE	0
161	PERCENT_TRIP_NONWRK	1	7	Percentage of non-business trip purpose	71.4		4	VEHICLE	0
162	ACC_A1	1	7	A model coefficient for estimation of number of accidents	-5.833		4	VEHICLE	0
163	ACC_A2	1	7	A model coefficient for estimation of number of accidents	0.675		4	VEHICLE	0
164	ACC_A3	1	7	A model coefficient for estimation of number of accidents	0.005		4	VEHICLE	0
165	MASS_FUEL	1	7	Mass of petrol used for a vehicle type (Petrol or Diesel)	Petrol		4	VEHICLE	0
166	EM_HC_0	1	7	A model coefficient for vehicle emission (aHC)	0.012		4	VEHICLE	0
167	EM_HC_1	1	7	A model coefficient for vehicle emission (rHC)	0		4	VEHICLE	0

168	EM_CO_0	1	7	A model coefficient for vehicle emission (aNOx)	0.055		4	VEHICLE	0
169	EM_CO_1	1	7	A model coefficient for vehicle emission (FRNOx)	0.17		4	VEHICLE	0
170	EM_NOX_0	1	7	A model coefficient for vehicle emission (aCO)	0.1		4	VEHICLE	0
171	EM_NOX_1	1	7	A model coefficient for vehicle emission (aSO2)	0.0005		4	VEHICLE	0
172	EM_PART_0	1	7	A model coefficient for vehicle emission (Prob_Pb)	0.75		4	VEHICLE	0
173	EM_PART_1	1	7	A model coefficient for vehicle emission (aPb)	0		4	VEHICLE	0
174	EM_CO2_0	1	7	A model coefficient for vehicle emission (aPM)	0.0001		4	VEHICLE	0
175	EM_SO2_0	1	7	A model coefficient for vehicle emission (bPM)	0		4	VEHICLE	0
176	EM_LEAD_0	1	7	A model coefficient for vehicle emission (aCO2)	1.8		4	VEHICLE	0
177	EMISSION_HC_ei	1	7	A model coefficient for vehicle emission (HC_ei)	0.999		4	VEHICLE	0
178	EMISSION_HC_bi	1	7	A model coefficient for vehicle emission (HC_bi)	0.03		4	VEHICLE	0
179	EMISSION_HC_ri	1	7	A model coefficient for vehicle emission (HC_ri)	20		4	VEHICLE	0
180	EMISSION_NOx_ei	1	7	A model coefficient for vehicle emission (Nox_ei)	0.812		4	VEHICLE	0
181	EMISSION_NOx_bi	1	7	A model coefficient for vehicle emission (Nox_bi)	0		4	VEHICLE	0
182	EMISSION_NOx_ri	1	7	A model coefficient for vehicle emission (Nox_ri)	11		4	VEHICLE	0
183	EMISSION_CO_ei	1	7	A model coefficient for vehicle emission (CO_ei)	0.999		4	VEHICLE	0
184	EMISSION_CO_bi	1	7	A model coefficient for vehicle emission (CO_bi)	0.05		4	VEHICLE	0
185	EMISSION_CO_ri	1	7	A model coefficient for vehicle emission (CO_ri)	4.8		4	VEHICLE	0
186	EMISSION_SO2_ei	1	7	A model coefficient for vehicle emission (SO2_ei)	0		4	VEHICLE	0
187	EMISSION_SO2_bi	1	7	A model coefficient for vehicle emission (SO2_bi)	0		4	VEHICLE	0
188	EMISSION_SO2_ri	1	7	A model coefficient for vehicle emission (SO2_ri)	0		4	VEHICLE	0
189	EMISSION_Pb_ei	1	7	A model coefficient for vehicle emission (Pb_ei)	0		4	VEHICLE	0
190	EMISSION_Pb_bi	1	7	A model coefficient for vehicle emission (Pb_bi)	0		4	VEHICLE	0
191	EMISSION_Pb_ri	1	7	A model coefficient for vehicle emission (Pb_ri)	0		4	VEHICLE	0
192	EMISSION_PM_ei	1	7	A model coefficient for vehicle emission (PM_ei)	0		4	VEHICLE	0
193	EMISSION_PM_bi	1	7	A model coefficient for vehicle emission (PM_bi)	0		4	VEHICLE	0
194	EMISSION_PM_ri	1	7	A model coefficient for vehicle emission (PM_ri)	4.8		4	VEHICLE	0
195	PCT_ACC_FATAL_CASE	1	8	Accident rate of fatal(death) accident in case/ 100 million veh-km	3.38		4	SUBSIDIARY	0
196	PCT_ACC_INJURY_CASE	1	8	Accident rate of injury in case/ 100 million veh-km	63.27		4	SUBSIDIARY	0
197	PCT_ACC_PROPERTY_CASE	1	8	Accident rate of property in case/ 100 million veh-km	968.16		4	SUBSIDIARY	0
198	PCT_ACC_FATAL_PERSON	1	8	Accident rate of fatal(death) accident in person/ 100 million veh-km	3.58		4	SUBSIDIARY	0
199	PCT_ACC_INJURY_PERSON	1	8	Accident rate of injury in person/ 100 million veh-km	120.99		4	SUBSIDIARY	0
200	PCT_ACC_PROPERTY_PERSON	1	8	Accident rate of property in case/ 100 million veh-km	642.45		4	SUBSIDIARY	0
201	AADT_INCREMENT_AVG	0	8	Average AADT increment rate in percent	0.1		4	SUBSIDIARY	0
202	AADT_INCREMENT_STDEV	0	8	Standard deviation of AADT in AADT	0.21		4	SUBSIDIARY	0
203	EUC_DEATH_HUMAN	1	8	Economic cost of human death per person	317340.6		4	SUBSIDIARY	0
204	EUC_DEATH_PROPERTY	1	8	Economic cost of property lose per case (death)	847.32		4	SUBSIDIARY	0

205	EUC_DEATH_SOCIAL	1	8	Economic cost of social cost per person	1317.11		4	SUBSIDIARY	0
206	EUC_INJURY_HUMAN	1	8	Economic cost of human injury per person	3095.64		4	SUBSIDIARY	0
207	EUC_INJURY_PROPERTY	1	8	Economic cost of property lose per case (injury)	847.32		4	SUBSIDIARY	0
208	EUC_INJURY_SOCIAL	1	8	Economic cost of social cost per person	1031.88		4	SUBSIDIARY	0
209	EUC_CAR_PROPERTY	1	8	Economic cost of car damage per case	813.76		4	SUBSIDIARY	0
210	EUC_CAR_SOCIAL	1	8	Economic cost of social lose per case	109.06		4	SUBSIDIARY	0
211	EUC_PROPERTY_PROPERTY	1	8	Economic cost of property damage per case	987.65		4	SUBSIDIARY	0
212	EUC_PROPERTY_SOCIAL	1	8	Economic cost of social lose per case	109.06		4	SUBSIDIARY	0
213	EUC_EMISSION_CO	1	8	Economic cost of CO emission per ton	6608		4	SUBSIDIARY	0
214	EUC_EMISSION_HC	1	8	Economic cost of HC emission per ton	7680		4	SUBSIDIARY	0
215	EUC_EMISSION_Nox	1	8	Economic cost of NOx emission per ton	7951		4	SUBSIDIARY	0
216	EUC_EMISSION_SO2	1	8	Economic cost of SO2 emission per ton	600		4	SUBSIDIARY	0
217	EUC_EMISSION_Pb	1	8	Economic cost of Pb emission per ton	0		4	SUBSIDIARY	0
218	EUC_EMISSION_PM	1	8	Economic cost of PM emission per ton	25957		4	SUBSIDIARY	0
219	EUC_EMISSION_CO2	1	8	Economic cost of CO2 emission per ton	126		4	SUBSIDIARY	0

Note: 1) Category: 1= Identification,
2= physical & operational characteristic,
3= pavement design variables,
4=maintenance & inspection history,
5=explanatory variables,
6=pavement condition,
7=vehicle fleet,
8=subsidiary data
2) Data set: 1= minimum level,
2= general level,
3=recommended level,
4= advanced level
3) HDM-4: 1= duplicated,
0= unduplicated

Appendix B: Standards for Generation of Artificial Pavement Deterioration Data

Table B.1 Combination of deterioration factors by network level

Num.Net	Administration			Environment			Traffic condition			Geometry		Pavement design		Road classification	
	Country	Agency	Network	Cold	Normal	Hot	High	Middle	Low	Flat	Mountain	HMA	Super	N.H	Expressway
1	Unknown	EAST	EN1		TRUE		TRUE			TRUE		TRUE		TRUE	
2		EAST	EN2		TRUE		TRUE			TRUE			TRUE	TRUE	
3		EAST	EN3		TRUE		TRUE				TRUE	TRUE		TRUE	
4		EAST	EN4		TRUE		TRUE				TRUE		TRUE	TRUE	
5		EAST	EN5		TRUE			TRUE		TRUE		TRUE		TRUE	
6		EAST	EN6		TRUE			TRUE		TRUE			TRUE	TRUE	
7		EAST	EN7		TRUE			TRUE			TRUE	TRUE		TRUE	
8		EAST	EN8		TRUE			TRUE			TRUE		TRUE	TRUE	
9		EAST	EN9		TRUE				TRUE	TRUE		TRUE		TRUE	
10		EAST	EN10		TRUE				TRUE	TRUE			TRUE	TRUE	
11		EAST	EN11		TRUE				TRUE		TRUE	TRUE		TRUE	
12		EAST	EN12		TRUE				TRUE		TRUE		TRUE	TRUE	
13		NORTH	NN1	TRUE			TRUE			TRUE		TRUE		TRUE	
14		NORTH	NN2	TRUE			TRUE			TRUE			TRUE	TRUE	
15		NORTH	NN3	TRUE				TRUE			TRUE	TRUE		TRUE	
16		NORTH	NN4	TRUE				TRUE			TRUE		TRUE	TRUE	
17		NORTH	NN5	TRUE					TRUE	TRUE		TRUE		TRUE	
18		NORTH	NN6	TRUE					TRUE	TRUE			TRUE	TRUE	
19		SOUTH	SN1			TRUE	TRUE				TRUE	TRUE		TRUE	
20		SOUTH	SN2			TRUE	TRUE				TRUE		TRUE	TRUE	
21		SOUTH	SN3			TRUE		TRUE		TRUE		TRUE		TRUE	
22		SOUTH	SN4			TRUE		TRUE		TRUE			TRUE	TRUE	41
23		SOUTH	SN5			TRUE			TRUE		TRUE	TRUE		TRUE	
24		SOUTH	SN6			TRUE			TRUE		TRUE		TRUE	TRUE	
25		WEST	WN1		TRUE		TRUE			TRUE		TREU		TRUE	
26		WEST	WN2		TRUE		TRUE			TRUE			TRUE	TRUE	
27		WEST	WN3		TRUE		TRUE				TRUE	TREU		TRUE	
28		WEST	WN4		TRUE		TRUE				TRUE		TRUE	TRUE	
29		WEST	WN5		TRUE			TRUE		TRUE		TREU		TRUE	
30		WEST	WN6		TRUE			TRUE		TRUE			TRUE	TRUE	
31		WEST	WN7		TRUE			TRUE			TRUE	TREU		TRUE	
32		WEST	WN8		TRUE			TRUE			TRUE		TRUE	TRUE	
33		WEST	WN9		TRUE				TRUE	TRUE		TREU		TRUE	
34		WEST	WN10		TRUE				TRUE	TRUE			TRUE	TRUE	
35		WEST	WN11		TRUE				TRUE		TRUE	TREU		TRUE	
36		WEST	WN12		TRUE				TRUE		TRUE		TRUE	TRUE	
37		HIGHWAY	HN1		TRUE			TRUE		TRUE		TRUE			TRUE

Table B.2 Assumed weighting factors for defining deterioration speed

No	Network		Environment			Traffic condition			Geometry			Pavement design			Road classification			Integration		
	Agency	Net.	w_e^c	w_e^r	w_e^i	w_t^c	w_t^r	w_t^i	w_g^c	w_g^r	w_g^i	w_p^c	w_p^r	w_p^i	w_f^c	w_f^c	w_f^c	$1+\sum w_s^c$	$1+\sum w_s^r$	$1+\sum w_s^i$
1	EAST	EN1	0	0	0	0.2	0.3	0.3	0	0	0	0	0	0	0	0	0	1.2	1.3	1.3
2	EAST	EN2	0	0	0	0.2	0.3	0.3	0	0	0	-0.2	-0.2	-0.2	0	0	0	1	1.1	1.1
3	EAST	EN3	0	0	0	0.2	0.3	0.3	0.13	0.05	0.08	0	0	0	0	0	0	1.33	1.35	1.38
4	EAST	EN4	0	0	0	0.2	0.3	0.3	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	1.13	1.15	1.18
5	EAST	EN5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
6	EAST	EN6	0	0	0	0	0	0	0	0	0	-0.2	-0.2	-0.2	0	0	0	0.8	0.8	0.8
7	EAST	EN7	0	0	0	0	0	0	0.13	0.05	0.08	0	0	0	0	0	0	1.13	1.05	1.08
8	EAST	EN8	0	0	0	0	0	0	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	0.93	0.85	0.88
9	EAST	EN9	0	0	0	-0.2	-0.3	-0.3	0	0	0	0	0	0	0	0	0	0.8	0.7	0.7
10	EAST	EN10	0	0	0	-0.2	-0.3	-0.3	0	0	0	-0.2	-0.2	-0.2	0	0	0	0.6	0.5	0.5
11	EAST	EN11	0	0	0	-0.2	-0.3	-0.3	0.13	0.05	0.08	0	0	0	0	0	0	0.93	0.75	0.78
12	EAST	EN12	0	0	0	-0.2	-0.3	-0.3	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	0.73	0.55	0.58
13	NORTH	NN1	0.2	0	0.1	0.2	0.3	0.3	0	0	0	0	0	0	0	0	0	1.4	1.3	1.4
14	NORTH	NN2	0.2	0	0.1	0.2	0.3	0.3	0	0	0	-0.2	-0.2	-0.2	0	0	0	1.2	1.1	1.2
15	NORTH	NN3	0.2	0	0.1	0	0	0	0.13	0.05	0.08	0	0	0	0	0	0	1.33	1.05	1.18
16	NORTH	NN4	0.2	0	0.1	0	0	0	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	1.13	0.85	0.98
17	NORTH	NN5	0.2	0	0.1	-0.2	-0.3	-0.3	0	0	0	0	0	0	0	0	0	1	0.7	0.8
18	NORTH	NN6	0.2	0	0.1	-0.2	-0.3	-0.3	0	0	0	-0.2	-0.2	-0.2	0	0	0	0.8	0.5	0.6
19	SOUTH	SN1	0	0.3	0.3	0.2	0.3	0.3	0.13	0.05	0.08	0	0	0	0	0	0	1.33	1.65	1.68
20	SOUTH	SN2	0	0.3	0.3	0.2	0.3	0.3	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	1.13	1.45	1.48
21	SOUTH	SN3	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	1	1.3	1.3
22	SOUTH	SN4	0	0.3	0.3	0	0	0	0	0	0	-0.2	-0.2	-0.2	0	0	0	0.8	1.1	1.1
23	SOUTH	SN5	0	0.3	0.3	-0.2	-0.3	-0.3	0.13	0.05	0.08	0	0	0	0	0	0	0.93	1.05	1.08
24	SOUTH	SN6	0	0.3	0.3	-0.2	-0.3	-0.3	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	0.73	0.85	0.88
25	WEST	WN1	0	0	0	0.2	0.3	0.3	0	0	0	0	0	0	0	0	0	1.2	1.3	1.3
26	WEST	WN2	0	0	0	0.2	0.3	0.3	0	0	0	-0.2	-0.2	-0.2	0	0	0	1	1.1	1.1
27	WEST	WN3	0	0	0	0.2	0.3	0.3	0.13	0.05	0.08	0	0	0	0	0	0	1.33	1.35	1.38
28	WEST	WN4	0	0	0	0.2	0.3	0.3	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	1.13	1.15	1.18
29	WEST	WN5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
30	WEST	WN6	0	0	0	0	0	0	0	0	0	-0.2	-0.2	-0.2	0	0	0	0.8	0.8	0.8
31	WEST	WN7	0	0	0	0	0	0	0.13	0.05	0.08	0	0	0	0	0	0	1.13	1.05	1.08
32	WEST	WN8	0	0	0	0	0	0	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	0.93	0.85	0.88
33	WEST	WN9	0	0	0	-0.2	-0.3	-0.3	0	0	0	0	0	0	0	0	0	0.8	0.7	0.7
34	WEST	WN10	0	0	0	-0.2	-0.3	-0.3	0	0	0	-0.2	-0.2	-0.2	0	0	0	0.6	0.5	0.5
35	WEST	WN11	0	0	0	-0.2	-0.3	-0.3	0.13	0.05	0.08	0	0	0	0	0	0	0.93	0.75	0.78
36	WEST	WN12	0	0	0	-0.2	-0.3	-0.3	0.13	0.05	0.08	-0.2	-0.2	-0.2	0	0	0	0.73	0.55	0.58
37	Highway	HN1	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	-0.2	-0.2	0.8	0.8	0.8

Appendix C: Derivation of Markov Exponential Hazard Model

1. Derivation process of the $\pi_{i,i+2}$,

First, integral calculus of the dz_{i+1} is;

$\pi_{i,i+2} \ = \ Prob[h(\tau_B) = i + 2|h(\tau_A) = i]$

$= \ \int_0^Z \int_0^{Z-z_i} q_{i+2}\,(Z_i, Z_{i+1}|\zeta_i \geq y_A) dz_i dz_{i+1}$

$= \ \int_0^Z \int_0^{Z-z_i} f_i(z_i)\, f_{i+1}(z_{i+1}) R_{i+2}(Z - z_i - z_{i+1}) dz_i dz_{i+1}$

$= \ \int_0^Z \int_0^{Z-z_i} \theta_i exp(-\theta_i z_i)\, \theta_{i+1} exp(-\theta_{i+1} z_{i+1}) exp\{-\theta_{i+2}(Z - z_i - z_{i+1})\} dz_i dz_{i+1}$

$= \ \int_0^Z \int_0^{Z-z_i} \theta_i \theta_{i+1} exp\{-\theta_{i+2} Z - \sum_{m=1}^{i+1} (\theta_m - \theta_{i+2}) z_m\}\, dz_i dz_{i+1}$

$= \ \int_0^Z \theta_i \theta_{i+1} exp(\,-\,\theta_{i+2} Z) exp\{-(\theta_i - \theta_{i+2}) z_i\} \left[\int_0^{Z-z_i} exp\{-(\theta_{i+1} - \theta_{i+2}) z_{i+1}\} dz_{i+1}\right] dz_i$

$= \ \int_0^Z \theta_i \theta_{i+1} exp(\,-\,\theta_{i+2} Z) exp\{-(\theta_i - \theta_{i+2}) z_i\} \frac{-1}{\theta_{i+1} - \theta_{i+2}} [exp\{-(\theta_{i+1} - \theta_{i+2})(Z - z_i) - 1] dz_i$

$= \ -\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}} \int_0^Z exp(-\theta_{i+2} Z) exp\{-(\,\theta_{i+1} - \theta_{i+2}) Z\} exp\{-(\theta_i - \theta_{i+2}) z_i\} exp\{-(\theta_{i+1} - \theta_{i+2})(-z_i)\} dz_i$
$+\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}} \int_0^Z exp(-\theta_{i+2} Z) exp\{-(\,\theta_i - \theta_{i+2}) z_i\} dz_i$

Solving the First Part;

$= \ -\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}} \int_0^Z exp(-\theta_{i+1} Z) exp\{-(\,\theta_i - \theta_{i+2}) z_i + (\theta_{i+1} - \theta_{i+2}) z_i\} dz_i$

$= \ -\,\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}} \int_0^Z exp(-\theta_{i+1} Z) exp\{-(\,\theta_i - \theta_{i+2}) z_i\} dz_i$

$= \ -\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}} \int_0^Z exp(-\theta_i z_i) exp\{-(\,\theta_{i+1}(Z - z_i)\} dz_i$

$= \ -\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}} \int_0^Z f_i(z_i) R_{i+1}(Z - z_i)\} dz_i$

$= \ -\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}} \pi_{i,i+1}$

$= \ -\frac{\theta_{i+1} \theta_i}{(\theta_{i+1} - \theta_{i+2})(\theta_i - \theta_{i+1})} \{-exp(-\theta_i Z) + exp(-\theta_{i+1} Z)\}$

And the Second Part;

$=-\frac{\theta_i \theta_{i+1}}{\theta_{i+1} - \theta_{i+2}}\ exp(-\theta_{i+2} Z)\ \int_0^Z exp\{-(\,\theta_i - \theta_{i+2}) z_i\} dz_i$

$=-\frac{\theta_i \theta_{i+1}}{(\theta_{i+1} - \theta_{i+2})(\theta_i - \theta_{i+1})}\ exp(-\theta_{i+2} Z)\ [exp\{-(\theta_i - \theta_{i+2}) Z\} - 1]$

$=-\frac{\theta_i \theta_{i+1}}{(\theta_{i+1} - \theta_{i+2})(\theta_i - \theta_{i+1})}\ exp(-\theta_i Z) + \frac{\theta_i \theta_{i+1}}{(\theta_{i+1} - \theta_{i+2})(\theta_i - \theta_{i+2})} exp(-\theta_{i+2} Z)$

$\boldsymbol{\pi_{i,i+2}}$ = ***The first part + The second part;***

$= -\frac{\theta_i\theta_{i+1}}{(\theta_{i+1}-\theta_{i+2})(\theta_i-\theta_{i+1})}\{-exp(-\theta_i Z) + exp(-\theta_{i+1}Z)\}$

$-\frac{\theta_i\theta_{i+1}}{(\theta_{i+1}-\theta_{i+2})(\theta_i-\theta_{i+2})}exp(-\theta_i Z) + \frac{\theta_i\theta_{i+1}}{(\theta_{i+1}-\theta_{i+2})(\theta_i-\theta_{i+2})}exp(-\theta_{i+2}Z)$

$= \frac{\theta_i\theta_{i+1}}{(\theta_{i+1}-\theta_i)(\theta_{i+2}-\theta_i)}exp(-\theta_i Z) + \frac{\theta_i\theta_{i+1}}{(\theta_i-\theta_{i+1})(\theta_{i+2}-\theta_{i+1})}exp(-\theta_{i+1}Z)$

$+\frac{\theta_i\theta_{i+1}}{(\theta_i-\theta_{i+2})(\theta_{i+1}-\theta_{i+2})}exp(-\theta_{i+2}Z)$

$= \sum_{k=i}^{i+2}\prod_{m=i}^{k-1}\frac{\theta_m}{\theta_m-\theta_k}\prod_{m=k}^{i+1}\frac{\theta_m}{\theta_{m+1}-\theta_k}exp(-\theta_k Z)$

2. Derivation process of the $\boldsymbol{\pi_{i,i+3}}$,

First, integral calculus of the $\boldsymbol{dz_{i+2}}$ ***is;***

$\pi_{i,i+3} = Prob[h(\tau_B) = i+3|h(\tau_A) = i]$

$= \int_0^Z\int_0^{Z-z_1}\int_0^{Z-\sum_{m=i}^{i+1}z_m} q_{i+3}(z_i, z_{i+1,} z_{i+2}|\zeta_i \geq y_A)\, dz_i dz_{i+1} dz_{i+2}$

$= \int_0^Z\int_0^{Z-z_1}\int_0^{Z-\sum_{m=i}^{i+1}z_m} \theta_i exp(-\theta_i z_i)\theta_{i+1}exp(-\theta_{i+1}z_{i+1})\theta_{i+2}exp(-\theta_{i+2}z_{i+2})exp\{-\theta_{i+3}(Z - \sum_{m=1}^{i+2}z_m)\}\, dz_i dz_{i+1} dz_{i+2}$

$= \int_0^Z\int_0^{Z-z_1}\int_0^{Z-\sum_{m=i}^{i+1}z_m} \prod_{m=i}^{i+2}\theta_m exp\{-\theta_{i+3}Z - \sum_{m=i}^{i+2}(\theta_m - \theta_{i+3})Z_m\}\, dz_i dz_{i+1} dz_{i+2}$

$= \int_0^Z\int_0^{Z-z_1}\prod_{m=i}^{i+2}\theta_m exp(-\theta_{i+3}Z)exp\{-\sum_{m=i}^{i+1}(\theta_m - \theta_{i+3})Z_m\}\left[\int_0^{Z-\sum_{m=i}^{i+1}z_m} exp\{-(\theta_{i+2} - \theta_{i+3})z_{i+2}\}\, dz_{i+2}\right] dz_i dz_{i+1}$

$= \int_0^Z\int_0^{Z-z_1}\prod_{m=i}^{i+2}\theta_m exp(-\theta_{i+3}Z)exp\{-\sum_{m=i}^{i+1}(\theta_m - \theta_{i+3})Z_m\}\frac{-1}{\theta_{i+2}-\theta_{i+3}}[exp\{-(\theta_{i+2} - \theta_{i+3})(Z - \sum_{m=i}^{i+1}z_m)\} - 1]dz_i dz_{i+1}$

$= -\frac{\prod_{m=i}^{i+2}\theta_m}{\theta_{i+2}-\theta_{i+3}}\int_0^Z\int_0^{Z-z_i} exp(-\theta_{i+3}Z)exp\{-(\theta_{i+2} - \theta_{i+3})Z\}exp\{-\sum_{m=i}^{i+1}(\theta_m - \theta_{i+3})z_m\}exp\{-(\theta_{i+2} - \theta_{i+3})(-\sum_{m=i}^{i+1}z_m)\}\, dz_i dz_{i+1} + \frac{\prod_{m=i}^{i+2}\theta_m}{\theta_{i+2}-\theta_{i+3}}\int_0^Z\int_0^{Z-z_i} exp(-\theta_{i+3}Z)exp\{-\sum_{m=i}^{i+1}(\theta_m - \theta_{i+3})z_m\}dz_i dz_{i+1}$

About the First Part,

$= -\frac{\prod_{m=i}^{i+2}\theta_m}{\theta_{i+2}-\theta_{i+3}}\int_0^Z\int_0^{Z-z_i} exp(-\theta_{i+2}Z)exp\{-\sum_{m=i}^{i+1}(\theta_m - \theta_{i+3})z_m + \sum_{m=1}^{i=1}(\theta_{i+2} - \theta_{i+3})z_m\}dz_i dz_{i+1}$

$= -\frac{\prod_{m=i}^{i+2}\theta_m}{\theta_{i+2}-\theta_{i+3}}\int_0^Z\int_0^{Z-z_i} exp(-\theta_{i+2}Z)exp\{-\sum_{m=i}^{i+1}(\theta_m - \theta_{i+2})z_m\}dz_i dz_{i+1}$

$= -\frac{\theta_{i+2}}{\theta_{i+2}-\theta_{i+3}}\int_0^Z\int_0^{Z-z_i} \theta_i\, exp(-\theta_i z_i)\theta_{i+1}exp(-\theta_{i+1}z_{i+1})exp\{-\theta_{i+2}(Z - z_i - z_{i+1})\}dz_i dz_{i+1}$

$$= -\frac{\theta_{i+2}}{\theta_{i+2}-\theta_{i+3}}\int_0^Z\int_0^{Z-z_i} f_i(z_i)f_{i+1}(z_{i+1})\,R_{i+2}(Z-z_i-z_{i+1})dz_idz_{i+1}$$

$$= -\frac{\theta_{i+2}}{\theta_{i+2}-\theta_{i+3}}\,\pi_{i,i+2}$$

$$= -\frac{\theta_{i+2}}{\theta_{i+2}-\theta_{i+3}}\,\sum_{k=i}^{i+2}\prod_{m=i}^{k-1}\frac{\theta_m}{\theta_m-\theta_k}\prod_{m=k}^{i+1}\frac{\theta_m}{\theta_{m+1}-\theta_k}exp(-\theta_kZ)$$

$$= -\frac{\theta_i\theta_{i+1}\theta_{i+2}}{\theta_{i+2}-\theta_{i+3}}\Big[\frac{1}{(\theta_{i+1}-\theta_i)(\theta_{i+2}-\theta_i)}exp(-\theta_iZ)+\frac{1}{(\theta_i-\theta_{i+1})(\theta_{i+2}-\theta_{i+1})}exp(-\theta_{i+1}Z)+\frac{1}{(\theta_i-\theta_{i+2})(\theta_{i+1}-\theta_{i+2})}exp(-\theta_{i+2}Z)\Big]$$

About the Second Part;

$$= \frac{\prod_{m=i}^{i+2}\theta_m}{\theta_{i+2}-\theta_{i+3}}\int_0^Z exp(-\,\theta_{i+3}Z)exp\{-(\theta_i-\theta_{i+3})z_i\}\left[\int_0^{Z-z_i} exp\{-(\theta_{i+1}-\theta_{i+3})z_{i+1}\}dz_{i+1}\right]dz_i$$

$$= \frac{\prod_{m=i}^{i+2}\theta_m}{\theta_{i+2}-\theta_{i+3}}\int_0^Z exp(-\,\theta_{i+3}Z)exp\{-(\theta_i-\theta_{i+3})z_i\}\,\frac{-1}{(\theta_{i+1}-\theta_{i+3})}\,[exp\{-(\theta_{i+1}-\theta_{i+3})(Z-z_i)\}-1]dz_i$$

$$= -\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_{i+2}-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})}\int_0^Z exp(-\,\theta_{i+1}Z)exp\{-(\theta_i-\theta_{i+3})z_i\}exp\{(\theta_{i+1}-\theta_{i+3})z_i\}dz_i+\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_{i+2}-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})}\int_0^Z exp(-\,\theta_{i+3}Z)exp\{-(\theta_i-\theta_{i+3})z_i\}dz_i$$

$$= -\frac{\theta_{i+1}\theta_{i+2}}{(\theta_{i+2}-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})}\pi_{i,i+1}+\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_{i+2}-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})}exp(-\theta_{i+3}Z)\frac{-1}{\theta_i-\theta_{i+3}}[exp\{-(\theta_i-\theta_{i+3})Z-1]$$

$$= -\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_{i+2}-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})(\theta_i-\theta_{i+1})}\{-exp(-\theta_iZ)+exp(-\theta_{i+1}Z)\}+\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_{i+2}-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})(\theta_{i+3}-\theta_i)}exp(-\theta_iZ)-\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_{i+2}-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})(\theta_{i+3}-\theta_i)}\;exp(-\theta_{i+3}Z)$$

$$= -\frac{\theta_i\theta_{i+1}\theta_{i+2}}{\theta_{i+2}-\theta_{i+3}}\Big[-\frac{1}{(\theta_{i+3}-\theta_i)(\theta_i-\theta_{i+1})}exp(\theta_iZ)-\frac{1}{(\theta_{i+1}-\theta_{i+3})(\theta_i-\theta_{i+1})}exp(-\theta_{i+1}Z)-\frac{1}{(\theta_{i+1}-\theta_{i+3})(\theta_{i+3}-\theta_i)}exp(-\theta_{i+3}Z)\Big]$$

$\boldsymbol{\pi_{i,i+3}}$ ***= The first part + The second part;***

$$= \Big[\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_{i+1}-\theta_i)(\theta_{i+2}-\theta_i)(\theta_{i+3}-\theta_i)}exp(-\theta_iZ)+\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_i-\theta_{i+1})(\theta_{i+2}-\theta_i)(\theta_{i+3}-\theta_i)}exp(-\theta_{i+1}Z)+\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_i-\theta_{i+2})(\theta_{i+1}-\theta_{i+2})(\theta_{i+3}-\theta_{i+2})}exp(-\theta_{i+1}Z)+\frac{\theta_i\theta_{i+1}\theta_{i+2}}{(\theta_i-\theta_{i+3})(\theta_{i+1}-\theta_{i+3})(\theta_{i+2}-\theta_{i+3})}exp(-\theta_{i+3}Z)\Big]$$

$$= \sum_{k=i}^{i+3}\prod_{m=i}^{k-1}\frac{\theta_m}{\theta_m-\theta_k}\prod_{m=k}^{i+1}\frac{\theta_m}{\theta_{m+1}-\theta_k}exp(-\theta_kZ)$$

3. Normalization of the $\boldsymbol{\pi_{i,j}}$

$$\pi_{i,j}\;=\;Prob[h(\tau_B)=j|h(\tau_A)=i]$$

$$= \int_0^Z\int_0^{Z-z_i}\dots\int_0^{Z-\sum_{m=i}^{j-2}z_m} q_j(z_i,\dots,z_{j-1}|\zeta_i\geq y_A)dz_i\dots dz_{j-1}$$

$= \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-2} z_m} \prod_{m=i}^{j-1} \theta_m exp\{-\theta_j Z - \sum_{m=i}^{j-1}(\theta_m - \theta_j) z_m\} dz_i \dots dz_{j-1}$

$= \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-2} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp\{-\sum_{m=i}^{j-2}(\theta_m - \theta_j) z_m\} exp\{-(\theta_{j-1} - \theta_j) z_{j-1}\} dz_i \dots dz_{j-1}$

$= \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-3} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp\{-\sum_{m=i}^{j-2}(\theta_m - \theta_j) z_m\} \int_0^{Z-\sum_{m=i}^{j-2} z_m} exp\,\{-(\theta_{j-1} - \theta_j) z_{j-1}\} dz_i \dots dz_{j-1}$

$= -\frac{1}{\theta_{j-1}-\theta_j} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-3} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp\{-\sum_{m=i}^{j-2}(\theta_m - \theta_j) z_m\}[exp\{-(\theta_{j-1} - \theta_j)(Z - \sum_{m=i}^{j-2} z_m)\} - 1]\, dz_i \dots dz_{j-2}$

$= -\frac{1}{\theta_{j-1}-\theta_j} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-3} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp\{-(\theta_{j-1} - \theta_j) Z\}\, exp\{-\sum_{m=i}^{j-2}(\theta_m - \theta_j) z_m\} exp\{-(\theta_{j-1} - \theta_j)(-\sum_{m=i}^{j-2} z_m)\} dz_i \dots dz_{j-2} +$
$\frac{1}{\theta_{j-1}-\theta_j} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-3} z_m} \prod_{m=i}^{j-1} \theta_m | exp(-\theta_j Z) exp\{-\sum_{m=i}^{j-2}(\theta_m - \theta_j) z_m\}\, dz_i \dots dz_{j-2}$

About the First Part;

$= -\frac{1}{\theta_{j-1}-\theta_j} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-3} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp\{-\sum_{m=i}^{j-2}(\theta_m - \theta_j) z_m + \sum_{m=i}^{j-2}(\theta_{j-1} - \theta_j) z_m\} dz_i \dots dz_{j-2}$

$= -\frac{1}{\theta_{j-1}-\theta_j} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-3} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_{j-1} Z)\, exp\{-\sum_{m=i}^{j-2}(\theta_m - \theta_{j-1}) z_m\}\, dz_i \dots dz_{j-2}$

$= -\frac{1}{\theta_{j-1}-\theta_j} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-3} z_m} \prod_{m=i}^{j-2} \theta_m exp(-\theta_{j-1} Z - \sum_{m=i}^{j-2}(\theta_m - \theta_{j-1}) z_m\}\, dz_i \dots dz_{j-2}$

$= -\frac{1}{\theta_{j-1}-\theta_j}\, \pi_{i,j-1}$

About the Second Part;

$= -\frac{1}{\theta_{j-1}-\theta_j} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-4} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp(-\sum_{m=i}^{j-3}(\theta_m - \theta_j) z_m\} \int_0^{Z-\sum_{m=i}^{j-3} z_m} exp(-\theta_{j-2} - \theta_j) z_{j-2}\}\, dz_i \dots dz_{j-2}$

$= -\frac{1}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-4} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp(-\sum_{m=i}^{j-3}(\theta_m - \theta_j) z_m\}\, [exp\{-(\theta_{j-2} - \theta_j)(Z - \sum_{m=i}^{j-3} z_m)\} - 1]\, dz_i \dots dz_{j-3}$

$= -\frac{1}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-4} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_{j-2} Z)\, exp(-\sum_{m=i}^{j-3}(\theta_m - \theta_j) z_m\}\, exp\{\sum_{m=i}^{j-3}(\theta_{j-2} - \theta_j) z_m\}\, dz_i \dots dz_{j-3} +$
$\frac{1}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)} \int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-4} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp\{-\sum_{m=i}^{j-3}(\theta_m - \theta_j) z_m\}\, dz_i \dots dz_{j-3}$

$=$
$\frac{\theta_{j-1}-\theta_j}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)}\pi_{i,j-2} + \frac{1}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)}\int_0^Z \int_0^{Z-z_i} \dots \int_0^{Z-\sum_{m=i}^{j-4} z_m} \prod_{m=i}^{j-1} \theta_m exp(-\theta_j Z)\, exp\{-\sum_{m=i}^{j-3}(\theta_m - \theta_j) z_m\}\, dz_i \dots dz_{j-3}$

Standardized by;

$\pi_{i,j} =$
$-\frac{\theta_{j-1}}{\theta_{j-1}-\theta_j}\pi_{i,j-1} - \frac{\theta_{j-1}\theta_{j-2}}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)}\pi_{i,j-2} - \cdots + \prod_{m=i+1}^{j-1}\frac{1}{\theta_m-\theta_j}\int_0^J \prod_{m=i}^{j-1}\theta_m exp(-\theta_j Z)\, exp\,\{-(\theta_i - \theta_j) z_i\} dz_i$

$= -\frac{\theta_{j-1}}{\theta_{j-1}-\theta_j}\pi_{i,j-1} - \frac{\theta_{j-1}\theta_{j-2}}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)}\pi_{i,j-2} - \cdots - \prod_{m=i+1}^{j-1}\frac{\theta_m}{\theta_m-\theta_j} exp(-\theta_j Z)[exp\{-(-\theta_i - \theta_j)Z\} - 1]$

$= -\frac{\theta_{j-1}}{\theta_{j-1}-\theta_j}\pi_{i,j-1} - \frac{\theta_{j-1}\theta_{j-2}}{(\theta_{j-1}-\theta_j)(\theta_{j-2}-\theta_j)}\pi_{i,j-2} - \cdots - \prod_{m=i+1}^{j-1}\frac{\theta_m}{\theta_m-\theta_j}\{exp(-\theta_i Z) - exp(-\theta_j Z)\}$

$= -\sum_{k=i}^{j-1}\prod_{m=k}^{j-1}\frac{\theta_m}{\theta_m-\theta_j}\pi_{i,k} + \prod_{m=i}^{j-1}\frac{\theta_m}{\theta_m-\theta_j} exp(-\theta_j Z)$

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