# Model Simulation and Health Risk Assessment of Traffic-Induced Air Pollution in Urban Environments: A Case Study of Kyoto City, Japan

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**2020**

# ABSTRACT

This research discusses the simulation of traffic-induced air pollution in Kyoto City, Japan in terms of emission, dispersion, health risk assessment. This research was completed in seven chapters as followed:

## Chapter 1 Introduction

Chapter 1 presents the overview of current situation, problem statements, research objectives and scopes, and outline of the dissertation.

## Chapter 2 Literature review

Chapter 2 reviews the previous studies on traffic characteristics, vehicle emission model (Computer Program to Calculate Emissions from Road Transport; COPERT model), air dispersion model (Operational Street Pollution Model; OSPM model), health risk assessment and framework of risk-based management.

## Chapter 3 Traffic characteristics and pollutant emission from road transport urban environment

Chapter 3 presents the traffic characteristics and emissions of air pollutants were predicted for two vehicle classifications (passenger cars and trucks) at five functional classes of roadways in Kyoto City, Japan (H-MLIT, H-P, MM, P and GM). The roadways are categorized into five functional classes such as highway under jurisdiction of Ministry of Land, Infrastructure, Transport and Tourism (H-MLIT), highway administered by prefectural authority (H-P), main municipal road (MM), prefectural road (P) and general municipal road (GM). A vehicle emission model, known as the Computer Programme to Calculate Emissions from Road Transport (COPERT), was utilised to compute the emission factors (EFs) and total emissions of air pollutants (exhaust particulate matter ($PM_{Exh}$), benzene, carbon monoxide (CO) and nitrogen oxide ($NO_x$)) and fuel consumption. The results show the EFs of pollutants (benzene, CO, NOx, $PM_{Exh}$, and fuel consumption) are substantial at lower travel speed (2–30kmph) and gradually decrease by the increase of travel speed and remains unchanged at mean higher speeds. H-MLIT with the most congested road segment (degree of congestion; min: 0.28, max: 2.52, mean: 1.38) has intensified vehicle

numbers (min: 6,415 units/day, max: 58,810 units/day and mean: 38,651 units/day) and the slower traffic flow movement (min: 7.2kmph, max: 55.0kmph and mean: 22.0kmph). Benzene (passenger cars: 0.007g/km, trucks: 0.007g/km) and CO (passenger cars: 1.079g/km, trucks: 0.671g/km) emissions are obviously more emitted from the passenger cars whereas the trucks are responsible for the greater emission of $NO_x$ (passenger cars: 68.882g/km, trucks: 310.048g/km), $PM_{Exh}$ (passenger cars: 0.006g/km, trucks: 0.041g/km) and fuel consumption (passenger cars: 0.007g/km, trucks: 0.007g/km). The EFs of pollutants were compared with the Japanese Emission Standards through JE05 and JC08 chassis dynamometer test cycles. The estimated EFs of NOx for both vehicle classification showed inconsistency with the EFs derived from the test cycles. These results may deploy as input in air quality dispersion modeling in urban areas for designing the air pollution abatement strategy.

## Chapter 4 Dispersion of pollutants in street canyon of urban environment

Chapter 4 discusses the use of Operational Street Pollution Model (OSPM) to predict the pollutant concentration ($NO_2$, CO, ozone, benzene, PM2.5, PM10 and suspended particulate matter (SPM)) in the urban street canyon of Kyoto City, Japan. The OSPM simulation reveals that all mean modelled pollutants concentration permitted to the environmental quality standard of Japan and World Health Organization. Road no. 9 under the category of highway administrated by the Ministry of Land, Infrastructure, and Transport (MLIT) can be classified as the most polluted road. The correlation analysis exhibits the pollutant concentrations are positively strong correlated to the traffic volume ($r$:0.302-0.834, $p<0.01$), wind speed ($r$:-0.418-0.641, $p<0.01$), wind direction ($r$:0.449-0.861, $p<0.01$), and aspect ratio (height/width) (r:0.305-0.875,p<0.01) of the urban street canyon, and vice-versa on travel speed ($r$:-0.427-(-0.735), $p<0.01$). Most pollutants such as NO2, CO, ozone, benzene, PM2.5 and SPM reveal good agreements to OSPM model due to higher $R^2$ (0.77-0.94) and IA (0.86-0.94), lower RMSE ($NO_2$ [0.006ppm], CO [0.079ppm], ozone [0.007ppm], benzene [0.074ug/m3], PM2.5 [3.767ug/$m^3$], and SPM [0.006ug/$m^3$]), MAE (NO2 [0.004ppm], CO [0.057ppm], ozone [0.005ppm], benzene [0.042ug/m3], PM2.5 [3.278ug/m3], and SPM [0.004ug/$m^3$]), and bias (4%-18%). However, PM10 indicates the moderate $R^2$ (0.47) and IA (0.60), lower RMSE (5.275ug/$m^3$), MAE (4.568ug/$m^3$), and bias (20%). The OSPM model overestimates the modelled concentrations due to the positive value of bias. Overall, the

OSPM model had proven to be an applicable model for predicting the pollutant concentration in the urban environment of Kyoto, Japan.

### Chapter 5 Health risk assessment of traffic induced air pollution in Kyoto City, Japan

Chapter 5 assesses the health risks associated with exposure to traffic induced air pollutants (nitrogen dioxide ($NO_2$), carbon monoxide (CO), ozone ($O_3$), benzene, suspended particulate matter, pm10 and pm2.5) via inhalation to infants, children and adults. Assessment of inhalation risk is based on the method proposed by US EPA utilizing hazard quotient (HQ) for non-carcinogenic effect and cancer risk (CR) for carcinogenic effect. HQ value for acute, intermediate (normal and worst-case) and chronic intermediate (normal and worst-case) exposure were determined for each pollutant, while cancer risk was calculated for chronic exposure of PM2.5 and benzene. Results revealed that the HQ value for all pollutants for acute and intermediate normal exposure were lower than 1.0 and CR for PM2.5 and benzene was lesser than the acceptable level ($10^{-4}$). Infants and children have higher tendency to be affected compared to adults for pollutants exposure, excluded the chronic worst-case condition. Nevertheless, the potential health risks with the different severity of risks may pose by the exposed groups when they inhale the pollutants for long-term exposure. Overall, the study population have a negligible risk for short term-exposure and vice-versa for the long-term chronic exposure.

### Chapter 6 Development a holistic framework risk-based assessment and management for traffic induced air pollution in urban area

Chapter 6 introduces the development a holistic risk management approach for traffic induced air pollution in urban environment. This approach incorporates the concept of urban sustainability and risk management proposed by United Nation Department of Economic and Social Affairs (2013) and the 2018 International Standard Organization (ISO) risk management 31000, respectively. An urban sustainability was built by standing four pillars such as economic, environment, social and government. A risk management approach integrates the principles, framework and process as one component and solely synchronized with the findings of this research. The element of risk management covers the elements customized, integrated, inclusive, dynamic, best available information, human and cultural factors, continual improvement, structured and comprehensive. The framework of risk management includes integration, design, implementation, evaluation and improvement. The risk management process adapts the principal of scope, context and criteria, risk assessment, risk analysis, risk treatment, monitoring and review and risk communication. It is intended to be a reference document to help policy makers, urban development departments and environmental practitioners to prepare, implement, and review the issue of transport and air pollution in the urban area.

## Chapter 7 Conclusion and Future Recommendation

Chapter 7 brings together the conclusion from each the preceding chapters and suggestion of promising area for future research.

# ACKNOWLEDGEMENT

First and foremost, praises and thanks to the Allah, the Almighty, for His showers of blessings throughout my research work to complete the research successfully.

I would like to express my deep and sincere gratitude to my research supervisor, Prof. Dr. Minoru Yoneda for allowing me to do research and providing invaluable guidance throughout this research. His dynamism, vision, sincerity, and motivation have deeply inspired me. It was a great privilege and honor to work and study under his guidance. I am incredibly grateful for what he has offered me.

I am extremely grateful to my parents, Haji Abdull bin Said and Hajah Zamaliah binti Daud for their love, prayers, caring and sacrifices for educating and preparing me for my future. I am very much thankful to my husband Muhammad Aryf bin Yusuf Rauf and my kids, Nur Dhya Afryna Khalisya, Muhammad Khalisy Khairullah and my late precious daughter Putri Aryana Khaisarah for their love, understanding, prayers and continuing support to complete this research work. Also I express my thanks to my sisters Nor Zaliza and Norasyikin, sister in law and brother in laws for their support and valuable prayers. My Special thanks goes to my labmate Maihani Ismail, Diana, Any, Fajri, Mohd Redzuan Ramli, Thuong and others for the keen interest shown to complete this thesis successfully.

As for the Japanese Government, I am grateful for the MEXT scholarship award for allowing me to conduct this research at Kyoto University. I am extending my gratitude to the students of Environmental Risk Analysis Laboratory, for their support during my research work. I have no valuable words to express my gratitude, but my heart is still full of favors received from every person.

# TABLE OF CONTENT

## CHAPTER 1 INTRODUCTION

## CHAPTER 2 LITERATURE REVIEW

## CHAPTER 3 TRAFFIC CHARACTERISTICS AND POLLUTANT EMISSION FROM ROAD TRANSPORT IN URBAN ENVIRONMENT

3.3 Results and Discussion

## CHAPTER 4 DISPERSION OF TRAFFIC-INDUCED AIR POLLUTION WITH OPERATIONAL STREET POLLUTION MODEL (OSPM) IN KYOTO CITY, JAPAN

## CHAPTER 5 HEALTH RISK ASSESSMENT OF TRAFFIC INDUCED AIR POLLUTANTS

5.2 Methodology

## CHAPTER 6 FRAMEWORK OF RISK BASED MANAGEMENT OF TRAFFIC INDUCED AIR POLLUTION

**CHAPTER 7 CONCLUSION AND RECOMMENDATION**

## LIST OF FIGURES

**Chapter 2**

**Chapter 3**

**Chapter 4**

Chapter 6

# LIST OF TABLES

Chapter 3

Chapter 4

Chapter 5

# LIST OF PUBLICATION

## Poster Presentation

1. An analysis of traffic characteristics in Kyoto City, Japan. Presented at The 10th Better Air Quality, Regional Conference. 2018 November: Awarded as the Best Poster Presentation
2. Estimation of traffic induced air pollution for municipal roads in Kyoto city, Japan. Presented at the World Clean Air Congress, Turkey. 2019 September

## Journal

1. Abdull, N., Yoneda, M. & Shimada, Y. Traffic characteristics and pollutant emission from road transport in urban area. *Air Qual Atmos Health* **13,** 731–738 (2020). https://doi.org/10.1007/s11869-020-00830-w
   Published date: May 15th, 2020.

# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

Air pollution is a global challenge and controlling air pollution will, *inter alia*, react to three sustainable development goals (SDG) indicators: SDG 3 (good health and well-being), SDG 11: sustainable cities and communities and SDG 13: climate action. Air pollution recognizes as the fifth risk factor for mortality (HEI, 2019), which responsible for the increment of people die with 4.2 million cases worldwide per year being attributable to outdoor air pollution (WHO, 2018). If the air pollution issue is not adequately controlled, by 2050, the number of mortalities will double (Lelieveld et al., 2015). UN Environmental Program highlights the proportion of deaths to specific diseases due to the ambient air pollution exposure such as ischaemic heart disease (40%), stroke (40%), chronic obstructive pulmonary disease (COPD) (11%), lung cancer (6%) and acute lower respiratory infections in children (3%) (UN Environmnent, 2014). A recent announcement by the International Agency of Research on Cancer (IARC) on the classification of outdoor air pollution as a carcinogenic to human (Group 1) or cancer-promoting agent. A good relationship also can be seen between exposure to outdoor air pollution and bladder cancer and lung cancer (IARC, 2013). While a large body of literature indicates that air pollution leads to the verbal impairment, the cognitive deficits (Zhang et al., 2018) and loss of workers productivity (He et al., 2019)

Recurring high levels of pollutants in an urban area with the great density of dwellers correspond to a shorter life span and higher cases of diseases, especially among infants and other susceptibility groups in communities (Zhou et al., 2014). A substantial proportion of air pollutions in urban areas contributed by the traffic emission from exhaust (complete and incomplete fuel combustion in the engine) and non-exhaust process (evaporation of fuel, tire, brake and road surface wear) (Nagpure et al. 2016, Shahbazi et al. 2016; Kwak et al. 2017). More attention to human health concerns resulting from traffic-induced air pollution imposes the necessity for predicting the association between human exposure and adverse health effects. This prediction highly relies on the pollutant dispersion from vehicle emission, which determines via on-site measurement and mathematical modeling and satellite remote sensing.

## 1.2 Statement of Problem

Most urban morphology typically design with a narrow street, dense structure, and high rise building, which flanked on both sides of the road (Fan et al., 2017; Scungio et al., 2013). These designs restrict the air ventilation and perform as a trap and pocket for the pollution, preventing the pollutants from dispersing and well-mixed in the air (Steinberga et al., 2019a). Compounding this challenge, intensive traffic loaded at the streets and local meteorology must be shown as contributors to the worsening of poor urban air quality (Dėdelė et al., 2019; Miao et al., 2014; Wen & Malki-Epshtein, 2018) whereas urban tends to be high-risk area. Driven by the extensive body of literature presenting associations between a broad spectrum of health effects and inhalation of poor air quality with densely human population in the urban area (Rojas-Rueda et al. 2013; He-Hua Zeng et al. 2017; Vette et al. 2013 ). Such risk requires the thoroughly investigation in providing the valuable information in controlling and managing the traffic-induced air pollution for sustaining the urban life (Jyoti Maji et al., 2016; Lim et al., 2012).

The risk management practice needs the information of pollutant concentration in air, commonly measure based on the fixed urban background monitoring station. However, this technique requires high allocations due to the frequency of sampling as well as the numerous numbers of sampling points due to extensive network links. The fixed-urban background air quality measurement stations in routine monitoring networks have the restriction capacity to facilitate the monitoring of pollutant dispersion at the microscale variability such as street levels (Solvang Jensen et al., 2009). The previous studies also prove that the underestimation of human exposure and some cases has no exposure among respondents by the monitoring data (De Nazelle et al., 2017; Ragettli et al., 2013).

Studies on air dispersion modeling have been established as an alternative for the fixed monitoring station. In an attempt to estimate the dispersion of traffic- induce air pollution, the vehicular emission model was used as input of the model. Despite knowing the potential health risk from traffic-induced air pollution, there is less research available in Japan, especially in Kyoto, to our knowledge. Motivated by the stated reasons, this research performs the investigation in estimating the dispersion of traffic-induced air pollution and characterizing their risk among urban dwellers in Kyoto City. This research implements the Operational Street Pollution Model (OSPM) as an effort to predict the dispersion of pollutants in an urban street canyon. This model combines a plume model (the direct impact of emitted pollutants from vehicle movement) and a box model to calculate the pollutant concentration (recirculation of pollutants in the street canyon due to the vortex flow).

The key parameters of the model are meteorological conditions (wind speed, wind direction, ambient temperature, global radiation) and street canyon configuration (street width, street length, street orientation, building height) and traffic emissions, and background concentrations of pollutants (Hung et al., 2010a). Many attempts have successfully conducted to evaluate the impact of street canyon configuration on pollutants concentrations (Berkowicz et al., 2006; Hung et al., 2010b; Ketzel M et al., 2012; Vardoulakis et al., 2014). The classification of street canyon is based on the aspect ratio; AR (building height / street width) as avenue (AR less than 0.5), regular (AR equal to ), 1.0) and deep (AR more than 1.0) (Lazi et al., 2016). (Hu &

Zhong, 2010; T.-B. Ottosen et al., 2016; T. Ottosen et al., 2016) only focused on the lower AR of street canyon configuration. There is no study conducted on the impact of high aspect ratio of street canyon on the pollutant concentration (Hood et al., 2020). More than 70% of aspect ratio of street canyon in Kyoto City exceed 1.0 and almost 40% are more than 2.0. This indicates that the urgency to evaluate the impact of high aspect ratio of urban street canyon by implementing OSPM model.

The OSPM model predict the pollutant concentration in terms of PM10, PM2.5, Ozone, $NO_2$, benzene, CO, NOx, Particle Number, Black Carbon and secondary PM (Amini et al., 2020; Khan et al., 2018; López-Pérez et al., 2019; T.-B. Ottosen et al., 2016; Rzeszutek et al., 2019; Steinberga et al., 2019b). To our knowledge, there is no prediction of suspended particulate matter (SPM) was made by implementing OSPM. According to Environmental Quality Standard of Japan, SPM is one of the air substances need to be considered in determining air quality index. Besides, the monitoring data of air pollutant do not consist of concentration of PM10. Hence, this study derives the modelled concentration of SPM and measured concentration of PM10 based on the modelled concentration of PM2.5 and PM10, and measured concentration of SPM, and PM2.5.

The pollutant concentration was implemented to investigate the inhalation health risk among urban dwellers. Then, all findings of this research were synchronized to develop a holistic approach in managing risk created by traffic-induced air pollution. As per our knowledge, most of the risk management framework exclusively establish without clear integrating the concept of urban sustainability. Hence, this research develops a holistic risk management approach by integrating the notion of sustainable development and the framework of risk management.

## 1.3 Research Objectives

This research consists of four (4) objectives:

1. To examine the traffic characteristics and emission of traffic-induced air pollution in the urban environment.
2. To investigate the dispersion of traffic-induced air pollution in the urban environment
3. To characterize the human health risk associated to the inhalation of traffic-induced air pollutants.
4. To develop a holistic risk-based management approach for traffic-induced air pollution in the urban environment.

## 1.4 Scope of Research

This research accentuates on the risk assessment of traffic-induced air pollution at five (5) functional classes of roadways in Kyoto City, Japan. Traffic characteristics of passenger cars and trucks (traffic volume, travel speed, and degree of congestion) were estimated based on the digitized data collected by the Ministry of Land, Infrastructure, Transport, and Tourism of Japan. A vehicle emission model, known as the Computer Program to Calculate Emissions from Road Transport (COPERT), was utilized to compute the emission factors (EFs) and total emissions of air pollutants in terms of exhaust particulate matter ($PM_{Exh}$), benzene ($C_6H_6$), carbon monoxide (CO), and nitrogen oxide ($NO_x$)). The Japanese Emission Standards of JE05 and JC08 chassis dynamometer test cycles were used to compare the results of simulated emission factors. Meteorological data, urban configuration, and the emission factors consequently use as the input for Operational Street Pollution Model (OSPM) to predict the dispersion of traffic-induced air pollutants. Statistical analysis was applied to investigate the prediction performance of the model.

The hazard quotient is determined to assess the health risk of inhalation exposure to the dispersion of air pollutants from traffic emission in urban settings. This research also provides a holistic framework for managing the health risk associated with inhalation of air pollution generated from vehicle emission.

## 1.5 Thesis Outline

The organization of thesis as follows:

a) Chapter 1: Introduction

This chapter briefly discusses the background of study, objectives as well as the scope of research.

b) Chapter 2: Literature Review

This chapter literally debates the vehicle emission models, air dispersion models, human health risks associated with the inhalation of traffic-induced air pollutants, and risk management approaches.

c) Chapter 3: Traffic Characteristics and Pollutant Emission from Road Transport Urban Area.

In this chapter, the traffic characteristics and emission factors and total emissions of air pollutants were predicted for two vehicle classifications (passenger cars and trucks) in Kyoto City, Japan. A vehicle emission model, known as the Computer Program to Calculate Emissions from Road Transport (COPERT), was utilised to compute the emission factors (EFs) and total emissions of air pollutants in terms of exhaust particulate matter ($PM_{Exh}$), benzene ($C_6H_6$), carbon monoxide (CO), and nitrogen oxide ($NO_x$)). The EFs of pollutants were compared with the Japanese Emission Standards through JE05 and JC08 chassis dynamometer test cycles.

d) Chapter 4: Dispersion of Traffic Induced Air Pollution in Urban Environments.

The Operational Street Pollution Model (OSPM) uses to predict the dispersion of traffic-induced air pollution in urban street canyons. The factors such as emission factors of pollutants, meteorological conditions, driving patterns and urban configuration comprehensively discussed.

e) Chapter 5: Health Risk Assessment on Traffic Induced Air Pollution

This chapter emphasizes the inhalation exposure to air pollution mainly emitted from traffic. This analysis highlights on cancer and non-cancer risks to the human population that arises from traffic-induced air pollution.

f) Chapter 6: Development a holistic risk-based management for traffic-induced air pollution in the urban environment

This chapter proposes a holistic framework of traffic-induced air pollutions by integrating the idea of urban sustainability and risk management. This chapter thoroughly discusses on the pillars of urban sustainability, principles, framework, and process of risk management approach

g) Chapter 7: Conclusion and Future Recommendation.

All findings of the research concluded, and the limitation and future recommendations also recorded.

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# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Introduction

This chapter emphasizes traffic characteristics, vehicle emission model (Computer Program to Calculate Emissions from Road Transport (COPERT) model), air dispersion model (Operational Street Pollution Model (OSPM)), health risk assessment and risk-based management of traffic-induced air pollution in urban area.

## 2.2 Traffic Characteristics

The determination of accurate vehicle emission has many restrictions due to the dynamic factors, such as vehicle emission standards becoming stringent, change in fuel composition, driving pattern, road properties, the vehicle itself (age, speed, load, and emission control technologies) and meteorological condition (Zhao et al., 2018). Emission models on vehicle representation have been developed to address this difficulty and thoroughly discussed in the literature review (Demir et al., 2013; Landolsi et al., 2017). Traffic characteristics are one of the significant factors in determining accurate vehicle emission, for instance, vehicle composition, flow volume, traffic density, speed profile, and infrastructure characteristics (e.g., type of road, road length, speed limit, and the number of traffic lanes). Pandian and co-workers stated that the flow volumes and vehicle speed are the variables used to estimate the emission because they are simply measurable (Adak et al., 2016; Pandian et al., 2009). The lower accuracy of speed measurements, such as single speed for all vehicles, may provide errors in vehicle emission. It notes that a single-speed does not explicitly represent the inadequate speed of vehicles without any consideration of vehicle driving dynamics (Ko, 2015). To overcome this circumstance, the average speed distributions of vehicles are required and may enhance the EF estimation for a grander scale of the network link.

In a real-world, the driving dynamics (e.g., driving behavior, engine performance, and degree of congestion) and the meteorological condition significantly influence the fluctuation in vehicle speed (Ryu et al., 2015; R Smit et al., 2008). He *et al.*, (2016) found that the congestion indexes indicate a key function in determining the traffic condition subsequently, providing a better understanding of the operation status of traffic networks. The decline in smooth, free-flowing conditions due to enhanced travel demand and/or deterioration in the capability of the vehicle to move (Robin Smit et al., 2008). As vehicles spend a longer time in congestion, idling, or crawling, and frequent acceleration and deceleration, the emission of pollutants become higher. Traffic composition is the proportion of traffic load per vehicle category and significantly relates to vehicle weight, fuel properties, and consumption, types of engine, and emission control technology (Grote et al., 2016). With the increase in vehicle volume, the road capacity has enhanced, resulting in a decline in the mean speed distribution of road and infrequent traffic interruptions. This unstable condition creates small disturbances in the traffic stream and changes the driving patterns; thus, vehicles experience a higher frequency of acceleration and deceleration events (Grote et al., 2016; Madireddy et al., 2011).

### 2.3 Vehicle Emission Model

Emission models on vehicle representation have been developed and classified as instantaneous, stochastic, or physical (Demir et al., 2013; Landolsi et al., 2017). In terms of the scale of input variables, emission models can be characterized as macroscopic or microscopic. Macroscopic models introduce the description of aggregated traffic parameters (such as vehicle kilometers traveled [VKT]) to approximate large-scale network emission rates according to the high-level relationship among density, flow, and speed of traffic flows. They are widely used to estimate the emission in a large-scale strategic level regardless of the specific activities of vehicle movement and the changes of driving modes which reduce the accuracy of the estimation (Adak et al., 2016; Franco et al., 2013; Misra et al., 2013). Microscopic models apply disaggregated treatment of input data and instantaneous driving conditions (speed and acceleration idle time) to calculate the vehicle fuel combustion and emission rates (Robin Smit et al., 2010). These models can provide the finest spatial and temporal resolution with an estimation of the second-by-second evolution of individual vehicle operation on the network. Such models have been used for estimating emission in terms of speed limit reduction and traffic signal coordination.

A category of vehicle emission models is average-speed models (COPERT, MOBILE, and EMFAC), traffic situation models (HBEFA and ARTEMIS), traffic variable models (TEE and Matzoros model), cycle variable models (MEASURE and VERSIT+), and modal models (PHEM and CMEM) (Madrazo & Clappier, 2018). The goal of each emission model is to provide appropriate emission factors (EFs) of pollutants, which known as the emitted mass of pollutants per vehicle for per kilometre driven or per volume of fuel consumed (Kristensson et al., 2004; Lee & Park, 2011). EFs play a significant role in the estimation of pollutant emissions from vehicles with the specified scale of attention, which can vary from local to national scales (Lejri et al., 2018).

### 2.3.1 COPERT Model

The COPERT model applies the principle of emission factors are based on the average-speed algorithms and can be considered as the standard emission inventory system for vehicle sources (X. Hu et al., 2018). The system architecture of model is a stand-alone software application, thus user-friendly, widely used and well-tested (Robin Smit & Ntziachristos, 2013).

The COPERT model was successfully developed by the European Environment Agency. According to the Tier 3 method explained by the EEA (2009) that is integrated in the COPERT model, vehicle emissions can be estimated.

The COPERT model represents the emission performance in terms of EFs, which are applied as the mass of pollutant emitted per unit distance (g/km). Generally, total emissions are calculated by means of Eq. 2.1 for each vehicle category (EEA, 2013):

$$E_{TOTAL} = E_{HOT} + E_{COLD} + E_{\mathrm{NE}} \tag{2.1}$$

Hot exhaust emission occurs after the engine and emission control system devices achieve their normal operating temperature. Most of the cold-start emissions are significant for local urban and rural driving. During this condition, the emissions are greater and highly subject to ambient conditions. The basic equation for calculating hot emission of the traffic link $j$ is presented in Eq. 2.2:

$$E_{Hot;i,j,k} = N_j \times M_{j,k} \times EF_{Hot;i,j,k} \tag{2.2}$$

where $E_{Hot;i,j,k}$ is the amount of hot emission (in g), $EF_{Hot;i,j,k}$ is the EF (in g/km) for pollutant $i$ relevant to vehicle technology $j$, $N_j$ is the number of vehicles belonging to vehicle technology $j$, and $\mathrm{M}_{j,k}$ is the length of road segment (in km) with traffic situation $k$.

Cold-start emission occurs when the engine and catalyst are warming up. Once the vehicles reach the standard operating temperature, the amount of cold-start emission is zero. However, cold-start emission starts to increase during the cooling down of the engine. Eq. 2.3 can be used to estimate the cold-start emission:

$$E_{Cold;i,j,k} = \beta_{i,j} \times N_j \times M_j \times EF_{Hot;i.j,k} \times \left[\left(\frac{EF_{Cold}}{EF_{Hot\,i,j}}\right) - 1\right] \tag{2.3}$$

where $E_{Cold,i,j}$ is the cold-start emission of pollutant $i$ produced by vehicle technology $k$ (cold-start emission occurs in the urban area), $\beta_{i,k}$ is the fraction of mileage driven with a cold engine or the catalyst operating below the light-off temperature for pollutant $i$ and vehicle technology $k$, and $EF_{Cold}/EF_{Hot,i,k}$ is the cold/hot emission quotient for pollutant $i$ and vehicle technology $k$.

Non-exhaust emissions are generated from particulate matters due to tires, brakes, road and resuspension of road dust, and evaporation of hydrocarbons via vehicle fuel systems, as indicated in Eq. 2.4:

$$E_{NE} = N_j \times M_j \times EF_{PM} \tag{2.4}$$

where $E_{NE}$ is the amount of non-exhaust emission (in gram), $EF_{PM}$ is the EF (unit: g/km) for PMs relevant to vehicle technology $j$, $N_j$ is the number of vehicles belonging to vehicle technology $j$, and $M_j$ is the length of road segment (in km) with traffic situation $k$.

## 2.4 Air Dispersion Modelling

A numerous dispersion model includes line, point, area, and volume sources (Fallah-Shorshani et al., 2017; Gibson, 2013). A line source emission refers to the emission of pollutants evenly distributed in single-dimensional and a long narrow source over an averaging time (typically estimates in hourly) (Wang et al., 2010) and usually applies for the emissions from the traffic movement on a roadway. Yamartino (2008) explains that the emission can consider as a line source if the wind direction is perpendicular to the line source of pollutants (Yamartino, 2008). Point source obviously emits from the small openings, locates either ground level or elevated level and recognizable and emits into a unidirectional wind in an infinite domain (i.e stack emission) (Stockie, 2011). Area source corresponds to two-dimensional source emission of pollutant such as forest fire landfill or the evaporation of organic compound from spillage event. Besides, three-dimensional source emission of air pollutants in a bulky quantity known as a volume source and commonly refers to dust emission, fugitive gaseous emission from pressurized equipment due to leaks or unintended release gaseous. Considering the aims of this paper, a line source emission model and its applicability in traffic emission induced air pollution issues are thoroughly discussed.

### 2.4.1 Operational Street Pollution Model

Urban street canyon is known as the presence of tall building on both sides of the street with the narrow road width (W. Hu & Zhong, 2010; Lazi et al., 2016; Raducan, 2008). Poor air quality in urban street canyons have been detected, frequently weakening to permit environmental standards due to reduced natural ventilation and intensified traffic emission (Dezzutti et al., 2018). The Operational Street Pollution Model (OSPM) is a street canyon pollution dispersion model that is based on pre- defined characteristics of flow structure and dispersion conditions in streets (Kakosimos et al., 2010). Very short prediction time, robust, computationally efficient and low cost are the advantages of this model which leads to the increment number of usages worldwide (Berkowicz et al., 1997; Kumar et al., 2016; Rzeszutek et al., 2018).

The OSPM model successfully developed by Hertel and Berkowicz (1989). The concept of OSPM model basically describes the combination of the plume model or the direct contribution from street traffic and a box model for the recirculating part of pollutants in the street to estimate the concentration of vehicle emission in the urban street canyon (Berkowicz *et al.*, 1997). The assumptions incorporated in OSPM model are:

1. A more homogenous distribution of vehicle movement and pollutant emission across the street canyon.
2. When a wind component aligns perpendicular to the street axis, the vortex

(recirculation zone) is generated in the street canyon.

3. The upwind receptor (leeward side) directly influences by the direct distribution from vehicle emission and polluted air created in the recirculation zone and a portion of urban background air.

4. The windward receptor particularly accounts for the urban background air and the pollutants outside the recirculation zone only.

5. As the wind speed is zero or is parallel to the street, concentration of pollutants at leeward and windward sides become equal.

6. The vertical dispersion is modelled assuming a linear growth of the plume with the distance from the source.

7. A box model explains the recirculation component.

8. Ambient turbulence and traffic-induced turbulence are counted for turbulence in the street.

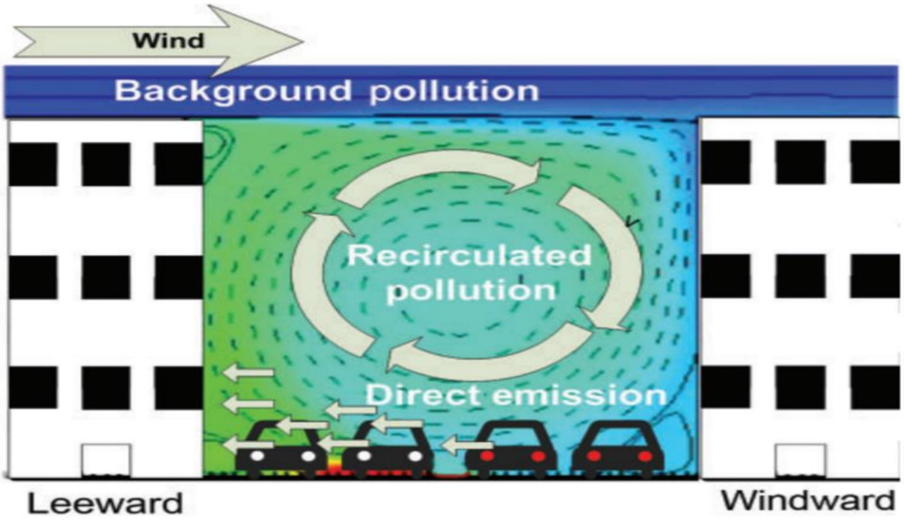

Figure 2.1 A schematic diagram of the flow and dispersion inside a street canyon, and the wind above roof level is blowing perpendicular to the street.

## 2.5 Health Risk Assessment

There is intensifying evidence of the effect of traffic-related air pollution on human health, published by multiple epidemiological studies (Chart-Asa & Gibson, 2015; Khreis et al., 2018; Lane et al., 2015; Levy et al., 2003). Such problems, in part, have led researchers to execute pollutant risk assessment to evaluate the potential human risk to the population living in the area of vehicle emission. The essential of risk assessment is now almost generally regarded as the crucial means to establish and adopt decision-making at the international, national or regional level. According to World Health Organization 2014 and US EPA, health risk assessment on air pollution can be investigated via quantitative or qualitative procedure by considering: 1) the quantity of pollution concentration, ii) the amount of exposure to the targeted people, and iii) the effect of pollutant exposure to human health. A conventional health risk assessment includes four main steps which are 1) hazard identification, 2) dose-response analysis, 3) exposure assessment, and 4) risk characterization.

Zhang & Batterman (2013) that health risks from congestion are potentially significant and that additional traffic can significantly increase risks, depending on the type of road and other factors. Appraisals of risk must consider travel time, the duration of rush hour, congestion-specific emission estimates, and uncertainties. Levy et al. (2010), the public health impacts on PM2.5 exposure due to congestion may be significant enough to be considered in future evaluations. Charman and co-workers (2017) conducted the human health risk assessment for gasoline exhaust. They found that air toxics have indicated that fuel emissions add negligibly to the increased level of ambient concentration.  However, this research did not carry out the effect of gasoline-powered sources on specific exposures to or concentration of toxic air substances in the microenvironment impacted by motorized emission.

## 2.6 Risk Management

Risk management can be typically efficient in minimizing environmental risks. US EPA defines risk management as an effort to determine what environmental risks occur and then ascertain how to manage those risks in a technique most excellent appropriate to protect human health and the environment. The latest ISO 31000 (2018) issued by the International Organization for Standardization (ISO) offers provides a universal approach to managing any kind of risks and is not industry and sector, can be customized to any organization, activity, including decision-making at all levels. This guidelines strongly support in achieving sustainable development goals no 3 (good health and well being), 8 (decent work and economic growth), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities), 14 (life below water), 15 (life on land) and 16 (peace, justice, and strong institutions). Three main components, in terms of principles, framework, and process, are essential in achieving the pragmatic risk management approach.

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# CHAPTER 3

# TRAFFIC CHARACTERISTICS AND POLLUTANT EMISSION FROM ROAD TRANSPORT IN URBAN ENVIRONMENT

## Abstract

In this work, the traffic characteristics and emissions of air pollutants were predicted for two vehicle classifications (passenger cars and trucks) at five functional classes of roadways in Kyoto City, Japan (H-MLIT, H-P, MM, P and GM). The roadways are categorized into five functional classes such as highway under jurisdiction of Ministry of Land, Infrastructure, Transport and Tourism (H-MLIT), highway administered by prefectural authority (H-P), main municipal road (MM), prefectural road (P) and general municipal road (GM). A vehicle emission model, known as the Computer Programme to Calculate Emissions from Road Transport (COPERT), was utilised to compute the emission factors (EFs) and total emissions of air pollutants (exhaust particulate matter ($PM_{Exh}$), benzene, carbon monoxide (CO) and nitrogen oxide ($NO_x$)) and fuel consumption. The results show the EFs of pollutants (benzene, CO, NOx, $PM_{Exh}$, and fuel consumption) are substantial at lower travel speed (2–30kmph) and gradually decrease by the increase of travel speed and remains unchanged at mean higher speeds. H-MLIT with the most congested road segment (degree of congestion; min: 0.28, max: 2.52, mean: 1.38) has intensified vehicle numbers (min: 6,415 units/day, max: 58,810 units/day and mean: 38,651 units/day) and the slower traffic flow movement (min: 7.2kmph, max: 55.0kmph and mean: 22.0kmph). Benzene (passenger cars: 0.007g/km, trucks: 0.007g/km) and CO (passenger cars: 1.079g/km, trucks: 0.671g/km) emissions are obviously more emitted from the passenger cars whereas the trucks are responsible for the greater emission of $NO_x$ (passenger cars: 68.882g/km, trucks: 310.048g/km), $PM_{Exh}$ (passenger cars: 0.006g/km, trucks: 0.041g/km) and fuel consumption (passenger cars: 0.007g/km, trucks: 0.007g/km). The EFs of pollutants were compared with the Japanese Emission Standards through JE05 and JC08 chassis dynamometer test cycles. The estimated EFs of NOx for both vehicle classification showed inconsistency with the EFs derived from the test cycles. These results may deploy as input in air quality dispersion modeling in urban areas for designing the air pollution abatement strategy.

## 3.1 Introduction

Recurring high level of pollutants from vehicle emission in urban areas with great density of dwellers correspond to public health in terms of shorter life span and higher cases of diseases, especially among infants and other susceptible groups in communities (Zhou et al., 2014, Kisku et., 2013). The estimation of accurate and reliable vehicle emission is crucial; however, the emission is hard to measure in real-world environments (Berkowicz et al., 2006). However, there is no assurance that real-world emissions follow the certification limits due to the diversity of vehicle design, fuelling characteristics, emission control systems, driving pattern, road properties, and the vehicle itself (e.g., age, speed, load, and emission control technologies) (Wang et al., 2018). Anenberg and co-workers (2017) claimed that about 4.6 million tons of $NO_x$ exceeded the certification emission limit in 2015. In Japan, fleet-wide on-road high-duty vehicles and light-duty vehicles contributed to 1% and 2% of excess diesel emissions, respectively. To solve this problem, emission models on vehicle representation have been implemented to allow reliable calculations of pollutant emissions in urban areas.

Vehicle emission models can be classified into five groups: average speed models (COPERT, MOBILE, and EMFAC), traffic situation models (HBEFA and ARTEMIS), traffic variable models (TEE and Matzoros model), cycle variable models (MEASURE and VERSIT+), and modal models (PHEM and CMEM) (Madrazo & Clappier, 2018). The average speed model presents the principle that the average emission factors (EFs) for pollutants and the given type of vehicle vary according to the average speed during a trip. EFs are the emitted mass of pollutants per vehicle for per kilometre driven or per volume of fuel consumed (Lee & Park, 2011). EFs play a significant role in the estimation of pollutant emissions from vehicles with the specified scale of attention, which can vary from local to national scales (Lejri et al., 2018). The effectiveness of these models highly relies on the EFs, which can be used to discuss the real emission level of pollutants on roadways. Zhao and co-workers (2018) claimed that the EFs are high due to great traffic volume with a slow traffic movement. The greater magnitudes of carbon monoxide (CO) and hydrocarbon (HC) are contributed by cars and taxis with higher quantities of traffic volume

This research adopts the COPERT model, which is the most popular and suitable tool for approximating the amount of pollutants from road transportation for local, regional, and national levels. COPERT has been successfully implemented by 22 European member states for official submission of annual national road transport inventories. A variety of research on COPERT have also been conducted in other countries, including China (Song et al., 2016), Ireland (Alam et al., 2018), Spain (Pérez et al., 2019), Greece (Fameli & Assimakopoulos, 2015), and Colombia (Mangones et al., 2020). Alam and co-workers (2018) integrated the COPERT tool to approximate vehicle emissions at the national scale and then integrated spatial mapping with a finer spatial scale for visualising the emission distribution at the street level based on the traffic volume. Song et al (2016) claimed that some models required a gigantic amount of traffic data input that might possibly not-well suited with the diverse national standards. In regards to the real situation, China has leading vehicle manufacturing technologies and the national vehicle emission standards are likely parallel to European countries (Ren et al., 2016), in which the COPERT model has good performances in estimating vehicle emissions. The Japanese vehicle emission standard is more stringent and among the strictest in the world (Anenberg et al., 2017; Kojima et al., 2016). Thus, these factors indicate that the use of COPERT model is also more reliable compared to other models in Japan.

In response to this issue, this research deals with the issue of traffic characteristics and the prediction of vehicle emission prediction using the COPERT model in urban areas. It is worth noting that the vehicles that movement inside an urban area may be diverse to those reached from vehicle registration records. The investigation covers five functional classes of roadways in Kyoto City, Japan. Here, the COPERT model predicts the EFs and total emissions of pollutants (benzene ($C_6H_6$), carbon monoxide (CO), nitrogen oxide ($NO_x$), exhaust particulate matter ($PM_{Exh}$)) and fuel consumption. The EFs derived from the COPERT model represent the vehicle emissions of urban condition in Japan. Then, the EFs were compared to the "Post New Long-Term Emission Standards" of vehicles in Japan. These results may be deployed as the input in air quality dispersion modelling in urban areas for designing the air pollution abatement strategy.

## 3.2 METHODOLOGY

The vehicle (passenger cars and trucks) emission factor and total emission of pollutants in terms of $PM_{Exh}$, benzene, CO, and $NO_x$ were successfully predicted via the COPERT model. Figure 3.1 shows a flow diagram of research methodology of this research.

### 3.2.1. Site Selection

This research selected five functional classes of roadways in Kyoto City, Japan as listed in Table 3.1. About 554 sampling point which represent the total road segment were chosen. These functional classes are categorised based on the function and administration of road. Urban expressway and national expressway were excluded because they do not permit the assumption of street pollution model for predicting the pollutant dispersion which will be explained in the next chapter.

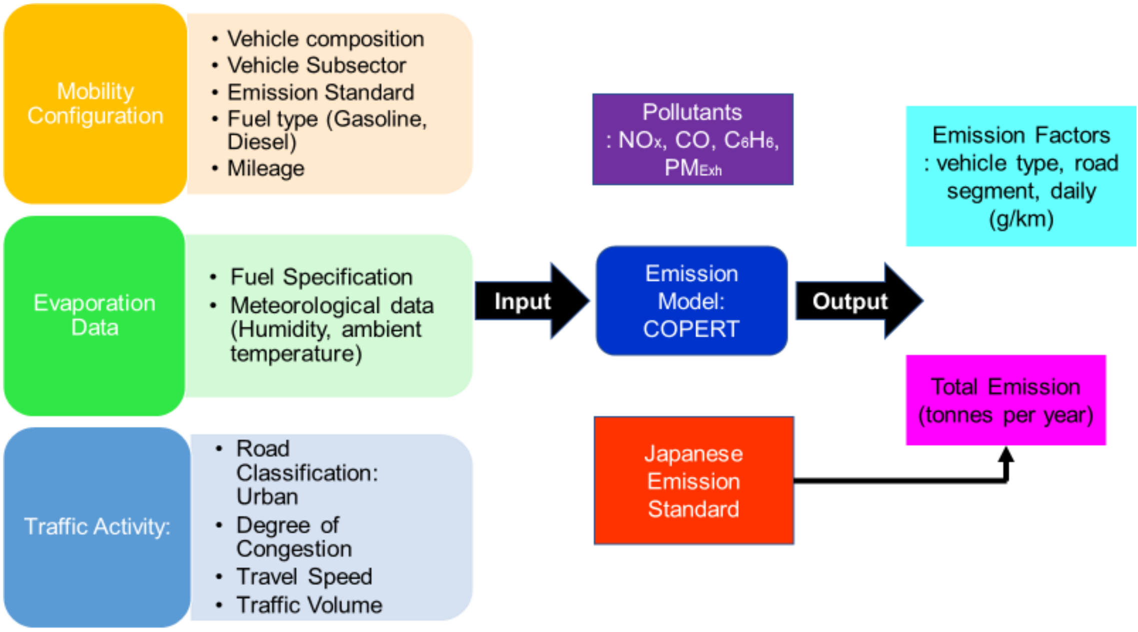


Fig. 3.1 Flow diagram of research methodology

### 3.2.2. Data Collection

This research used a various input of data and their sources for predicting the EF of pollutants as tabulated in Table 3.2. Table 3.3 shows the Japanese vehicle classifications and specifications. Traffic volume and travel speed were collected on weekdays during autumn (October, November, and December) seasons for the years 2014 and 2015, respectively. Traffic volume surveys and travel speed surveys rely on the ITS detectors installed on the road segments (i.e., almost every 2 km) that recorded traffic volume and travel speed every 5 min.

Based on the Report of the Kyoto City traffic census of 2015 (MLIT of Japan, 2015), the detailed traffic survey data with respect to the 12- and 24-h basis are presented for each road segment. The data for 12-hours basis, the data were further analysed via the interpolation technique for estimating the 24-h measurement. The 12-h observation started from 07:00 until 19:00, with the congestion period in the morning and evening started from 07:00 until 09:00, and

17:00 until 19:00, respectively. Each directional flow of traffic was considered in terms of uplink and downlink during on-congestion and non-congestion. For traffic characteristics in terms of vehicle count was reported hourly data and daily basis, while the travel speed represents for the daily basis for uplink and downlink network.

Table 3.1. Functional Classes of Roadway, Road administrator and Road Network (MLIT, Japan).

| **Functional Classes of Roadway** | **Administrator** | **Road Network** | **Road Length (km)** |
|---|---|---|---|
| National Highway (H-MLIT) | National government (MLIT) | 1, 9, 24, 171, and 367 | 69.37 |
| National Highway (H-P) | National government prefectures | 13, 15, 29, 30, 31, 32, 35, 36, 37, 38, 40, 50, 61, 67, 68 and 79 | 94.6 |
| Main Municipal Road (MM) | Municipalities | 181, 182, 183, 184, 185, 187 and 188 | 52.21 |
| Prefectural Road (P) | Prefecture | 101, 103, 104, 105, 106, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 123, 125, 126, 127, 129, 130, 131, 132, 133, 134, 135, 136, 139, 140, 141, 142, 143, 201, 202, 203, 204, 205, 206, 207, 241, 281 and. 733. | 117.65 |
| General Municipal Road (GM) | Municipalities | 42, 45, 46, 47, 49, 54, 69, 74, 94, 102, 105, 113, 116, 119, 124, 134, 139, 143, 157, 159, 160, 171, 176, 177, 182, 185, 189, 192, 195, 196, 216, 301, 302, 303 and 1024. | 77.204 |

Table 3.2 The input and source of data for COPERT simulation.

| Input | Source |
|---|---|
| Fuel Characteristics | https://www.transportpolicy.net/standard/japan-fuels-diesel-and-gasoline/ |
| Emission Standard | Motor Vehicle Exhaust Emission Standards, Ministry of Environment of Japan |
| Meteorological Condition | Japan Meteorological Agency |
| Vehicle Composition | The motor industry of Japan report, 2015. Japan Automobile Manufacturer Association (JAMA) |
| Vehicle Speed, Vehicle Count, Degree of Congestion, Fuel Consumption, Mileage | Report of the Kyoto City traffic census of 2015 (MLIT of Japan, 2015) |

Table 3.3. The Japanese vehicles classification and specification (Eriko, 2011).

| **Vehicle Classification** | **Vehicle Sub-classification** | **Specification** |
|---|---|---|
| Passenger Car | K-car (light motor vehicle) | Maximum length: 3.4m<br>Maximum width: 1.48m<br>Maximum height: 2.0m<br>Maximum displacement: 660cc |
| | Compact Car | Maximum length: 4.7m<br>Maximum width: 1.7m<br>Maximum height: 2.0m<br>Maximum displacement: 2000cc |
| | Normal Car | All passenger cars other than above |
| Trucks | K-Truck (light truck) | Maximum length: 3.4m<br>Maximum width: 1.48m<br>Maximum height: 2.0m<br>Maximum displacement: 660cc<br>Maximum load capacity: 350kg |
| | Compact Truck | Maximum length: 4.7m<br>Maximum width: 1.7m<br>Maximum height: 2.0m<br>Maximum displacement: 2000cc (except for Diesel and CNG)<br>Maximum load capacity: 2000~3000kg (ambiguous) |
| | Normal Truck | All trucks other than above such as bus |

The recorded traffic data were subsequently analysed in terms of degree of congestion by using Eqs. 3.1–3.3:

$$F = 1 + (E\text{-}1) \times P_t \qquad (3.1)$$

where $F$ is the magnification rate and $E$ is the constant for converting passenger cars to heavy vehicles (i.e., trucks (unitless)). In this case, $P_t$ is the mixing rate of heavy vehicles during peak hours (volume of trucks during peak hours (units/12-h observation)/total volume of vehicles during peak hours (units/12-h observation)). The actual number of vehicles was converted to passenger cars ($A_{12}$) via the multiplication between $F$ and the total number of vehicles for the 12-h observation ($T_{12}$) as presented in Eq. 3.2:

$$A_{12} = T_{12} \times F \qquad (3.2)$$

Then, the degree of congestion can be estimated using Eq. 3.3:

$$Degree\ of\ Congestion = \frac{A_{12}}{C_{12}} \qquad (3.3)$$

where $C_{12}$ is the 12-h road capacity (units/12-h observation).

### 3.2.3 Estimation of Pollutant Emission

COPERT is an average speed emissions model at the macroscale, so the average vehicle velocity is the main input in all calculations. The COPERT model represents the emission performance in terms of EFs, which are applied as the mass of pollutant emitted per unit distance (g/km). However, Samaras et al.(2016) implement the COPERT model for micro-scale estimation of pollutants emission. In addition, it can also be utilized for micro inventories (road segment, region and city scale inventories) which implemented in this research. In running the COPERT model, the variables as tabulated in Table 3.2 was used as the input. The vehicle composition refers to The Motor Industry of Japan report, 2015 published by Japan Automobile Manufacturer Association (JAMA). The fuel consumption (annually data), mileage data (annually data), travel speed (24 hour basis) traffic number (hourly basis) refers to the data published by MLIT of Japan in the Report of the Kyoto City traffic census of 2015. The meteorological condition data (ambient temperature and humidity) was selected based on the date of monitoring reported by Japan Meteorological Agency. As an attempt to predict the emission factors, the mean travel speed for each road segment was calculated based the uplink and downlink speed during congestion and non-congestion condition.

For the micro scale analysis, COPERT implement a quite straightforward approach for calculating the hot exhaust emissions for each road segment as indicated in Eq. 3.4.

$$E_{i,j,k} = N_j \times M_{j,k} \times EF_{i,j,k} \tag{3.4}$$

where $E_{Hot;i,j,k}$ is the amount of hot emission (in g), $EF_{Hot;i,j,k}$ is the EF (in g/km) for pollutant $i$ relevant to vehicle technology or classification $j$, $N_j$ is the number of vehicles belonging to vehicle technology or classification $j$, and $M_{j,k}$ is the length of road segment (in km) with traffic situation $k$.

Finally, the total hot exhaust emissions of the pollutant $i$ from the entire area ($E_{area}$) are calculated by summing the emissions of individual road segment as indicated in Eq. 3.5

$$E_{area} = \sum E_{i,j,k} \tag{3.5}$$

The predicted values were compared to the Japanese Emission Standards in order to analyze the capability of COPERT model to estimate vehicle emissions in Japan. This research did not take into consideration effect of driving pattern (idling, cruising, accelerate and accelerate) of vehicle due to limitation data published by the MLIT. The COPERT model is classified as an average speed model, which assumes that the prediction of emission factors applies the for a certain pollutant and a given type of vehicles varies according to the mean speed during a trip.

## 3.3 Results and Discussion

### 3.3.1. Traffic Characteristics

Traffic characteristics are discussed in terms of diurnal variation of traffic, traffic composition, traffic volume, travel speed and degree of congestion as postulated in Figures 3.2, 3.3 and 3.4. These figures were plotted based on the mean values. Table 3.3 tabulates the descriptive analysis of the traffic characteristics. Most of the passenger cars in Japan are typically powered by gasoline. With respect to the trucks, the diesel engine of a standard truck (88.28%) has a large proportion than the gasoline-powered standard truck (11.72%). However, a proportion of small truck is almost balanced with gasoline of 54% and diesel of 46%.

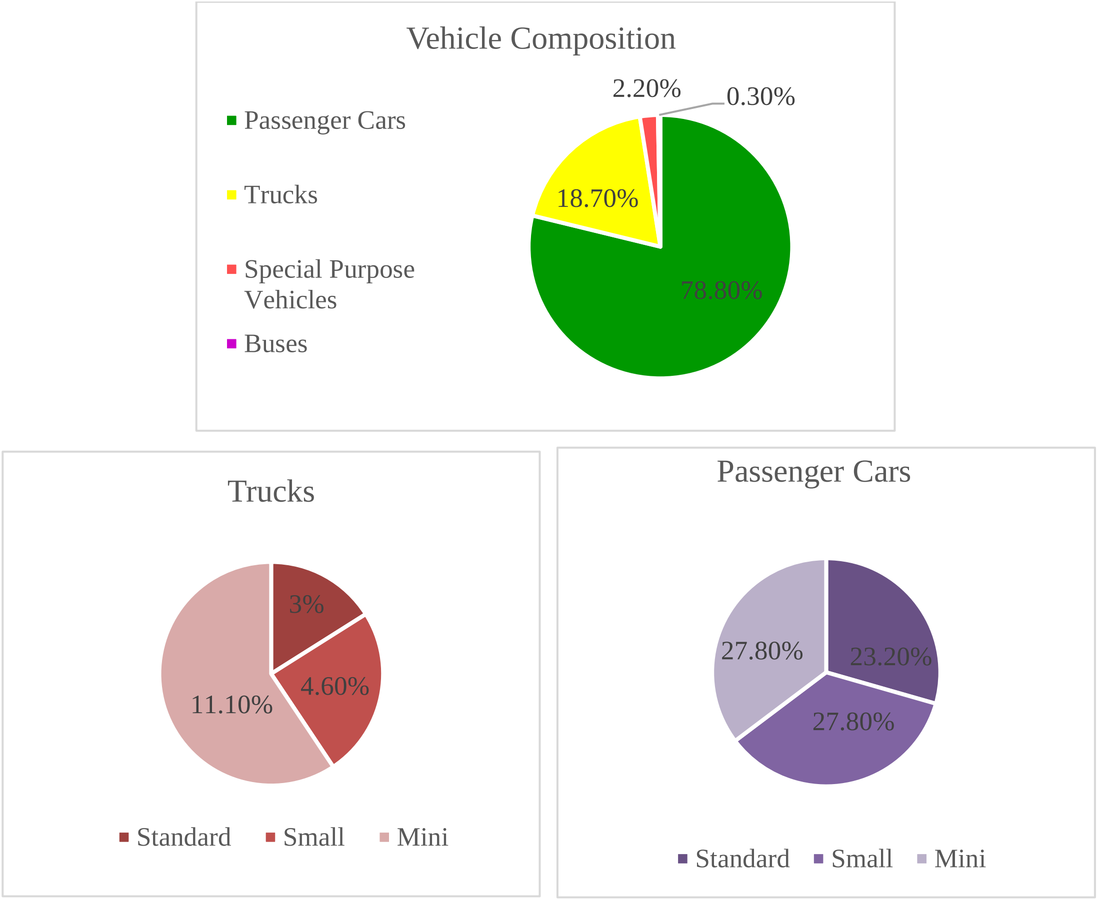
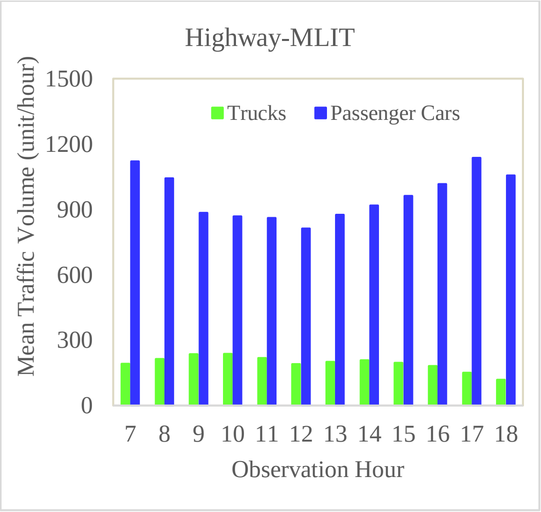


Figure 3.2. Vehicle composition in Japan.

The presence of trucks imposes the physical effects on the surrounding traffic flow due to their length and size. Truck drivers mainly keep a constant travel speed. In contrast, passenger cars have a higher tendency to change manoeuvres of lane and have an increased frequency of acceleration and deceleration, leading to an increase in the degree of congestion. In an attempt to achieve a low-carbon society in 2020 to 2030, approximately 5.4% of the next-generation vehicles, such as hybrid, electric, plug-in hybrid, fuel cells, and clean diesel vehicles were distributed over the country by 2015 (Faivre D'arcier & Lecler, 2014). All functional class of roadways indicate the increment trend in traffic volume during morning peak hours (07:00 until 09:00) as well as evening peak hours as presented in Figure 3.3. This trend can be found for both type of vehicles; passenger cars and trucks. Evening rush hours tend to be more concentrated and heavier than morning. It is believed that during rush hours, urban residents going and coming from secular employment, contributes the road congestion. Note that during lunch hour in the afternoon (12:00 o'clock), the traffic volumes were plummeted. Pertaining mean travel speed, the max values of mean travel speed at the highways and municipals road indicate that the vehicles were not exceeded the speed limits of 60 kmph and 50 kmph, respectively. However, the prefectural roads show the max value of mean travel speed did not permit the speed limits of 50 kmph. In terms of min value of mean travel speed, all the values are not more than 22.0 kmph which consider as a lower speed. Prefectural roads show the lowest mean travel speed of 1.8 kmph which located at Tambabashi Station Line (road no. 121) with the limited space of road width (4.5m).

The H-MLIT roads (min: 6,415 units/day, max: 58,810 units/day and mean: 38,651 units/day) and H-P roads (min: 203 units/day, max: 63,052 units/day and mean: 13,293 units/day) exhibit the greater total traffic volume. It believes that the highway intended to serve the multi-activities such as an excessive number of vehicles travelling with high mobility levels and long trip length. The peak total traffic volume reached at the road no 1 under the functional class of highway administered by MLIT. In contrast, the lower total traffic volumes are achieved at the prefectural roads with the min, max and mean values are 486 units/day, 39,813 units/day, and 13,293 units/day, respectively. Both of municipal roads indicate the moderate values of total traffic volume (main municipal [min, max and mean are: 7,129 units/day, 40,402 units/day and 21,612 units/day]) and general municipal [min, max and mean are: 3,023 units/day, 48,263 units/day and 18,616 units/day]).

It is pertinent to note that the degree of congestion can be considered as the indicator of congestion for instance, the road has the congestion degree more than 1.0 can be considered as the congested road. The higher degree of congestion value, the severe congestion occurs. Mean degree of congestion indicates that most of the roadways have experienced on congestion condition, excludes the highway under the jurisdiction of prefecture government. The most congested roadway occurred at the road no. 185. (Kanshuuji hinooka-sen) with the degree of congestion value is 8.78. The traffic flew at this road with the lower mean travel speed of 17.5 kmph and moderate traffic volume of 8,160 units/day. The traffic movement becomes severe and congested due to additional factor which is the road width with the limited area (4.5 m).



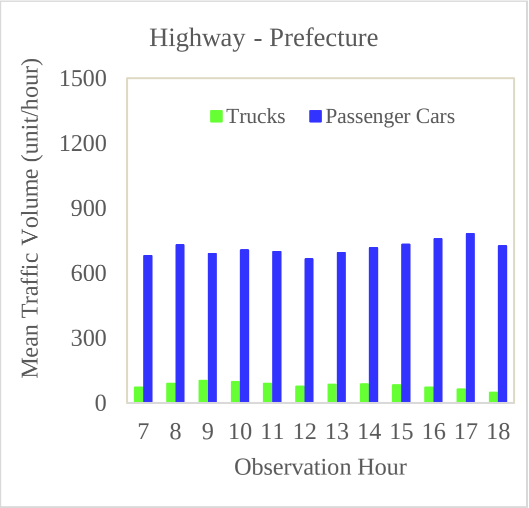
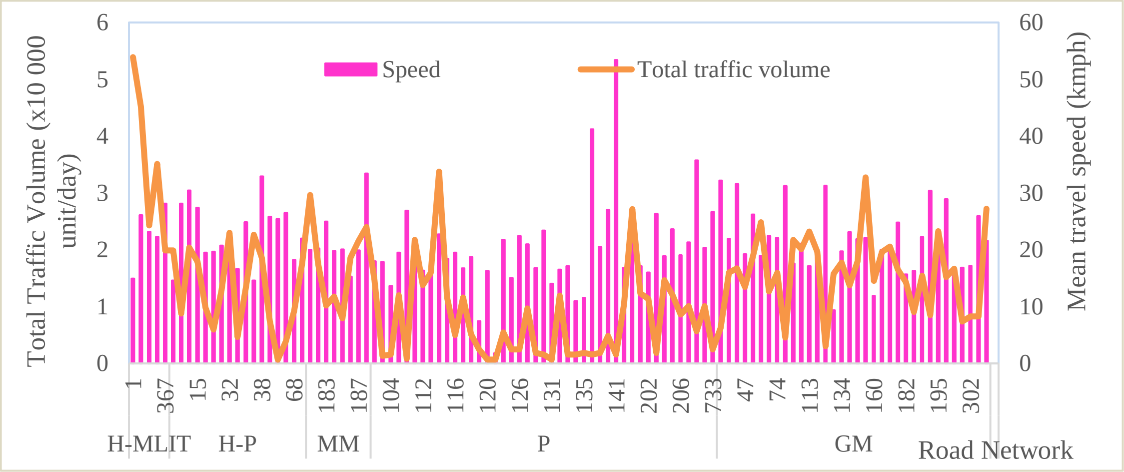
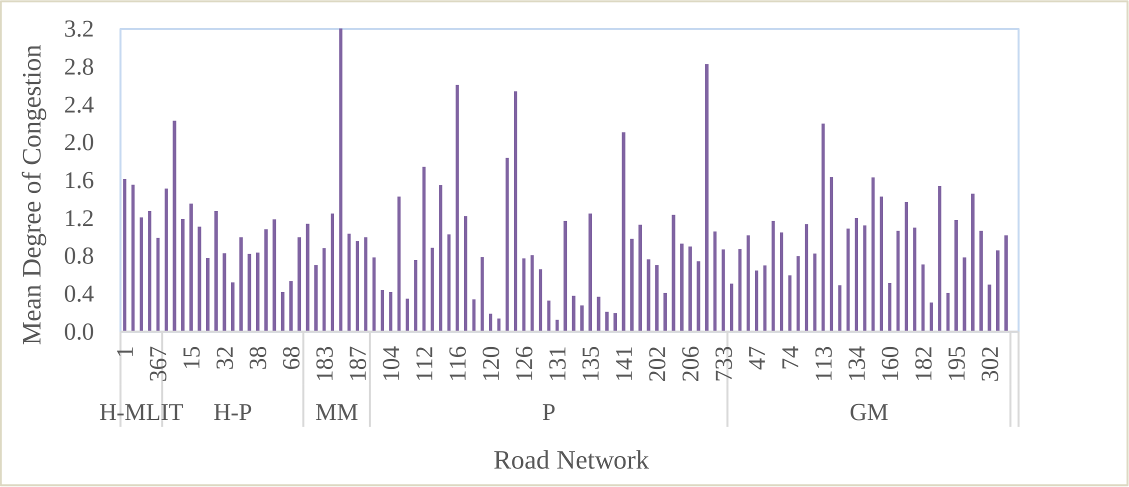


Figure 3.3. Diurnal variation of passenger cars and trucks.

With the increase in the traffic volume and enhanced road capacity, there is a decline in the mean speed distribution of road and frequent traffic interruptions. This unstable condition creates small disturbances in the traffic stream and changes the driving pattern, with a higher frequency of acceleration and deceleration events experienced by vehicles. Subsequently, it can be assumed that the traffic emissions worsened due to the greater degree of congestion.



(a)



(b)

Figure 3.4. Traffic characteristics, a) Total traffic volume, mean travel speed and b) degree of congestion.

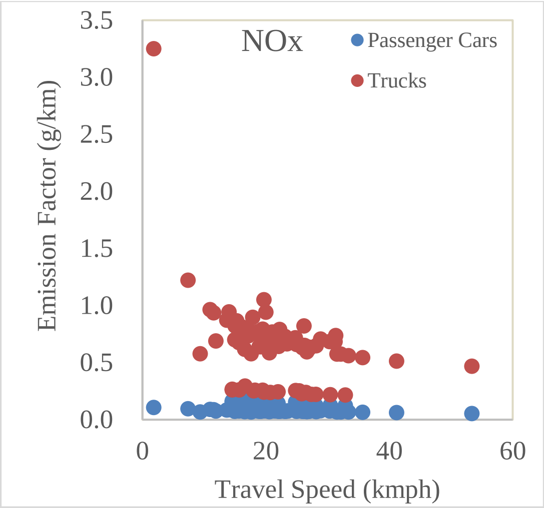
### 3.3.2. Estimation of Traffic Emission

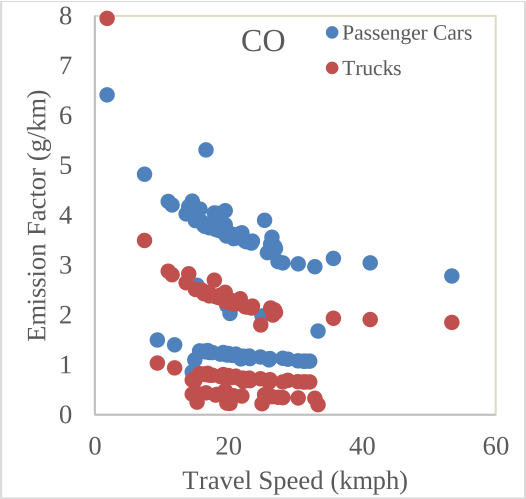
A signalized urban intersection controls the traffic pattern of roadways in the urban area of Kyoto City with the frequent shift of driving patterns such as acceleration and deceleration, idling, and cruising. Thus, this condition involves frequent gearshift and high-power interval, more vehicles spend a longer time at the signalised intersection and greater amount of fuel consumption (Choudhary & Gokhale, 2016). Figure 3.5 depicts the EF of pollutants and fuel consumption as a function of vehicle speed. Table 3.4 tabulates the mean value of EFs of pollutants and fuel consumption of each roadway. The trend of EFs and fuel consumption expose that the greater values at the lower mean travel speed (2 – 30 kmph) and consequently, gradually decrease by the increasing of travel speed. Besides, they remained unchanged at higher speeds. This finding is comparable to Jung et al. (2011) was similar trend in EFs. They found that EFs were larger magnitude at the vehicle speed 4.7 and 24.6 kmph and remained smaller at the faster travel speed (34.1 to 97.3 kmph). Besides, Guor et al mentioned that the vehicles emission becomes concentrated in the speed range of 0-10 km/h (Guor et al., 2020). The faster mean travel speeds result in a shorter driving period in urban areas, which then causes a lower magnitude of EFs. It is believed that the high-speed phase of vehicles performed by lower combustion temperature over steady state conditions is accounted for low engine pollutants.

In contrast, the movement of vehicles with lower mean speed causes incomplete fuel combustion inside the engine chamber, leading to an increase in pollutants emission. As indicated in Figure 3.5, the peak EF of pollutants and fuel consumption can be reached at road no. 121 under the classification of prefectural road. The traffic characteristics of this road reveals that passenger car volume is 608 unit/day, truck is 69 unit/day, degree of congestion is 0.14. The mean vehicle speed is about 1.8 kmph which considerably very slow and can be recognized as a major contributing factor of largest EFs of pollutants and fuel consumption. Regarding the vehicle type, the EFs of CO and benzene for passenger cars are greater than those of trucks, which can be attributed to the high traffic flow of passenger cars. This is not surprising since the presence of passenger cars in the traffic composition emits more CO emission.

Table 3.4. Traffic Characteristics of Five Functional Class of Roadways.

| Roadway | | Passenger cars | Trucks | Total volume | Mean Speed | Congestion Degree | Road width |
|---|---|---|---|---|---|---|---|
| H-MLIT | Min | 6034 | 381 | 6415 | 7.20 | 0.25 | 8.00 |
| | Max | 52957 | 12204 | 58810 | 55.0 | 2.52 | 54.40 |
| | Mean | 34057 | 4594 | 38651 | 22.0 | 1.38 | 23.35 |
| H-P | Min | 185 | 9 | 203 | 9.33 | 0.02 | 4.00 |
| | Max | 54902 | 8487 | 63052 | 52.3 | 4.37 | 50.00 |
| | Mean | 11650 | 1643 | 13293 | 22.0 | 0.97 | 15.33 |
| MM | Min | 6626 | 503 | 7129 | 7.9 | 0.54 | 4.50 |
| | Max | 35141 | 5498 | 40402 | 36.2 | 8.78 | 27.00 |
| | Mean | 18966 | 2646 | 21612 | 19.7 | 1.24 | 20.31 |
| P | Min | 400 | 66 | 486 | 1.8 | 0.05 | 3.30 |
| | Max | 35660 | 5829 | 39813 | 53.4 | 4.42 | 28.00 |
| | Mean | 9893 | 1267 | 11159 | 19.4 | 1.03 | 12.51 |
| GM | Min | 2718 | 305 | 3023 | 8.8 | 0.31 | 5.00 |
| | Max | 41697 | 7016 | 48263 | 39.2 | 2.26 | 50.00 |
| | Mean | 16323 | 2293 | 18616 | 20.6 | 1.02 | 21.82 |





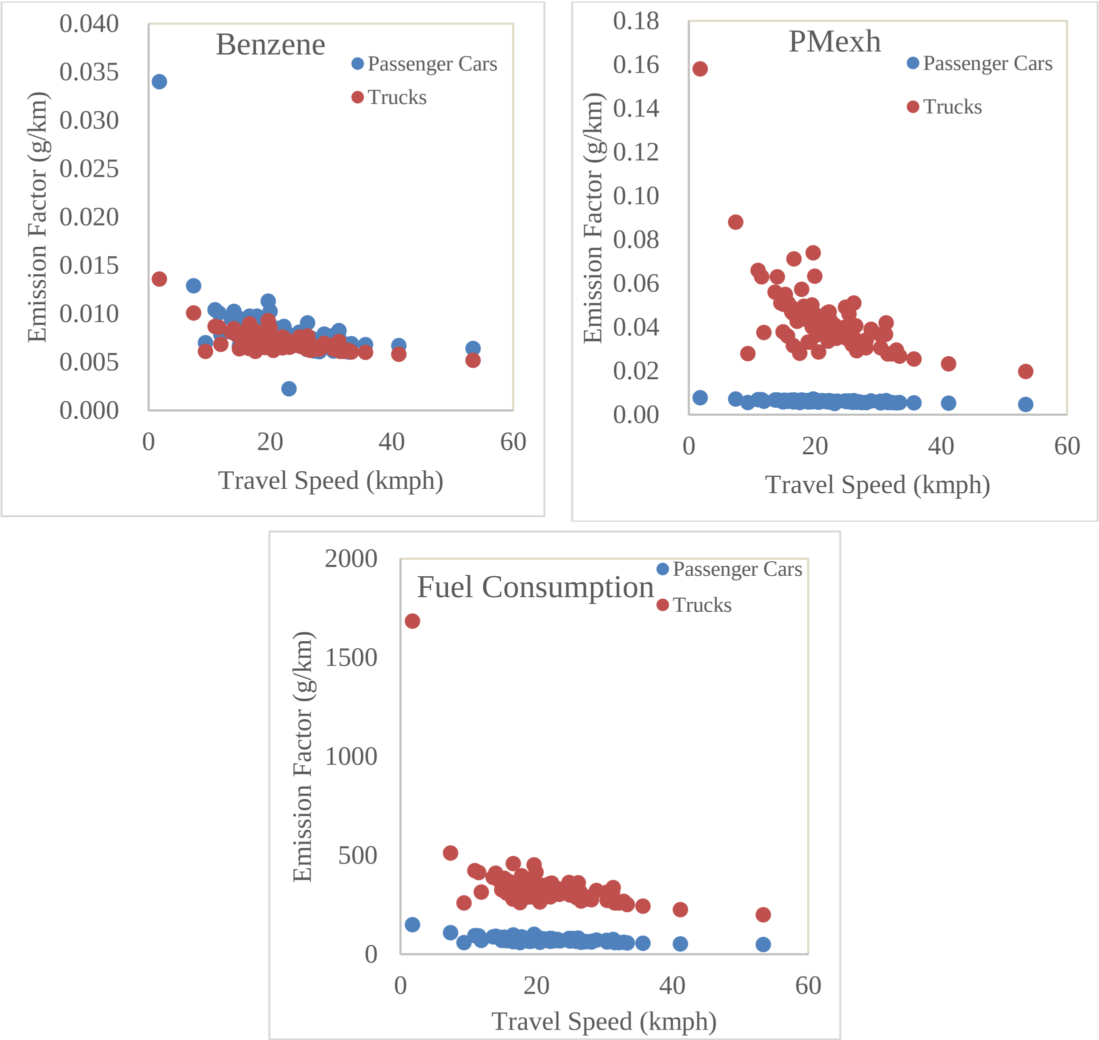


Figure 3.5 Speed-dependent emission factor of pollutants and fuel consumption

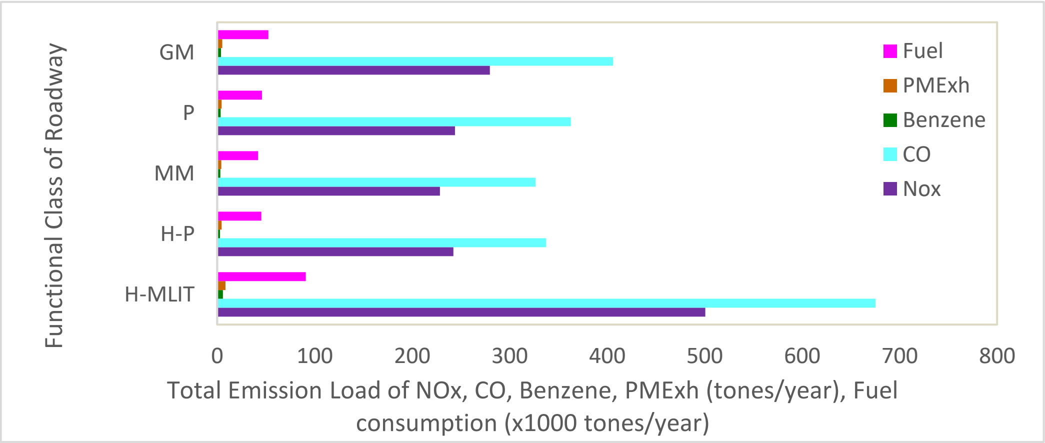


Figure 3.6 Total emission load of pollutants and fuel consumption

With respect to the fuel quality standard applied in Japan (gasoline mandatory and standard specifications), the content of benzene is 1% volume max in gasoline (e.g., passenger cars). The presence of benzene is caused by tailpipe emission and evaporative emission, which can be generally grouped into hot soak, diurnal, permeation, running loss, and refuelling processes. In urban areas, rapid acceleration of trucks due to the combination of high engine load and oxygen obtainability offers the generation of $NO_x$. The EFs of $NO_x$ has a contrasting trend to CO; meanwhile, the EFs of trucks exhibited about ten-fold of $NO_x$ more than passenger cars.

The annual total emissions of pollutants were predicted based on the COPERT model as presented in Figure 3.6. As presented in Table 3.5, the vehicles driven at highway road (H-P) managed by prefectural government points out the highest EFs of pollutants and fuel consumption. The estimation of total emission is based on the total distance of the road and the EFs. In this case, the largest total emission occurs at the H-MLIT road, this condition significantly influenced by the highest number of vehicles driven at this road, longest the distance of road segments and greater the EFs.

### 3.3.3. Comparison with the Japan Emission Regulation

In 2015, the Japanese exhaust emission standards relied on “new long-term target values for gasoline-powered and diesel-powered vehicles” implemented between 2005 and 2009. The chassis dynamometer test cycles such as JC08 and JE05 (known as ED12) provide the generalised estimate of speed-time profiles in terms of means of duration and frequency as presented in Table 3.5. The dynamics of the driving cycle of JC08 is a 1,204 s long speed profile with a total distance of 8.171 km, the average speed of 24.4 km/h (34.8 km/h when not considering the idling condition), the fastest speed of 81.6 km/h, the load ratio of 29.7%, and the measurement of hot and cold start. In accordance to urban driving conditions JE05 is introduced, which is applicable as a transitory test. The pattern of JE05 stretches out to 1,800 s, the average speed of 26.94 km/h, the top speed of 88 km/h, and the measurement of cold and hot start.

Table 3.5. Mean emission factors of pollutants at five functional class of roadways and the Japanese exhaust emission standards.

| Road Classification | Passenger Cars | | | | |
|---|---|---|---|---|---|
| | NOx | CO | Benzene | PMExh | Fuel |
| H-MLIT | 0.072 | 1.079 | 0.007 | 0.006 | 68.882 |
| H-P | 0.174 | 2.435 | 0.009 | 0.007 | 90.211 |
| MM | 0.076 | 1.059 | 0.008 | 0.006 | 72.041 |
| P | 0.079 | 1.250 | 0.009 | 0.006 | 77.968 |
| GM | 0.076 | 1.958 | 0.008 | 0.006 | 77.461 |
| Test cycle (JC08) | 0.080 | 1.92 | | 0.007 | |
| **Road Classification** | **Trucks** | | | | |
| | NOx | CO | Benzene | PMExh | Fuel |
| H-MLIT | 0.674 | 0.671 | 0.007 | 0.041 | 310.048 |
| H-P | 0.295 | 0.456 | 0.009 | 0.062 | 401.613 |
| MM | 0.705 | 0.650 | 0.007 | 0.048 | 319.763 |
| P | 0.811 | 0.832 | 0.007 | 0.057 | 370.146 |
| GM | 0.714 | 0.748 | 0.007 | 0.054 | 353.560 |
| Test cycle (JE05) | 0.208 | 2.711 | | 0.489 | |

According to the overview of the emission standard for all values over the approximated EFs, the values are not fully consistent. The assessment revealed that the EFs of pollutants for passenger cars were only overestimated for the NOx at the highway administrated by prefectural government. Whereas, all the functional class of roadways are not permitted to the emission standard of NOx for the trucks. The EFs of benzene could not be compared because the emission standard only presents the emission standard for non-methane hydrocarbons (NMHC). This finding is an excellent agreement to the research conducted by Anenberg *et al.*, 2017. They suggested that the NOx emission exceeded the certification limits under the tightened Japan emission standard. Concerns have been expressed that excess EFs may contribute by the slower travel speed of vehicles.

In this study, vehicle speed was not calculated under the idling condition; therefore, the mean speed of JC08 (i.e., 34.8 km/h) was selected for comparison with the reported vehicle speed. This explains why the EFs of pollutants are not in the range of the Japanese enforceable emission standard. The traffic condition with low vehicle speed would significantly increase the emission of pollutants due to lesser engine loads and excessive leaning of the mixing ratio of fuel to air, hence leading to imbalance in the functioning condition of the engine (Pathak et al., 2016). Besides, the JC08 and JE05 tests were conducted under the experimental condition with the vehicles attached and running on loading controllable rollers, thus maintaining an immobile state. The type-approval procedures with chassis dynamometer test cycle did not represent real-world driving condition. These tests used sophisticated vehicle technology, neglecting the deterioration factors of vehicles markedly influenced by the age of the vehicle and the accumulated mileage. For instance, the degradation of vehicle exhaust after the treatment system performance seems to occur steadily over the observed longer lifetime of vehicles.

## 3.4 Conclusion

The COPERT model was used to predict the emission factors and total emission of pollutants and fuel consumption for the five functional class of roadways in Kyoto City. The H-MLIT can be claimed as the most congested road due to highest mean degree of congestion. In conjunction with the greatest traffic volume, this road reveals as the highest emitting road of pollutants and fuel consumption. The trend of EFs highlight that the EFs are greater at the lowest speed phase, while increase and remain with the increasing of travel speed. A comparison was made to the Japanese regulatory emission standards. The NOx emission for both types of vehicles reveal the non-compliance of estimated values. This finding indicates the suitability of COPERT model in estimating the emission of pollutants in the roadways of Japan. Besides, it may provide a platform for future improvements by means of pollution control strategy.

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# CHAPTER 4

# DISPERSION OF POLLUTANTS IN STREET CANYON OF URBAN ENVIRONMENT

## Abstract

The Operational Street Pollution Model (OSPM) was adopted to predict the pollutant concentration ($NO_2$, CO, ozone, benzene, PM2.5, PM10, and suspended particulate matter (SPM)) in the urban street canyon, Kyoto City, Japan. The OSPM simulation reveals that all mean modelled pollutants concentration permitted to the environmental quality standard of Japan and World Health Organization. Road no. 9 under the category of highway administrated by the Ministry of Land, Infrastructure, and Transport (MLIT) can be classified as the most polluted road. The correlation analysis exhibits the pollutant concentrations are positively strong correlated to the traffic volume ($r$:0.302-0.834, $p<0.01$), wind speed ($r$:-0.418-0.641, $p<0.01$), wind direction ($r$:0.449-0.861, $p<0.01$), and aspect ratio (height/width) (r:0.305-0.875,p<0.01) of the urban street canyon, and vice-versa on travel speed ($r$:-0.427-(-0.735), $p<0.01$). Most pollutants such as NO2, CO, ozone, benzene, PM2.5 and SPM reveal good agreements to OSPM model due to higher $R^2$ (0.77-0.94) and IA (0.86-0.94), lower RMSE ($NO_2$ [0.006ppm], CO [0.079ppm], ozone [0.007ppm], benzene [0.074ug/m3], PM2.5 [3.767ug/$m^3$], and SPM [0.006ug/$m^3$]), MAE (NO2 [0.004ppm], CO [0.057ppm], ozone [0.005ppm], benzene [0.042ug/m3], PM2.5 [3.278ug/m3], and SPM [0.004ug/$m^3$]), and bias (4%-18%). However, PM10 indicates the moderate $R^2$ (0.47) and IA (0.60), lower RMSE (5.275ug/$m^3$), MAE (4.568ug/$m^3$), and bias (20%). The OSPM model overestimates the modelled concentrations due to the positive value of bias. Overall, the OSPM model had proven to be an applicable model for predicting the pollutant concentration in the urban environment of Kyoto, Japan.

## 4.1 Introduction

Traffic congestion and urban morphology have caused no significant enhancement of air pollution in the urban environment, regardless of extensively practiced vehicle emission control strategies (Kastner-Klein, Fedorovich, Ketzel, Berkowicz, & Britter, 2003). Street canyon represents urban morphology that restricts natural air ventilation via the dynamical process (Hunter, 1992), leads the real non-linear fluctuations in pollutant concentration, and the frequent aperiodic peaks occur for short periods (Zhong, Cai, & Bloss, 2016). These factors, combined with the aspects that the emission of pollutants take place near the ground level and inside the street canyon itself, very close to the receptors, may have harmful human health consequences (Khreis, de Hoogh, & Nieuwenhuijsen, 2018). Hence, it is of great importance to understand the distribution of traffic-related air pollutants in the urban environment. Extensive use of the fixed-urban background air quality monitoring station in investigating the human exposure within large scale surrounding the monitor station. However, this technique has inadequate capabilities such as uncontrol meteorological parameters, challenging to interpret data, high cost, and small scale for spatial coverage (Zhong et al., 2016).

To solve this gap, there is a plethora of air dispersion models have been developed in the past years for assessing vehicular pollution. The vast applications of air dispersion models also incorporate undesirable weaknesses of the discrepancy of model results. It is due to the magnitude of errors and biases owing to the scarcity of complicated physical and chemical mechanisms in the model, imprecisions of emission inventories, and meteorological information (Henneman, Liu, Hu, Mulholland, & Russell, 2017). A well-known Gaussian Plume Dispersion model originated from the concept of advection and diffusion. It can determine the pollutant concentrations emitted from the continuous source at wind velocity and turbulent diffusivity remain constant. Table 4.1 summarizes gaussian dispersion models by means of source emission, pollutants, scale, and limitation of model.

Previous studies discussed on the application of air dispersion model in assessing the road traffic emission in Japan. Yoshikawa (1998) applied an integrated Roadside Air Quality Simulation Model (RsAQSM) which developed in the Japan Clean Air Program (JCAP II). RsAQSM is a micro scale traffic model, comprises of a transient emission estimation model, and a wind and advection/diffusion model (CFD calculation). They validated the developed model by evaluating the dispersion of $NO_2$ and fine particles at the intersection roads with constructed medium height buildings in Tokyo (Ito & Yoshikawa, 2009; Yoshikawa, 1998). Olivardia and co-workers (2019) applied the CFD-coupled chemical reaction model in analyzing the pollutants (NO, NO2, and O3) dispersion in urban street canyon of Osaka area. The limitation of that research is the small analysis domain which defined as 200 m × 200 m × 150 m. As a result, the particular findings may not well represent the complex terrain of urban area such as street, highways, uneven building heights and sidewalks (Olivardia et al., 2019). Ma (2015) examined the dispersion and scavenging of NOx induced from expressways of Fukuoka, Japan. The modified Gaussian dispersion model and the Lagrange type below-cloud scavenging model were simulated to estimate the dispersion of NOx and wet removal of diesel exhaust particles.

OSPM is a semi-empirical dispersion model which apply the parameterization of flow and dispersion conditions in street canyons (Ketzel M et al., 2012). Accurate estimation of pollutant concentrations in urban area needs information of the flow condition in street, the urban morphology by means of street canyon configuration and meteorological parameters (Berkowicz et al., 1997). OSPM successfully developed by Department of Environmental Science at Aarhus University and has been tested against data monitor stations in Denmark (Ketzel et al., 2007; Ottosen et al., 2016) and other countries such as Canada (Wang, Fallah-Shorshani, Xu, & Hatzopoulou, 2016), Serbia (Lazi et al., 2016), Poland (Rzeszutek, Bogacki, Bździuch, & Szulecka, 2018), Ireland (Ganguly & Broderick, 2010), Vietnam (Tho Hung et al.,, 2010), China (Wang et al., 2016).

This research explores for the first time the applicability of the OSPM model in Kyoto, Japan. OSPM model was selected due to its' capability to apply in the heterogeneity urban terrain such as high rise building and chemical transformation between NO-O3–NO (Hvidtfeldt et al., 2018) as well as physical processes in street canyon. In this research, the dispersion of air pollutants emitted from urban road transport in a realistic street canyon was predicted. Urban configuration, traffic activity, meteorological condition and emission factors are required as the input for OSPM model. Real time monitoring data was used to validate the performance and applicability of OSPM model.

Table 4.1 Gaussian dispersion models by means of source emission, pollutants, scale and limitation of model.

| **Model** | **Model Type** | **Pollutants** | **Scale** | **Limitation and References** |
|---|---|---|---|---|
| HIWAY2 (US EPA) | Line | Non-reactive gases | Local | This model is not suggested for low wind speed and complex environment. (Holmes & Morawska, 2006). |
| CALINE-4 (California Line Source Dispersion Model) | Line | CO, $CO_2$, NO2 TSP and PM10/PM2.5 | Local | A complex terrain feature (e.g. hilly road) did not consider in estimation (Dhyani et al., 2013). It failed in heterogeneity of traffic (Dhyani and Sharma, 2017) and stable state of wind (Chen et al., 2009) |
| OSPM (Operational Street Pollution Model) | Box and Line | NOx, PM10, PM2.5, PM exhaust and PM non exhaust, Benzene, NO2, NO, O3. | Local | This model did not consider the cooling of the exhaust plume after emission, which contributes to the formation of SOA particles. Besides, it also not suitable for the short time estimation (Holmes & Morawska, 2006) |
| AERMOD | Volume | NOx, Benzene | Regional | It needs more detailed meteorological information, which relatively difficult to obtain in many cities (Chen et al., 2009). It underestimated the pollutant concentration due to external factors such as local mixing and meteorology (Nameghi, Xu, Lee, & Henshaw, 2013). |
| **Model** | **Model Type** | **Pollutants** | **Scale** | **Limitation and References** |

| | | | | |
|---|---|---|---|---|
| CALPUFF | Multi layer non-steady state Gaussian Puff | Gas, Particulate | Regional | It is not recommended to use when the wind speed under the stable condition (Fallah-Shorshani, Shekarrizfard, & Hatzopoulou, 2017) |
| IIT Line Source (IITLS) | line | SO, SPM, NOx | Local | A complex terrain feature did not consider in estimation (Goyal et al., 2006). |
| CAL3QHC | line | PM2.5, PM10 | Local | A poor model performance in evaluating the mixed traffic, high rise building and calm condition (Chen et al., 2009) |
| ADMS-Road | 3D Quasi Gaussian Plume | NOx, NO2 and PM10 | Local | Only suitable for simple street canyon. The junction effect may not be possible to simulate. (Hirtl & Baumann-Stanzer, 2007). |
| RLINE | line | CO, NOx, PM2.5 | Local | It simulates physical dispersion processes but not chemical processes.<br>The model formulation does not consider reaction and wet deposition (Zhai et al., 2016). |

## 4.2 Methodology

Modelling study was simulated the pollutant concentration at 595 road segments at five functional class of roadway in Kyoto City as presented in Chapter 3. Figure 4.1 shows a research methodology of this chapter. The prerequisite of OSPM model are urban configuration, meteorological condition, traffic characteristics and emission factors. The predicted concentrations of pollutants were then analyzed in terms on descriptive and correlation analysis and model performance. The OSPM was estimated air pollutants such as PM10, PM2.5, $NO_2$, CO, benzene and $O_3$. Regarding particulate matter, the available air monitoring data only presented pollutants PM2.5 and SPM. This study derived the estimated concentration of SPM based on the measured concentration of PM2.5 and SPM, the predicted concentration of PM10 and PM2.5. The estimated concentrations of pollutants were then compared to the Environmental Quality Standard of Japan. The estimated pollutant concentrations were statistically analysed by means of descriptive and correlation analysis. The model performance was also tested by using the statistical indicators.

### 4.2.1 Urban configuration

Urban configuration was determined using paper maps (building height), traffic census data of MLIT (road distance and road width), and google earth pro (building height). The dimension of street canyon is basically stated in terms of aspect ratio between building height (H) and road width (W), and road length (L) (the road distance between two major intersections) and building height (H). However, the ratio of road length to building height was not discussed here because the road distance information that reported by MLIT expressed in the total length of road segments. The term of avenue canyon, regular and deep canyon refer the ratio of H/W with the value of 0.5, 1.0 and 2.0, respectively.

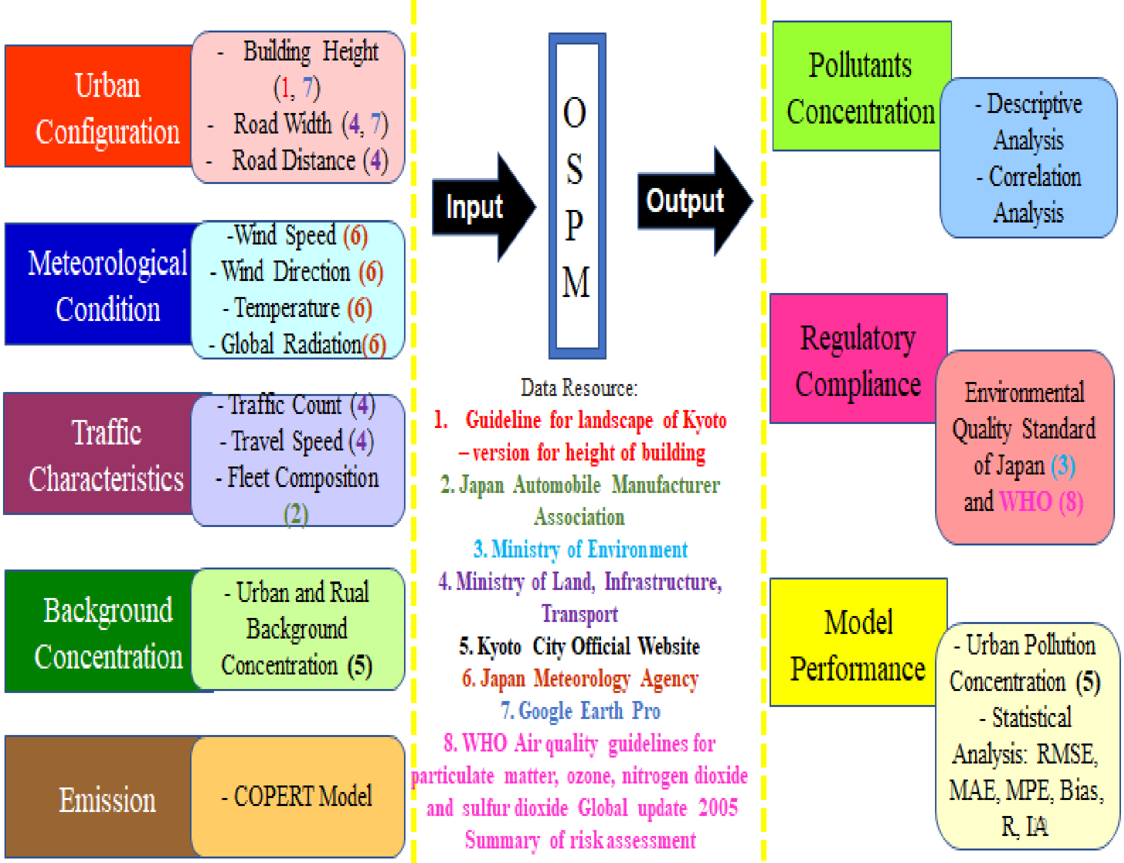


Figure 4.1 A research flow of this chapter

### 4.2.2 Meteorological Condition and Background, Urban Background and Urban Concentration of Pollutants

The meteorological condition (temperature, solar radiation, wind speed and wind direction) and, background concentration of pollutants at rural and urban area were collected from the Kyoto City website and Japan Meteorological Agency. The regional and urban background concentration of pollutants data were based on the measured concentration at the fixed monitoring site of Nantan Station and Mibu Station, respectively. Nantan Station was selected due to the lowest population and industrial activity at this area. Fushimi station, Yamasina station, Kamigyo station, Nishikyo-ku station, Omiya, and Shijo Kawaramachi Station were chosen as urban monitoring stations.

### 4.2.3 Traffic Characteristics and Emission Factors

Traffic characteristics such as traffic volume and travel speed were analysed based on the Report of Traffic Census 2015 published by MLIT. The traffic composition was based on the report of "The Motor Industry of Japan, 2015" prepared by Japan Automobile Manufacturer Association. Emission factors are based on the output of COPERT model which thoroughly discussed in Chapter 3.

### 4.2.4 OSPM simulation

The OSPM model simulation are operated based on the total concentration of pollutant at a receptor on the street is given by Eq. 3.1:

$$C_s = C_d + C_r + C_b \tag{3.1}$$

where $C_s$ is the total concentration, $C_d$ is the direct contribution, i.e. the direct flow of pollutants from vehicles to monitor, $C_r$ is the recirculation element due to the wind vortex and, $C_b$ is the urban background concentration of the pollutant. $C_d$ is estimated using a Gaussian plume model as shown in Eq. 3.2:

$$Cd = \sqrt{\frac{2}{\pi}} \frac{Q}{\omega \sigma_\omega} \left[\ln\left(\frac{\sigma_z}{h_0}\right)\right] \tag{3.2}$$

where $Q$ is the rate of release of emissions in the street, $W$ is the street width, $\sigma_z$ is the vertical dispersion parameter at the receptor point, $h_0$ is a constant that accounts for the height of initial pollutant dispersion (empirical value: 2 m), and $\sigma_w$ is the vertical velocity fluctuation due to mechanical turbulence produced by wind and vehicle traffic in the street. This is elucidated by Eq. 3.3:

$$\sigma_\omega = \sqrt{(\alpha u)^2 + (\sigma_{\omega 0})^2} \tag{3.3}$$

where $u$ is the street-level wind speed, $\alpha$ is a proportionality constant (empirically assigned the value of 0.1), and $\sigma_{w0}$ is the traffic-induced turbulence (practically assigned the value of 0.1 m $s^{-1}$), calculated by Eq. 3.4:

$$\sigma_{\omega o} = b \left(\frac{NVS^2}{W}\right)^{1/2} \tag{3.4}$$

Where $b$ is an aerodynamic drag coefficient (empirically assigned the value of 0.3), $N$ is the number of vehicles flowing the street per time unit, $V$ is the mean vehicle travel speed, and $S^2$ is the road surface occupied by a single-vehicle. Traffic-induced turbulence plays an imperative role in the dispersion of pollutants in the street, mainly in low wind-speed circumstances.

A simple box model calculates the contribution from recirculation. It expects that the canyon vortex has the shape of a trapezium, with the maximum length of the upper edge being half the vortex length. The ventilation of the recirculation zone takes place through the edges of the quadrilateral, but the ventilation can be restricted by the occurrence of a downwind building, if the building intercepts one of the edges. This is estimated by Eq. 3.5:

$$\mathrm{Cr} = \frac{Q}{w} \frac{L_r}{\sigma_{wt} L_t + u_t L_{s1} + u L_{s2}} \tag{3.5}$$

where $L_r$, $L_t$, $L_{s1}$,and $L_{s2}$ are dimensions of the re- circulation zone, which has the shape of a trapezium; $L_r$, $L_t$, $L_{s1}$,and $L_{s2}$ are the length of the root edge, top edge and two slant edges of the trapezium, respectively; $\sigma_{wt}$ is the ventilation velocity of the canyon stated as in Eq. 3.6::

$$\sigma_{wt} = \sqrt{(\alpha u_t)^2 + F_{roof} \sigma_{w0}^2} \tag{3.6}$$

where $u_t$ is the roof-level wind speed, and $\alpha$ and $F_{roof}$ are proportionality constants with values of 0.1 and 0.4, respectively.

### 4.2.5 Estimation of Modelled SPM and Measured PM10

The simulation results of OSPM model do not present the concentration of SPM. Besides, the monitoring air pollutants do not has the concentration of PM10 which represent the urban background concentration. Hereby, this research estimated the modelled SPM and measured PM 10 by deriving the concentration on modelled PM10 and PM2.5, and measured concentration of SPM and PM2.5 as follows:

PM10(measured) = SPM(measured) *X* PM10(measured)/SPM(measured) (3.7)

It assumes that PM10(measured)/SPM(measured) can be substituted in average by PM10(modeled)/SPM(modeled), which is expressed by PM10(modelled)/SPM(modelled).

PM10(measured)= SPM(measured)*X* PM10(modelled)/SPM(modelled) (3.8)

SPM(modelled)=PM2.5(modelled)*X* SPM(modelled)/PM2.5(modelled) (3.9)

The assumption of SPM(modelled)/PM2.5(modelled) can be substituted in average by SPM(measured)/PM2.5(measured), which is expressed by SPM(measured)/PM2.5(measured).

SPM(measured)/PM2.5(measured) = $A$ (3.10)

PM10(modelled)/SPM(modelled) = PM10(modelled)/(PM2.5(modelled) $X$ A) (3.11)

When $A$ assumes as a constant, then:

PM10(modelled)/SPM(modelled)=PM10(modelled)/PM2.5(modelled)/$A$= $B/A$ (3.12)

$B$ is average of PM10(modelled)/PM2.5(modelled) and assume it is a constant.

$B$ = PM10(modelled)/PM2.5(modelled) (3.13)

So that, the approximation of PM10(measured) (Eqs 3.8 – 3.12) at each location or time by using Eq 3.14:

PM10(measured)= SPM(measured) $X$ $B/A$ (3.14)

SPM(modelled)= PM10(modelled) $X$ $A/B$ (3.15)

Eq 3.15 can uses to make a comparison between SPM measured and modelled. It can also simply consider that: PM10(measured)/SPM(measured) can be substituted by PM10(modelled)/SPM(measured) in average, then it can get from Eq (3.7):

PM10(measured)=SPM(measured) $X$ PM10(modelled)/SPM(measured) (3.16)

### 4.2.6 Model Performance Evaluation

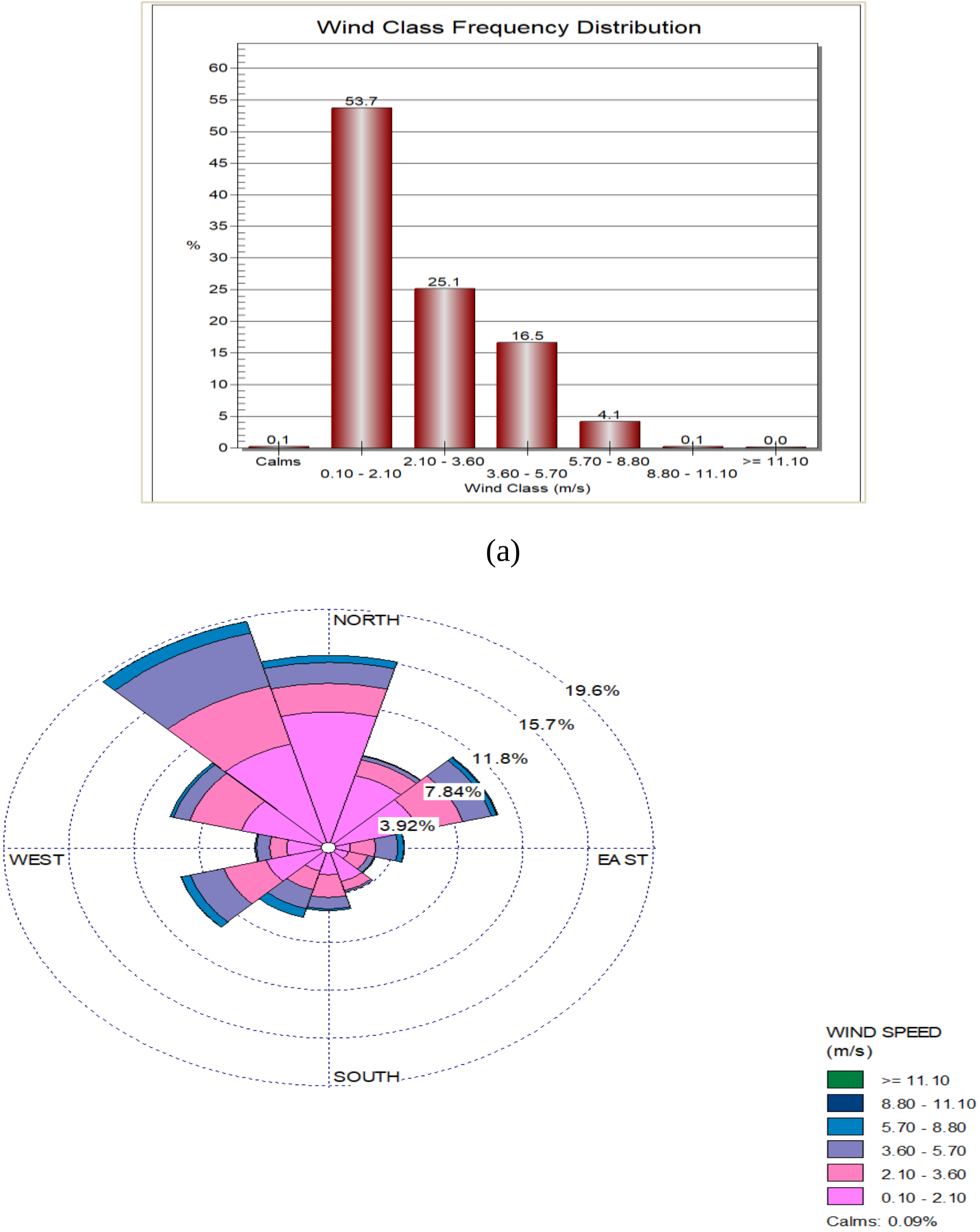
Model performance describes the pollutant concentration was assessed in terms of a statistical indicator such as root mean square error (RMSE), mean absolute error (MAE), bias and index of agreement. The linear regression analysis was conducted to determine the dependence of the modelled concentration and the measured concentration of pollutants.

## 4.3 Result and Discussion

### 4.3.1 Factors of Air Dispersion in Street Canyon

Figures 4.2 exhibits the wind rose of October and November in 2015 which collected based on the data published by Japan Meteorological Agency. About 19.5% of wind direction dominantly blew from North West. The low wind speed of 0.1 to 2.10 m/s (53.7%) is the dominant prevailing wind speed typically in autumn season. The street canyon configuration data were tabulated in Figure 4.3 in terms of building height, street width, aspect ratio and orientation of street canyon. The aspect ratio of HMLIT roads, MM roads and GM roads are mainly in the region of <0.1 which can be characterized as avenue street canyon. While, HP roads and P roads are dominated by the greatest distribution of aspect ratio $1.0 < H/W < 2.0$, known as deep street canyon. On the other hands, the GM roads are mainly designated as a lower aspect ratio $0.3 < H/W < 0.7$ and characterized as a shallow street canyon.

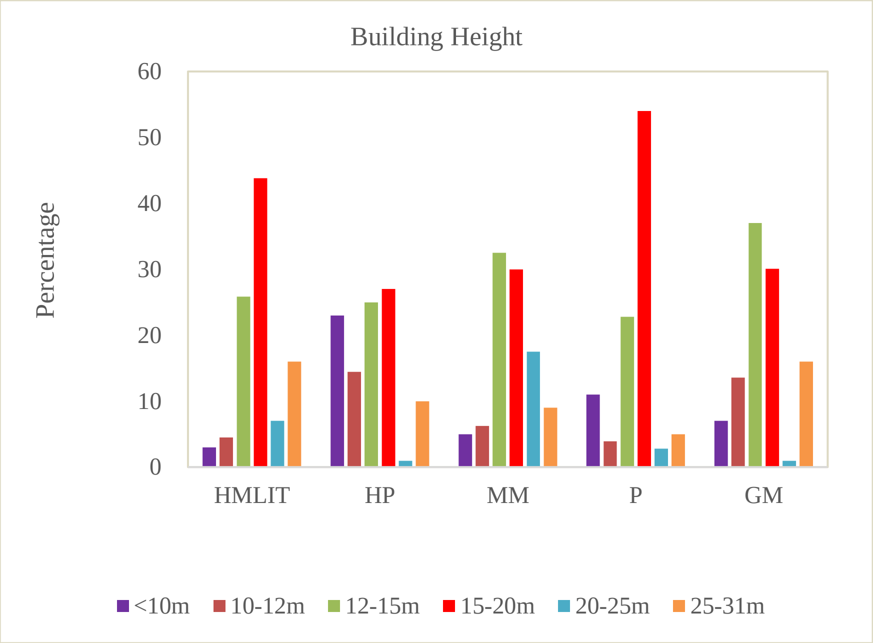
The dispersion of pollutant in urban street canyon is highly dependent to the flow pattern and the street canyon geometry. It can be explained in terms of isolated roughness flow, wake interference flow and skimming flow correspond to aspect ratio $H/W < 0.3$, $0.3 < H/W < 0.7$ and $H/W > 0.7$. So that, the flow pattern at GM roads are characterized by isolated roughness flow regime, HMLIT and MM roads as wake interference flow regime and, HP and P roads as skimming flow regime. The characteristics of isolated roughness flow are the flow patterns in street canyon are almost the same. Although wake interference flow can be described by the appearance of more complex flow pattern as a result of the interference of building waves and the spreading of vertical and horizontal plume allowing the advection mechanism for pollutant exchanges. The skimming flow regime repressed the dispersion mechanism in street canyon due to the pollutant exchange only relied on the turbulent diffusion then, the plume seems to be confined within the street canyon space (Garbero, 2008).



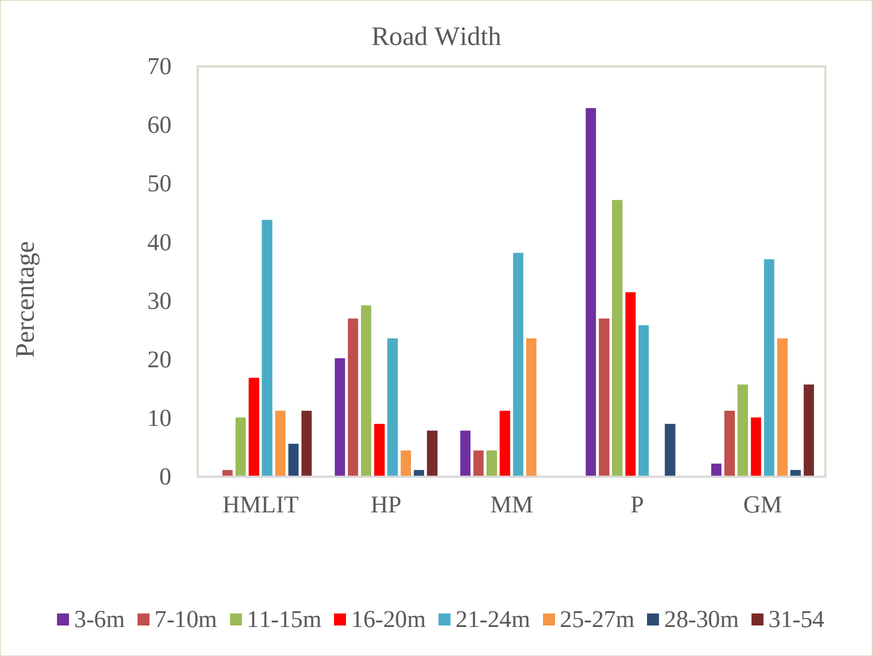
(a)

(b)

Figure 4.2. Meterorological condition a) Histogram of wind class frequency distribution and, b) wind rose diagram.

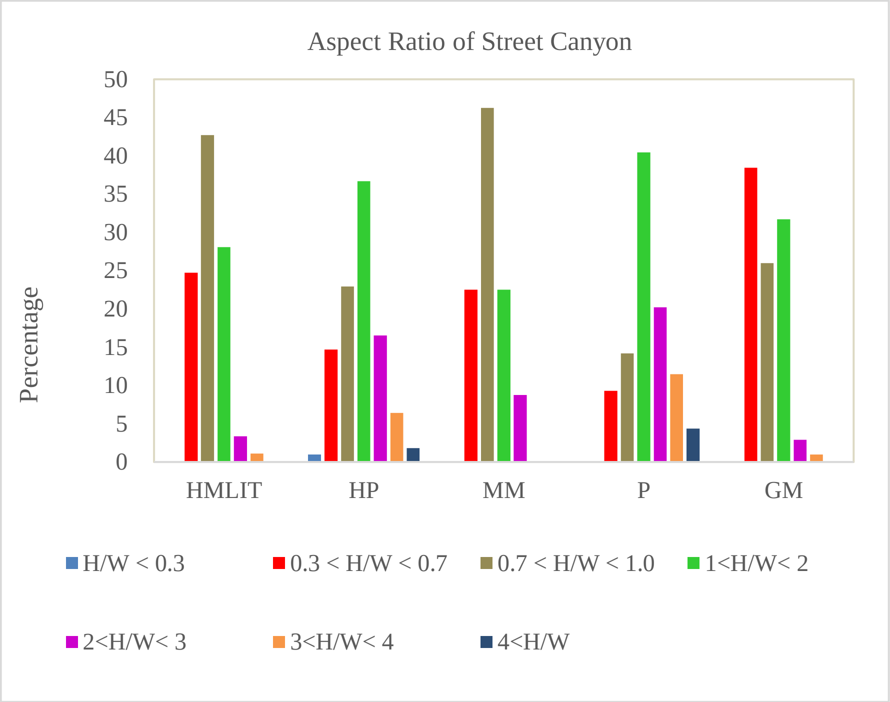


(a)



(b)

Figure 4.3 Urban Morphology in terms of a) Building height, b) street width, c) aspect ratio street canyon, d) street orientation



(c)

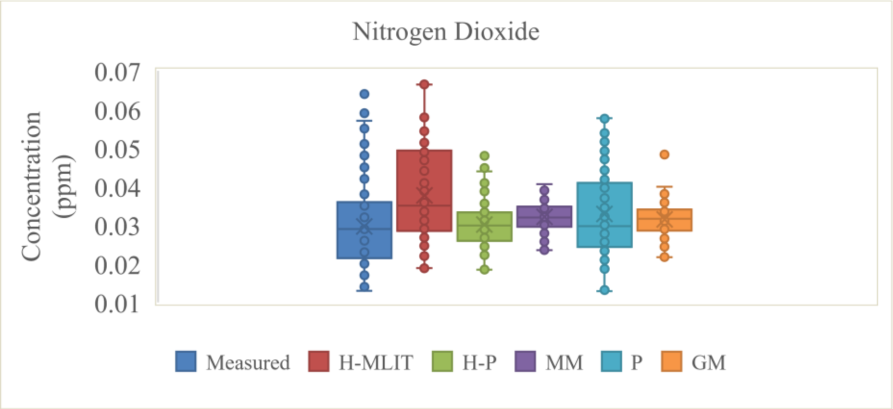
(d)

Figure 4.3 Urban Morphology in terms of a) Building height, b) street width, c) aspect ratio street canyon, d) street orientation

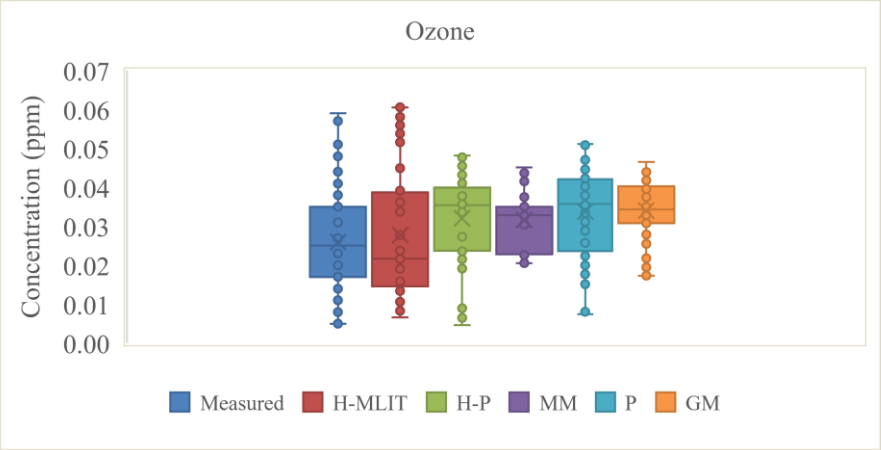
The street orientation is plotted based on the wind direction. As indicated in the wind rose diagram, the prevailing wind blew are 310 – $330^0$. The plotted histogram of street orientation is based on the wind direction such as street orientation which located at $320^0$ is considered as $0^0$. The angle of street orientations is categorized by means of parallel (0-40 and 140-180), oblique (41-80 and 101-140) and perpendicular (81-100). Almost 60% of the street orientation are oblique position to the wind direction, 30% is orientated in the parallel direction and only small portion is perpendicular angle.

### 4.3.2 Pollutant Concentration at Five Functional Classes of Roadway

Figure 4.4 and Table 4.2 exhibits the box and whisker plot and descriptive analysis of the modelled and measured pollutants for five functional class of roadways, respectively. The Box and Whisker plots were used to illustrate the distribution of the pollutant concentration in terms of the lower quartile, upper quartile, median, minimum and maximum in each of the five functional class of roadways. Most of the pollutants indicate the peak value at the HMLIT road, excludes the benzene and carbon monoxide which show the greatest concentration at prefectural and main municipal roads. The peak value and interquartile of $NO_2$, ozone, benzene, PM2.5, PM10, SPM are 0.066ppm (0.029-0.049ppm), 0.061ppm (0.015-0.037ppm), 1.484ug/$m^3$ (0.982-0.988ug/$m^3$), 29.49ug/$m^3$ (17.96-22.05 ug/$m^3$), 37.13 ug/$m^3$ (28.728-32.598 ug/$m^3$), 71.114 (21.108-39.211 ug/$m^3$). Even though the peak concentration of CO (1.026ppm) was reached at the HP road, the maximum mean value (0.590ppm) was detected at the MM road. The peak concentration mostly was reached at the road no. 9 (CO, ozone, SPM and PM2.5) and road no. 171 (NO2 and PM10).



(a)



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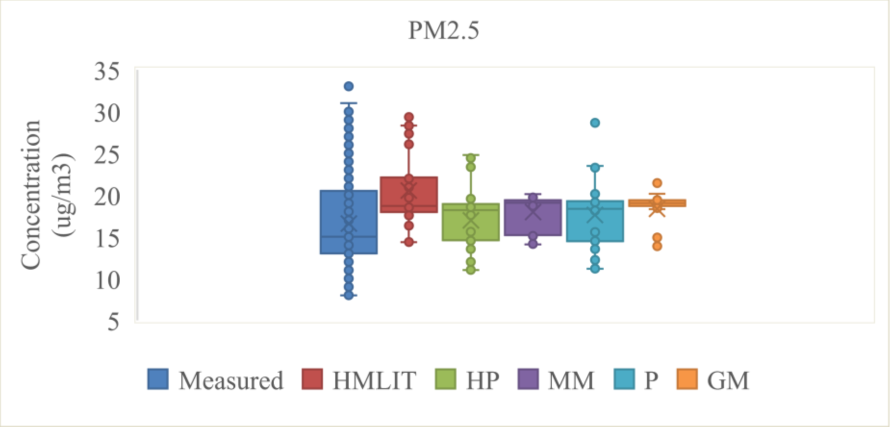
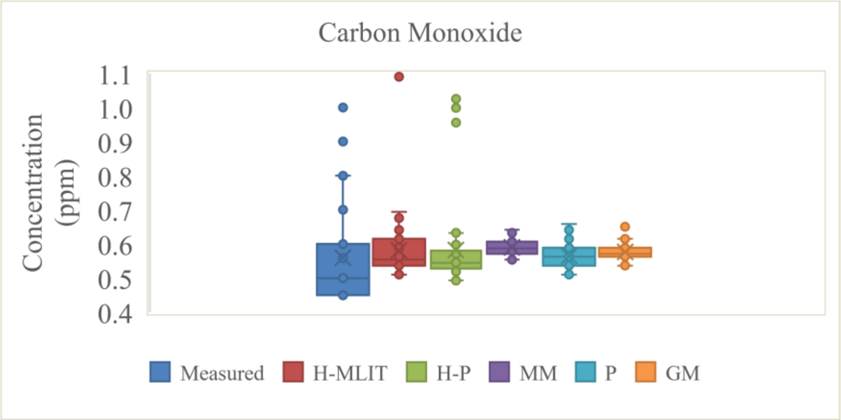
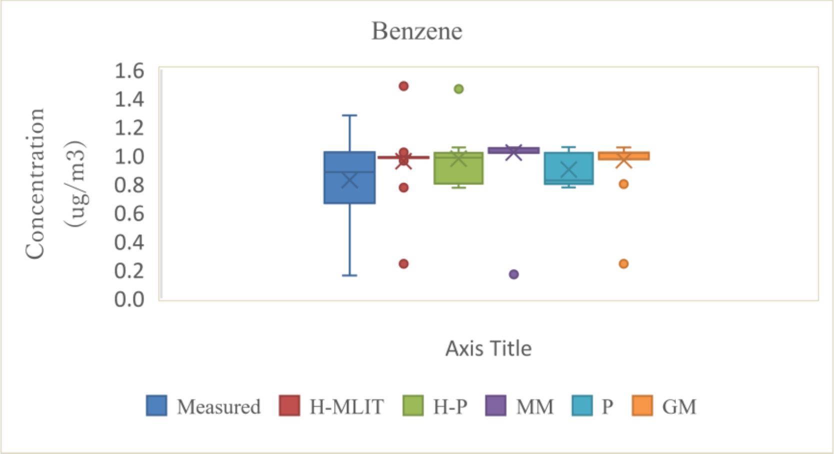


(c)

Figure 4.4. Modelled and measured pollutants concentrations for five functional class of roadways. Box indicates the interquartile range showing the 25th and 75th percentile. Circle outside the whiskers denoted outliers (a) NO2, b) ozone, c) PM2.5



(d)



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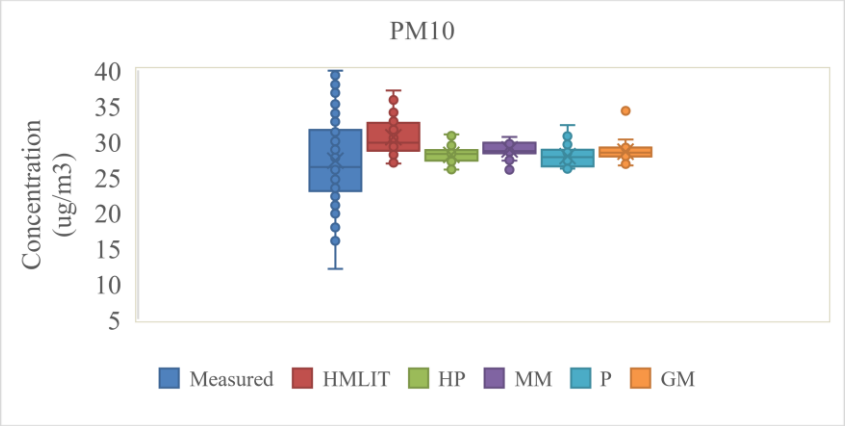
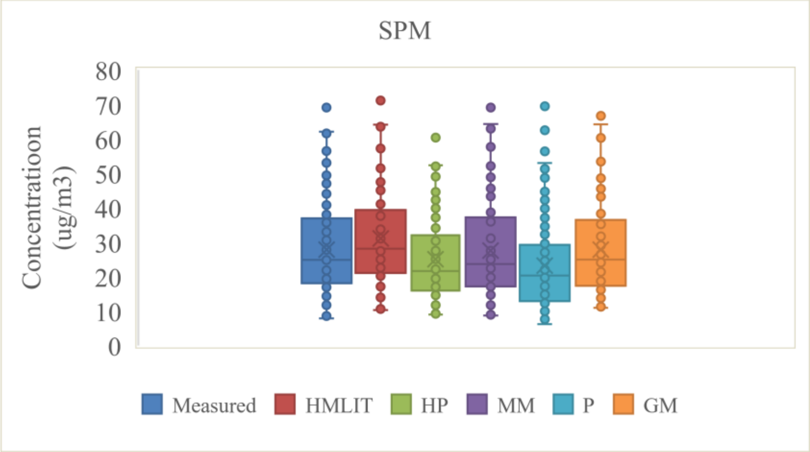


(f)

Figure 4.4. Modelled and measured pollutants concentrations for five functional class of roadways. Box indicates the interquartile range showing the 25th and 75th percentile. Circle outside the whiskers denoted outliers (d) CO, e) benzene, f) PM 10



(g)

Figure 4.4. Modelled and measured pollutants concentrations for five functional class of roadways. Box indicates the interquartile range showing the 25th and 75th percentile. Circle outside the whiskers denoted outliers (g) SPM.

The HMLIT reveals the greater pollutants concentration consequently, a summary of the increment sequence of pollutants are exhibited in Table 4.3. The road no. 9 can be summarized as the most polluted road and then, followed by road no. 171. The traffic patterns of road no. 9 are traffic volume: 23,425 to 56,381 units/day, travel speed: 14.2 to 45 kmph, congestion degree: 0.99 to 1.98, building height: 12-50m, road width; 12.5 to 50m, road distance: 0.1-2.6km, and aspect ratio of street canyon; 0.91-1.16. To narrow down road no. 9, Gojo Dori indicates the most polluted road which contributed by the congested traffic (traffic volume: 50603 unit/days, travel speed: 15.7kmph, degree of congestion; 1.76) and high aspect ratio of street canyon:1.25 (building height: 25m and road width: 22m) and shorter road distance (0.1km). Road no. 171 exhibits the greatest concentration of NO2 and PM10. This road indicates the slower movement of traffic with travel speed 17.4 kmph, degree of congestion 0.84, traffic volume 21,320 unit/days and the aspect ratio of H/W is 1.1. It suggests that the presence of Meishin expressway which is closely adjacent to this road significantly enhances the NO2 and PM10 concentration. Regarding the compliance to standard limit, the mean value was compared to Environmental Quality Standard of Japan and World Health Organization. All pollutants reveal that the compliance to environmental quality standard.

Table 4.2. Modelled and measured pollutants concentrations

| Pollutant | | Measured | HMLIT | HP | MM | P | GM | Standard Limit |
|---|---|---|---|---|---|---|---|---|
| NO2 | mean | 0.030 | 0.038 | 0.030 | 0.032 | 0.033 | 0.032 | Daily average for hourly: 0.04-0.06 ppm (EQS) (1978) |
| | min | 0.013 | 0.019 | 0.018 | 0.024 | 0.013 | 0.022 | |
| | max | 0.064 | 0.066 | 0.048 | 0.041 | 0.058 | 0.048 | |
| | median | 0.029 | 0.035 | 0.030 | 0.032 | 0.030 | 0.032 | |
| | q1 | 0.022 | 0.029 | 0.026 | 0.030 | 0.024 | 0.029 | |
| | q3 | 0.036 | 0.049 | 0.033 | 0.034 | 0.041 | 0.034 | |
| CO | mean | 0.559 | 0.577 | 0.580 | 0.590 | 0.565 | 0.577 | Daily average for hourly: 10 ppm (EQS) (1973) |
| | min | 0.450 | 0.511 | 0.493 | 0.554 | 0.511 | 0.537 | |
| | max | 1.000 | 1.090 | 1.026 | 0.641 | 0.659 | 0.650 | |
| | median | 0.500 | 0.554 | 0.545 | 0.585 | 0.563 | 0.572 | |
| | q1 | 0.450 | 0.537 | 0.528 | 0.572 | 0.537 | 0.563 | |
| | q3 | 0.600 | 0.615 | 0.580 | 0.607 | 0.589 | 0.589 | |
| O3 | mean | 0.026 | 0.028 | 0.032 | 0.032 | 0.034 | 0.034 | Hourly value: 0.06 ppm (EQS) (1973).<br>8-hour daily average: 0.061 ppm, WHO, (2005) |
| | min | 0.005 | 0.007 | 0.005 | 0.021 | 0.007 | 0.017 | |
| | max | 0.059 | 0.061 | 0.048 | 0.045 | 0.051 | 0.047 | |
| | median | 0.025 | 0.022 | 0.035 | 0.033 | 0.036 | 0.034 | |
| | q1 | 0.017 | 0.015 | 0.024 | 0.023 | 0.024 | 0.031 | |
| | q3 | 0.035 | 0.037 | 0.038 | 0.035 | 0.042 | 0.040 | |
| Pollutant | | Measured | HMLIT | HP | MM | P | GM | Standard Limit |
| Benzene | mean | 0.883 | 0.983 | 0.983 | 1.018 | 0.824 | 0.972 | Annual average: 3.0 ug/m3 (WHO) – |
| | min | 0.160 | 0.242 | 0.774 | 0.166 | 0.775 | 0.241 | |
| | max | 1.278 | 1.484 | 1.468 | 1.054 | 1.056 | 1.054 | |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | median | 0.883 | 0.983 | 0.983 | 1.018 | 0.824 | 1.017 | There is no daily standard limit |
|  | q1 | 0.671 | 0.982 | 0.801 | 1.017 | 0.800 | 0.993 |  |
|  | q3 | 1.021 | 0.988 | 1.017 | 1.051 | 1.016 | 1.019 |  |
| PM2.5 | mean | 15.64 | 18.69 | 16.97 | 17.951 | 19.28 | 18.362 | 24 hour standard; 35µg/m3 (EQS) (2009) |
|  | min | 8.000 | 14.350 | 11.030 | 14.070 | 11.180 | 13.890 |  |
|  | max | 33.000 | 29.490 | 24.770 | 20.090 | 28.770 | 21.430 |  |
|  | median | 15.000 | 18.690 | 18.180 | 19.065 | 18.340 | 19.030 |  |
|  | q1 | 13.000 | 17.960 | 14.610 | 15.205 | 14.490 | 18.685 |  |
|  | q3 | 20.000 | 22.050 | 18.930 | 19.355 | 19.280 | 19.370 |  |
| PM10 | mean | 26.38 | 30.585 | 28.21 | 28.655 | 27.80 | 28.42 | 24 hour standard; 50µg/m3 (WHO) |
|  | min | 12.079 | 26.890 | 26.040 | 26.000 | 26.150 | 26.600 |  |
|  | max | 39.956 | 37.130 | 30.970 | 30.620 | 32.270 | 34.300 |  |
|  | median | 26.378 | 29.795 | 28.260 | 28.655 | 27.800 | 28.420 |  |
|  | q1 | 23.000 | 28.728 | 27.410 | 28.325 | 26.480 | 27.890 |  |
|  | q3 | 31.616 | 32.598 | 28.770 | 29.788 | 28.820 | 29.095 |  |
| SPM | mean | 0.028 | 0.031 | 0.025 | 0.028 | 0.023 | 0.027 | Daily average for hourly: 0.10 mg/m3 (EQS) (1973) |
|  | min | 0.008 | 0.010 | 0.009 | 0.009 | 0.006 | 0.011 |  |
|  | max | 0.069 | 0.071 | 0.060 | 0.069 | 0.069 | 0.067 |  |
|  | median | 0.025 | 0.028 | 0.022 | 0.023 | 0.020 | 0.025 |  |
|  | q1 | 0.018 | 0.021 | 0.016 | 0.017 | 0.013 | 0.017 |  |
|  | q3 | 0.037 | 0.039 | 0.031 | 0.037 | 0.029 | 0.03 |  |

Table 4.3 A summary of the increment sequence of pollutants at the HMLIT road.

| **Pollutants** | **Road and Sequence** |
|---|---|
| $NO_2$ | 367 < 9 < 1 < 24 < 171 |
| CO | 367 < 171 < 1 < 24 < 9 |
| Ozone | 24 < 171 < 367 < 1 < 9 |
| PM2.5 | 24 < 367 < 171 < 1 < 9 |
| PM10 | 367 < 9 < 1 < 24 < 171 |
| SPM | 24 < 171 < 367 < 113 < 9 |

### 4.3.3 Correlation Analysis

The Spearmans's rank correlation coefficient for all pollutants and the influencing factors of air dispersion are tabulated in Table 4.4. Traffic volume indicates that significant correlations were found between traffic volume and most of the pollutants. PM10. Very strong positively correlations between traffic volume, benzene (r:0.834, p>0.01), and NO2 (r:0.798, p>0.01) at HMLIT road and PM10 (r:0.823, p>0.01) and (r:0.708, p>0.01) at P roads and MM roads, respectively. It recommends that the emission of pollutants are proportional to the traffic volume (Kumar, Fennell, & Britter, 2008) leads to the greater emission of pollutants in the street canyon of urban.

Travel speed depicts the strong negatively correlated to pollutants, particularly ozone (r:-0.681, p>0.01) at HMLIT road, PM10 (r:-0.735, p>0.01) at HP road and CO (r:-0.725, p>0.01) at MM road. Referring Table 4.3, all average travel speeds of vehicles were not exceeded than 22 kmph, which considered low. It believes that the vehicles spent most of the time driving at lower travel speed. Additionally, moving vehicles can be claimed as added obstacles for the near surface recirculating wind. It substantially influences pollutant dispersion in street canyon by changing air flow and introducing turbulence characteristics, especially at the lower portion of a street canyon (Gross, 2016). Free flow of traffic at the faster travel speed enhance the magnitude of turbulence characteristics in the wake region behind the vehicles. In addition, the traffic-turbulence induced occurs at the ground of middle line of street canyon as the traffic were driven in the middle region of the road (Zhang, Gu, & Yu, 2017). This phenomenon promotes the ventilation of street canyon and then, allows the dilution process of pollutants (Yazid & Salim, 2014). It helps to improve the air quality along the midblock of a street canyon (Thaker & Gokhale, 2016).

The correlation between street canyon aspect ratio and pollutant concentration are mostly positive correlation with significant difference 0.01. Higher aspect ratio have positive correlation with higher pollutant concentration levels. The very positively strong correlations were be found between aspect ratio and benzene (r:0.875 p<0.01) at HP road. The positively strong correlations were distinguished for benzene (r:0.711, p<0.01) at the P road, CO (r:0.732, p<0.01) at P road, respectively. The strong correlation between CO and benzene to the aspect ratio can be explained by the greater aspect ratio of HP and P roads particularly more than 1.0. Besides, some of these roads indicate the very deep street canyon due to the presence of aspect ratio more than 4.0.

The presence of high-rise buildings in urban morphology promotes the creation of high building canopy which increases the mixing height of air flows. The taller building may form numerous vortices in street canyon (Sanath Edussuriya & Chan, 2015) reduces the air exchange rate of street canyon. As a result, the pollutants accumulates in the street canyon and reduces the performance of pollutant removal (Liu, Cheng, Leung, & Leung, 2011). Besides, the leeward airflow in the vertical axis which generally consists of flow structure in the lower part of the street canyon, hindering the dispersion of pollutants into the upper part (Li et al., 2020). A smaller aspect ratio exhibits the better pollutant dispersion due to better wind distribution by means of good air exchange at ground level and outside air of street canyon (Aquilina & Micallef, 2004; Mat Santamouris, 2006).

Most of the wind speed and pollutant concentrations were mostly not correlated. Nonetheless, CO (r:0.418, p<0.01) at HP roads, $NO_2$ (r:0.402, p<0.01) at GM roads and benzene (r:0.641, p<0.01) at HP roads show the negatively correlation to wind speed. This finding also indicates a similarity to research conducted by Ghafghazi & Hatzopoulou (2015). They suggested that a negative association between wind speed and NO2 as the wind speed increase, the NO2 concentration reduce. The air flow in the street canyon has a coupling effect to the above roof-imposed wind flow. In this case, the wind speed out of canyon is below threshold value (2.0 m/s) so that, the coupling effect is lost. The vortex recirculation is do not also created, resulting the lack of pollutants advection which allows the higher average of pollutant concentration. Conversely, a stable vortex recirculation is formed in street canyon when the wind speed is larger than the threshold value (Mat Santamouris, 2006). The greater magnitude of wind speed, the stronger vortex was formed due to the increasing turbulent intensity.

The wind direction has positively strong correlations value measured for the NO2 (r:0.861, p<0.01) at MM roads and PM10 (r:0.623, p<0.01) at GM roads. This finding shows a similar result found by (Kim & Guldmann, 2011) which reveals the positive correlation to NO2 and CO. Most of the wind direction blew from the oblique angle consequently, reveals the lower pollutant concentration in street canyon as suggested by (Kumar et al., 2008). When the wind flow approaches the perpendicular angle, the pollutant concentration increases.

Table 4.4 A correlation analysis of pollutant concentration and factors of dispersion.

**. Correlation is significant at the 0.01 level (2-tailed).

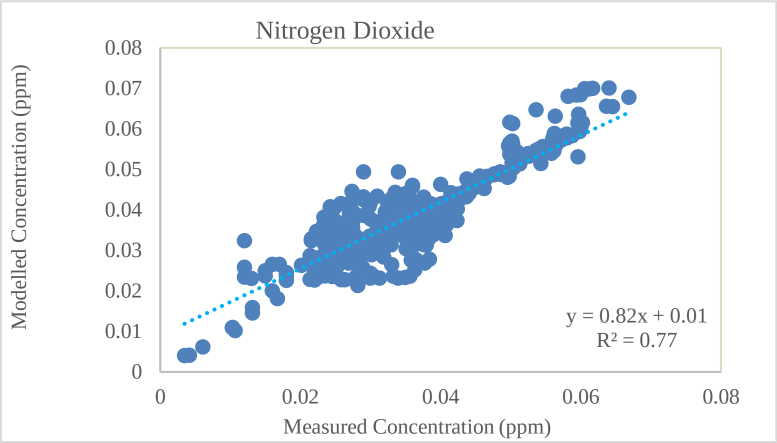
*. Correlation is significant at the 0.05 level (2-tailed).

| Factors | Roadway | PM2.5 | PM10 | SPM | CO | NO2 | O3 | Benzene |
|---|---|---|---|---|---|---|---|---|
| Traffic Volume | HMLIT | **0.445**** | 0.165 | **0.302**** | 0.065 | **0.798**** | **0.418**** | **0.834**** |
| | HP | 0.206 | **0.641**** | **0.418**** | 0.017 | 0.247 | 0.112 | **0.338**** |
| | MM | **0.267*** | **0.708**** | -0.138 | **0.765**** | 0.249 | **0.664**** | **0.661**** |
| | P | **0.446**** | **0.823**** | 0.021 | **0.449**** | **0.518**** | 0.068 | 0.138 |
| | GM | **0.418**** | **0.641**** | 0.31 | **0.515**** | 0.132 | **0.486**** | **0.29*** |
| Travel Speed | HMLIT | **-0.445**** | 0.158 | **0.317**** | 0.077 | **-0.283**** | **-0.681**** | 0.169 |
| | HP | -0.187 | **-0.735**** | **0.427**** | -0.103 | 0.165 | -0.166 | -0.142 |
| | MM | 0.194 | 0.119 | 0.252* | **-0.725**** | **-0.588**** | -0.105 | 0.162 |
| | P | **-0.451**** | -0.031 | -0.440* | **-0.451**** | -0.168 | -0.151 | -0.334 |
| | GM | 0.017 | **0.243*** | -0.223* | **-.287**** | 0.114 | **-0.297** | 0.132 |
| Aspect Ratio | HMLIT | 0.138 | 0.029 | 0.002 | **0.350*** | **0.556**** | **0.325**** | 0.201 |
| | HP | **0.202*** | **0.384*** | 0.115 | 0.193 | **0.201*** | 0.092 | **0.875**** |
| | MM | 0.123 | **0.305**** | 0.013 | 0.179 | **0.282*** | **0.380**** | **0.330**** |
| | P | -0.02 | 0.215 | 0.013 | **0.732**** | **0.482**** | -0.085 | **0.711**** |
| | GM | 0.138 | 0.029 | **0.243*** | **0.471**** | -0.148 | -0.211 | 0.082 |
| Wind Speed | HMLIT | -0.036 | -0.061 | 0.09 | -0.078 | 0.106 | -0.1 | 0.074 |
| | HP | -0.05 | 0.035 | 0.094 | **0.418**** | 0.063 | 0.046 | **0.641**** |
| | MM | -0.082 | 0.04 | -0.022 | 0.107 | -0.105 | 0.065 | -0.025 |
| | P | **-0.324*** | -0.009 | -0.091 | 0.003 | 0.066 | -0.025 | -0.015 |
| | GM | 0.051 | 0.042 | -0.068 | -0.029 | **0.402*** | -0.16 | -0.138 |
| Wind Direction | HMLIT | 0.087 | -0.132 | **0.369*** | 0.312 | 0.143 | -0.233 | 0.04 |
| | HP | 0.036 | 0.257 | -0.165 | 0.180 | **0.404*** | -0.191 | **0.449**** |
| | MM | -0.151 | 0.312 | 0.301 | 0.049 | **0.861**** | 0.069 | -0.017 |
| | P | **0.551**** | 0.364 | 0.117 | 0.004 | 0.218 | -0.087 | 0.039 |
| | GM | 0.436 | **0.623**** | 0.296 | 0.156 | -0.118 | -0.289 | 0.189 |

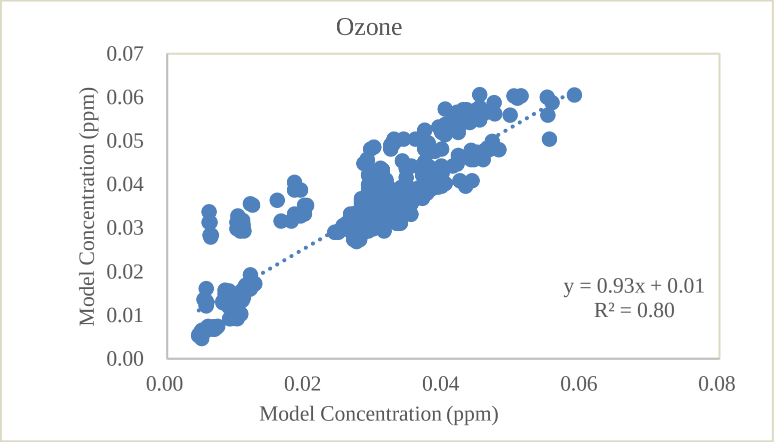
### 4.3.4 Model Performance Evaluation

The performance of OSPM model evaluated through the comparison between modeled and measured pollutants concentration at the same spatio-temporal scales. The statistical indicators applied for this purpose include RMSE, MAE, bias index of agreement and coefficient of determination ($r^2$) as tabulated in Table 4.5. The modelled concentrations were drawn against the measured concentration and the linear best-fit were plotted as shown in Figure 4.5. The linear regression analysis was adopted to evaluate the dependence of the modelled concentration and measured concentration. Coefficient of determination ($r^2$) is an indicator of how well the predicted pollutant concentration fits the measured pollutant concentration. The prediction of pollutant concentrations by OSPM are good, with the $r^2$ values of $NO_2$, CO, ozone, benzene, PM2.5 and SPM are 0.77, 0.81, 0.80, 0.76, 0.88, 0.94, respectively. However, PM10 indicates the moderate performance with the best-fit value is 0.47. All statistical tests reporting a P-value of <0.001 was considered as statistically significant. The measured PM10 were deduced based on the concentration of SPM and PM2.5 which leads to the uncertainty of the model.

The fitness of modelled concentration to the measured concentration can be indicates by RMSE. The small RMSE value between measured and modelled pollutant concentrations was calculated for $NO_2$ [0.006ppm], CO [0.079ppm], ozone [0.007ppm], benzene [0.074ug/m$^3$], PM2.5 [3.767ug/m$^3$], and SPM [0.006ug/m$^3$]. While, the MAE values are $NO_2$ [0.004ppm], CO [0.057ppm], ozone [0.005ppm], benzene [0.042ug/m$^3$], PM2.5 [3.278ug/m$^3$], and SPM [0.004ug/m$^3$]. In the most cases, $NO_2$, CO, ozone and benzene and SPM exhibit the lower RMSE, which results the smaller MAE. OSPM overestimated the predicted concentration for all pollutants with the positive value of bias, range from 4% to 20%. As similar with $r^2$, the index of agreement (0.60) of PM 10 also lower compared to other pollutants. SPM reveals the highest index of agreement between modelled and measured of concentration with the value of 0.94. The lower index agreement shows poor agreement between modelled and measured pollutant concentration. Likewise, PM10 results are in poor agreement with the measurement. This is due to the estimation of measured concentration PM10 deduced from the measured and modelled concentration of PM2.5 and SPM.

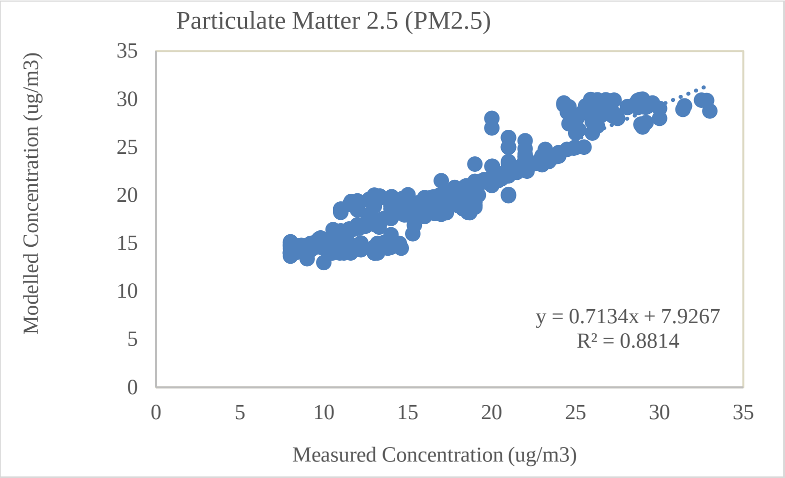


(a)

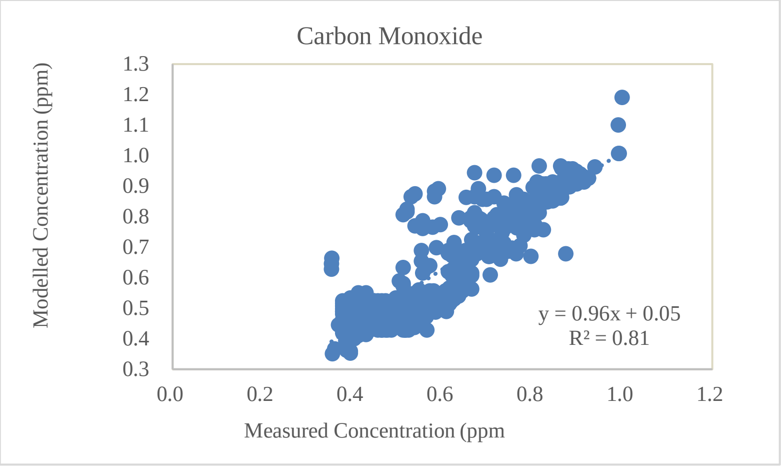


(b)

Figure 4.5 Scatter plot of predicted pollutant concentration against measured pollutant concentration (a) nitrogen dioxide, b) ozone,



(c)



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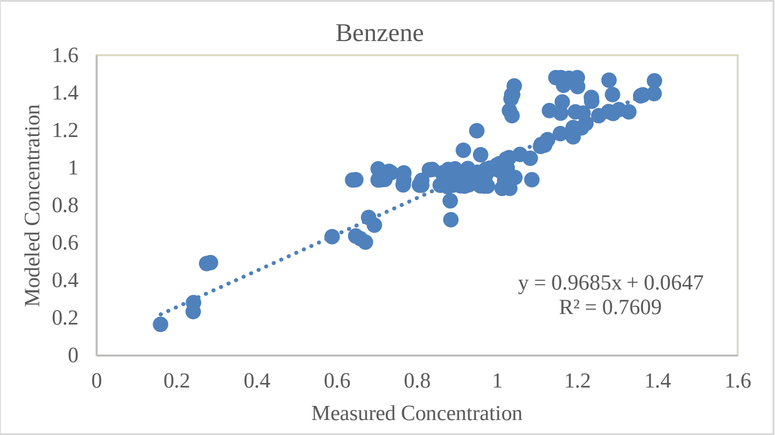
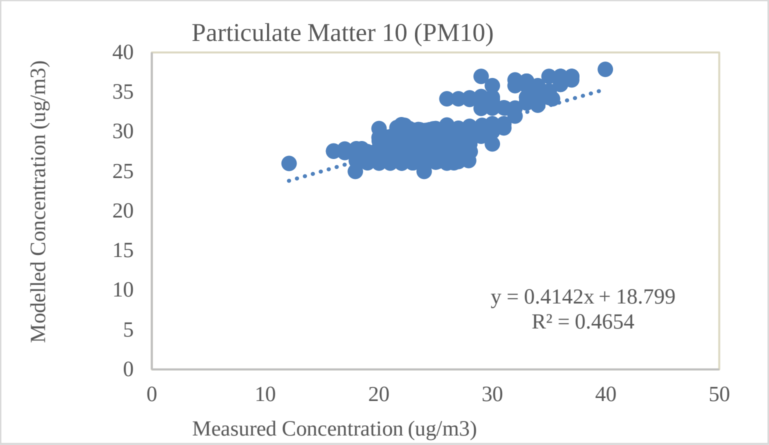
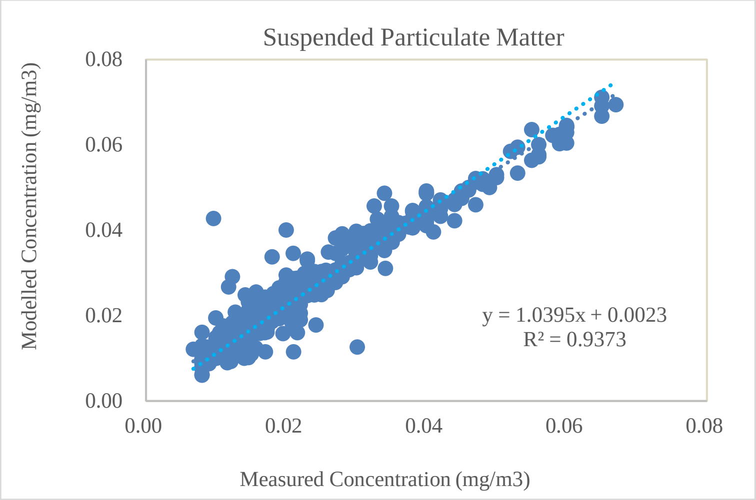


(e)

Figure 4.5 Scatter plot of predicted pollutant concentration against measured pollutant concentration c) PM2.5 (d) carbon monoxide, e) benzene



(f)



(g)

Figure 4.5 Scatter plot of predicted pollutant concentration against measured pollutant concentration f) PM10 and (g) Suspended Particulate Matter.

Table 4.5 A statistical indicator of OSPM model performance between modeled and measured pollutant concentration.

| | $NO_2$ | CO | Ozone | Benzene | PM10 | PM2.5 | SPM |
|---|---|---|---|---|---|---|---|
| unit | ppm | ppm | ppm | ug/m3 | ug/m3 | ug/m3 | mg/m3 |
| RMSE | 0.006 | 0.079 | 0.007 | 0.074 | 5.275 | 3.767 | 0.006 |
| MAE | 0.004 | 0.057 | 0.005 | 0.042 | 4.568 | 3.278 | 0.004 |
| BIAS (%) | 18.088 | 5.382 | 17.877 | 3.771 | 19.588 | 18.199 | 14.525 |
| IA | 0.889 | 0.939 | 0.906 | 0.911 | 0.602 | 0.855 | 0.940 |
| R2 | 0.770 | 0.810 | 0.800 | 0.760 | 0.470 | 0.880 | 0.937 |

## 4.4 Conclusion

OSPM model was utilized to predict the pollutant concentration in urban street canyon. The findings reveal that HMLIT roadway shows the highest pollutant concentration in urban street canyon. Based on the increment sequence of the pollutant concentration for each road under HMLIT roadway, Gojo Dori which located at road no. 9 can be classified as the most polluted road. Gojo Dori is the congested road (degree of congestion: 1.76) with the higher traffic volume 50,603unit/days, slower travel speed (15.7kmph), high aspect ratio of street canyon (1.25) and shorter road distance (0.1km). Comparison of the modelled and measured concentration with the Environmental Quality Standard of Japan and World Health Organization, all pollutant concentrations were permitted the standard limit. The spearman correlation analysis results depict that the influencing factors of pollutant dispersion such as traffic volume, wind speed, wind direction, aspect ratio are positively strong correlation to the pollutant concentration. Otherwise, travel speed indicates the negatively strong correlation to the pollutant concentration. The statistical indicator was adopted to evaluate OSPM model for predicting the pollutant concentration. PM10 indicates the highest RMSE and MAE, and greater percentage of bias and relatively lower value of $r^2$. Otherwise, OSPM model indicates the best-fitted and accuracy to the modelled concentration of the $NO_2$, CO, ozone, benzene, PM2.5 and SPM due to the lower RMSE, MAE and bias, and greater $r^2$ and index of agreement. Most of the pollutants were overestimated by the OSPM model due to positive percentage of bias. Overall, OSPM model had proven to be an applicable air dispersion model for urban street environment in Japan.

## Reference

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# CHAPTER 5

# HEALTH RISK ASSESSMENT OF TRAFFIC INDUCED AIR POLLUTANTS

## Abstract

This research assesses the health risks associated with exposure to traffic induced air pollutants (nitrogen dioxide ($NO_2$), carbon monoxide (CO), ozone ($O_3$), benzene, suspended particulate matter, pm10 and pm2.5) via inhalation to infants, children and adults. Assessment of inhalation risk is based on the method proposed by US EPA utilizing hazard quotient (HQ) for non-carcinogenic effect and cancer risk (CR) for carcinogenic effect. HQ value for acute, intermediate (normal and worst-case) and chronic intermediate (normal and worst-case) exposure were determined for each pollutant, while cancer risk was calculated for chronic exposure of PM2.5 and benzene. Results revealed that the HQ value for all pollutants for acute and intermediate normal exposure were lower than 1.0 and CR for PM2.5 and benzene was lesser than the acceptable level ($10^{-4}$). Infants and children have higher tendency to be affected compared to adults for pollutants exposure, excluded the chronic worst-case condition. Nevertheless, the potential health risks with the different severity of risks may pose by the exposed groups when they inhale the pollutants for long-term exposure. Overall, the study population have a negligible risk for short term-exposure and vice-versa for the long-term chronic exposure.

## 5.1 Introduction

In 2018, more than 55% world’s population live in cities area. This trend is increasing: 1.5 times to 6 billion, adding 2 billion more people living in urban (World Bank, 2020). European Environmental Agency (EEA) reports that commuters on metropolitan area such as London and Budapest are expected to travel more than an hour to work (EEA, 2013). According to OECD (2011), people allocate their time for commuting to and from work with the mean value of 8436 minutes or 140 hours and 36 minutes annually and becomes greater up to 30% for the gigantic megapolis areas. A survey on time use and leisure activities which conducted by the Department of Statistics of Japan (2016) published that approximately male and female spends on commuting time for work and school 0.43 hours and 0.23 hours, respectively. Commuters such as pedestrian and cyclist where high flow of vehicles on busy streets coexist, increase the exposure to urban air pollutants which often do not permit air quality standards, striking a considerable risk of development of several illnesses (de Nazelle, Bode, & Orjuela, 2017). Not only commuters, the near-road community (e.g. individuals working or living near major roads) also facing the health risk associated to traffic-induced air pollution (Noomnual & Shendell Derek G, 2017; Schultz, Litonjua, & Melén, 2017; Zhang, 2010), which accentuated inhalation exposure (Cepeda et al., 2017; Grana, Toschi, Vicentini, Pietroiusti, & Magrini, 2017; Vette et al., 2013; Zhang, 2010).

WHO (2013) stated that main emission source which posing an emerging health risk are road transport (40.7%), space heating and air conditioning (15.0%), shipping (8.8%), energy production and distribution (6.2%), industrial processes (metal industries) (6.2%) and agriculture (5.3%). Road emission is of special concern in terms of the contribution to the health impact of air pollution, principally critical in urban area (von Schneidemesser et al., 2019). Students live in downtown area expose to traffic induced air pollution result in participating physical activity, commuting to and from school due drop-off and pick up traffics, walking or cycling (Crilley et al., 2013). Schultz et al., 2017 suggested that the. Kim et al., 2016 reported that the frequency of children exposed to the higher level of traffic related air pollutant have lower lung function compared to those exposed to the lower level of pollutants asthma and allergic rhinitis treatment significantly increased with exposure to pollutants (NO2 and black carbon). Knittel and co-workers (2011) explored the relationship between infant mortality and traffic emission. They found that carbon monoxide indicated the most correlated, while PM10 and ozone less correlated to infant mortality.

In conjunction with deleterious health consequences of exposure to traffic-related air pollutants and urban sustainable quality of life, there is a clear necessity to investigate more realistic level of pollutant exposures (Dias Do Vale, 2014). A human health risk assessment is the process to predict the probability or chance and nature of exposure to hazardous substance. Zhang (2010) investigate the risk characterization of NO2 during traffic congestion for on- and near-road populations at freeway and arterial scenarios. The results recommend that health risks from congestion are possibly significant, and that the incremental impacts can vary substantially depending on the type of road and many other factors. Adamiec & Jarosz-Krzemińska (2019) assessed non-carcinogenic and carcinogenic health risk for both children and adults associated with the ingestion, dermal contact and inhalation of sidewalk dust at the trafficked road. They exposed that the largest health risk for children and adults is associated with the ingestion of sidewalk dust.

The health risk information is significantly beneficial for urban planners and policy maker and need more research will be conducted. Human exposure to air pollution is more frequent based on the fixed urban monitoring. However, the findings always underestimated the exposure of population, some researches indicate there are no or small relationship between human exposure to air pollutants (De Nazelle, Bode, & Orjuela, 2017; Ragettli et al., 2013). Thus, this study used the predicted pollutant concentration (CO, NO2, benzene, ozone, SPM, PM10 and PM2.5) at the street level to investigate the human health risk assessment (HHRA) via inhalation among urban dwellers. According to health risk assessment method for non-carcinogenic effects, hazard quotient was calculated correspond to the potential risk to health impact. On the other hand, carcinogenic risk from chronic exposure were evaluated for each exposed group (infant, children and adult).

## 5.2 Methodology

HHRA was conducted based on the framework developed by WHO, 2016. The HHRA framework has four components: hazard identification, dose–response assessment, exposure assessment and risk characterization.

### 5.2.1. Hazard identification

Hazard identification is a qualitative step implemented to explore damaging health effects (e.g., carcinogenicity, neurotoxicity, and developmental toxicity) for human following exposure to a hazardous agent. In this research, hazard identification divides the traffic induced air pollutants into two type; carcinogenic and non-carcinogenic. Carcinogenic pollutants are benzene and PM2.5, while non-carcinogenic are CO, $NO_2$, ozone and PM10. These pollutants concentrations were predicted based on the OSPM model which thoroughly discussed in Chapter 4.

### 5.2.2. Dose-response assessment

Dose response assessment involves evaluating the relationship between the dose of an agent received and the occurrence of adverse health effects from the exposure air pollutants (WHO, 2016). The intended aim of this step is to identify a threshold of exposure to pollutants which will cause adverse effects. However, this research did not conduct this step. Dose-response were assessed based on the standard limit which recommended by Environmental Quality Standard of Japan and World Health Organization.

### 5.2.3 Exposure Assessment

Exposure assessment involves the determination of the source, amount, duration of potential exposure to pollutant. Such analysis requires the identification of exposed population, sensitive sub-population and potential exposure route of entry. This research chooses a scenario assessment technique as duration of exposure, inhalation as a route of entry into human body, and three exposed groups which infant, children and adult. A scenario assessment technique includes acute (1-hour exposure), normal (average exposure) and worst-case (continuous exposure; intermediate (24-hours) and chronic (annual)) period of exposure.

An acute, chronic exposure of non-carcinogenic pollutants and exposure duration such as PM10, CO, $NO_2$, $O_3$ calculated based on Eqs 5.1 - 5.3, respectively.

$$AHD = \frac{C \times IR}{BW} \quad \text{(acute exposure)} \tag{5.1}$$

$$ADD = \frac{C \times IR \times ED}{BW \times AT} \quad \text{(chronic exposure)} \tag{5.2}$$

$$ED\ (exposure\ duration) = ET\ x\ EF\ x\ DE \tag{5.3}$$

where AHD is the average dose of inhalation for 24-hour (μg/kg/hour), ADD is the average daily dose of the chemical of interest (μg/kg/day), ET is the exposure time (hour/day), C is the amount of the chemical in ambient air (μg/m3), IR is the inhalation rate (m3/ day), ED is the exposure duration (days), BW is the body weight of the exposed group (kg), AT is the averaging time (days), DE is the duration of exposure (year) and

EF is the exposure frequency (days/year). The EF value is estimated on the basis that a person will be absent from his place of abode (study area) for 14 days yearly.

Table 5.1 tabulates frequency (EF), duration (DE) and averaging time (AT) of exposure for exposed group. Table 5.2 shows exposure time for normal and worst-case scenarios for acute, intermediate and chronic exposures. Table 5.3 exhibits mean inhalation rates and body weights of the exposed group such as infants (age: birth to 1 year), children (age: 6-12 year) and adut (age: 19-75 year)

Table 5.1 Frequency (EF), duration (DE) and averaging time (AT) of exposure for exposed group (Matooane and Diab (2003) and US EPA (1997)).

| Exposed group | Exposure Frequency (EF) | Duration of Exposure (DE) | Averaging Time (AT) |
|---|---|---|---|
| Infant | 350 | 1 | 365 (1x365) |
| Children | 350 | 12 | 4,380 (12x365) |
| Adult | 350 | 30 | 10,950 (30x365) |

Table 5.2 Exposure time (hours) for normal and worst-case scenarios for acute, intermediate and chronic exposures (Matooane and Diab (2003) and US EPA (1997)).

| Exposed Group | Exposure Time | | | | |
|---|---|---|---|---|---|
| | Intermediate | | | Chronic | |
| | Acute | Normal | Worst case | Normal | Worst case |
| Infant | 1 | 1 | 24 | 14.6 ((350/24)×1) | 350 (1×350) |
| Children | 1 | 6 | 24 | 1,050((4,200/24)×6) | 4,200 (12×350) |
| Adult | 1 | 3 | 24 | 10,500(10,500/24)×3) | 10,500 (30×350) |

For carcinogens, the lifetime average daily dose (LADD) and SF for the PM2.5 and benzene inhalation exposure route was used in the assessment of cancer risk as shown in Eq. 5.4:

$$LADD = \frac{C \times IR \times ET \times EF \times ED}{AT \times BW} \qquad (5.4)$$

Table 5.3 Mean inhalation rates and body weights of the exposed population (Matooane and Diab (2003) and US EPA (1997)).

| Exposed Group | Mean Inhalation rate (m3/24-hours) | | |
|---|---|---|---|
| | Acute | Chronic | Body Weight |
| Infant | 0.3 | 6.8 | 11.3 |
| Children | 1.2 | 13.5 | 45.3 |
| Adult | 1.2 | 13.3 | 71.8 |

### 5.2.4. Risk Characterization

Risk characterization is the quantitative prediction of the health risk of exposure to pollutant. It includes risk to individual, population and ecological impacts. It comprises the information on characterization and communication of magnitude and breadth of risk. In this research, risk characterization is determined based on the hazard quotient (HQ) (non-carcinogenic) and cancer risk (carcinogenic) as stated in Eqs 5.5-5.8.

$$HQ = \frac{ADD}{REL} \text{ (chronic exposure)} \qquad (5.5)$$

$$HQ = \frac{AHD}{REL} \text{ (acute exposure)} \qquad (5.6)$$

Cancer Risk = LADD x SF (carcinogenic exposure) (5.7)

$$SF = \frac{Unit\ risk}{BW\ X\ IR} \qquad (5.8)$$

where REL is the dose at which significant adverse health effects will occur in exposed groups compared with the unexposed group. LADD represents the lifetime average dose [mg/kg-day] and SF is the slope factor [kg-day/mg]. Unit risk of PM2.5 and benzene are 0.008ug/m$^3$ and 2.2x10$^{-6}$ug/m$^3$.

In this study, the term ‘reference exposure level’ (REL) refers to standard limit of ambient air set by Environmental Quality Standard of Japan and World Health Organization as presented in Table 5.4.

Table 5.4 Standard limit of air pollutants set by Environmental Quality Standard of Japan and World Health Organization.

| Pollutants | 1-hr | 8-hrs | 24-hrs | Annual |
|---|---|---|---|---|
| CO | 22900* | 0 | 0 | |
| NO2 | 400* | | 75 -113 | |
| O3 | 118 | | | |
| SPM | 0 | | 100 | 40* |
| PM10 | | | 50* | 20* |
| PM2.5 | | | 35* | 15* |
| Benzene | | | | 3 |

* Recommended Standard Limit by WHO, 2017.

Unit: ug/m$^3$

## 5.3 Result and Discussion

### 5.3.1 Non-carcinogenic health risk

Table 5.5 tabulates the mean and standard deviation of modelled pollutants concentrations ($NO_2$, CO, $O_3$, benzene, SPM, PM10 and PM2.5) at roadways. The mean and standard deviation values are based on the concentration of pollutants emitted from vehicles and dispersed in Kyoto City. A comparison was made between modelled pollutants concentration and the standard limit of air pollutants set by Environmental Quality Standard of Japan and World Health Organization. All pollutants concentration was permitted to the standard limit for 1-hour, 8-hours, daily and annually set by EQS, Japan and WHO. It exhibits that the urban population especially road users were exposed to relatively low level of pollutants.

Table 5.5 Modelled pollutants concentration at roadways

| Pollutants | $NO_2$ | CO | Ozone | Benzene | SPM | PM10 | PM2.5 |
|---|---|---|---|---|---|---|---|
| Mean | 33 | 57.78 | 3.2 | 0.0956 | 26.8 | 28.73 | 18.25 |
| SD | 0.008 | 0.061 | 0.0176 | 0.06 | 12.99 | 1.878 | 3.394 |

Unit: ug/m$^3$

Tables 5.6-5.10 depicts the hazard quotients for acute, normal and worst-case exposure scenarios to $NO_2$, CO, $O_3$, SPM and PM10. The estimation of acute exposure for non-carcinogen is based on 1 hour of exposure to pollutants. The HQ value of PM10 could not determine because the standard limit of exposure for 1 hour is not available. All pollutants (except PM10) reveal that the HQ for acute exposure is less than 1.0 which suggest an insignificant risk, even for high susceptibility groups such as infant and child. An intermediate exposure of pollutants corresponds to daily exposure, nevertheless standard limit of 24 hours exposure is not available for ozone. As an alternative, 8hours exposure was took account to calculate an intermediate exposure of ozone. The HQ under normal condition of intermediate effect for all pollutants are less than 1.0. It recommends that the negligible risk of exposure to pollutant for all exposed group. However, the HQ value of SPM (0.899) and PM10 (0.988) for child are obviously closed to 1.0, having a possibility deteriorates health impact such as lower respiratory infections (e.g. pneumonia, asthma, bronchitis). However, there is higher likelihood of health risk (HQ<1) associated 24-hour exposure for worst-case condition to $NO_2$, ozone (except adult (0.772)), SPM and PM10 for each exposed group.

Table 5.6 Hazard quotients for acute, normal and worst-case exposure scenarios to nitrogen dioxide ($NO_2$) at a variety levels of exposures for infant, child and adult.

| Exposed group | Acute | intermediate | | chronic | |
|---|---|---|---|---|---|
| | | normal | worst case | normal | worst case |
| Infant | 4.37E-03 | 3.36E-01 | 8.07E+00 | 1.39E+01 | 3.33E+02 |
| Child | 4.36E-03 | 5.03E-01 | 4.00E+00 | 4.94E+02 | 1.98E+03 |
| Adult | 2.75E-03 | 1.59E-01 | 2.48E+00 | 3.84E+02 | 3.07E+03 |

Table 5.7 Hazard quotients for acute, normal and worst-case exposure scenarios to carbon monoxide (CO) at a variety levels of exposures for infant, child and adult.

| Exposed group | Acute | intermediate | | chronic | |
|---|---|---|---|---|---|
| | | normal | worst case | normal | worst case |
| Infant | 1.19E-04 | 2.59E-03 | 6.23E-03 | No standard limit for annual exposure | |
| Child | 1.19E-04 | 7.71E-03 | 3.08E-02 | | |
| Adult | 7.52E-05 | 2.40E-03 | 1.92E-02 | | |

Table 5.8 Hazard quotients for acute, normal and worst-case exposure scenarios to ozone ($O_3$) at a variety levels of exposures for infant, child and adult.

| Exposed group | Acute | intermediate | | chronic | |
|---|---|---|---|---|---|
| | | normal | worst case | normal | worst case |
| Infant | 1.20E-03 | 1.04E-01 | 2.51E+00 | No standard limit for annual exposure | |
| Child | 1.20E-03 | 3.10E-01 | 1.24E+00 | | |
| Adult | 7.56E-04 | 9.64E-02 | 7.72E-01 | | |

Table 5.9 Hazard quotients for acute, normal and worst-case exposure scenarios to suspended particulate matter (SPM) at a variety levels of exposures for infant, child and adult.

| Exposed group | Acute | intermediate | | chronic | |
|---|---|---|---|---|---|
| | | normal | worst case | normal | worst case |
| Infant | 6.96E-03 | 3.03E-01 | 7.26E+00 | No standard limit for annual exposure | |
| Child | 6.94E-03 | 8.99E-01 | 3.60E+00 | | |
| Adult | 4.38E-03 | 2.79E-01 | 2.23E+00 | | |

Table 5.10 Hazard quotients for acute, normal and worst-case exposure scenarios to particulate matter 10 (PM10) at a variety levels of exposures for infant, child and adult.

| Exposed group | Acute | intermediate | | chronic | |
|---|---|---|---|---|---|
| | | normal | worst case | normal | worst case |
| Infant | No Standard Limit of 1-hr exposure | 3.32E-01 | 7.98E+00 | 1.21E+01 | 2.91E+02 |
| Child | | 9.88E-01 | 3.95E+00 | 4.32E+02 | 1.73E+03 |
| Adult | | 3.07E-01 | 2.46E+00 | 3.36E+02 | 2.69E+03 |

Under intermediate exposure to non-carcinogens, infants appear more likely to be affected by worst-case condition than children and adults, although for normal exposure, children have more tendency to be affected. Nhung et al., 2018 discussed that the short-term effect of pollutants (PM10, PM2.5, NO2 and CO) exposure among children. They found that the pollutants levels were positively associated with hospitalization for lower respiratory infections (e.g. pneumonia, asthma, bronchitis). The associations were stronger for children aged from 1 to 5 years. Children impose the higher risk due to the immaturity of their biological systems, larger lung surface area, the greater inhalation rate than adult and spend more time outdoors for physical activities (Bell, Zanobetti, & Dominici, 2013; Saadeh & Klaunig, 2015).

Only the chronic effects of $NO_2$ and PM10 exposure can be calculated, whereas the threshold exposure limit value of CO, ozone and PM2.5 are not available. The HQ value for NO2 and PM10 are largely exceeded 1.0 under chronic exposure for both normal and worst-case condition. It predicts that the severe health impact may pose by the exposed group due to the inhalation of $NO_2$ and PM10 for long term period. According to the Institute for Health Metrics and Evaluation, the lower respiratory infection, lung cancer and chronic obstructive pulmonary disease (COPD) ranked as no 4, 5 and 9 out of the top 10 cause of death by 2017 in Japan. Based on this kind of information, it can be suggested that exposure to air pollutants are major risk factor of mortality. Similar to intermediate exposure, children may have greater risk than infants and adults for normal exposure, while adults indicate may impose largest risk when expose to pollutants under the worst-case chronic exposure. Schikowski et al. (2005) proposed that the people live at near-road with busy traffic inhaled $NO_2$ and PM10 for a long term exposure. As a result, people might have the potential health risk of developing COPD and a destruction of pulmonary function.

### 5.3.2 Carcinogenic Health Risk

Non- carcinogenic and carcinogenic effects of benzene and PM2.5 to infants, children and adults were estimated based on the hazard quotient and cancer risk value as presented in Table 5.11. As tabulated in Table 5.11, the HQ of benzene and PM2.5 for all exposed group are clearly lower than 1.0. Infants ($2.24 \times 10^{-4}$; PM2.5, $5.89 \times 10^{-5}$;benzene) rather than children ($1.07 \times 10^{-4}$; PM2.5, $2.81 \times 10^{-5}$; benzene) and adults ($1.57 \times 10^{-4}$; PM2.5, $4.12 \times 10^{-5}$; benzene) are more likely to be affected by non-carcinogenic exposure of PM2.5 and benzene. On the other hands, for cancer risk, adults ($1.31 \times 10^{-8}$; PM2.5, $1.89 \times 10^{-13}$; benzene) indicate the less affected by exposure to both pollutants. The exposure among infants, children and adults were lower than $1.0 \times 10^{-5}$ and $1.0 \times 10^{-6}$ are acceptable by WHO and US EPA respectively. This value indicates that chronic inhalation exposure to PM2.5 and benzene pose negligible risks to three exposed groups.

Table 5.11. Non-cancer and cancer risk of PM2.5 and benzene for three exposed groups.

| | Exposed Group | PM2.5 | Benzene |
|---|---|---|---|
| HQ | Infant | 2.24E-04 | 5.89E-05 |
| | Child | 1.07E-04 | 2.81E-05 |
| | Adult | 1.57E-04 | 4.12E-05 |
| Cancer risk | Infant | 5.30E-07 | 7.65E-12 |
| | Child | 3.30E-08 | 4.76E-13 |
| | Adult | 1.31E-08 | 1.89E-13 |

## 5.4 Conclusion

Health risk assessment was conducted on the traffic induced air pollutants on three main groups such as infants, children and adults. All the pollutants were permitted to standard limit set by Environmental Quality Standard of Japan and World Health

Organization. Findings from the currently available studies reveal that the HQ value of all pollutants under acute and normal intermediate exposure conditions for the non-carcinogenic effects were not exceeded than 1.0. However, the exposed groups may have the potential detrimental health impacts with the different severity due to the HQ values are larger than 1.0 for the worst-case and chronic exposure scenarios  Pertaining PM2.5 and benzene, the carcinogenic effect was calculated based on cancer risk which lower than the limit set by US EPA. Thus, the present results indicate no significant risk from inhalation exposure both pollutants. As overall, these results present the needs for traffic emission control in order to avoid the long-term health impacts due to inhalation risk among the urban dwellers.

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# CHAPTER 6

# DEVELOPMENT OF RISK MANAGEMENT APPROACH OF TRAFFIC INDUCED AIR POLLUTION IN URBAN ENVIRONMENT

## Abstract

The goal of this chapter is to develop a holistic risk management approach for traffic induced air pollution in urban environment. This approach incorporates the concept of urban sustainability and risk management proposed by United Nation Department of Economic and Social Affairs (2013) and the 2018 International Standard Organization (ISO) risk management 31000, respectively. An urban sustainability was built by standing four pillars such as economic, environment, social and government. A risk management approach integrates the principles, framework and process as one component and solely synchronized with the findings of this research. The element of risk management covers the elements customized, integrated, inclusive, dynamic, best available information, human and cultural factors, continual improvement, structured and comprehensive. The framework of risk management includes integration, design, implementation, evaluation and improvement. The risk management process adapts the principal of scope, context and criteria, risk assessment, risk analysis, risk treatment, monitoring and review and risk communication. It is intended to be a reference document to help policy makers, urban development departments and environmental practitioners to prepare, implement, and review the issue of transport and air pollution in the urban area.

## 6.1 Introduction

Urbanization refers to the increasing number of people shift from rural to urban area. The unprecedented rate of urbanization has been confronting major drawbacks to environment, social and economics (Mori and Christodoulou, 2012). The urban area has spurted various challenges such as poverty, unaffordable housing price, poor water and sanitation, traffic congestion, increase energy demand, spreading of diseases, joblessness, development of slum and growth of crime rate. The urgency of inclusive solution is required for future enhancement and resilience, known as a sustainability. In conjunction with urbanization and sustainability issue, sustainable development goals (SDG) reflects to the Goal-11 "Make cities and human settlements inclusive, safe, resilient and sustainable". The fundamental of urban sustainability has gain great attention, nevertheless its definition is controversial (Ferr, 2016). Camagni (1998) proposed the definition of urban sustainable development as a process of synergetic integration and co-evolution among the great subsystems making up a city (economic, social, physical and environmental), which guarantees the local population a non-decreasing level of wellbeing in the long term, without compromising the possibilities of development of surrounding areas and contributing by this towards reducing the harmful effects of development on the bio-sphere" (Camagni, 1998). The realm of sustainability crucially comprises three pillars (environmental, economic and social dimensions) is considered to assist in designing a holistic risk-based framework (Ozturkoglu et al., 2019).

One of the main concerns connected with sustainable development is that risk, uncertainty, and information inadequacy. Concerning risks, we need to comprehend disparities about the nature of these issues and build more operative and formalized strategies to integrate it into the policy-making and management process with regard to sustainability (Edjossan-Sossou et al., 2020; Madani & Lund, 2011). Therefore, a risk-based approach was suggested to be integrated to accomplish the sustainable development goal. In case of urban sustainability and risk management, this chapter develops a holistic risk-based management of traffic emission in urban environment of Kyoto City, Japan by integrating the theory of sustainable development and the 2018 revised International Standard Organization (ISO) risk management 31000. It specifically designed to provide a guided plan for managing risk created by the pollutant emission from traffic in urban environment for achieving more sustainability.

## 6.2 Development of a holistic risk management approach for traffic induced air pollution.

A various technique has been employing by many international, national and local authority to assess, manage, and communicate the risk. The operational of this technique working with intricate and divergent information and tends to have a consistency when working with cross-cutting issues of risks. The root cause of inconsistencies is inefficient risk judgement, malfunctions of risk communication and failure of risk management. Besides, the approach deals with risk are typically applied to solve the difficulties individually, not used deliberately. Figure 6.1 illustrates the proposed sustainable risk-based management approach of traffic induced air pollution in urban area. This deductive approach facilitates the top-down method to break down the sustainability concepts into the pillars and priority areas, consequently applied the concept of risk management. The risk management use the new version of International Standard Organization (ISO) risk management 31000 which revised in the year of 2018. There is a clear dotted blue line to separate two parts of approach, whereas the upper side refers to sustainable development, and the lower side theoretically discusses the ISO risk management 31000 (2018).

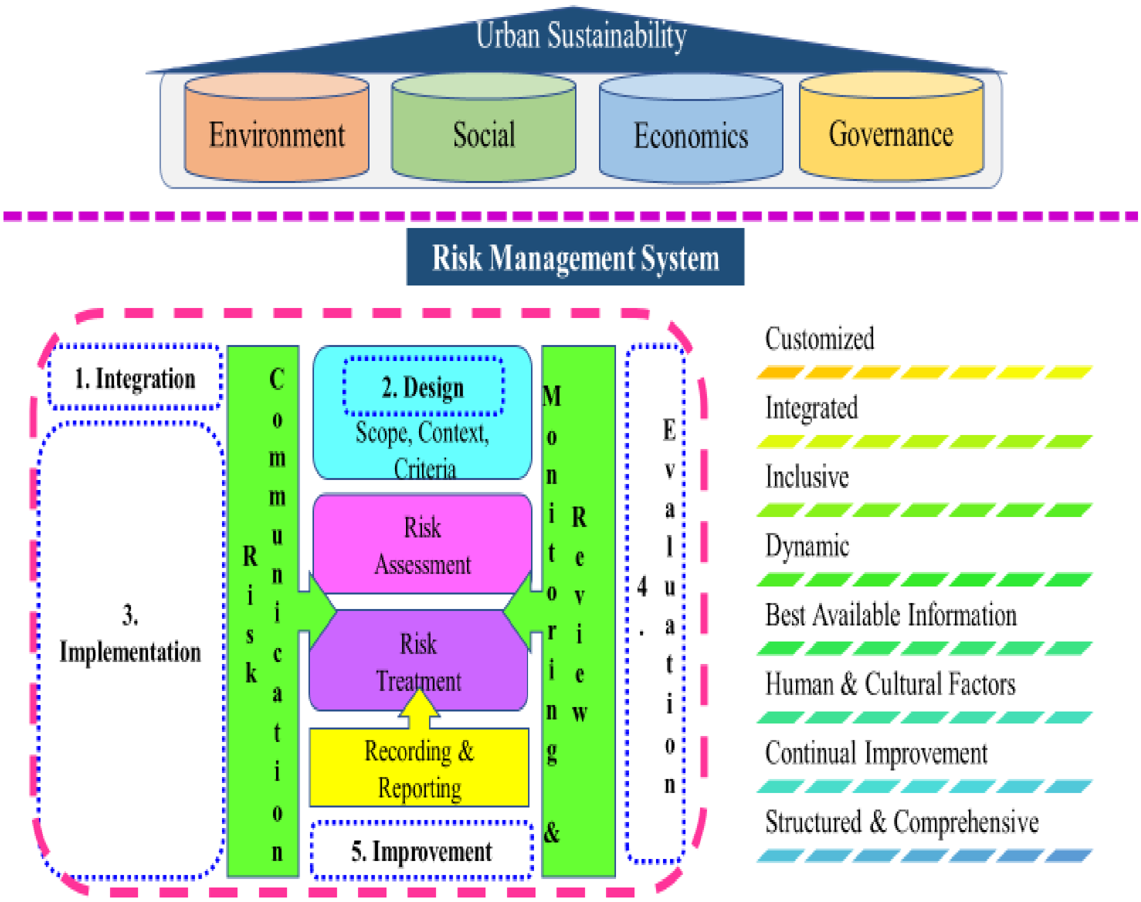

**Figure 6.1 A holistic and inclusive framework of risk-based management of traffic induced air pollution.**

## 6.3 Urban Sustainability

The concept of sustainability development was adopted at the upper side of risk management system. Since this research conducted in urban area, the term of "urban sustainability" was implemented. The traditional pillars of sustainable development only applied three components which are economics, environments and social development. This research embraced the concept of urban sustainability suggested by United Nations Department of Economic and Social Affairs (2013) for instance, economic development, environmental development, social development and effective urban governance. Figure

6.2 shows the integration between urban sustainable pillars and sectors such as: (1) Empowerment of All People, (2) Achievement of Good Health and Longevity Planet, (3) Creating Growth Markets, Revitalizing Rural Areas, and Promoting Science, Technology and Innovation, (4) Sustainable and Resilient Land Use, Promoting Quality Infrastructure, (5) Energy Conservation, Renewable Energy, Climate Change Counter-measures, & Sound Material-Cycle Society, (6) Conservation of Environment, including Biodiversity, Forests and the Ocean, (7) Achieving Peaceful, Safe and Secure Societies, (8) Strengthening the Means and Frameworks for the Implementation of the SDGs. These sectors are the Eight Priority Area set by the Japan government in National Implementation Framework on SDG Promotion in 2016 (Ministry of Foreign Affairs of Japan, 2017). This research can be claimed as a constructive effort to promote SDG by creating the synergistic between priority areas of SDG.

## 6.4 Risk Management Approach

Risk Management defines as the process of identifying, evaluating, selecting, and executing actions to reduce risk to human health and ecosystems. The goal of risk management is scientifically sound, cost-effective, integrated actions that reduce or prevent risks while considering social, cultural, ethical, political, and legal considerations" (U.S. Presidential/Congressional Commission on Risk Assessment and Risk Management, 1997). The second part concern a holistic risk management framework that highlights the interconnected main components: principles, framework and process. A process is embedded into the framework to sustaining a risk management approach of traffic induced air pollution.

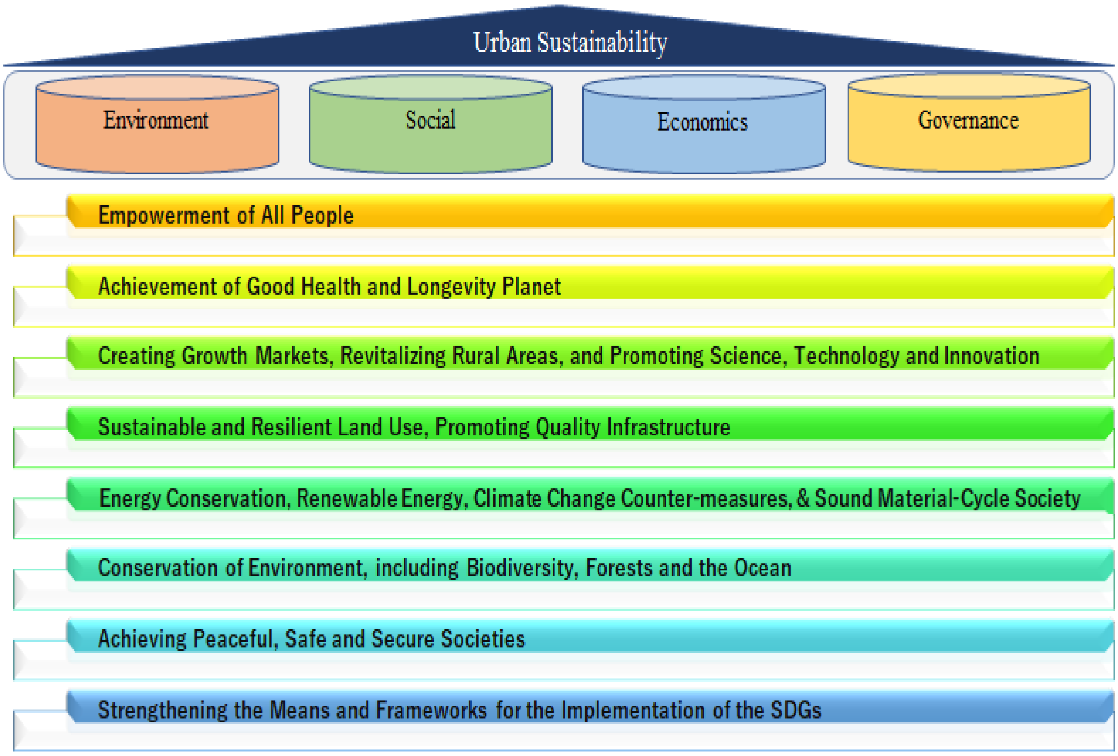

Figure 6.2 Integration between urban sustainable pillars and eight priority sectors of SDG.

### 6.4.1 Principles of Risk Management Approach

There are eight (8) interrelated principles that underlie effective risk management: 1) Integrated: risk management should be integrated into all activities and planning of organization, 2) Structured and comprehensive: The most reliable and excellent risk management outcomes can be achieved by generating and succeeding a comprehensive and structured risk management approach. All elements of risk management must be in properly coordinated. 3) Customized: The risk management framework and process are customized and actionable to the stakeholder needs, and external and internal context associated to its targets, 4) Inclusive: Knowledge, views, and perception of organization must be inclusive and acknowledge due to suitably and periodically involvement. As a result, it can increase the awareness and provide information of risk management to them. 5) Best available information: All information such as previous, current and future information, uncertainties and limitation are take into consideration to obtain efficient risk management. Organization easily accesses to any information periodically and clear manner. 6) Human & cultural factors: The risk managers should create the integration and inculcation of human and cultural element in risk management. As a result, people will absorb the element of risk management in their culture and human life. 7) Continual improvement: With continual improvement in risk management, each stage or level of process should be reviewed on the continual basis based on experience and learning process. and 8) Dynamic: Risk is not a rigid element so that, it needs the anticipation, detection, address, and reactions on any changes and events from normal to frequent changes in appropriate and timely manner.

### 6.4.2 Framework of Risk Management Approach

Risk management framework was developed by inserting process elements, as one component as displayed in Figure 6.3 shows. A holistic framework of risk management approach is a crucial practice implemented to handle a myriad of risks holistically and inclusively. The organization should confirm that the risk management approach assimilated into all activities, strengthen leadership and develop commitments. This framework constructed through a continuous step such as integration, design, implementation, evaluation and improvement.

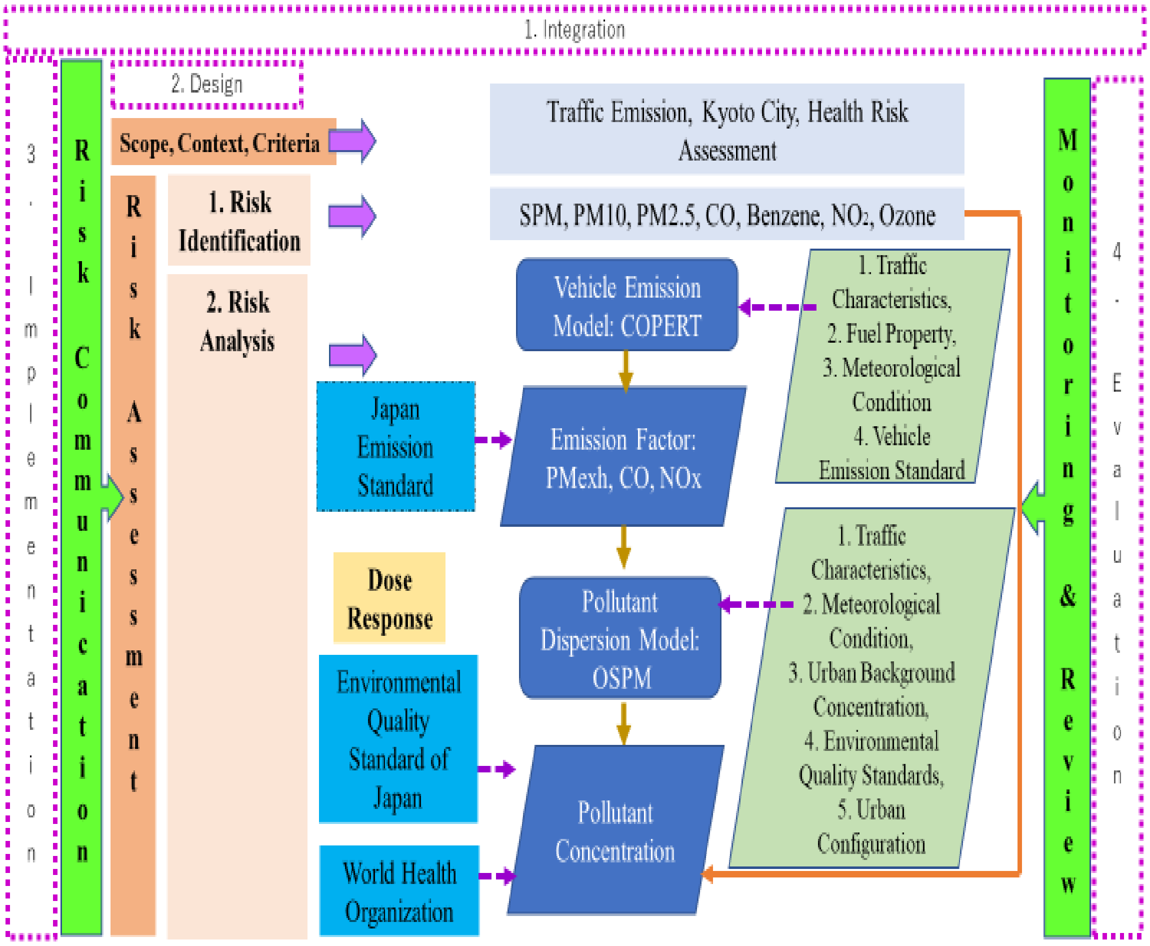

Figure 6.3 A holistic framework of risk management for traffic induced air pollution in Kyoto, City, Japan.

During conducting the risk management, the element of risk management is important to effectively communicate with stakeholders with regards to the potential risks via implementing the science-based approach. Risk communication is an effort to convey, disperse and transmit the information of risks (risk assessments, models use and procedures) between risk assessors, risk managers and public. Risk communication tools include written, verbal or visual evidence encompassing information about risks. The risk managers help the urban dwellers especially for those affected to traffic induced air pollution to understand the process of risk assessment and management, to provide useful and scientific knowledge of the hazards and involve with the process of decision making on treating the risks. It must be a two-way conversation to obtain the effective risk communication.

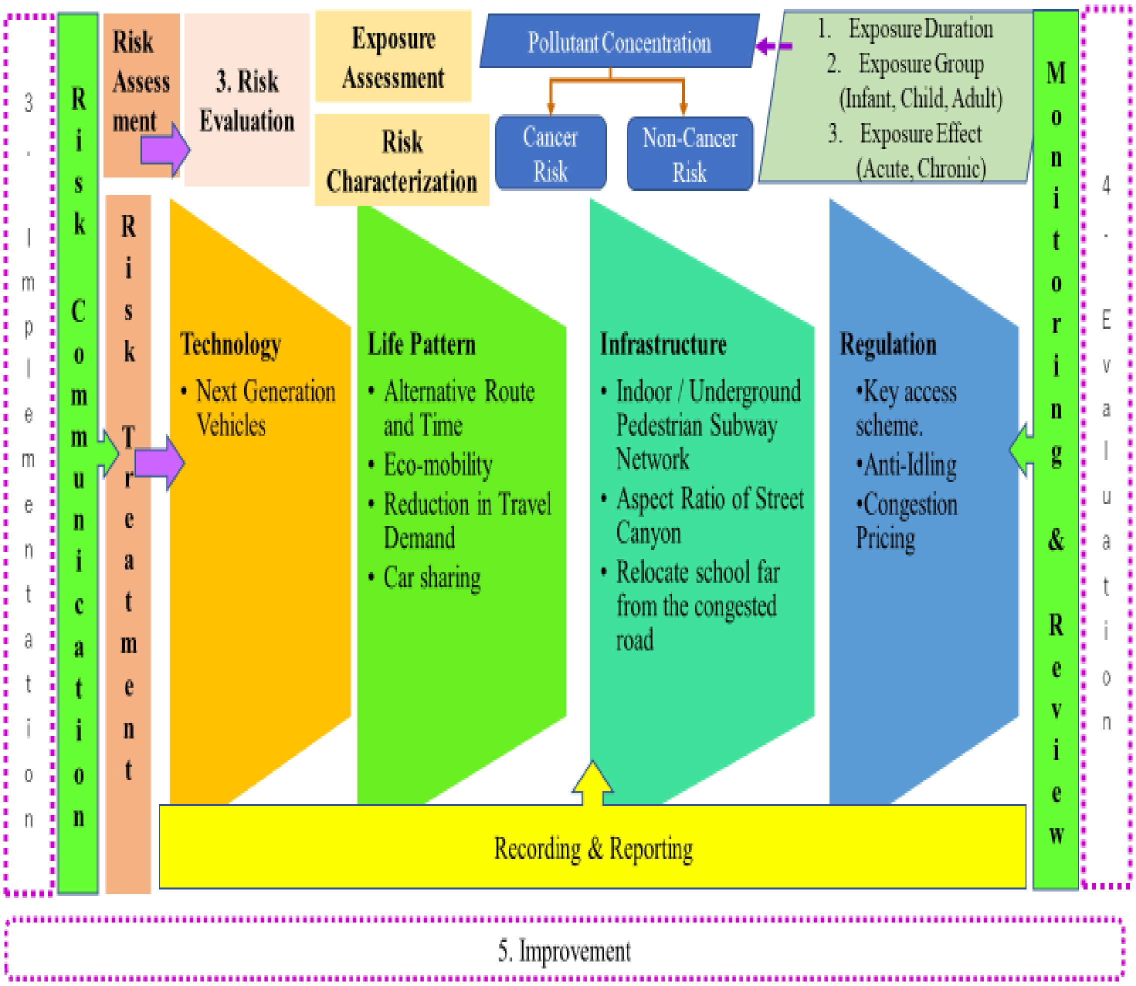

Figure 6.3 An extension of the risk management framework for traffic-induced air pollution in Kyoto, City, Japan.

### 6.4.2.1 Integration

The first step of risk management framework is integration, which is a flexible, iterative process and tailored to, not separated from the aim, governance, leadership and commitment, strategy, objectives, and operations. These aspects hinge on knowledge, implementation on risk management, responsibilities, and management in every part of governmental structure, NGO's, research and education, citizen, a private company, and urban residents. The management structure of each organization should translate and address authority direction into the coordinated strategy and associated objectives obliged to obtain the desired level of sustainable risk management performance and long-term practicability. This is important in determining and efficiently executing, cost-effective and informed risk management decisions.

#### 6.4.2.2 Design

The second step of framework is designing step, a vital element and brainstorming process in developing practical and holistic risk management. When designing the framework, thorough and comprehensive planning should be used by risk managers. There are elements should take into consideration, but not restricted to 1) identify the objectives (as discussed in Chapter 1), values, expectations and needs of conducting risk management of traffic induced air pollution. 2) capabilities of risk management in terms of role, governance and accountabilities of implementing risk management, 3) examine social, economic, political and cultural elements which significantly influence the effectiveness of risk management, 4) recognize legal binding relates to risk management such policies (Environmental protection policy, Health policy, Science and technology policy, urban policy), standard, guidelines and strategies (Basic Environment Plan, National Spatial Strategy, Health Japan 21 and Basic Plan on Transport Policy), and 5) any difficulties and uncertainties in conducting risk management. 6) investigate the allocation resource to perform risk management in terms of financial support, skilled workforce, document and procedures, available information (input data), and knowledge system (software used).

### 6.4.2.3 Implementation

Implementation step in risk management framework considers the appropriate strategies by taking into consideration time and resources, all aspects of making effective decisions and ensure all levels in organization structure fully understand risk management. During implementing the risk management step, the progress of proactive risk treatment also needs to monitor, monitoring and controlling risks, and updating the risk information, occasionally, and systematic reanalyzing risks should perform. Engaging and awareness of stakeholders towards risk management are the essential factor of the decision-making procedure. The benefits of stakeholder engagement in the risk management approach are to compromise the public values, improve the credibility and accountability of the organization in charge of managing risk, create more acceptance and readily implement the risk management decision. In the developed framework, the implementation steps interlink to risk assessment, risk treatment, risk communication.

In this context, risk assessment is a coordinated process to estimate the magnitude of negative health impact from the traffic induced air pollution exposure. The sub-stages of risk assessment are risk identification, risk analysis and risk evaluation, which also similar with the health risk assessment method (hazard identification, dose response analysis, exposure assessment and risk characterization) suggested by US EPA. Risk identification is needed to explore, recognize and explain risks which relies on the previous and up-to-date information relates to risks. This research identifies air pollutants (suspended particulate matter, PM10, PM2.5, carbon monoxide, benzene, nitrogen dioxide, and ozone) from traffic emission as an environmental risk which highly possibly to give impact to human health.

Risk analysis is the process to investigate the nature of risks, characteristics and level. This process entails a detailed exploration on uncertainties, risk source, likelihood, scenarios, existing risk control and their effectiveness. The aim of risk analysis step is to characterize the risk generated from the traffic induced air pollution. It starts with the estimation of emission factors of pollutants by COPERT model were then compared to the Japanese Dynamometer Chassis Test Cycle. The prediction of pollutant dispersion conducted via the implementation of OSPM model. The findings were evaluated in terms of permitting to the standard limit of pollutant concentration set by Environmental Quality Standard of Japan and World Health Organization, respectively which also can be considered as a dose-response analysis. The last sub-stage of risk assessment is risk evaluation which uses as a guidance in making the efficient decision. This sub-stage were determined the local people exposure and characterized the inhalation risk by referring to the US EPA Health Risk Assessment Methodology by means of hazard quotient (HQ) for non-carcinogenic effect and cancer risk (CR) for carcinogenic effect. Based on this finding, the additional action can take into a consideration for improvement such as risk control options.

Risk treatment is a process to choose and execute opportunities for controlling the risks via proposing, selecting, implementing, and assessing the effectiveness of risk control. Clarification for risk treatment is broader than solely economic considerations and should make by the organization's objectives, risk criteria, and available resource. Risk treatments might not produce the expected outcomes and could produce unintended consequences. Monitoring and review need to be an integral part of the risk treatment implementation. The remaining risk should document and subject to monitoring, review and, where appropriate, further treatment. The risk treatment plans aim to determine how the treatment options selected will be enforced, so that the procedures understood by those concerned and progress against the plan can be tracked.

This framework divides the risk treatment strategies into four main components technology, life pattern, infrastructure and regulation. **Technology**: The establishment of advanced vehicle technology and cleaner fuels considerably enhance the quality of air. In 2015, only 7 percent of vehicles in Japan used alternative fuels such as hydrogen, hybrid, electric, biodiesel, and natural gas. According to government white paper on energy (2017), the total sales of gasoline and diesel in 2016 are more significant than the alternative fuels by 54.8% and 31.4%, respectively. The Japan Government has set up the policy to increase the ratio of next-generation vehicles (e.g., hybrid vehicles, electric vehicles [EVs], plug-in hybrid vehicles [PHEVs], fuel cell vehicles [FCVs], clean diesel vehicles, and compressed natural gas [CNG] vehicles) to all new vehicles to 50% - 70% by 2030. The users and automobile manufacturers should take part in the direction of strategy accomplishment.

**Life patterns** such as 1) alternative route and time, 2) eco-mobility, 3) reduction in travel demand are the proposed pragmatic effort to control the risk of traffic-induced air pollution in the urban environment. 1) alternative route and time: the urban resident can avoid road congestion via intensive use of an intelligent transport system, consequently, promotes the shortening travel period. The organization should offer flexible working hours to the sub-coordinates so that it can reduce the need for people to commute at peak hours. 2) eco-mobility approaches with a pyramid concept can assist in solving the traffic-induced air pollution, which also contemplates a people-centered aspect on in what way urban residents move in cities, energizing active mobility as well as co-benefit of physical health. Better public areas and facilities built to encourage walking, biking, and mass transit render communities healthy and cleaner air. 3) reduction in travel demand: population density and compatible structure in urban area play a decisive role in minimizing travel demand. The higher the population density, the shorter the distances between the locations of different activities, and the higher the number of people who can comfortably to coordinate the eco-mobility. The substantial urban population density, the easier to offer convenience, and quick access to the public transit system, thus reducing the need for private motor vehicles. The sprawling structure of cities leads to prolonging travel trips and the necessity for private motorized vehicles. A policy can develop to control or maintain population density, intensive eco-mobility, and encourage citizens to choose the alternative routes and period of travel time so that the vehicle emission can well be managed. Besides, Japan citizen classifies as an aging community requires less travel demand so that, this strategy is very suitable to implement in urban area of Japan.

The strategies of risk treatment for urban **infrastructure** are underground pedestrian subway network, lower aspect ratio of street canyon and re-locate school away from the congested road. 1) indoor or underground pedestrian subway network: the findings of this research reveals that the long term inhalation exposure of urban dwellers to traffic-induced air pollution may pose deleterious health impacts. By introducing the underground pedestrian subway network, especially in densely populated areas, may reduce the urban dwellers to the exposure to pollutants from road traffic. This infrastructure promotes transit-oriented development in central areas, linking main buildings, subway and train station with the tunnel underneath streets, which reducing conflict the pedestrian crossing at an intersection, reducing parking space as well as lowering vehicle emission. 2) Lower aspect ratio of the street canyon: The research reveals that the aspect ratio between building height and road width has an impact on the quality of air in urban streets. It suggests that the aspect ratio of the street canyon in the urban environment should not more than 1.0, whereas the higher value than 1.0 can considers as a high aspect ratio. This condition avoids the dispersion of pollutants so that, high pollutant concentration entraps in the urban street. 3) re-locate school away from the congested road: a previous study proves that children at school more expose to air pollution, especially schools near to the congested road. Besides, this study indicates that children have a potential health impact on long-term exposure to pollutants emitted from the vehicles. The school should be re-locating, especially school near to the high congested road. The pick-up and drop routine of a school bus or parents' vehicles tend to increase the amount of emission during idling condition of vehicles. It is a reasonable effort for the school to restrict the idling vehicles near to the schools.

Regulation aspects include key access scheme, anti-idling, and congestion pricing. 1) key access scheme: In urban area, the majority of travel mode is a short distance travel which cause the cold-start engine condition and consequently allows the greater emission of pollutants. As a strategy for risk treatment, it recommends that to restrict the private vehicle (conventional powered vehicles) access in urban area especially at the high-density population and during the peak hours. As for example, the gasoline private cars will not allow to access the low emission zone during congestion period from 07:00 to 09:00 and 16:00 to 18:00. Besides, the delivery system of freight should be prohibited during the peak hours, which minimizes the freight travelling during this designated period, then the degree of congestion will decrease. In addition, the vehicles powered by conventional fuel should be phase out from accessing the urban area. This type of vehicles are the major contributor to air pollution in urban streets. 2) anti idling: the local authority should enforce the anti-idling at roadside then, the congestion can easily reduce. The presence of idling vehicles at the roadside cause the other vehicles to decelerate for safety purpose and change the traffic lane which lowering the vehicle speed. 3) congestion pricing: it can be applied to the vehicle which use the road in urban area during the congestion hours. Besides, the toll road in urban area can also be implemented as the vehicles enter to the busy urban road, then these vehicles must pay a charge of congestion. In some low emission zones, the more polluting vehicles must pay more if they access the low emission zone.

#### 6.4.2.4 Evaluation

The evaluation step embeds to the monitoring and review process. The organization will coordinate the periodic assessment of success in risk management and determine whether the plans smoothly carried out as expected. Based on the assessment results, the introduction of new aspect of information, internal and external changes can influence on the risk management system, and often needs to be replicated. The advantages of risk evaluation, especially for stakeholders, will examine whether the action has been successful, considering drawbacks, uncertainties and gaps. Once the weakness or benefits was determined, the organization should carry out the improvement plan for future advancement of risk management. The plan basically helps the organization to make effective decision by analyzing the risk treatment cost, improvement of human health and economic benefits of traffic induced air pollution (Xie et al., 2018). There are obstacles to accomplishing costly aspects of risk mitigation and adaptation plans under current economic conditions. Additional research are necessary on how much health co-benefits decrease the cost of traffic induced air pollution strategies

#### 6.4.2.5 Improvement

The organization should reinforce and continually conduct the risk management framework to address any internal or external changes. The organization should re-develop plans, task, process of risk management once the relevant gaps or opportunity of improvement has achieved such as disruptive change or contingencies occur, changes of governmental policies, identification or alteration to health risks and breakthrough innovation for fuel option.

## 6.5 Conclusion

A practical and step-by-step guidance of risk management approach of traffic-induced of air pollution in urban area was developed. The developed risk management approach successfully integrates the notion of sustainable development and risk management. The concept of urban sustainability was constructed by supporting four pillars of sustainable development in terms of environment, economics, social and governance. While, the risk management approach integrated the principle, framework and process as one element, which synchronizes to the finding of this research. As a result, this approach can be claimed as a major contribution of this research in providing a concrete guidance to catalyze a new design of risk-based management on air pollution from traffic emission in urban environment.

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# CHAPTER 7

# CONCLUSION AND FUTURE RECOMMENDATION

## 7.1 Conclusion

Poor air quality is a significant environmental risk to human health. The worsening of air quality is a critical issue, especially in the urban area, and has interlinkage to densely population, road congestion, and high-rise building arrangements. As an attempt to address this issue, a comprehensive study conducted on the risk assessment and management of urban air pollution related to traffic emission. This research estimated the emission factors of vehicles, predicted the dispersion of traffic-induced air pollutants in the urban street canyon, assessed the health impacts of human exposure and developed a holistic framework risk-based for assessing and managing the risks of traffic-induced air pollutant.

The vehicle emission estimation was carried out at the five functional classes of roadways (highway under the jurisdiction of Ministry of Land, Infrastructure, Transport and Tourism (H-MLIT), highway administered by prefectural authority (H-P), main municipal road (MM), prefectural road (P) and general municipal road (GM) in Kyoto city, Japan. The traffic emission factor of pollutants (exhaust particulate matter ($PM_{Exh}$), benzene, carbon monoxide (CO) and nitrogen oxide ($NO_x$)) and fuel consumption of passenger cars and trucks were estimated by using the well-established vehicle emission model, known as the Computer Programme to Calculate Emissions from Road Transport (COPERT). The inputs such as mobility configuration (vehicle composition and subsection, emission standard, fuel type and mileage), evaporation data (fuel specification and meteorological condition (Japan Meteorological Agency), and traffic activity (degree of congestion, traffic volume, and travel speed; based on the survey conducted by MLIT, 2015)) are required.

The description of traffic characteristics as following:

1) the number of vehicles flew during peak hour were higher than a normal hour.

2) the proportion of passenger cars were more significant than truck.

3) mean values of travel speed were not more than 22.0 kmph which considered as slow travel speed.

4) the most congested road segment achieved at road no. 185 under prefectural road due to lower mean travel speed and moderate traffic volume.

5) H-MLIT roads can be classified as the most congested of functional class of roadway.

The summary of EFs estimation findings summarized as per listed:

1) The trend of EFs and fuel consumption exposed the higher values at the lower mean travel speed (2 – 30 kmph) consequently, gradually decreased by the increasing of travel speed and remained unchanged at the higher speeds,

2) The movement of vehicles with lower mean speed causes incomplete fuel combustion inside the engine chamber, leading to an increase in EFs.

3) The EFs of CO and benzene for passenger cars are higher than those of trucks, which attributed to the high traffic flow of passenger cars.

4) Trucks are the major emitter of $PM_{exh}$ and $NO_x$ due to ten-fold of EFs of $PM_{exh}$ and $NO_x$ more than passenger cars.

5) The peak EF of pollutants and fuel consumption can be reached at road no. 121, under the classification of highway administrated by prefectural road due to the slowest traffic movement.

6) The most substantial total emission occurs at the H-MLIT road. This condition significantly influenced by the highest number of vehicles driven at this road, longest the distance of road segments and greater EFs.
8) The estimated EFs of NOx for both vehicle classification showed inconsistency with the EFs derived from the JE05 and JC08 chassis dynamometer test cycles.

The Operational Street Pollution Model (OSPM) was used to predict the pollutant concentration ($NO_2$, CO, ozone, benzene, PM2.5, PM10, and suspended particulate matter (SPM)) in the urban street canyon, Kyoto City, Japan. The prerequisites of the OSPM model are urban configuration, meteorological condition, traffic characteristics, and emission factors. The main findings of pollutant concentration and the influencing factors are:
1) The substantial pollutant concentrations found at the H-MLIT with road no 9. is the most polluted road.
2) All modeled concentrations of pollutants permitted to the environmental quality standard.
3) The pollutant concentrations are positively strong correlated to the traffic volume, wind speed, wind direction, and aspect ratio (height/width) of urban street canyon. Otherwise, travel speed indicates the negatively correlation to the pollutant concentration.
4) The statistical performance indicator between measured and modeled pollutant concentrations of NO2, CO, benzene, ozone, SPM and PM2.5 are acceptable with the higher value of $R^2$ and index of agreement and lower RMSE as well as bias.
5) The OSPM model had proven to be an applicable model for predicting the pollutant concentration in the urban environment of Kyoto, Japan.

The potential health impacts via inhalation risk from the urban dwellers exposure to traffic-induced air pollution was conducted based on the Health Risk Assessment (HRA) approach. The findings of HRA as follows:

1) The hazard quotients (HQ) value for all pollutants for acute and intermediate normal exposure were lower than 1.0 and cancer risk (CR) for PM2.5 and benzene was lesser than the acceptable level ($10^{-4}$).

2) Infants and children have a higher tendency to be affected compared to adults for pollutant exposure, excluded the chronic worst-case condition.

3) The potential health risks with the different severity of risks may pose by the exposed groups when they inhale the pollutants for long-term exposure.

4) The study population has a negligible risk for short term-exposure and vice-versa for long-term chronic exposure.

Since the health risk assessment result indicated that the urban dwellers might pose potential health impacts due to long-term exposure to traffic-induced air pollution, this research developed a holistic framework of risk-based assessment and management. A framework is a continual improvement process and designed explicitly by four main aspects: 1) Concept generation, 2) Risk assessment, 3) Adaptive risk management and 4) Risk communication. A concept generation is constructed based on three pillars of urban sustainability suggested by the World Economic Forum: social, environmental, and economics. It intends to be a reference document to help policymakers, urban development department and environmental practitioners to prepare, implement and review the issue of transport and air pollution in the urban area.

## 7.2 Future Recommendation

The recommendations for future study are:

1) MLIT conducted the traffic survey during autumn season. This research recommended that MLIT to carry it out during winter and summer because the vehicle drivers will tend to use the heating or air conditioning, which enhances the internal engine combustion engine. This condition results in greater pollutant emission and has significant impacts on human health. Chen *et al.*, 2013 stated that the seasonal effect, especially winter and summer, was substantial to the PM10 emission and acute effect to particulate air pollution.
2) A traffic survey conducted by HMLIT only focused on two types of vehicles; passenger cars and trucks. As a result, vehicle emission estimation also based on these two kinds of vehicles without considering another type of vehicle such as motorcycles. The estimation of traffic emission might larger than the current estimation by adding the motorcycles as an input of vehicle composition. Fukuda *et al.*, 2013 claimed that motorcycles tend to consume fuel and emit more pollution than passenger cars.
3) The results of modeled pollutants concentration that simulated use OSPM model was compared to the urban concentration collected at the fixed monitoring station with most of the monitoring probe located at the rooftop of the building. It is proposed that the monitoring of air pollutants should carry out at near-road in order to get accurate results of traffic-induced air pollutants.
4) The OSPM model does not evaluate traffic behavior such as congestion, idling, acceleration, deceleration, and stop-and-go of vehicles, which promote a significant impact on the dispersion of pollutants. Hence, it is suggested that future works should incorporate this kind of traffic behavior because they provide a considerable impact on the emission factors of pollutants. For instance, the elevation of emission factors

occurs during the acceleration phase of driving.

5) Road no. 9 was claimed as the most polluted road. A further investigation should be carried out, such as the detailed representations of the atmospheric flow and the transformation of air pollutant transformations via physical and chemical processes by employing the computational fluid dynamics (CFD). On the other hand, the relationship between outdoor air on indoor air quality can also be performed, such as the indoor and outdoor ratio, penetration, and infiltration mechanisms of pollutants into indoor air (William and Boddy, 2005; Pathak *et al.*, 2016).

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