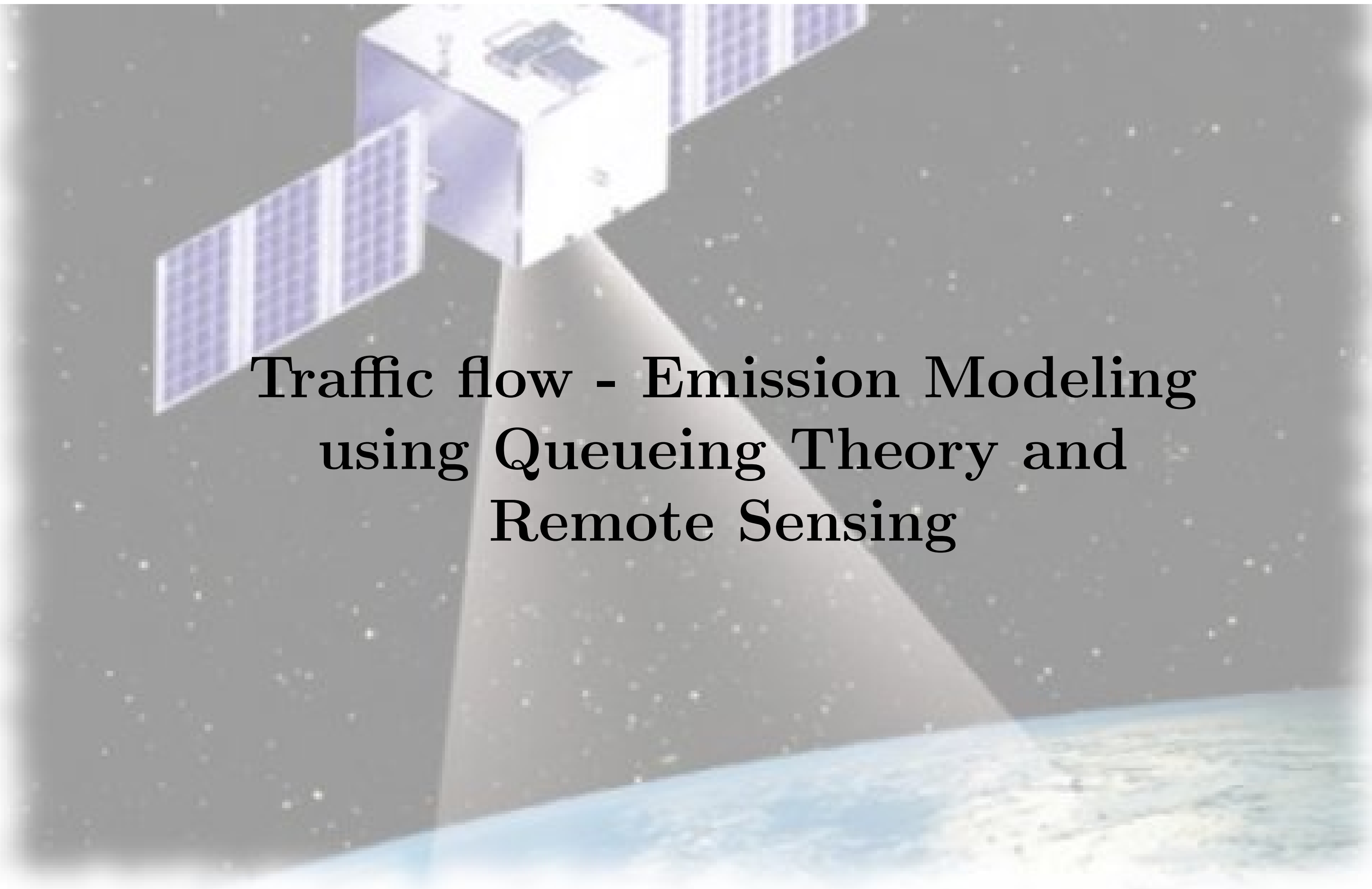
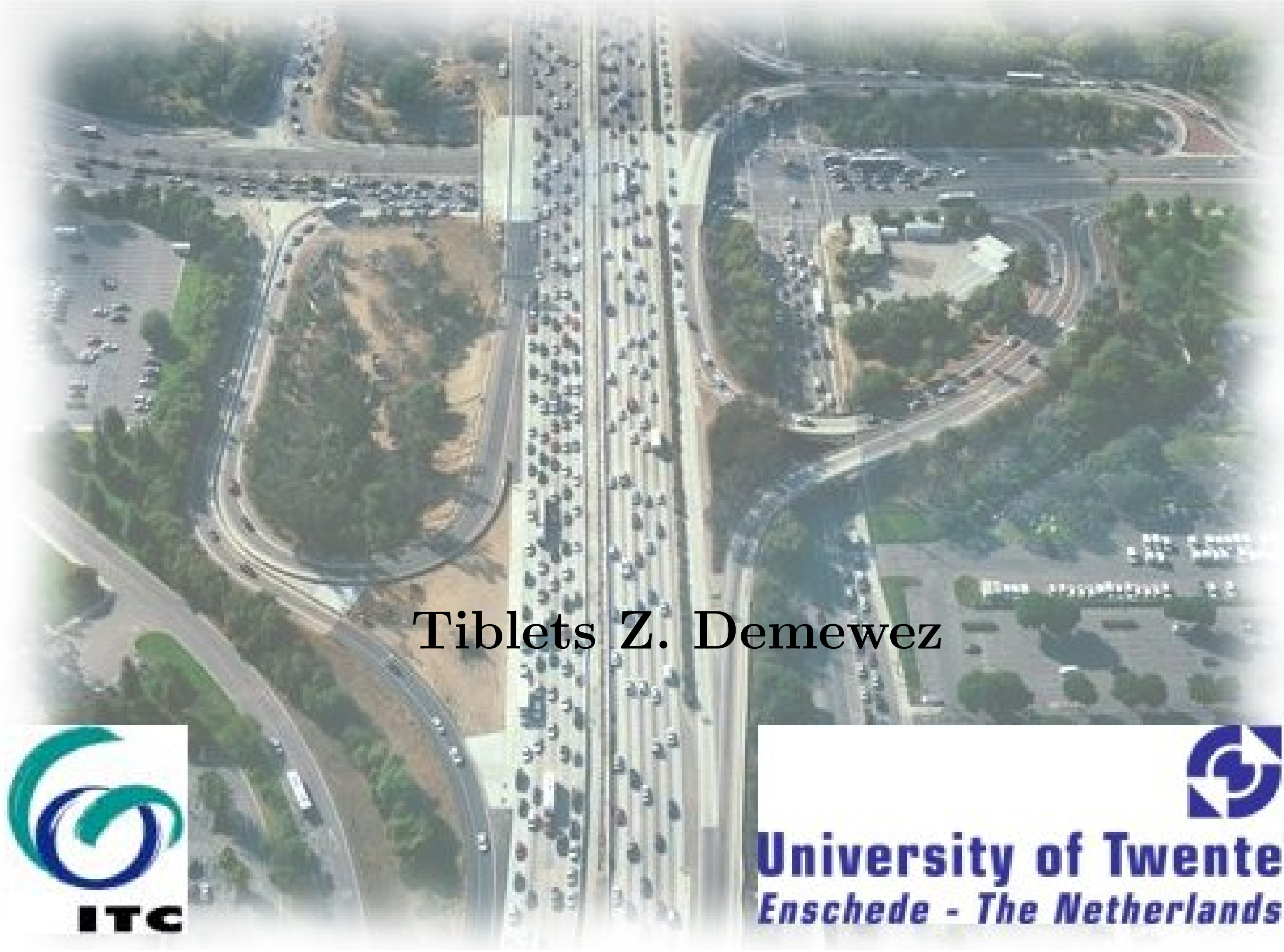


Traffic flow - Emission Modeling using Queueing Theory and Remote Sensing



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Traffic flow - Emission Modeling using Queueing Theory and Remote Sensing

by
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Abstract

Air pollution in urban areas is a major cause of health problems. Among the various sources that are contaminating cities atmosphere, traffic related air pollution is a major one. The reason is a rapid growth of traffic intensity without expansion of roads and other related infrastructures. The main objective of this study was to develop and implement a method that predicts the concentration of PM_{10} from traffic in a highway network around an urban area. A comparison was made among the predicted concentration, remotely sensed data and observed air quality data for validation.

Queueing theory was used to model traffic flow on a highway network around Rotterdam. Each stretch of the road and each merging point of roads on the highway was modelled as a queue with Poisson arrival rate of vehicles and state dependent service rate. State dependency of service rates enables the travel time to be determined by the total number of vehicles in the queue. With these rates, hourly steady state probabilities for each queue and for the network of queues were obtained. These probabilities were employed to find the average number of vehicles per hour and average speed, and also the rest performance measures. The outputs were used to forecast hourly total emission of PM_{10} from all vehicles followed by computation of total concentration of the pollutant by considering the effect of weather, dilution and tree factors. For these, an emission model CAR II (Calculation of Air pollution from Road traffic) which delivers hourly concentration level of PM_{10} from road traffic based on different factors was adopted. In addition, remotely sensed images were acquired to derive a relationship between Aerosol Optical Thickness (AOT), observed PM_{10} data and predicted PM_{10} values.

The results showed that queueing model describes traffic flow in a reasonable way and its output can be used to compute average speed of vehicles. The comparison performed between in-situ measured PM_{10} and AOT resulted in a negative correlation which tells that AOT cannot be used estimate PM_{10} emitted from road traffic. It rather better estimates the background concentration of PM_{10}. From linkage made between in-situ measured PM_{10} and predicted PM_{10}, it can be concluded that AOT better estimate PM_{10} in a daily basis than in hourly.

Acknowledgements

This thesis marks the end of the remarkable journey I took in the last two years carrying out my Masters study. Its successful completion, however, would not have been possible without the support of several people.

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Contents

List of Figures

List of Tables

Notation

i, j, k	link or intersection queues/stations.
r	vehicle type.
J	number of queues in the network.
t	time.
$n_i(t)$	number of vehicles in station i at time t.
$\vec{n_i}(t)$	a vector of number of vehicles in each station of the network at time
$n_i(t)$	number of vehicles in the network at time t and state space
e_i	a unit vector having 1 at the i^{th} position and 0 in the others
$\lambda_i(t)$	arrival rate of queue i at time t.
$q(n_i(t))$	is the rate of row of vehicles on station i per unit time t.
$v(n_i(t))$	speed of a vehicle when there are n_i vehicles on the road at time t.
$v_{free-flow}$	free flow speed.
n_{i-jam}	jam density of station i.
P_{ij}	routing probability form station i to station j
$\rho_i(t)$	the occupancy rate of the station i at time t.
$\pi_i(n_i(t))$	the steady state probability of station i having n_i number of vehicles at time
$\phi_i(t)$	number of transitions per unit time from state $n_i - 1$ to n_i
b_i	normalization constant.
$E(L_i(t))$	expected number of vehicles at station i at time t.
θ	dilution factor.
$A/B/C$	A: function of an inter-arrival time of customers, B: function of service time
E	emission.
N	Number of vehicles per day.
F_m	Fraction of medium trucks.
F_v	Fraction of heavy trucks.
F_b	Fraction of bus group.
E_p	Emission factor for personal cars.
E_m	Emission factor for medium truck traffic.

E_v	Emission factor for heavy truck traffic.
E_b	Emission Factor for buses.
FS	Fraction of stagnant cars.
E_*	Emission Factor of vehicle class * fraction of stagnant cars.
v	average speed of a vehicle.
v^2	second moment speed of a vehicle.
v^3	third moment speed of vehicles.
$C_{yr-concentration}$	annual average concentration contribution by traffic.
E	emission.
F_t	trees factor.
F_{regio}	region factor in relation to meteorology.

Abbreviations

AOT	**A**erosol **O**ptical **T**hickness
CAR	**C**alculation of **A**ir **P**ollution from **R**oad traffic
D	**D**eterministic
FCFS	**F**irst **C**ome **F**irst **S**erved
G	**G**eneral
IS	**I**nfinite **S**ervers
LCFS	**L**ast **C**ome **F**irst **S**erved
M	**M**arkovian
MODIS	**MOD**erate-Resolution **I**maging **S**pectroradiometer
PM	**P**articulate **M**atter
PS	**P**rocessor **S**haring

Chapter 1

Introduction

The goal of this chapter is to introduce the general overview of the thesis and to define the problem and objectives of the work. Section 1.1 presents the study motive and problem statement, section 1.2 discusses research identification, section 1.3 defines research questions and section 1.4 gives the outline of the thesis.

1.1 Study motive and problem statement

Air pollution has a large effect on human health and on the environment. From the effects that have been observed so far, irritation of respiratory organs is specified as one of the most crucial ones. The World Health Organisation states that 2.4 million people die each year from causes directly attributable to air pollution. It is estimated that 3400 - 5700 people in the Netherlands have died prematurely through short term exposure to air pollution in 2003 (Van de Kassteele, 2006). Having realised these consequences, the European Union has placed air quality at the top of its thirteen quality of life indicators list (Tulloch and Li, 2004).

Air pollution in urban areas is a major cause of health problems. Among the various sources that are contaminating the urban atmosphere, traffic related air pollution is a major one. Poor public transport and driving with high speed specified as some of the reasons. Lindgren et al, (2009) investigates traffic exposure associated with allergic asthma and allergic rhinitis and showed that living within 100m from a road with a traffic intensity of more than 10 cars per minute (compared with having no heavy road within this distance) was associated with asthma prevalence.

It has been a hardly achievable situation for human beings to have a pollution free environment to live in. Different methodologies, policies and technologies could be applied to reduce pollution to such a level that does not harm human health and the environment. For this, air quality modelling is essential since it describes the real situation in mathematical terms that enables prediction of the occurrence of a pollutant which can not be done by observations alone. This study aims to develop a model that predicts the concentration of one of air pollutants emitted from road traffic. The prediction serves for describing the existing situation which could be followed by a list of possible solutions that may assist decision makers to set policies for future infrastructures by considering the quality of the air. These could help in turn to protect residents around roadways from exposure to pollutants.

As traffic flow is described as a function of the number of vehicles and speed of vehicles, these variables are used in this study to describe the environmental impact of traffic flows. Queueing theory is used to describe traffic behaviour at intersections (Vandaele, 2000). Thus, in this study, queueing theory is used to describe uninterrupted traffic flows and the results are employed to assess environmental impact of traffic flow.

In this study, traffic flow in a highway network was modelled by splitting the network into two classes: stretches of the roads (links) and intersections of the highways. Each of these was modelled as state dependent queues that let vehicles pass through the roads on the highway whereas the network as a whole was modelled as an open network of queues. From each of the queues, relevant performance measures were calculated that were used as an input for an adopted emission model delivering the concentration of PM_{10} based on the total number of vehicles per hour, the proportion of different vehicle types and the average speed of vehicles. The emission model also integrates weather, tree and dilution factors. These are followed by matching the predicted concentration levels with observed PM_{10} values and remotely sensed data.

The problem of this thesis is to predict hourly concentrations of one of the most important air pollutants that indicate the poor quality of the air we breath which is named as Particulate Matter (PM). PM is a very small particle that is suspended on air and water. It has different categories based on the size of the particle. This study focuses on particulate matter with aerodynamic diameter of less or equal to 10 μm (PM_{10}). For this, a queueing model is developed by partitioning the highway into links and intersections. The model estimates the hourly mean number of vehicles and average speed of vehicles on each of the partitions of the highway network. These outputs are used as data for an adopted emission model that enables the prediction of concentration of PM_{10} emitted from vehicles on the network. Afterwards, a linkage is made among the concentration of predicted and in-situ measured PM_{10} and remotely sensed data or Aerosol Optical Thickness (AOT). AOT is the degree to which aerosols (very small particles of liquid or solid suspended in a gas) prevent the transmission of light. Finally, a simple linear regression analysis is carried out to investigate the relation between the predicted PM_{10} and observed PM_{10}, predicted PM_{10} and remotely sensed data, and measured PM_{10} and remotely sensed data.

1.2 Research identification

This section discusses the goals and requirements that will be researched in this thesis. Section 1.2.1 presents the general objectives and additional requirements of this work. Then the specific objectives identified to achieve the general objectives are listed in section 1.2.2 and section 1.3 presents research questions.

1.2.1 Objectives

The objective of this study is to develop a method that predicts the concentration of air pollutant from road traffic in a highway network and implement it within a specific area. And to integrate the predicted concentrations, remotely sensed data and observed air quality data to validate the output of the model and identify their relationship.

1.2.2 Specific objectives

To attain the general objective of this study, the following specific objectives are identified.

- Describing traffic flow on highway network using queueing theory models.
- Developing of a suitable emission model from an existing model that is associated with the queueing model.
- Validating and predicted concentration of PM_{10} with measured concentration of PM_{10} and remotely sensed data.
- Relating measured concentration of PM_{10} with remotely sensed data.

1.3 Research questions

For the purpose of achieving the aforementioned objectives two tasks should be accomplished: the development of a queueing model that gives the expected number of vehicles on a link and intersection of a road at any point in time in stationary, and average speed of vehicles that is used as an input data for an adopted emission model in order to get predicted concentration of PM_{10}. Afterwards, the emission model is revised in such a way that the employed emission factor depends on the average speed of vehicles and it is compatible with the output of the queueing model. In addition, linkage of predicted PM_{10} values with in-situ measured PM_{10} and remotely sensed data is carried out.

During this the following questions should be answered.

1. How well does queueing model describe traffic flow?
2. How can the queueing and the emission model best used?
3. How are in-situ measured PM_{10} related to AOT?
4. How are predicted PM_{10} values related to in-situ measured PM_{10} data?
5. How are AOT correlated with predicted PM_{10}?

1.4 Outline of the thesis

This thesis is organised in the following way. Chapter 1 outlines the study motive and problem statement and then states the objectives of the study. Chapter 2 discusses the theoretical background of queueing theory, traffic models, remote sensing and emission models. The methodology employed to meet the objectives of the study follows in chapter 3. Chapter 4 presents the list of data used to implement the developed model. In chapter 5, the results acquired by implementing the model in Rotterdam highway network is presented. Finally, chapter 6 gives the discussion based on the results and chapter 7 presents the conclusion.

Chapter 2

Theoretical background

This chapter outlines the theoretical background of traffic models and queueing models that are applied in this study. Section 2.1 gives a background description of queueing theory, section 2.2 introduces traffic models, and section 2.4 and 2.5 discuss modelling air pollution from traffic models and remote sensing air quality respectively.

2.1 Queueing theory

Queueing theory is a branch of applied probability theory that studies waiting lines or queues. It is applicable in different disciplines such as transportation, communication systems, logistics, computer systems etc. A basic queueing model is described below.

Customers arrive to a system to get a service. Based on the length of the queue, newly arriving customers may or may not wait before they get served and leave the system. This process is shown on Figure 2.1.

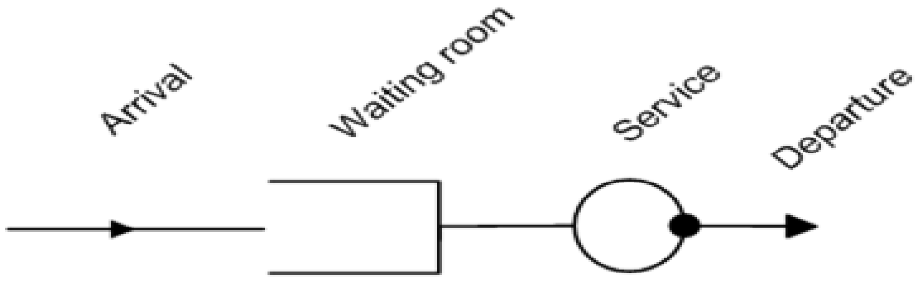


FIGURE 2.1: Basic queueing model

Queueing models are characterised by the following:

- Arrival process: what distribution do vehicles follow when they arrive to the connections? Do they arrive one by one or in batch?
- Service process: how long does it take for a vehicle to leave the connection? What is the service distribution?
- Service discipline: in what order are the customers being served? Typical orders are First Come First Served (FCFS), Last Come First Served (LCFS), Processor Sharing (PS) or Infinite Server (IS).
- Service capacity: how many servers are available to serve customers?
- Waiting room: what is the capacity of the waiting room?
- Behaviour of customers: are customers patient enough to wait for service?

The queueing model is denoted by the Kendall notation. i.e. a three letter notation $A/B/C$ characterising queues. The first letter specifies the inter-arrival time of customers (the inverse of the arrival rate), the second letter specifies the service time of customers and the third letter specifies the number of servers used in the system. For example, we could have a queueing model denoted by $M/M/1$, $M/G/3$, or $M/D/\infty$. Here, M is used in place of A if the inter-arrival time is exponential, G if it is general distribution and D if it is deterministic. The same could be applied to B as well; M is for exponential service time, G is for a general distribution and D is for deterministic service time. The number of servers could range from 1 to ∞. Infinite server does not mean that there is an infinite number of servers, rather there is enough capacity that customers can always be served without having to wait in a queue.

The main purpose of analysing queueing models is to acquire mean performance measures. These are the average number in the queue, or the system, the average time spent in the queue, or in the system, the statistical distribution of those numbers or times, the probability that the queue is full, or empty, and the probability of finding the system in a particular state.

A network of queues is a collection of service stations. Networks of queues are categorised differently based on flow of customers in and out of the network. These are open and closed network of queues. In open network of queues, customers are allowed to enter and leave the network, whereas in the closed network of queues, neither entrance nor departure is allowed, the customers rather rotate in the network (Zijm, 2003). Thus, the network could be modelled as a collection of queues which is called a network of queues.

The Mathematical Modelling is as follows:
Indices:
i, j, k queues/stations
J number of queues in the network
n_i: number of customers at station i at time t

$\vec{n} = (n_1, n_2, ..., n_J)$: state of the network at time t
$n = |\vec{n}| = \sum_{i=1}^{J} n_i$: number of customers in the network at time t

The possible values of n and n_i form a state spaces S and S_i respectively. Formally, the following defines the state spaces:

$S = \{\vec{n} = (n_1, n_2, ..., n_J) : n_j \geq 0, \forall j = 1, 2, .., J\}$

$S_i = \{n_i, n_i \geq 0 \ \forall i = 1, 2, ..., J\}$
Let $e_i = (0, ..., 0, 1, 0, ..., 0)$, 1 in the i^{th} position, i.e. the i^{th} unit vector.

A customer arrives at one of the service stations in a network with an arrival rate and routes from one server to another. The rotation of customers from one server to another in the network is determined by a routing probability which is the probability of selecting a way to a certain destination from a possible set of choices. Each of the stations in the network has its own characteristics. As a result, all the mathematical formulation is done for each of the stations independently and it is used for the formulation of the whole network.

Routing probability

When service for a customer is completed at station i, he enters another station j with probability P_{ij} or leaves the network with probability P_{i0} = 1 - $\sum_{j \neq 0} P_{ij}$. These probabilities form a routing matrix P of order J which is given as:

$$P = (P_{ij})$$

Arrival rates

The arrival rate to each of the stations in the network varies depending on the number of stations attached to it. An arrival rate to station i is defined as follows:

$$\lambda_i = \gamma_i + \sum_{j=1}^{J} \lambda_j P_{ji}, i = 1, 2, ..., J \tag{2.1}$$

where γ_i is rate of arrival from outside the network, P_{ji} is a routing probability from station i to j.

Service rates

The service rate of a station in the network is defined as the time it takes for a customer to get a service. ϕ_i denotes the service rate of station i in the network.

Transition rates

Transition rate is defined as the probability per time unit the system makes a transition from one state to another state (Nelson, 2000). While customers route from one station to another station in the network, the following transitions can be identified (Kelly, 1976).
Suppose the following notations are interpreted as follows:

- Customers transit from station i to station j: $\vec{n} - e_i + e_j$
  This tells us that when the number of customers at station i reduces by one, station j has one more customer.
- arrival: $n_i + 1$
  A customer arrives from external source to station i in the network.
- departure: $n_i - 1$
  A customer departs from station i to outside of the network.

Suppose the following definition holds, then the transition rates in the network are given as:

- Arrival: $q(n_i, n_i + 1) = \lambda_0$, i = 1, 2, ..., J
- Internal transition: $q(\vec{n}, \vec{n} - e_i + e_k) = \phi_i P_{ik}$, i=j = 1, 2, ..., J
- Departure: $q(n_j, n_j - 1) = \phi_i P_{j0}$, j = 1, 2, ..., J

Occupation rates

The occupation rate of a single server is defined as the fraction of time the server is busy serving requests (Nelson, 2000). It is the product of arrival rate and service rate.

The occupancy rate of station i in the network is given by:

- $\rho_i = \frac{\lambda_i}{\phi_i} \quad for \quad i = 1, 2, ..., J$

$\rho = (\rho_1, \rho_2, ..., \rho_J)$

2.1.1 Equilibrium distributions

Having defined the characteristics of each of the queues in the network, we can now define the equilibrium distribution of the number of customers in a station per unit time. Equilibrium or steady state distribution is defined as the probability of having n number of vehicles at station i.

In order to see how the equilibrium distribution is derived, assume a Poisson distributed arrival rate λ_i to station i and exponentially distributed service rate ϕ_i. Then, the flow diagram on Figure 2.2 describes the behaviour of station i in a queueing network.

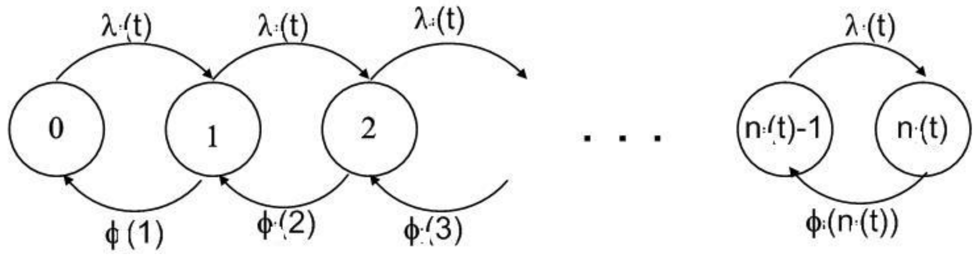


FIGURE 2.2: Flow diagram

The arrows show possible transitions from one state to another state. Whenever a customer arrives to a station, there will be a transition from state $n_i - 1$ to state n_i with rate λ_i. And when a customer departs from the station, the transition is from state n_i to state $n_i - 1$ with rate ϕ_i. The number of transitions per unit time from state $n_i - 1$ to state n_i, which is also called the flow from state $n_i - 1$ to state n_i, is equal to π_i, the fraction of time the system is in state n_i, times λ_i, the rate at which arrivals occur while the system is in state $n_i - 1$.

By equating the flow out of state n_i and into state n_i, we can determine the equilibrium distribution. Specifically, we apply global balance principle which states that for each set of states S_i, the flow out of set S_i is equal to the flow into that set (Adan, et al., 2002).

Hence we get the following equations.

$$\begin{aligned}
\lambda_i \pi_i(0) &= \phi_i \pi_i(1) \\
\lambda_i \pi_i(1) &= \phi_i \pi_i(2) \\
&\vdots \\
\lambda_i \pi_i(n_i - 1) &= \phi_i \pi_i(n_i)
\end{aligned}$$

Substituting one equation into another iteratively, we obtain

$$\pi_i(n_i) = \pi_i(0) \frac{\lambda_i}{\phi_i}^{n_i} = \pi_i(0) \rho_i^{n_i} \tag{2.2}$$

$$\sum_{n_i=0}^{\infty} \pi_i(n_i) = \sum_{n_i=0}^{\infty} (\pi_i(0)\rho_i^{n_i}) = 1$$

This implies,

$$b_i = \pi_i(0) = (\sum_{n_i=0}^{\infty} (\rho_i^{n_i}))^{-1} = 1 - \rho_i$$

where b_i is a normalization constant.

Substituting $b_i\pi_i(0)$ in equation 2.2, we find the equilibrium distribution which is given below on Equation 2.3.

$$\pi_i(n_i) = (1 - \rho_i)\rho_i^{n_i} \tag{2.3}$$

for $i = 1, 2, ..., J$

The equilibrium distribution of the whole network is the product of the equilibrium distribution of each of the stations, which can be mathematically be stated as follows:

$$\Pi(n) = \prod_{j=1}^{J} \pi_i(n_i) \tag{2.4}$$

2.1.2 Performance measures

From the formulated equilibrium distribution, the following performance measures could be calculated.

- mean waiting time in a queue
- mean sojourn time (waiting time plus service time) in a system
- distribution of the number of customers in the system
- distribution of the number of customers in the queue
- probability that the queue is full or empty

The aforementioned performance measures can easily be determined after the equilibrium distribution is obtained. The following shows a simple derivation of EL_i, which can be used directly to obtain other performance measures.

$$EL_i = \sum_{n_i=0}^{\infty} n_i \pi_i(n_i) \quad (2.5)$$

$$= \sum_{n_i=0}^{\infty} n_i(1-\rho_i)\rho_i^{n_i} \quad (2.6)$$

$$= \frac{\rho_i^{n_i}}{(1-\rho_i)} \quad (2.7)$$

2.2 Traffic models

Traffic flow, in mathematics and engineering, is the study of interactions between vehicles, drivers, and infrastructure (including highways and traffic control devices), with the aim of understanding and developing an optimal road network with efficient movement of traffic and minimal traffic congestion problems. It can be defined as the total number of vehicles passing a given point in a given time, expressed in vehicles per hour.

Traffic flows can be divided into two primary types: uninterrupted versus interrupted traffic flows (Van Woensel and Vandaele, 2006). Uninterrupted flow is determined by interaction of vehicle with vehicles and vehicles with the road whereas interrupted flow regulated by an external means.

Since the study focuses on vehicles driving on a highway network, uninterrupted traffic flow is discussed.

A traffic model is classified into three main categories based on the level of details. These are microscopic, mesoscopic and macroscopic models. Microscopic models deal with vehicles, macroscopic models deal with flows and mesoscopic models merge macroscopic with microscopic models.

Microscopic models describe the behaviour of each vehicles based on the theories of how they are guided through traffic. Car-following theories are categorized as this model. Macroscopic models aggregate all individual vehicles and describe them as flows. These models represent the traffic in terms of flow, average speed and density. Greenshield's speed-flow-density relationship is specified as an example (Greenshield, 1993). Macroscopic models can give a good representation of traffic dynamics in terms of queueing, delays and average speeds (Rouwette, 2008).

2.3 Speed density flow relationship

The general density flow relationship which is given as (Vandaele et al, 2000):

$$q = nv \tag{2.8}$$

where q: flow, n: density and v: speed

From Greenshield's traffic model speed is defined as (Greenshield, 1935):

$$v = v_{(free-flow)}(1 - \frac{n}{n_{jam}}) \tag{2.9}$$

where
v - speed of a vehicle
$v_{(free-flow)}$ - free flow speed
n_{jam} - jam density (the maximum number of vehicles a road can accommodate)

Thus, flow can be rewritten as:

$$q = vn = v_{(free-flow)}(1 - \frac{n}{n_{jam}})n \tag{2.10}$$

From traffic flow theory, jam density is computed in the following way (Rouwette, 2008).

$$density\ at\ capacity = \frac{capacity\ per\ lane}{speed\ at\ capacity} \tag{2.11}$$

$$speed\ at\ capacity = \frac{free\ flow\ speed}{2} \tag{2.12}$$

The Highway capacity manual define capacity per lane as follows (Highway capacity manual, 2002):

$$\begin{aligned} capacity\ per\ lane = Base\ capacity \times Peak\ hour\ factor \\ \times number\ of\ lanes \\ \times fraction\ of\ heavy\ trucks - f_b \end{aligned}$$

And base capacity is defined as:

$$\begin{aligned} Base\ capacity &= 2,4000\ \ for\ free\ flow\ speed \geq 112kmh^{-1} \\ &= 700 + 10 \times v_{(free\ flow\ speed)}\ for\ free\ flow\ speed \leq 112kmh^{-1} \end{aligned}$$

where: Peak hour factor = 0.92
f_b (adjustment factor for driver population) = 1
fraction of heavy trucks: obtained from data.

$$capacity\ per\ lane = 2300 \times (fraction\ of\ heavy\ trucks + fraction\ of\ light\ trucks); \tag{2.13}$$

From Equations 2.11 and Equation 2.12, jam density is calculated as:

$$jam\ density = 2 \times (density\ at\ capacity) \tag{2.14}$$

$$= \frac{4 \times capacity\ per\ lane}{free\ flow\ speed} \tag{2.15}$$

2.4 Modelling air pollution from road traffic

Prediction of pollution in an unopened space area, like an urban area is much more difficult than prediction in open space areas. In open space areas, there are no obstacle for the air to disperse. That means that the prediction site is situated in a place where there are no buildings or vegetation that might influence air movement in the surrounding. In this case, wind speed and wind direction have a direct impact on air dispersion. In urban areas however these factors are hindered by other factors, like buildings and vegetation. Studies have found out that presence of buildings increases the concentration of pollution in urban areas (Nowak et al., 1998). Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmospheric environment.

Various models have been developed to predict the concentrations of air pollution in different areas by taking account the contribution of different sources in the surrounding. These models are developed for different sources of pollution such as point sources (industries) and mobile sources (road traffic). Among the models that are developed to quantify air pollution from road traffic, California Line Source Dispersion Model (CALINE-4), Roadway Construction Emissions Model (version 5.1) are specified, Calculation of Air pollution from Road traffic (CAR II), Operation Street Pollution Model (OSPM) are mentioned. In this study, the model is used to find the concentration of PM_{10}.

The emission model that is used to find the contribution of vehicles in highway is web based CAR model (Calculation of Air pollution from Road traffic) (InfoMil, 2007). It is developed to calculate air quality in/along street. It delivers the contribution of road traffic in city streets, and a line-source model that delivers the contributions from roads outside cities, mostly along motorways.

CAR II works in the basis of classes, like street type, vehicle category and speed type. The emission factor varies based on the vehicle types. The vehicle types that are considered here are personal cars, light duty and heavy duty. Moreover, the speed types are categorized based on the allowed average speed a vehicle could drive on a road. The street types are described by the buildings along the road.

The method for calculating air quality considers the following situations:

- the road is located within an urban environment;

- the maximum covered distance is the distance from the centre buildings, with a maximum of 30 or 60 m measured from the road axis depending on road type;
- there is little or no difference in altitude between the road and the surrounding;
- along the road are protecting structures, like noise barriers;
- the road is free of tunnels

This model calculates background yearly average concentration of different pollutants like benzene, Nitrogen oxides (NO_x), Carbon Monoxide (CO), Particulate Matter (PM_{10}). Among those, we are interested in PM_{10} having health threshold 50 μ gm^{-3} in 24 hour average which should not exceed 35 days per year.

2.4.1 Calculation methods

This section presents the methods that are used to calculate the concentration levels.

The calculation is based on road type which is categorised by speed types. This category depends on the buildings in the surrounding and roadway respectively. We are interested in road through open fields, occasionally buildings or trees within a radius of 100m. And the speed type is general highway: typical highway traffic, an average speed of about 65 km h^{-1}, average about 1 stop per 5 km.

For the calculation, it is necessary to have road traffic emissions. This emission is based on the number of cars and trucks per day and emission factors (emissions per vehicle per meter). The height of the emission factor depends on the speed type and vehicle category.

Tree factor

As the presence of trees affect the level of concentration of pollutants, the tree factor is incorporated in the calculation. Tree factor is a unitless measure of presence of trees along a roadway. Since the highway network we are dealing with is situated in an area where there are almost no trees, the tree factor is we use is one which is assigned for such areas (InfoMill, 2007).

Weather factor

Among different weather factors that affect air pollution, only wind speed is taken into account. The factor is attained by dividing 5 by the average wind speed at the day of interest (InfoMill, 2007).

$$W_f = \frac{5}{W_s} \tag{2.16}$$

where: W_f is weather factor and W_s is wind speed

Dilution

The dilution factor considers the air pollution dispersion from the surrounding caused by different factors. It depends on the distance from the road axis to the place where the pollution is predicted. The factor varies form one road type to another road type. For multi-lane highways, it is given as (InfoMill, 2007):

$$\theta = 0.725 S^{-0.77 \frac{(S+2.7)}{S}} (-0.0011S + 1.2) \tag{2.17}$$

where θ is dilution factor and S is distance from the road axis.

The dilution function is only valid between the edges of the road and the primary buildings. This means that Equation 2.17 applies to S ranging from 5m to 30m.

2.4.2 Emission calculation

The emission from traffic for all substances other than benzene is calculated using the following formula (InfoMill, 2007):

$$E = [(1 - FS)((1 - (F_m + F_v + F_b))E_p + F_m E_m + \tag{2.18}$$

$$F_v E_v + F_b E_b) + FS((1 - (F_m + F_v + F_b))E_{p,d} \tag{2.19}$$

$$+F_m E_{v,d} + F_b E_{b,d})] \frac{1000N}{24 \times 3600} \tag{2.20}$$

where
E: Emission [μg m^{-1} s^{-1}]
N: Number of vehicles per day [24 hours^{-1}]
F_m: Fraction of medium trucks [-]
F_v: Fraction of heavy trucks [-]
F_b: Fraction of buses group [-]
E_p: Emission factor for personal cars [g km^{-1}]
E_m: Emission factor for medium truck traffic [g km^{-1}]
E_v: Emission factor for heavy truck traffic [g km^{-1}]
E_b: Emission factor for buses [g km^{-1}]
FS: Fraction of stagnant cars [-]
$E_{*,d}$: Emission factor of vehicle class * fraction of stagnant cars [g km^{-1}] * (speed class d)

The emission factor is a function of speed which is given as follows:

$$E(g/km) = (a + bv + cv^2 + dv^3 + e/v + f/v^2 + +g/v^3) \times x \tag{2.21}$$

where v, v^2 and v^3 are average speed, second moment and third moment speed of vehicles respectively.

The coefficients of this equation vary based on vehicle type, fuel type and engine size. The computation of the total emission is done, however, for all vehicles on a certain road. Therefore, the emission factor formula is rewritten by taking the proportion of each types of vehicles, fuel type and engine size into account. The list of coefficients are found on Appendix C.

The average speed, second and third moment of speed that are used in the formula are calculated by integrating the queueing and traffic flow model.

2.4.3 Concentration calculation

The method for calculating the annual average concentration is equal for all substances. The standard formula for calculating the annual average concentration contribution is (InfoMill, 2007):

$$C_{yr-concentration} = 0.62 \times E \times \theta \times F_b \times F_{region} \tag{2.22}$$

where
$C_{yr-concentration}$: annual average concentration contribution by traffic
E: emission
F_b: tree factor
F_{region}: region factor in relation to meteorology
θ: dilution factor
0.62: adjustment factor

2.5 Air quality monitoring

In order to tackle the problems caused by air pollution, air quality monitoring is of great importance. The main purpose of air quality monitoring is to acquire data and information that are helpful to have a clear plan for the reduction of emission from different sources by undertaking different actions, like giving technical support to decision makers and source apportionment studies that are used for air quality forecasting. Moreover, air quality monitoring has a vital role in delivering information towards the public so that they take advance measures not to be exposed to dangerous pollutants.

In-situ and remote sensing are the two main monitoring techniques for air quality. In addition, spatial interpolation technique and atmospheric dispersion models are applied to predict in places where air quality is not being measured. Each of the methods has advantages and disadvantages with respect to spatial coverage, accuracy, cost and others.

In-site air quality measurement is widely used to acquire spatial data for air quality monitoring. It is carried out by installing ground based sensors in different places of a specific area. The measurement alone however cannot give an accurate description of the total concentration of all pollutants (Koelemeijer, 2006); in particular, in urban areas there are many sources of a specified pollutant and interference with buildings and vegetation. Hence, there is a need for a large number of stations with a large number of grounds based sensors that may turn out to be very costly.

Remote sensing air quality is another way of acquiring data with a better spatial coverage. There are many satellite instruments that could be used for monitoring air quality. Among them Moderate-Resolution Imaging Spectroradiometer (MODIS) is specified as one. MODIS uses aqua and terra satellites to acquire satellite images from land and ocean respectively. Estimation of PM from AOT may fill the gap between in-situ air quality measurement stations and used to obtain PM data from places where there is no in-situ measurement station (Hoyningen-Huene, et al., 2007).

An aerosol is a tiny particle suspended on the atmosphere. Aerosol Optical Thickness (AOT) is a measure of the extinction and scattering of light by particles in a total column from the satellite to the ground. It is proportional to particulate concentration and dimensionless; values typically range from 0 (clear, no haze) to 1 (very hazy, smoky or dusty). So, the aforementioned instrument provides MODIS AOT. The advantage of MODIS aerosol data is, it is cost effective and accurate pollution monitoring system when it is used in conjunction with ground-based observation (Chu, et al., 2003).

Data retrieval of AOT is not possible under cloudy conditions. Values are retrieved only if there are > 12 cloud-free pixel area each of them having 500m resolution out of 20×20 pixels of 500m resolution which is equivalent to 10×10 km^2 area. The value is reported in 10×10 km^2 resolution.

There are different two algorithms for AOT retrieval that are used for satellite images that are taken from land and ocean. The algorithms follow different steps to acquire AOT values (Koelemeijer, 2006).

Studies have been conducted to correlate MODIS AOT with the ground based measurements. As a result a study in USA showed that hourly AOT derived from MODIS and $PM_{2.5}$ has a high correlation ($R = 0.7$), whereas the monthly has excellent agreement ($R > 0.9$). From these we can conclude that MODIS AOT has a good contribution for air quality monitoring (Wang and Christopher, 2003).

Chapter 3

Methodology

This chapter discusses the methodology that is developed and/or adopted in this study. Section 3.1 presents the queueing model, section 3.2 introduces an adopted emission model, section **??** gives a brief description on the integration of results and section 3.3 illustrates the structure and information flow of the methodology.

3.1 Queueing model

A queueing model is a mathematical tool in queueing theory that is used to approximate a real queueing situation. This section gives a detailed explanation about how queueing theory is used to model highway traffic flow.

3.1.1 General overview

In a highway network vehicles arrive from different directions; it could be from two or more directions depending on where the highway is located. They flow through individual links and they split close to any intersection. Thereafter, the vehicles flow via another link and encounter another intersection where they split again and may join other vehicles in the highway or leave the network.

When vehicles arrive at an intersection from different links attached to it, they split into various ways. Some of them turn to the right and merge with other vehicles that are driving from left to straight to the right direction. The others split to the left and join vehicles that are driving from right to left. An example of a highway intersection is on Figure **??**.

FIGURE 3.1: Highway Intersection

There are three points at which vehicles that pass through the intersection merge and use one roadway. During merging there could be congestion since vehicles from different directions come to one point in space. For this reason, each of the merging points will be modelled as a queue with a state dependent service time.

In our context, a queue with a state dependent service time models flow of vehicles through an intersection arriving with a specific rate and departing after a given time depending on the amount of traffic in that intersection.

When there a flow of heavy traffic from one of the links, a flow to the intersection stations is influenced by the congestion that might occur at a splitting point. As the links are modelled as a state dependent service time queues, however, the arrival to the merging queues is determined by the departure rate from the link queues.

Vehicles may not drive smoothly through the network; there are times when the flow is hindered by congestion at the intersections due to several reasons, for example there could be poor management of the roadways, the flow of vehicles exceeds the capacity of the roadway or there are accidents. This results in delay which turns out to increase the sojourn time of a certain vehicle in the highway network in one hand. In addition, this increases emission of pollutants to the surroundings.

To develop a model that predicts the concentration of air pollution which is emitted from the vehicles in the highway network, the flow of the vehicles is analysed using queueing models.

3.1.2 Network description

The development of the queueing model is conducted on the highway network of Rotterdam city, The Netherlands. Figure 3.2 shows the highway network in Rotterdam.

Figure 3.2: Rotterdam road system (Google maps, 2009)

The diagram below shows the network representation of the road system in Rotterdam.

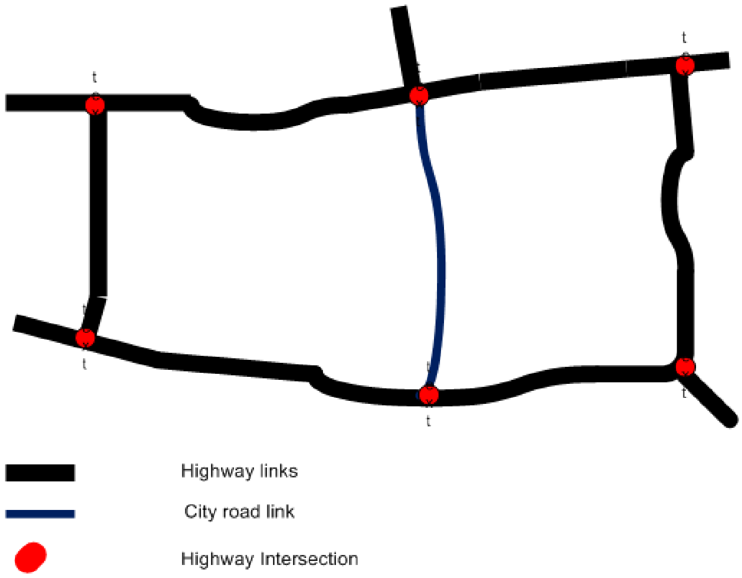


FIGURE 3.3: Highway Network

The network in Figure 3.3 contains 6 intersections and 7 links (edges). Links are bidirectional but they have their own characteristics and they are capable of passing on incoming traffic flow to the outgoing intersections. Hence, there are 14 links that can be seen independently.

To give a better explanation about the network, we consider the arrival and service process of the vehicles. We will assume that any arrival of vehicles, either to the network or the stations in the network follows a Poisson distribution, i.e. there is exponential inter-arrival time. It expresses the probability of a number of events occurring in a fixed period of time if these events occur with a known average rate and independently of the time since the last event. We assume that the arrival process of each of the queues is a time dependent Poisson process.

Below is the representation of the highway in Figure 3.3 as network of queues. The set of three or four queues in a rectangle represent the merging queues which is given in Figure 3.5.

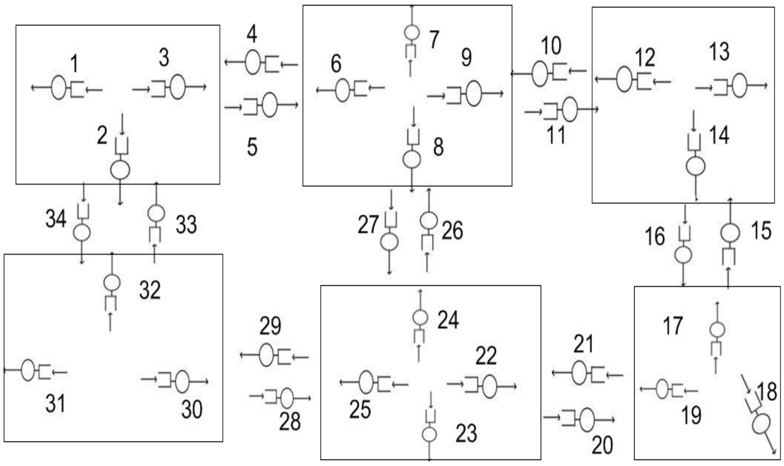


FIGURE 3.4: Network of Queues

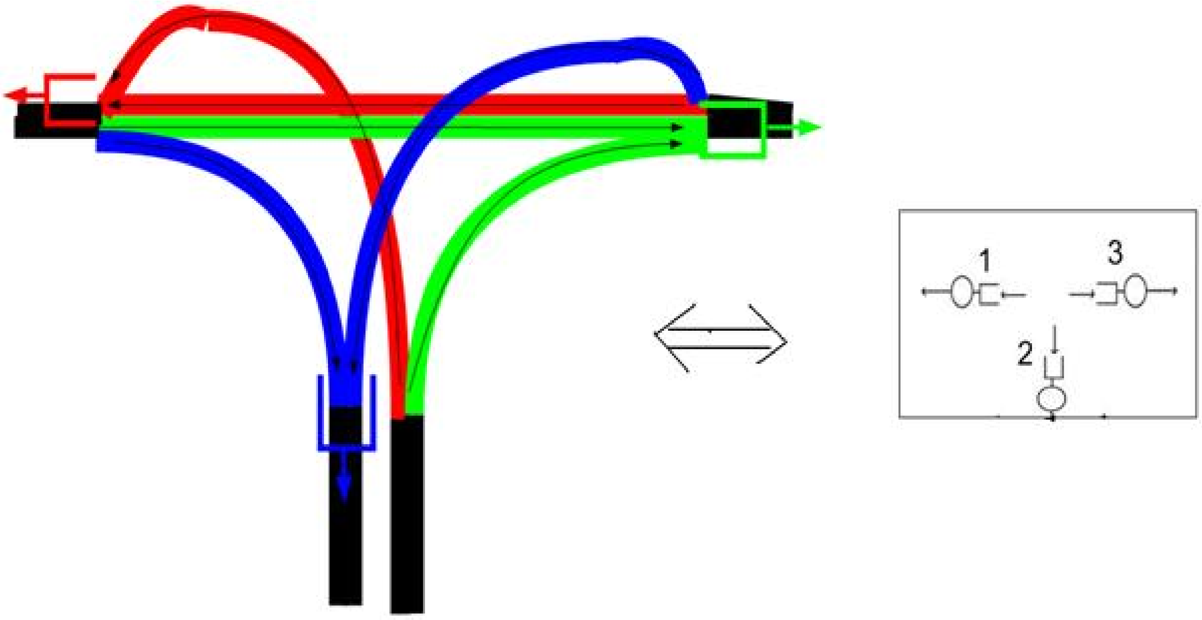


FIGURE 3.5: Queue representation of an intersection queues

As can been seen in Figure 3.4, arriving vehicles get served in one of the intersection queues and move to one of the link queues that are attached to the intersections or leave the network. This routing of vehicles to one of the alternatives is determined by a probability which is called the routing probability. Subsequently, vehicles arriving to the link queues again route to the nearest intersection with a probability one as there are no other ways to move to.

So, the network considered in this study consists of 34 queues: 20 intersection queues and 14 link queues. Vehicles arrive to the network with a certain rate and are served based on the service rate of their respective queues.

While a vehicle arrives through one of the queues at an intersection, either of these happens: the server is busy so there are vehicles in the queue or the server is empty. If the former one holds, the vehicle should spend some time in the queue until the ones that arrived before are served. Then it gets its service and leaves the system with a routing probability to one of the links attached to the intersection. But if the server is empty, any vehicle that arrives during this time gets served immediately.

The Mathematical Modelling of queueing theory presented on section 2.1 related to the case study of Rotterdam highway network follows:

Indices:
i, j, k queues/stations
r vehicle types (personal cars, light duty, heavy duty)
J number of queues in the network (34)
t time
$n_i(t)$: number of vehicles in station i at time t

$\vec{n}(t) = (n_1(t), n_2(t), ..., n_J(t))$: a vector containing the number of vehicles in each station of the network at time t
$n(t) = |\vec{n}(t)| = \sum_{i=1}^{J} n_i(t)$: number of vehicles in the network at time t

The state space of the network is given by The possible values of $n(t)$ and $n_i(t)$ form a state space $S(t)$ and $S_i(t)$ respectively. They are given as:

$S(t) = \{\vec{n(t)} = (n_1(t), n_2(t), ..., n_J(t)) : n_j(t) \geq 0, \forall j = 1, 2, ..., 34\}$

$S_i(t) = \{n_i(t), n_i(t) \geq 0\} \forall i = 1, 2, ..., 34$
Let $e_i = (0, ..., 0, 1, 0, ..., 0)$, 1 in the i^{th} position, i.e. the i^{th} unit vector.

$n_i(t) = 0, 1, 2, ..., n_{i_{jam}}$
Let $e_i = (0, ..., 0, 1, 0, ..., 0)$, 1 in the i^{th} position, i.e. the i^{th} unit vector.

Arrival rates

The arrival rate to each station varies depending on the place where the station is located. For the intersection queues, it is the sum of the arrival rates of vehicles at time t from links that are attached to the intersection. For the link queues, it is the departure from the intersection queues at time t.

Arrival rate of queue i at time t is denoted by $\lambda_i(t)$.

The detailed expression of the arrival rates is given in appendix A.

Service rates

The service time of all the stations depend on the state of the station $n_i(t)$ denoting the number of vehicles in the station at time t. In other words, $n_i(t)$ is the density of a road represented by station i.

The service rate of a station is the rate at which vehicles leave the stations. This is equivalent to the rate of flow of vehicles on a link or intersection. On section 2.3, it is explained that rate of flow of vehicles depend on speed and density, and it is given by Equation 2.10. Thus, the service rate of vehicles at a specific time t when there are n_i number of vehicles at station i is given by $1/q(n_i(t))$, where $q(n_i(t))$ is given as:

$$q(n_i(t)) = v(n_i(t)).n_i(t) = v_{free-flow}(1 - \frac{n_i(t)}{n_{i_{jam}}}).n_i(t) \tag{3.1}$$

Therefore, the state dependent service rate $\phi_i(n_i(t))$ is given as:

$$\phi_i(n_i(t)) = v_{free-flow}(1 - \frac{n_i(t)}{n_{i_{jam}}}).n_i(t) \tag{3.2}$$

with $\phi_i(n_i(t)) > 0$ if $n_i(t) > 0$.

Routing probability

Routing probability form station i into station j, P_{ij} is the probability that a vehicle routes to a certain link from possible links while arriving at an intersection. In this study, it is given by one divided by the number of links attached to an intersection. Appendix B provides all the routing probabilities used in this study.

Occupation rates

The occupancy rate of the stations in the network is given as:

- $\rho_i(t) = \frac{\lambda_i(t)}{E(\phi_i(n_i(t)))} \quad for \quad i = 1, 2, ..., 34$

  $\rho_k(t) = \rho_j(t) + \rho_l(t)$, where $\rho_j(t)$ and $\rho_l(t)$ are occupancy rates of adjacent link stations j and l respectively.

$\rho(t) = (\rho_1(t), \rho_2(t), ..., \rho_{34}(t))$ is the occupancy rate of the network.

3.1.3 Equilibrium distributions

The equilibrium distribution of the number of vehicles in a station per unit time t is defined as the probability of having n number of vehicles at station i, at time t. The derivation of an equilibrium distribution is given on section 2.1.1.

Whenever a vehicle arrives to a station, there will be a transition from state $n_i(t)-1$ to state $n_i(t)$ with rate $\lambda_i(t)$. And when a vehicle departs from the station, the transition is from state $n_i(t)$ to state $n_i(t)-1$ with rate $\phi_i(n_i(t))$. The number of transitions per unit time from $n_i(t)-1$ to $n_i(t)$, which is also called the flow from $n_i(t)-1$ to $n_i(t)$, is equal to $\pi_i(n_i(t))$, the fraction of time the system is in state $n_i(t)$, times $\lambda_i(t)$, the rate at which arrivals occur while the system is in state $n_i(t)-1$.

By equating the flow out of state $n_i(t)$ and into state $n_i(t)$, the equilibrium distribution is given by

$$\pi_i(n_i(t)) = b_i(t)\frac{\lambda_i(t)^{n_i(t)}}{\prod_{r=1}^{n_i(t)}\phi_i(r)(t)} i = 1, 2, ..., J \tag{3.3}$$

where $b_i(t)$ is a normalization constant defined as

$$b_i(t) = \pi_i(0)) = (\sum_{n_i(t)=0}^{\infty}(\frac{\lambda_i(t)^{n_i(t)}}{\prod_{r=1}^{n_i(t)}\phi_i(r)(t)}))^{-1}$$

Since the equilibrium distribution of the whole network is the product of the equilibrium distribution of each of the stations, it is given as follows:

$$\Pi(n(t)) = \prod_{j=1}^{J}\pi_i(n_i(t)) \tag{3.4}$$

3.1.4 Performance measures

The performance measure we are interested in is:

- $E(L_i(t))$: the mean number of vehicles at station i

After the equilibrium distribution is obtained, it is calculated as

$$EL_i(t) = \sum_{n_i(t)=0}^{n_{i_{max}}} n_i(t)\pi_i(n_i(t)) \tag{3.5}$$

$$= \sum_{n_i(t)=0}^{n_{i_{max}}} n_i(t)b_i\frac{\lambda_i^{n_i}}{\prod_{r=1}^{n_i}\phi_i(r)} \tag{3.6}$$

3.1.5 Relationship to emission model

From the queueing model, the expected number of vehicles is acquired. Then it is used to compute average speed of vehicles, second moment and third moment of speed of vehicles which are needed to compute the emission factor for each vehicle. In addition, the expected number of vehicles is applied directly on the emission model to compute total emission.

3.2 Emission model

The negative contribution of vehicles to the quality of air in the vicinity of the highway network under this study is calculated by CAR (Calculation of Air pollution from Road traffic) II model described on section 2.4. This model works in the basis of classes such as street type, vehicles category as well as speed type. It also incorporates different types of vehicles and used to find the concentrations of different types of pollutants. Moreover, the model uses a constant emission factor which is already calculated with a fixed speed of vehicles of a road.

This emission model is revised in such away that it is compatible with the queueing model and fits with the considered conditions in the study. The model delivers annual concentration of different pollutants. Among them, the case for PM_{10} was chosen.

The input data for the model are daily average number of vehicles, fraction four vehicle types: personal cars, light trucks, bus group and heavy trucks. In addition to this emission factor for each type of vehicles and fraction of stagnant cars are taken as an input data. The queueing model, however, delivers hourly average number of vehicles of all the vehicle in general though it takes into account the fraction of three types of vehicles such as personal cars, light trucks and heavy trucks. For this reason, the number 24 is removed from the emission formula on Equation 2.18. Moreover, the fraction of bus group is excluded as bus group is classified as light trucks in the traffic data.

The emission factors applied in CAR emission model assumes constant emission factor categorised by road type and speed type. This is relaxed by employing speed dependent emission factor formula of PM_{10} developed by the UKs National Atmospheric Emission Inventory (NAEI). The formula takes average speed, second moment and third moment of speed of vehicle. It then gives emission factor of the specified pollutant in gram per kilometre. It also takes into account European emission standard factor of Euro I, II, III and IV. The formula is shown on Equation 3.7.

$$E_f(g/km) = (a + bv + cv^2 + dv^3 + e/v + f/v^2 + +g/v^3) \times x \qquad (3.7)$$

where v, v^2 and v^3 are average speed, second moment and third moment speed of vehicles respectively. x denotes a scale factor for European emission standard factor, it varies for Euro I, II, III and IV. The coefficients are given on AppendixC.

The formula is developed for each types of vehicles with varying fuel type and engine size. The considered fuel types in the emission factor formula are petrol and diesel and engine sizes of 1.4 litre, 1.4 - 2.0 litre and > 2.0 litre. The computation of the total emission is done, however, for all vehicles at once. Hence, the emission factor formula was rewritten by taking the proportion of each types of vehicles, fuel type and engine size into account. The proportion of vehicle types was used from the available traffic data and the proportion of fuel type and engine size were obtained from the Statistics Netherlands (CBS) and some of them were used assumed. Table **??** gives the employed proportions.

As the vehicles that are being used since 2005 - 2008 are Euro IV, scale factor for Euro IV is used along with the emission factor formula.

Equation 3.8 shows the reformulated emission formula.

$$E = [((1 - (F_m + F_v)) + F_m + F_v) \times E_f] \times \frac{1000N}{3600} \tag{3.8}$$

where
E: Emission [μg m^{-1} s^{-1}]
N: Number of vehicles per hour
F_m: Fraction of medium trucks [-]
F_v: Fraction of heavy trucks [-]
E_f: Emission factor [g km^{-1}]

Since this equation gives emission in μg m^{-1} s^{-1}, it is multiplied by 3600 in order to get hourly emission. This is then used to compute hourly concentration of PM_{10} plugging in Equation 3.8 to Equation 2.22.

3.3 Structure and information flow diagram of the model

This section describes the information flow of the overall model that is used to implement Rotterdam case study data. It is implemented on C++ programming language.

The program starts by reading six input data from the user and one from a database. These six data are the length of the road, the fraction of personal, light duty and heavy duty cars, the free flow speed, the total arrival rates of vehicles to the road, wind speed and the distance of the measuring station from the road. These data can be either entered interactively one by one from the console or can be read from a file based on the preference of the user. The data that is input from a database is the proportion of vehicles with their engine size and fuel type which is always read from an input file.

Then the jam density of the road is computed by taking the length of the road, fraction of personal cars, light duty and heavy duty as well as the free flow speed as an input. The jam density of the road and the free flow speed are then used to calculate the state dependent service time which in turn is used with total arrival rate of vehicles on the road to get the equilibrium distribution of number of vehicles.

The equilibrium distribution of number of vehicles is then used to compute the following two. Expected number of vehicles. Second and third moment of number of vehicles.

These above two outputs leads to the computation of Average speed of vehicles and Second and third moment of speed of vehicles.

The proportion of vehicles with their engine size and fuel type is used to calculate the emission factor of vehicles along with the fraction of personal, light duty and heavy duty cars as well as the above listed two outputs. The emission factor in turn is used to get the total emission from vehicles making use of the already computed expected number of vehicles and second and third moment of number of vehicles.

After this only two computations are left to get the final desired outputs which are dilution factor and weather factor. These are calculated from the user data distance and wind speed respectively. Finally total concentration is computed from dilution factor and weather factor.

The program is capable of writing the outputs either to the console or to a file based on the preference of the user. In addition, it allows the user to repeatedly perform the entire computation process for new set of data without the need to exit the program.

Figure 3.6 gives the flow chart.

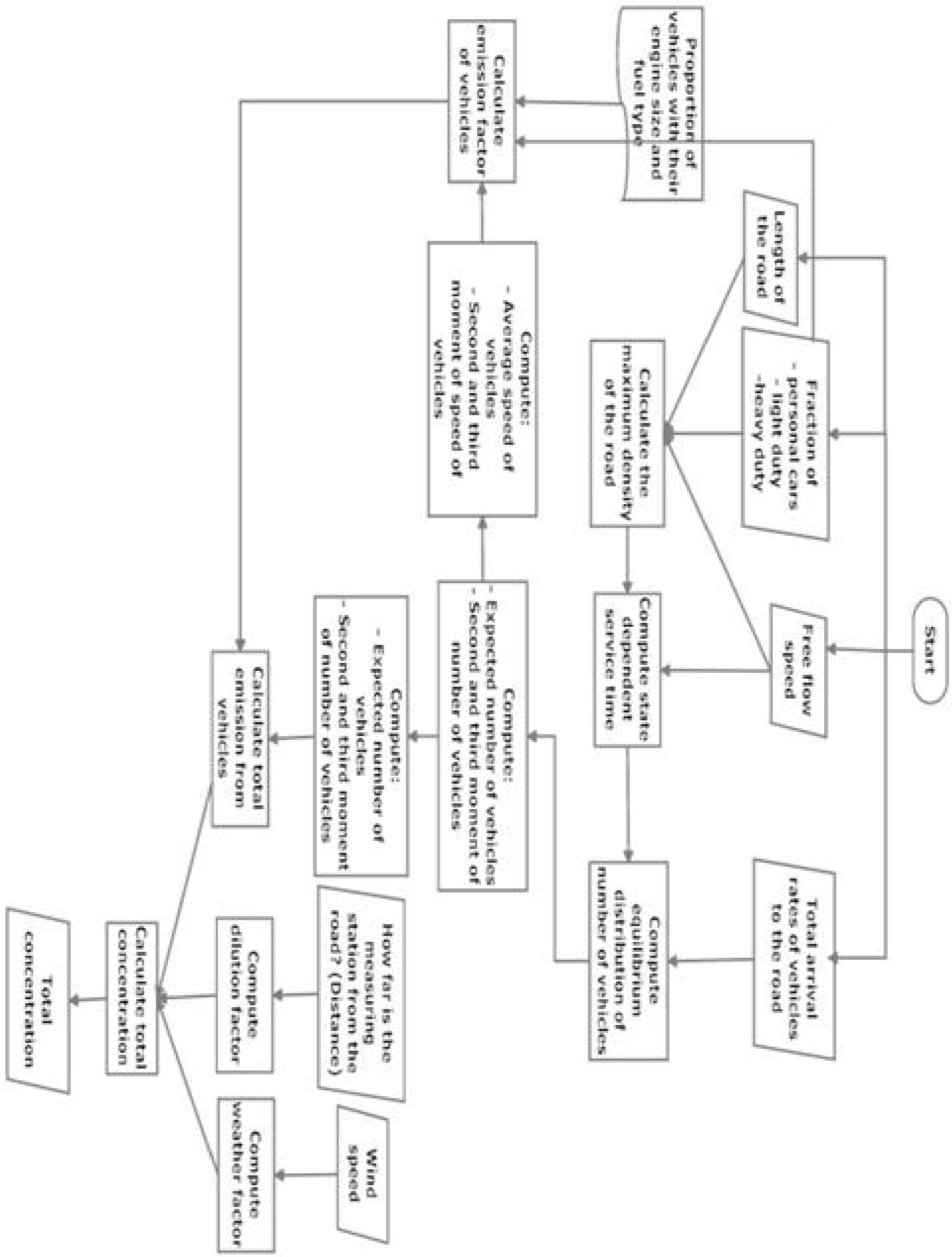


FIGURE 3.6: Structure and information flow diagram of the model

Chapter 4

Rotterdam case study data

This chapter gives a brief description of the study area and introduces the various sources of data that are used to implement the developed model in the area. Section 4.1 describes the study area, section 4.2 presents list of data sets with their corresponding sources and section 4.3 reports the preparation employed on the data sets to make them ready for input.

4.1 Study area

The queueing model described in chapter 3 is implemented on a city of Rotterdam which is situated in the west of The Netherlands. Rotterdam is the second largest city in the country inhibited by 584,046 people in 2006. The city consists of highway, industries, port, rivers and others. The port is one of the largest ports in the world having the first position in Europe. Rotterdam is covered by 319 km^2 including the highway network under study.

4.2 Data source

The data are offered by Ministry of Transport, Public Works and Water Management of the Netherlands, Directorate General Rijkswaterstraat (RWS), Royal Netherlands Meteorological Institute (KNMI) and The Netherlands Environmental Assessment Agency (PBL). Below list of the data sets with their description is presented.

4.2.1 Traffic data

Traffic count

Hourly traffic data for nine counting stations located on different parts of the highway network is available. These data are categorised by vehicle types such as personal cars, light trucks and heavy trucks. Buses are classified as light trucks. Among the available stations, the ones that are situated at the nodes of the highway network shown on Figure 3.4 are used.

For each vehicle type, hourly traffic data of all lanes available on a single road is counted. These data are sorted out according to the entrance and exit of vehicles.

Length of road

The length of each of the links and intersections on the highway network of Rotterdam was measured from the Google map.

4.2.2 Emission data

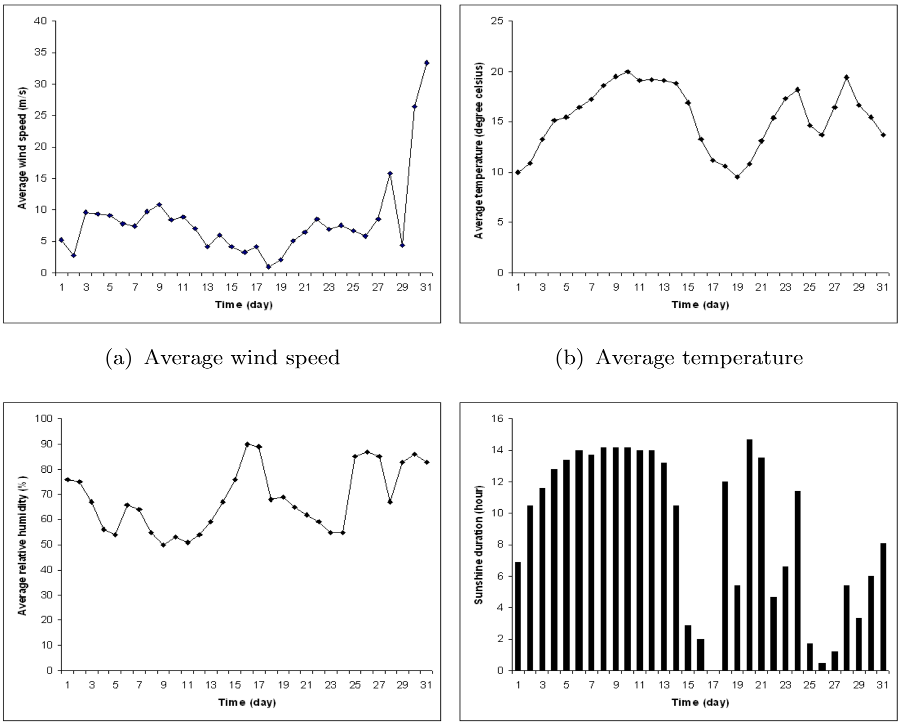
Meteorology Data

There is only one meteorology station in Rotterdam situated around the centre of the city centre. At this station, the measurement of wind speed, wind direction, relative humidity, temperature and others is conducted. For our study, daily average data for these data are available for May 2008.

4.2.3 Validation data

Ground Based Air Quality Measurement Data

In the area of Rotterdam, there are two in-situ air quality monitoring stations at a distance of 9km. The two stations are named as Floreslaan and Bentinckplein located at geographic coordinates of (4.46150, 51.92630) and (4.32908, 51.91323) respectively. They are shown on Figure 4.3. On these stations, the concentration level of hourly different pollutants including PM_{10} is measured. For this study, hourly data of PM_{10} for the month of May 2008 measured in the stow stations is available. They are directly used for implementing of the model.



(a) Average wind speed

(b) Average temperature

(c) Relative humidity

(d) Sunshine hour

FIGURE 4.1: Weather condition in Rotterdam on May, 2008 (KNMI website, 2009)

Remotely sensed data

The study area is covered with MODIS aerosol product is acquired from MODIS aerosol products. This is downloaded from NASA website. The products are available for the whole month of May 2008 having different over pass time.

The concentration of aerosol is strongly affected by the meteorological factors: wind speed, average temperature, rainfall and relative humidity (Singh, et al, 2000 and Demewez, 2008). The concentration increases during the time when there is no wind and high temperatures. High rainfall and high relative humidity contribute to lowering aerosol concentrations. For these reasons and as the weather condition on May 13, 2008 was relatively better to download MODIS aerosol product, May 13 was chosen for investigating the output of the model that is implemented using the available data. The weather condition on May 13 is explained as follows. Average wind speed was low relative to the other days in May, average temperature was almost equal to the maximum in May, relative humidity is higher than the lowest value in May and there were 13 hours of sunshine.
Figure 4.1 shows the weather condition in Rotterdam on May 2008.

The MODIS aerosol product of Netherlands and its surrounding that was taken on May 13 is shown on Figure 4.2.

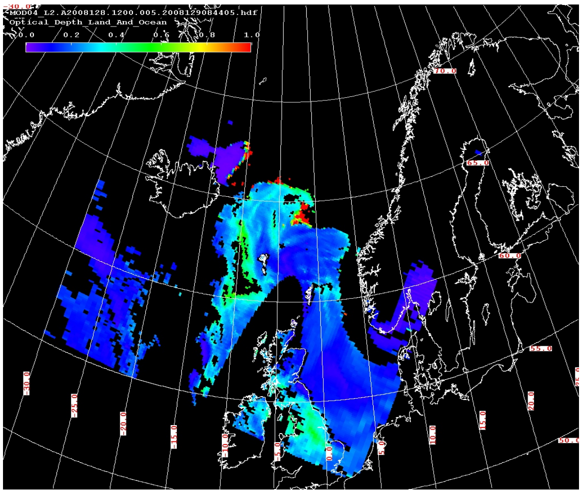


FIGURE 4.2: MODIS aerosol product acquired on May 13, 2008 (NASA website, 2009)

The blue color on Figure 4.2 shows that there was a clear air on that day, the light green color shows that the quality of air was moderate and the red color tells that the quality of the air was dangerous.
Figure 4.3 shows the location of traffic count station, in-situ air quality measurement stations and meteorology station.

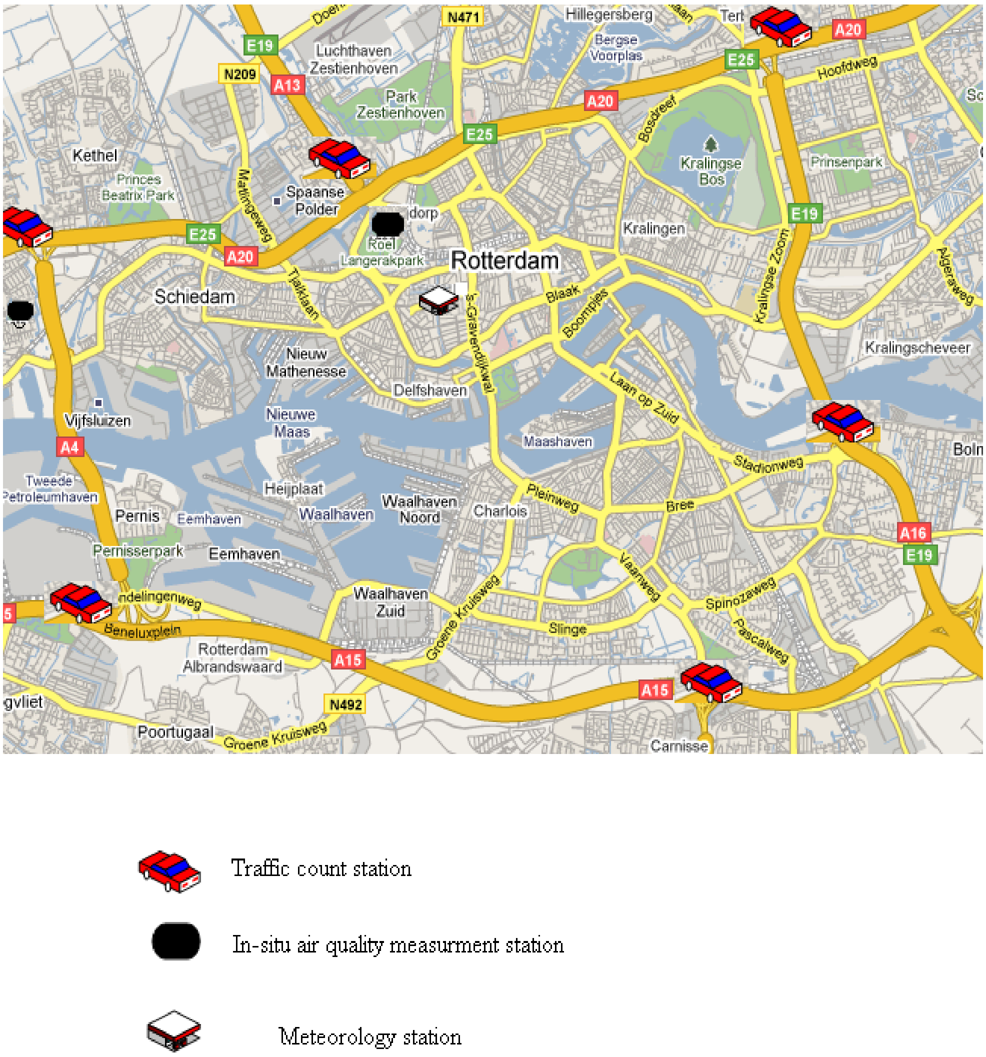


FIGURE 4.3: The location of the traffic, meteorology and air quality data stations in the vicinity of Rotterdam highway network (Google maps, 2009)

4.3 Data preparation

Traffic data

For each date and hour, the sum of the traffic counts of the lanes having the same direction is computed. Some lanes represent arrival to a link and the rest represent departure of vehicles from a link. This is followed by the computation of the sum of traffic counts of the three types of vehicles.

Arrival to a certain station is obtained partially from the traffic count and the rest is computed from the arrival rate equations which is presented on Appendix A by assuming all the routing probabilities to be 1/2. Rewriting the arrival rate equations, we find a system of linear equations having a coefficient matrix of dimension 34. Solving this system, the arrival rates for all the stations were obtained. Then the fraction of vehicles of all types is computed. These are done for each hour and date of May 2008.

The assumption that routing probability is 1/2 indicates that the vehicles that were driving through one road split to two different roads equally.

Remotely sensed data

MODIS aerosol product delivers AOT values with 10×10 km resolution. From these product four pixels that associate with the study area were selected and the corresponding AOT values were picked.

The following table summarizes the required datasets with their characterstics.

Serial No	Data set	Location	Number of stations	Temporal resolution	Spatial resolution	Availability	Remark
1	Traffic data	Rotterdam	6	Hourly		Yes	
2	In-situ measured air quality data	Rotterdam and the surrounding	2	Hourly	Point	Yes	Available for PM_{10} pollutant
3	Meteorology data	Rotterdam		Daily		Yes	Available for wind speed, wind direction
4	MODIS aerosol product	Rotterdam and the surrounding		Daily	10 km	Yes	Available for an average of 9 days

TABLE 4.1: List of datasets

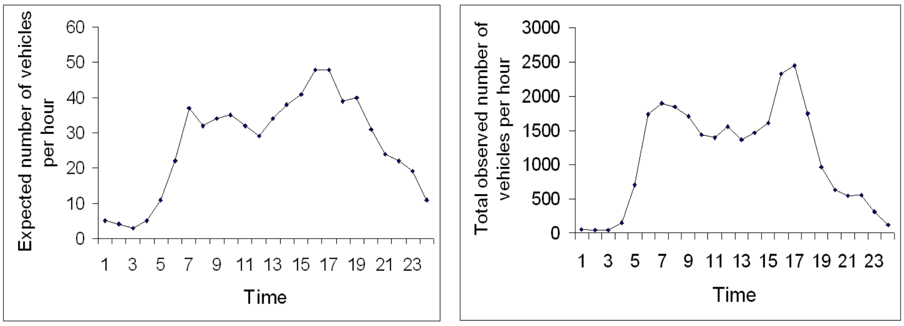
Chapter 5

Results

This chapter presents the results obtained by implementing the queueing model and CAR II emission model on a data of Rotterdam area. Section 5.1 gives the results from the queueing model which predicts hourly expected number of vehicles in a certain link or intersection of a highway network, section 5.2 presents the results obtained by integrating the queueing model with CAR emission model, section 5.3 presents the relation between in-situ measured PM_{10} and AOT and the linkage between in-situ measured PM_{10} and AOT, and predicted PM_{10} and AOT is discussed in section 5.4 and section 5.5 respectively.

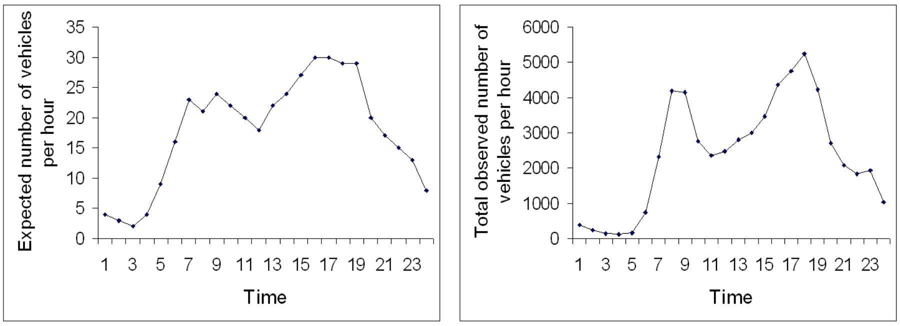
5.1 Queueing model result

The queueing model delivers hourly predicted number of vehicles on each road link and intersection of the highway network in Rotterdam. To validate the queueing model, an investigation was made to determine the relation between the pattern of the predicted number of vehicles and traffic count with time. For this, station 1 and station 16 stations representing link stations and intersection stations respectively were selected and the graphs of hourly expected number of vehicles and observed number of vehicles with time were plotted. May 13 was chosen to represent the month as it had a relatively bright day with no wind and relative humidity. Figures 5.1 and 5.2 illustrate the behaviour of the time pattern of the expected and observed number of vehicles.



(a) Expected number of vehicles vs time (b) Total Observed number of vehicles vs time

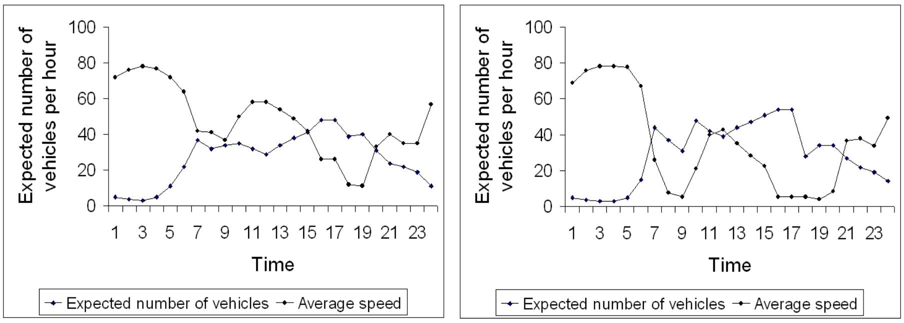
FIGURE 5.1: The comparison between observed and predicted number of vehicles at station 1 of Figure 3.4 on May 13



(a) Expected number of vehicles vs time (b) Total observed number of vehicles vs time

FIGURE 5.2: The comparison between observed and predicted number of vehicles at station 16 of Figure 3.4 on May 13

After obtaining the expected number of vehicles from the queueing model, the average speed of vehicles on each link of the highway network was computed. This was done by applying expectation on both sides of Equation 2.10 to acquire an average speed of vehicles. To check whether the queueing model works properly with respect to the average speed, expected number of vehicles and estimated average speed were plotted with time for the same two stations in the highway network. Figure 5.3(a) and Figure 5.3(b) illustrate this for May 13, 2008 respectively.



(a) Intersection station (b) Link station

Figure 5.3: Expected number of vehicles and average speed at an intersection (station 1) and a link (station 16) of Figure 3.4 on May 13

As can be seen on Figures 5.6(a) and 5.6(b), whenever speed decreases, number of vehicles increase and vise versa. This is a logical way of looking at speed and flow relationship.

Next quantitative validation was performed to investigate the accuracy of the queueing model. The same two stations were chosen. For those stations, there are corresponding traffic count stations which can be seen on Figure 3.4. The validation was done by matching the hourly expected number of vehicles and the hourly departing number of vehicles which are obtained from traffic count station situated in the vicinity of the prediction stations.

Figure 5.4 and Figure 5.5 show the relation between hourly expected number of vehicles and the total observed hourly number vehicles at the two stations.

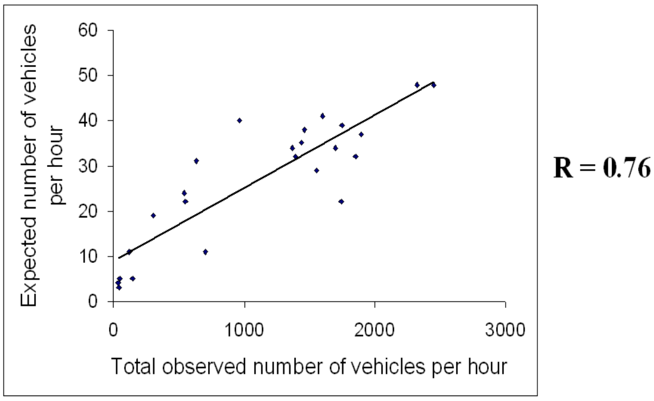


Figure 5.4: Relationship between hourly total observed number of vehicles and expected number of vehicles at an intersection (station 1) of Figure 3.4 on May 13

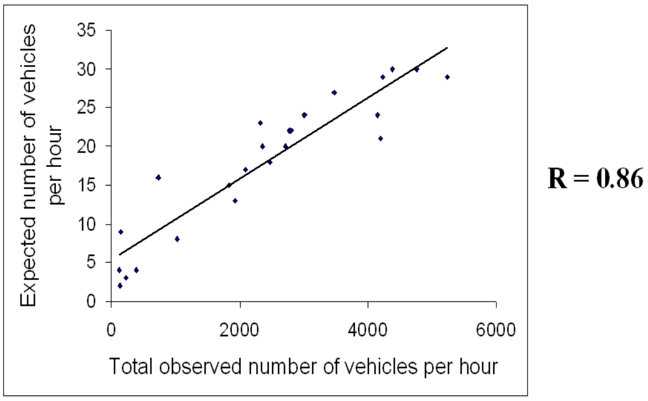
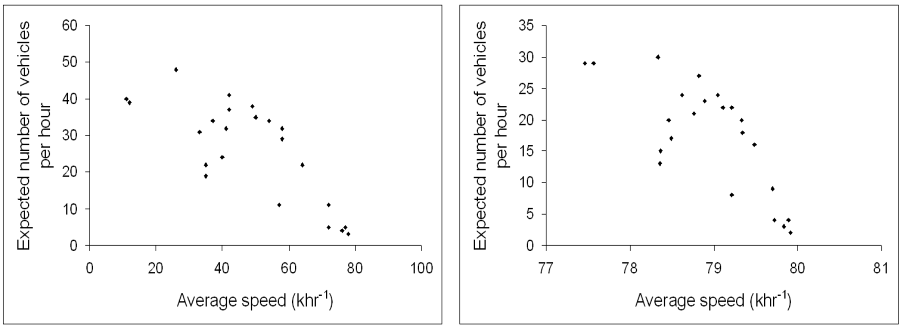


FIGURE 5.5: Relationship between hourly total observed number of vehicles and expected number of vehicles at a link (station 16) on Figure 3.4 station on May 13

The scatter plots on Figure 5.4 and 5.5 show a linear correlation of 0.76 and 0.87 between observed traffic count and expected number of vehicles for the two stations respectively.

In addition, flow versus speed has also been plotted to see how well the general speed-flow relationship for uninterrupted traffic flow is represented. This is presented on Figure 5.6.



(a) Intersection station

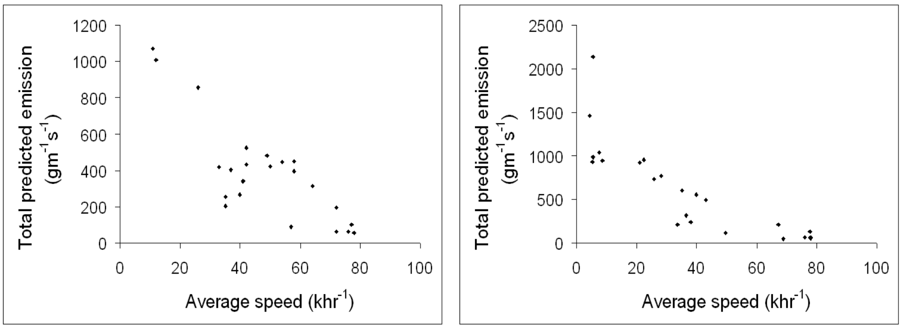
(b) Link station

FIGURE 5.6: Relation between flow of vehicles and average speed at an intersection (station 1) and a link (station 16) station on Figure 3.4 on May 13

5.2 Integration of queueing model and emission model

The output of the queueing model was used as an input for the modified CAR II emission model that was used to calculate the concentration of PM_{10}s. Particularly, expected number of vehicles were used to calculate average speed of vehicles which was then employed to compute emission factor using speed dependent formula. These were used to compute hourly total emission of PM_{10} at an intersection and link of a road as well as the concentration of PM_{10} which takes into account weather, dilution and tree factors.

The relation between emission and average speed of vehicles was investigated to examine the dependency of emission on speed of vehicles. As can be seen on Figure **??**, while the speed of a vehicle increases, the concentration of PM_{10} decreases and after speed exceeds 55 km h^{-1} - 60 km h^{-1} emission increases while speed increases. The queueing model result presented on 5.1 showed that when average speed decreases, the expected number of vehicle grows. This relationship is explained as large number of vehicles in a specific road results in speed reduction. On Figures 5.7(a) and 5.7(a) the comparison made between total emission emitted from hourly expected vehicles driving through a station and their corresponding average speed is shown.

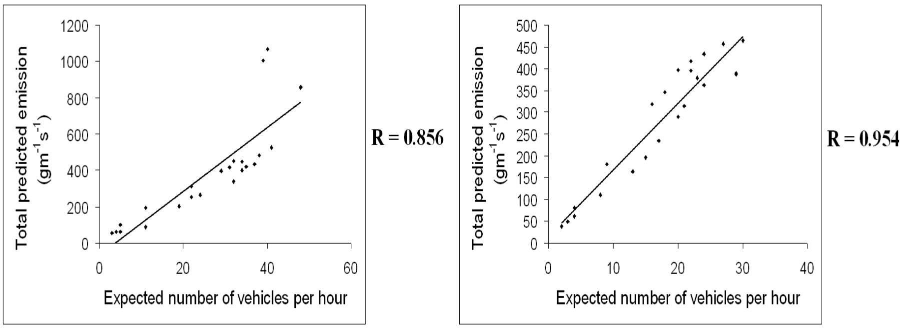


(a) Intersection station (b) Link station

FIGURE 5.7: The relation between total emission and average speed for intersection (station 1) and link (station 16) of Figure 3.4 on May 13

Figures 5.7(a) and 5.7(b) show that when speed increases, emission decreases which is in accordance with the speed emission relationship given on **??**. The relation is not fully observed because the amount speed limit used in the queueing model.

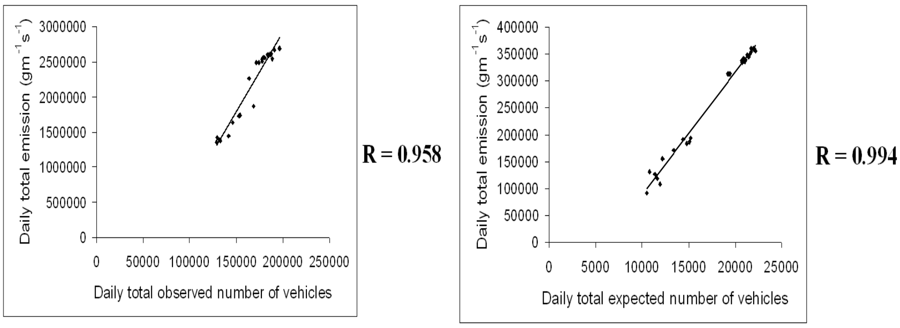
Figures 5.8(a) and 5.8(b) illustrate the relation between emission and expected number of vehicles for intersection and link stations respectively. On these two figures, it can be noticed that while number of vehicles increase, emission increase. Their relationship resulted in a correlation of 0.856 and 0.954 for intersection and link station respectively.



(a) Intersection station (b) Link station

FIGURE 5.8: Emission versus expected number of vehicles for intersection (station 1) and link (station 16) of Figure 3.4 on May 13

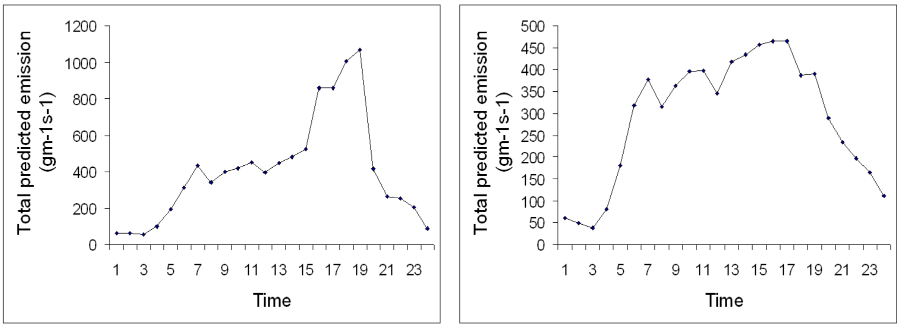
In order to identify the value added by queueing model for the estimation of emission, daily total emission from the whole network was computed by considering the observed total number of vehicles entering to the network from different directions and assuming these vehicles drive with the maximum speed, 80 kmh^{-1}. Then a comparison was made between the observed number of vehicles and total emission which resulted in a correlation of 0.958. In the contrary, a comparison was performed between the daily total expected number of vehicles in the network and total emission calculated with varying speed. This relation has a correlation of 0.994. Figures 5.9(a) and 5.14 show the relationship performed based on observed number of vehicles and predicted number of vehicles respectively.



(a) Daily total emission vs observed number of vehicles (b) Daily total emission vs expected number of vehicles

FIGURE 5.9: The relationship between daily number of vehicles and total emission from the whole network of Figure 3.4 on May, 2008

In order to find out how effective the integration of the queueing model and emission model was, the hourly total emission was plotted against time for representative of link and intersection stations.



(a) Intersection station (b) Link station

Figure 5.10: The variation of emission within time for intersection (station 1) and link (station 16) of Figure 3.4 on May 13

Figures 5.10(a) and 5.10(b) show how emission from road traffic behaves during the day. It can be seen that lowest emission is in the midnight and the highest is in the rush-hour, late in the afternoon.

5.3 Relationship between in-situ measured PM_{10} and AOT

In this section, the relation between in-situ measured air quality data and remotely sensed data was examined. The in-situ measure concentration level of PM_{10} was acquired from two monitoring stations located in the vicinity of the highway network and the AOT values that were obtained from four pixels covering the highway network. The value of AOT is not always available because of cloudy weather condition. So, out of the 31 days in May 2008, on average the values of 9 days are available for the two, three or four 10×10 km pixels which cover the highway network. Figure 5.11 illustrates the time series of the average of available AOT values of the four pixels and on Figures 5.12 and 5.13 show hourly and daily average in-situ measured PM_{10} from the two air quality monitoring stations.

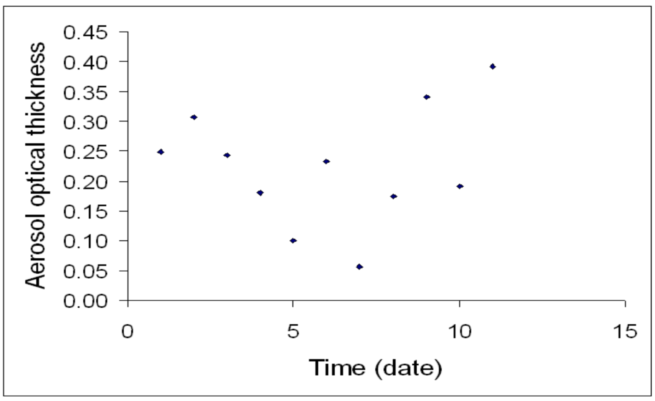


Figure 5.11: AOT time series for available values on May, 2008

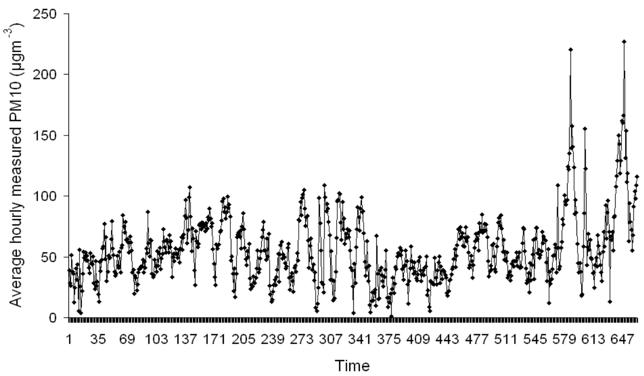


FIGURE 5.12: Average hourly measured PM_{10} of two air quality monitoring stations located in the vicinity of the highway network (May, 2008)

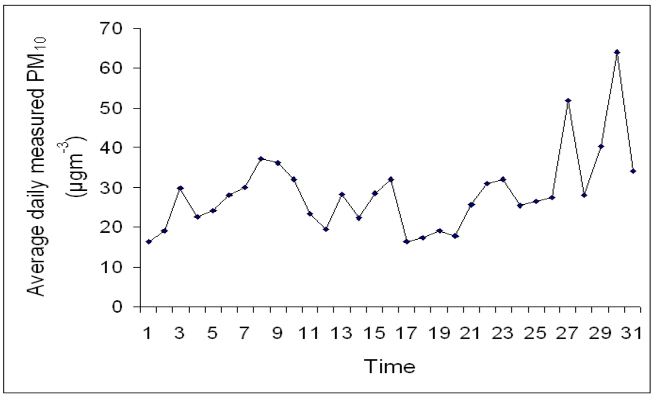


FIGURE 5.13: Average daily measured PM_{10} of two air quality monitoring stations located in the vicinity of the highway network (May, 2008)

The average AOT values were linked with hourly measured PM_{10} observed at the closest time to the overpass time of the satellite data. This relation resulted in a correlation coefficient of 0.006. In addition, the linkage between daily average measured PM_{10} and the average AOT values was carried out which resulted in a correlation coefficient of 0.005.

Figures 5.14 and 5.15 illustrate the relation in hourly and daily basis respectively.

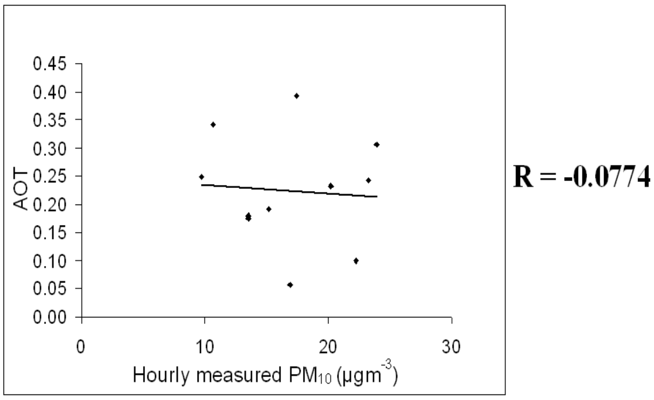


FIGURE 5.14: The relation between hourly AOT and measured PM_{10} for the whole station on May

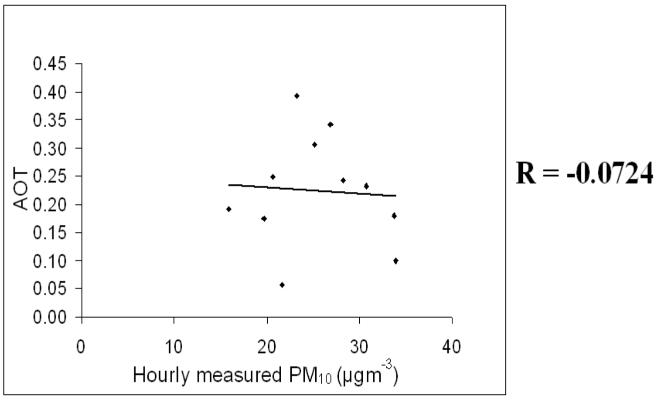


FIGURE 5.15: The relation between daily AOT and measured PM_{10} for the whole station on May

Both Figure 5.14 and Figure 5.15 depict that the these two air quality data have almost no correlation.

5.4 Relationship between in-situ measured PM_{10} and predicted PM_{10}

This section discusses the comparison made between the concentration of PM_{10} and in-situ measured PM_{10}.

On figures 5.16 and 5.17, the time series of hourly and daily total predicted concentration of PM_{10} is shown.

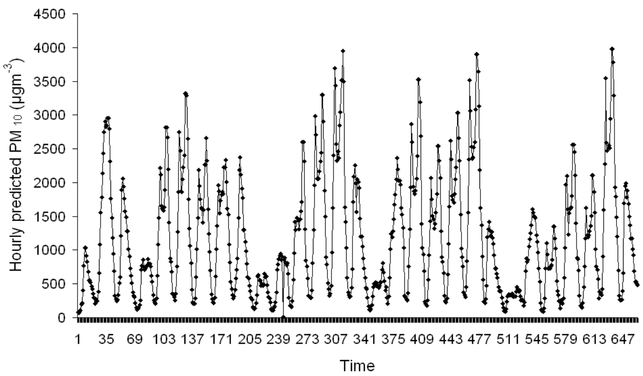


FIGURE 5.16: Total hourly predicted PM_{10} of the whole network (May, 2008)

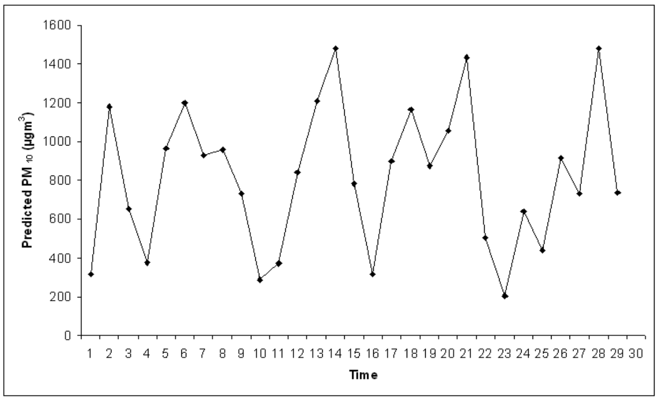


FIGURE 5.17: Total daily predicted PM_{10} of the whole network (May, 2008)

The relation between the estimated concentration of PM_{10} and observed (in-situ measured) PM_{10} was carried out in two ways. First, the sum of the total predicted concentration of PM_{10} from the whole network was taken and compared with the average of the two measured PM_{10} stations. This was done in an hourly and a daily basis on May 13, 2008. The results for both hourly and daily basis are illustrated on figures 5.18 and 5.19 respectively.

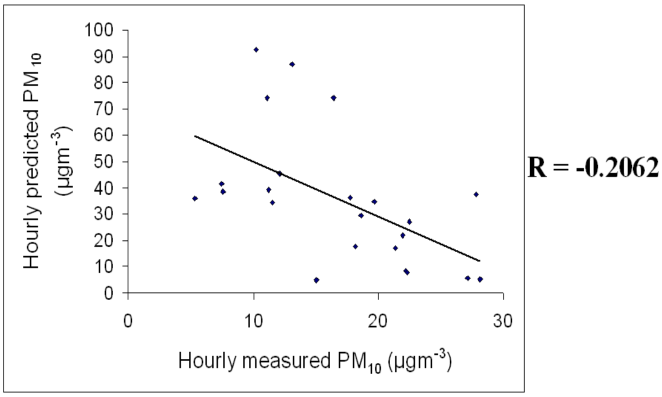


FIGURE 5.18: Comparison of hourly measured PM_{10} vs hourly predicted PM_{10} of the whole network on May 13

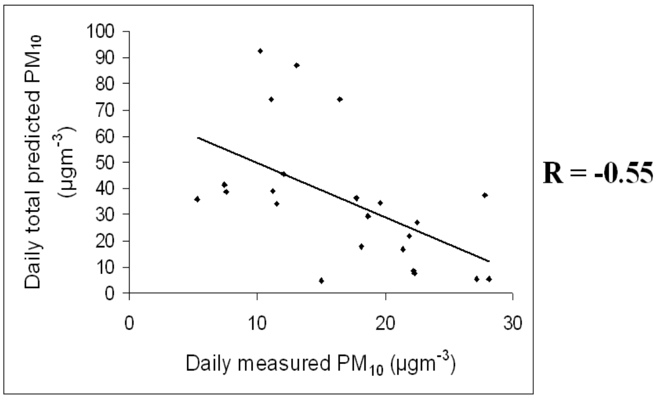


Figure 5.19: Daily measured PM_{10} vs predicted PM_{10} of the whole network on May, 2008

The hourly and daily comparisons on Figure 5.18 and 5.19 resulted in a correlation of -0.2062 and -0.55 respectively.

Second, among the stations in the whole network, the stations in the proximity of the in-situ air quality monitoring stations were identified. In addition to the identification of the stations, an assessment had been made to ensure whether the stations have pollution contribution to the surrounding where they are situated. This is because wind direction plays a role in dispersing the polluted air to different areas. For example, if the wind direction was south-east and the stations are on the north-west direction, the stations that are situated in the opposite direction of the wind direction were used to make a comparison. Or if the wind direction was north-east, the stations that are located on the opposite side are used. This was followed by finding the sum of the predicted concentration of PM_{10} from the identified stations on hourly and daily basis.

Figures 5.20 and 5.21 show the relation between the sum of hourly and daily predicted concentration of identified traffic stations near by Floreslaan air quality monitoring station whereas figures 5.22 and 5.23 show similar comparison made in the vicinity of Bentinckplein air quality monitoring station. The following figures illustrate the relationship between the sum of total predicted concentration of PM_{10} and observed PM_{10} that were measured in the specified stations.

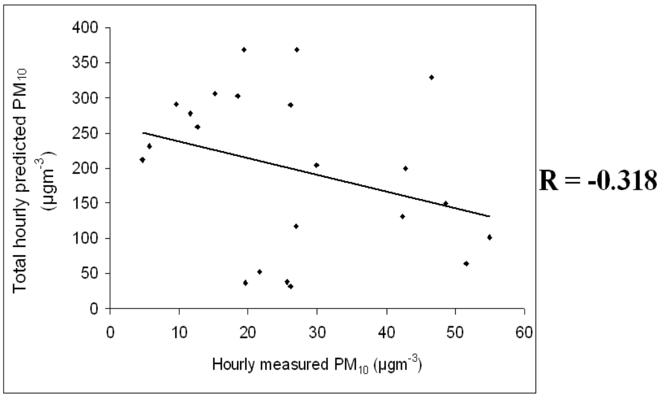


FIGURE 5.20: The comparison of hourly measured PM_{10} at Floreslaan air quality monitoring station and predicted PM_{10} at near by traffic stations on May 13

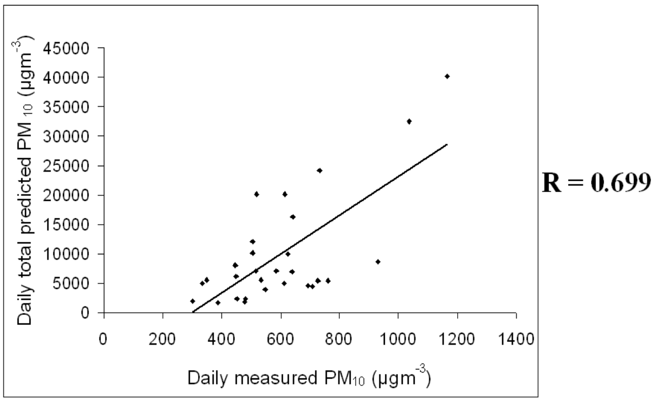


FIGURE 5.21: The comparison of daily total measured PM_{10} at Floreslaan air quality monitoring station and predicted PM_{10} at near by traffic stations on May

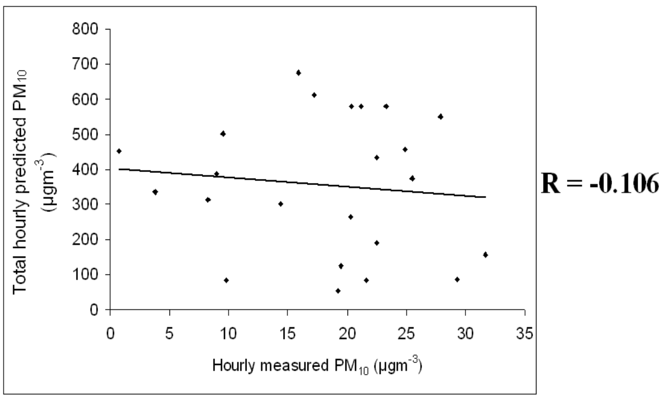


FIGURE 5.22: The comparison of hourly measured PM_{10} at Bentinckplein air quality monitoring station and predicted PM_{10} at near by traffic stations on May 13

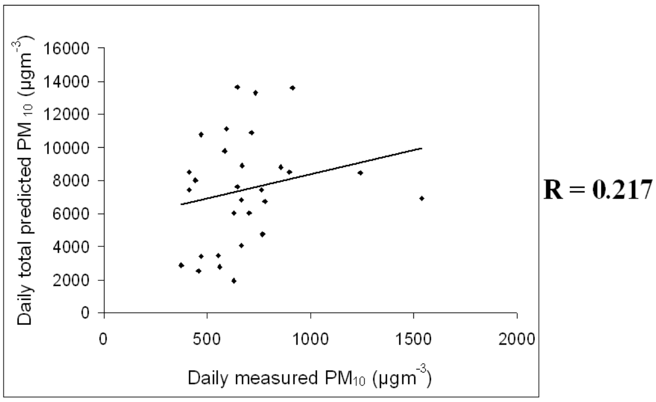


FIGURE 5.23: The comparison of daily measured PM_{10} at Bentinckplein air quality monitoring station and predicted PM_{10} at near by traffic stations on May

Figure 5.18 shows the predicted PM_{10} and measured PM_{10} are less correlated. This reads that there is a noise in the hourly relationship on May 13. Figure 5.19 demonstrates the same relation with daily basis. It can be seen that the estimated PM_{10} is more correlated with the measured PM_{10} for the daily relationship.

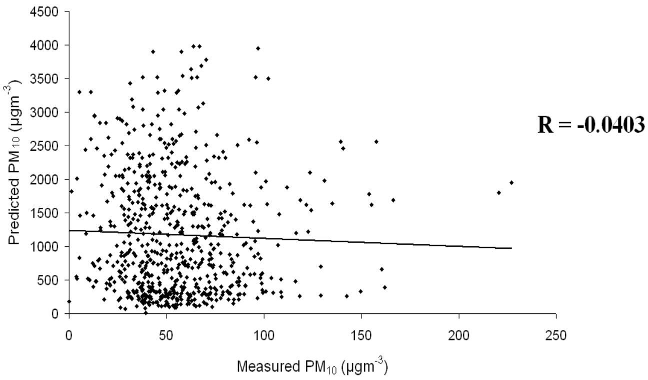


FIGURE 5.24: The comparison of total hourly predicted PM_{10} of the whole network and total hourly measured PM_{10} from the two air quality monitoring stations located in the vicinity of the highway network on May

Figure 5.24 depicts the relation made between total hourly concentration of PM_{10} from the whole network and total hourly measured PM_{10} from the two air quality monitoring stations shown on Figure 4.3. This relation resulted in a correlation of -0.0403.

5.5 Relationship between predicted PM_{10} and AOT

Following the comparison of measured PM_{10} with the predicted PM_{10}, a linkage is made between remotely sensed data (AOT) and predicted PM_{10}. This is performed by taking the sum of the predicted concentration of PM_{10} from the whole stations in the highway network at times when the remotely sensed data is available and taking the average AOT values of four pixels covering the highway network and its surrounding. Figure 5.25 and 5.26 show the result in hourly and daily basis respectively.

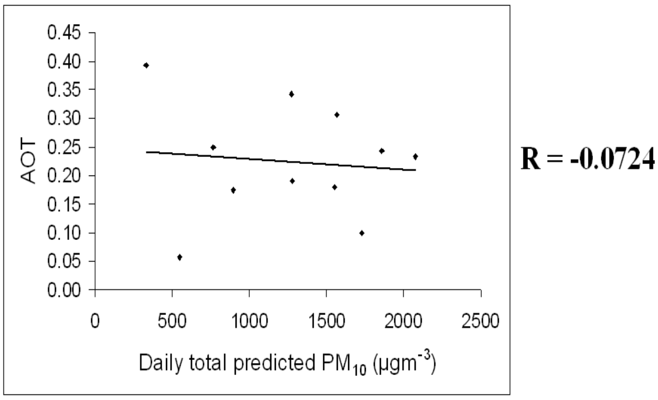


FIGURE 5.25: The comparison of hourly AOT values covering the whole network and predicted PM_{10} of the whole network on May 13, 2008

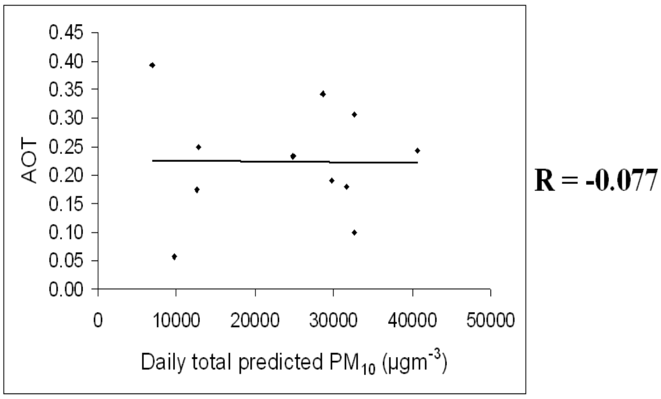


FIGURE 5.26: The comparison of daily AOT values covering the whole network and predicted PM_{10} of the whole network on May

On figures 5.25 and 5.26 it can be seen predicted PM_{10} and AOT has almost no relationship both in hourly and daily basis.

In this chapter, the results acquired by implementing the queueing model and the emission model were presented. In addition, the linkage made among the predicted concentration of PM_{10} obtained from the emission model, in-situ measured PM_{10} and AOT were investigated.

Chapter 6

Discussion

This chapter discusses the results achieved by implementing the queueing model and the integration of the queueing model with the emission model. It also discusses the results obtained from the investigation of the relation among different air pollution data.

The hourly expected number of vehicles were calculated from the queueing model and these were employed to find hourly average speed of vehicles using Greenshield's 1993 speed formula from traffic flow models. These results were applied to the revised emission model to produce the hourly concentration level of PM_{10} in all the intersection and link stations on Rotterdam highway network. These concentrations were then used to make a linkage with in-situ PM_{10} measured in the vicinity of the highway network and remotely sensed data. Section 6.1 discusses the results achieved form the queueing model, section 6.2 presents results obtained from the integration of the queueing model and emission model. The results of the statistical correlation made among the in-situ measured PM_{10}, predicted PM_{10} and aerosol optical thickness is discussed on sections 6.3, 6.4 and 6.5.

6.1 Queueing model result

The results in section 5.1 showed that the expected number of vehicles behaves more or less the same as the real traffic data. Both attain peak traffic in the same range of time and the lowest traffic was also observed at the same time. This tells us that the behaviour of the queueing model is according to the behaviour of real life traffic flow in road system. Subsequent to this validation, a comparison was made between the real traffic data counted in the vicinity of a station where expected number of vehicles is determined, and the expected number of vehicles to identify accuracy of the queueing model. The correlation between the hourly traffic count and expected number of vehicles at an intersection station is 0.76 and at a link station is 0.86. These results show that state dependent queueing model describes traffic flow in a reasonable way. The unexplained variability may be due to the queueing model did not take into account all the factors affecting traffic flow. For example, the model is developed by assuming there is no exit to another road in a specific link station connecting two intersection stations, but in reality there is some spacing where vehicles could turn to while driving from one intersection to another intersection. In addition, the good relationship tells us that the result can be used to estimate the average speed of vehicles in the highway as the speed flow relationship which is conveyed in Figure 5.6 shown a closer pattern to the Greenshield's 1993 speed-flow relationship.

The expected number of vehicles and the average speed of vehicles with time were plotted both to determine whether the queueing model are in accordance with general traffic models. The expected number of vehicles and average speed behave in a logical way, in a sense that when number of vehicles increase, average speed decreases. This tells us that the queueing model behaves in a way that vehicles and speed are related.

6.2 Integration of queueing model and emission model result

Integrating the queueing model with the revised emission model, the concentration of PM_{10} was estimated. In order to insure the revised emission model delivers the proper emission from vehicles in the highway, the relation between total emission and average speed was constructed for both intersection and link stations. These relation showed that emission decreases while speed increases. Afterwards, a comparison was performed between expected number of vehicles and total emission. As a result, a correlation of 0.856 and 0.954 were obtained for an intersection and a link station respectively.

From the result we can see that expected number of vehicles is significantly correlated with total emission at intersection and link stations. This tells that the prediction of the emission model align with the real behaviour of emission verses vehicles in a road system since when the number of vehicles increases, the emission increases.

To know the value added by the queueing model to the emission model for determining expected number of vehicles, a comparison was performed between daily total emission that used an input from queueing model and expected number of vehicles, and another comparison was made between daily total emission that does not use queueing model and observed number of vehicles. Both comparisons resulted in an excellent correlation of 0.994 and 0.958 respectively. These tell us the queueing model did not add many value in determining the total emission from the whole network.

6.3 Relationship between in-situ measured PM_{10} and AOT

The average of in-situ measured PM_{10} from two point air quality monitoring stations in the vicinity of the highway network was compared with the average of more than or equal to two pixel AOT values out of four pixels covering the highway network. The hourly and daily average relation resulted in a correlation of -0.0774 and -0.0724 respectively. The unexplained variability can be seen in different aspects. Firstly, AOT is a measure of the extent to which very small particles in the atmosphere hinder the passage of light through them whereas PM_{10} is also a tiny particle with 10 μm aerodynamic diameter suspended on the air. AOT incorporates all PM with different diameter and other particles that are not classified as PM as well. Secondly, the measurement of PM_{10} was conducted at two stations nearby a road system to find out the contribution of road traffic to the quality of the air in a limited area whereas the AOT value is acquired for all areas covering the highway network. Thus, the PM_{10} does not tell us about the concentrations on the whole highway network and the background concentrations which resulted from different sources of pollutants such as industries, ships and dusts from construction. In the other hand, AOT tells about all the tiny particles resulted from all sources of pollutants in the highway and its surroundings. Thirdly, the unavailability of AOT values for all days in May. Only one month time series data with 11 available data values were used to make the comparison which does not really represent the whole month. Above all, the weather condition and the case that Rotterdam is located around a sea have a role in determining their agreement as the extraction of AOT is very much affected by weather condition.

Different studies have been conducted to compare the temporal and spatial correlation of AOT and PM_{10}. Koelemeijer (2006) showed that the hourly correlations of AOT and PM_{10} across Europe at a rural background stations and traffic stations are 0.39 and 0.17 respectively. These were performed by using 2003 time series of AOT and PM_{10} with 3 and 11 stations for rural background and traffic stations respectively. The daily average relationship at 8 rural background stations 26 traffic stations for the same year resulted in a correlation of 0.35 and 0.15 respectively. In addition, he showed that the hourly and daily comparison at a background stations resulted in a correlation of 0.32 and 0.21 respectively. These were conducted using 10 stations for hourly and 54 stations for the daily comparison. These results show that the background stations have higher correlation than the traffic stations both in hourly and daily basis. Koelemeijer (2006) has also investigated the spatio-temporal correlation between yearly average PM_{10} and AOT. He found out that the correlation is 0.58. This was undertaken by considering 142 rural background stations across Europe. Wang and Christopher (2003) investigated the relation between AOT and hourly $PM_{2.5}$ measured in seven locations in Jeffersen country, Alabama and found out a good correlation of 0.7 expressing most aerosol were in the well-mixed lower boundary layer during the overpass times of MODIS satellite. He had also identified that the relation between monthly average $PM_{2.5}$ and AOT is excellent with a correlation coefficient of 0.9. comparing these results and our result, we can say that AOT is not strong enough to estimate PM_{10} acquired from road traffic. It rather helps in estimating the background concentration of PM_{10} as the background stations are more representative of 10×10 km^2 area observed by satellite (Koelemeijer, 2006). Moreover, it can be said that the data values used this study are not sufficient to perform a comparison.

6.4 Relationship between predicted PM_{10} and in-situ measured PM_{10}

The comparison carried out between the hourly predicted concentration of PM_{10} from the whole network and the average of hourly measured PM_{10} from the two air quality monitoring stations resulted in a correlation of -0.2062. And the daily average comparison resulted in a correlation of -0.55. Subsequently, measured PM_{10} at a specific stations was compared with the predicted PM_{10} from near by road traffic stations on May 13 in hourly and daily basis. These linkage came up with correlations of -0.318 and -0.10604 at stations Floreslaan and Bentickplein respectively. The daily average relationships have a correlation of 0.699 and 0.217 for the two stations respectively. Finally, a comparison was performed for the whole month hourly time series of the total measured PM_{10} from the two air quality monitoring stations and total predicted PM_{10} from the whole network. This relationship resulted in a correlation (-0.04034).

The relation conducted for the whole network has lack of correlation both in hourly and daily basis. The reasons may be due to the following. First of all, the predicted PM_{10} is the sum of all the stations in the network whereas the measured PM_{10} gives the concentrations in the vicinity of the two air quality monitoring stations which are in a distance of around 10 km. We thus note that these two air quality measurement stations do not give all the concentrations of PM_{10} emitted from the vehicles pass through the whole network. Second of all, the modified emission model does not constitute all the factors affecting vehicle emission. For example, it does not take into account the acceleration and deceleration of vehicles which has a role in determining the emission factor of vehicles (Teng et al., 2002). In addition, the model is developed with an assumption of vehicles drive with a homogeneous average speed per hour which limits speed variability in this time interval. Further drawback of the emission model is the proportions of vehicles using different fuel types and engine size were assumed while calculating the emission factor of a vehicle using speed dependent formula. These play a role in creating a noise.

From the comparison performed on the daily average measured PM_{10} and near by traffic stations, a correlation of 0.699 and 0.217 were obtained at stations Floreslaan and Bentickplein respectively. The result with a correlation of 0.699 tells us that there is a good relation between the daily average measured PM_{10} and predicted PM_{10}. This may be due to the right traffic stations that contribute to the surrounding where the air quality monitoring station were chosen. In contrary, the same relation for different station resulted in a lower correlation coefficient, 0.217. This difference may be due to the location of the monitoring station is located around the centre of Rotterdam city which is surrounded by long buildings. These buildings do not allow the air quality monitoring station to measure all the pollutants in the surrounding. Moreover, the dilution factor is calculated with the assumption that the prediction is conducted along the edge of the road. The reason is the dilution function can calculate a dilution factor in the vicinity of 5 m to 30 m from the road axis where the emission is expelled.

6.5 Relationship between predicted PM_{10} and AOT

The relation between hourly predicted PM_{10} from the whole network and AOT values resulted in a correlation of -0.0724 whereas the daily average predicted PM_{10} and AOT values also resulted in correlation of -0.0774. The unexplained variability's mentioned on sections 6.3 and 6.4 also applies to this relationship.

Chapter 7

Conclusion

Road traffic is one of the sources of air pollution in urban areas. Quantifying the concentrations level of air pollution assists in protecting human health and the environment as it provides information for checking the compliance of with the air quality standards. The goal of this thesis was to predict the concentration level of PM_{10} from a highway network and investigate the relationship with in-situ measured PM_{10} and remotely sensed data (AOT). In this chapter, the conclusion made from the whole results are presented.

Description of traffic flow using queueing model

From the results achieved by implementing the model on Rotterdam highway, it can be concluded that a queueing model with state dependent service rate and Poisson arrival processes can be employed to describe traffic flow as the relation made between the real traffic data and modelled data resulted in a good correlation. It also indicated that the result can be used to estimate the average speed of vehicles by associating the model with traffic flow models.

Integration of emission model with queueing model

Comparisons show that the emission model best fits with the queueing model as the correlation of the expected number of vehicles and the total emission from the whole network is reasonably good. The behaviour of the total emission with speed also leads to this conclusion. In addition, an investigation made to identify the values added by the queueing model in determining the expected number of vehicles that are applied on the emission model in order to estimate the concentration of PM_{10}. From this, it can be concluded that the queueing model did not add a significant values to the emission model since the total emission obtained by using observed data resulted in as good correlation as the total emission calculated using an output from the queueing model.

Relation between in-situ measured PM_{10} and AOT

The comparisons performed on in-situ measure PM_{10} and AOT on both the daily and hourly basis showed negative correlation. From these results and other findings by other researcher, we can conclude that AOT can not be used to estimate PM_{10} resulted from road traffic. It can be also be said that AOT can not be used to monitor PM_{10} in small spatial and temporal scale.

Relation between in-situ measured PM_{10} and predicted PM_{10}

This relation showed how predicted PM_{10} correlated with in-situ measured PM_{10}. There is a good correlation in the daily basis conducted at specific stations. The comparison made for the whole network resulted a negative correlation that tell us that the emission model well predicts PM_{10} in the vicinity of the road system.

Relation between predicted PM_{10} and AOT

The comparison of predicted PM_{10} and Aerosol Optical Thickness (AOT) both on hourly and daily basis showed anti-correlation. From these results, it can be concluded that AOT has insignificant contribution in determining the concentration of PM_{10} from road traffic in fine temporal and spatial resolution.

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Appendix A

Arrival rates

In this appendix, the arrival rate of each of the link and intersection stations in a highway network of Rotterdam is provided. The texts under each equations describe the arrival processes in a certain station.

$\lambda_1 = \lambda_4 P_{4,1} + \lambda_{33} P_{33,1}$
Arrival to station 1 is from station 4 and 33 with a certain routing probability.

$\lambda_2 = \lambda_0 P_{0,2} + \lambda_4 P_{4,2}$
Arrival to station 2 is from external station and station 4 with a certain routing probability.

$\lambda_3 = \lambda_0 P_{0,3} + \lambda_{33} P_{33,3}$
Arrival to station 3 is from external station and station 33 with a certain routing probability.

$\lambda_4 = \lambda_6$
Arrival to station 4 is only from station 6.

$\lambda_5 = \lambda_3$
Arrival to station 5 is only from station 3.

$\lambda_6 = \lambda_{26} P_{26,6} + \lambda_{10} P_{10,6} + \lambda_0 P_{06}$
Arrival to station 6 is from external station, stations 33 and 10 with a certain routing probability.

$\lambda_7 = \lambda_{10} P_{10,7} + \lambda_5 P_{5,7} + \lambda_{26} P_{26,7}$
Arrival to station 7 is from station 5, 10 and 26 with a certain routing probability.

$\lambda_8 = \lambda_0 P_{0,8} + \lambda_5 P_{5,8} + \lambda_1 0 P_{10,8}$
Arrival to station 8 is only from external station and station 5 with a certain routing probability.

$\lambda_9 = \lambda_5 P_{5,9} + \lambda_0 P_{0,9} + \lambda_{26} P_{26,9}$
Arrival to station 9 is from external station, stations 5 and 26 with a certain routing probability.

$\lambda_{10} = \lambda_{12}$
Arrival to station 10 is only from station 12.

$\lambda_{11} = \lambda_9$
Arrival to station 11 is only from station 9.

$\lambda_{12} = \lambda_{15} P_{15,12} + \lambda_0 P_{0,12}$
Arrival to station 12 is from external station and station 15 with a certain routing probability.

$\lambda_{13} = \lambda_{11} P_{11,13} + \lambda_{15} P_{15,13}$
Arrival to station 13 is only from stations 11 and 15 with a certain routing probability.

$\lambda_{14} = \lambda_{11} P_{11,14} + \lambda_0 P_{0,14}$
Arrival to station 14 is from external station and station 11 with a certain routing probability.

$\lambda_{15} = \lambda_{14}$
Arrival to station 15 is only from station 14.

$\lambda_{16} = \lambda_{17}$
Arrival to station 16 is only from station 17.

$\lambda_{17} = \lambda_0 P_{0,17} + \lambda_{20} P_{20,17}$
Arrival to station 17 is from external station and station 20 with a certain routing probability.

$\lambda_{18} = \lambda_{16} P_{16,18} + \lambda_{20} P_{20,8}$
Arrival to station 18 is from stations 16 and 20 with a certain routing probability.

$\lambda_{19} = \lambda_{16} P_{16,19} + \lambda_0 P_{0,9}$
Arrival to station 19 is from external station and station 16 with a ceratin routing probability.

$\lambda_{20} = \lambda_{22}$
Arrival to station 20 is only from station 22.

$\lambda_{21} = \lambda_{19}$
Arrival to station 21 is only from station 19.

$\lambda_{22} = \lambda_{27} P_{27,22} + \lambda_{28} P_{28,22} + \rho_0 P_{0,22}$
Arrival to station 22 is from stations 27, 28 and external station with a certain

routing probability.

$\lambda_{23} = \lambda_{27}P_{27,23} + \lambda_{28}P_{28,23} + \rho_{21}P_{21,23}$
Arrival to station 23 is from stations 21, 27 and 28 with a certain routing probability.

$\lambda_{24} = \lambda_{28}P_{28,24} + \lambda_{21}P_{21,24} + \lambda_{0}P_{0,24}$
Arrival to station 24 is from external station, stations 21 and 28 with a certain routing probability.

$\lambda_{25} = \lambda_{27}P_{27,25} + \lambda_{21}P_{21,25} + \lambda_{0}P_{0,25}$
Arrival to station 25 is from external station, stations 21 and 27 with a certain routing probability.

$\lambda_{26} = \lambda_{24}$
Arrival to station 26 is only from station 24.

$\lambda_{27} = \lambda_{24}$
Arrival to station 27 is only from station 24.

$\lambda_{28} = \lambda_{30}$
Arrival to station 28 is only from station 30.

$\lambda_{29} = \lambda_{25}$
Arrival to station 29 is only from station 25.

$\lambda_{30} = \lambda_{34}P_{34,30} + \lambda_{0}P_{0,30}$
Arrival to station 30 is from external station and station 34 with a certain routing probability.

$\lambda_{31} = \lambda_{29}P_{29,31} + \lambda_{34}P_{34,31}$
Arrival to station 31 is from stations 29 and 34 with a certain routing probability.

$\lambda_{32} = \lambda_{29}P_{29,32} + \lambda_{0}P_{0,32}$
Arrival to station 32 is from external station, and station 29 with a certain routing probability.

$\lambda_{33} = \lambda_{32}$
Arrival to station 33 is only from station 32.

$\lambda_{34} = \lambda_{2}$
Arrival to station 34 is only from station 2.

Appendix B

Routing probabilities

The following listed probability equations convey the routing probabilities that sum to one.

- $P_{4,1} + P_{4,2} = 1$
- $P_{0,2} + P_{0,3} = 1$
- $P_{26,6} + P_{26,7} + P_{26,9} = 1$
- $P_{10,6} + P_{10,7} + P_{10,8} = 1$
- $P_{0,6} + P_{0,8} + P_{0,9} = 1$
- $P_{5,7} + P_{5,8} + P_{5,9} = 1$
- $P_{15,12} + P_{15,13} = 1$
- $P_{11,13} + P_{11,14} = 1$
- $P_{0,12} + P_{0,14} = 1$
- $P_{20,17} + P_{20,0} = 1$
- $P_{0,17} + P_{0,19} = 1$
- $P_{16,18} + P_{16,19} = 1$
- $P_{27,22} + P_{27,23} + P_{27,5} = 1$
- $P_{28,22} + P_{28,23} + P_{28,24} = 1$
- $P_{21,23} + P_{21,25} + P_{21,26} = 1$
- $P_{0,24} + P_{0,22} + P_{0,25} = 1$
- $P_{0,30} + P_{0,32} = 1$
- $P_{34,30} + P_{34,34} = 1$
- $P_{29,31} + P_{29,32} = 1$

Appendix C

Vehicle emission factor formula

PM Emission Factor - Speed Coefficients

Based on review and assessment of new factors for Euro I and II vehicles given in TRL Database of Emission Factors, September 2001 (Barlow, Hickman and Boulter) and reconsideration of scaling factors for Euro III, IV vehicles by NETCEN

EF(g/km) = (a + b.v + c.v^2 + d.v^e + f.ln(v) + g.v^3 + h/v + i/v^2 + j/v^3).x **Emission Function**

v is speed in kph

			a	b	c	d	e	f	g	h	i	j	x
Petrol ca	Pre-Euro I	< 1.4 l	0.0324	-0.00040	0	0	0	0	2.21E-08	0.377	0	0	1
		1.4 - 2.0 l	0.0227	-0.00028	0	0	0	0	1.48E-08	0.427	0	0	1
		> 2.0 l	0.0232	-0.00058	4.3E-06	0	0	0	0	0.582	0	0	1
	Euro I	< 1.4 l	0.00244		-8.5E-07				8.72E-09	0.008			1
		1.4 - 2.0 l	0.00307						8.35E-09				1
		> 2.0 l	0.00672		-1.5E-06				1.52E-08				1
	Euro II	< 1.4 l	0.00356	-0.00013	1.4E-06								1
		1.4 - 2.0 l	0.0024	-4.6E-05					5.59E-09				1
		> 2.0 l	0.0024		-1.6E-06				1.73E-08				1
	Euro III	< 1.4 l	0.00356	-0.00013	1.4E-06								1
		1.4 - 2.0 l	0.0024	-4.6E-05					5.59E-09				1
		> 2.0 l	0.0024		-1.6E-06				1.73E-08				1
	Euro IV	< 1.4 l	0.00356	-0.00013	1.4E-06								1
		1.4 - 2.0 l	0.0024	-4.6E-05					5.59E-09				1
		> 2.0 l	0.0024		-1.6E-06				1.73E-08				1
Diesel ca	Pre-Euro I	< 2.0 l	0.131	0	-1.4E-05	0	0	0	1.54E-07	2.16	0	0	1
		> 2.0 l	0.282	-0.00399	2.6E-05	0	0	0	2.53E-08	1.32	0	0	1
	Euro I	< 2.0 l	0.189	-0.00176					8.93E-08	-3.84	60	###	1
		> 2.0 l	0.0857	-0.0009					7.56E-08	1.02		-5	1
	Euro II	< 2.0 l	0.0722		-1.8E-05				1.51E-07				1
		> 2.0 l	0.113		-2.2E-05				2E-07			30	1
	Euro III	< 2.0 l	0.0722		-1.8E-05				1.51E-07				0.7
		> 2.0 l	0.113		-2.2E-05				2E-07			30	0.7
	Euro III + tr	< 2.0 l	0.0024	-4.6E-05					5.59E-09				1
		> 2.0 l	0.0024		-1.6E-06				1.73E-08				1
	Euro IV	< 2.0 l	0.0722		-1.8E-05				1.51E-07				0.35
		> 2.0 l	0.113		-2.2E-05				2E-07			30	0.35

Petrol LG	Pre-Euro 1		0.03472		-1.5E-05				1.56E-07	0.393			1
	Euro I		0.00307	0	0	0	0	0	8.35E-09	0	0	0	1
	Euro II		0.0024	-4.6E-05	0	0	0	0	5.59E-09	0	0	0	1
	Euro III		0.0024	-4.6E-05	0	0	0	0	5.59E-09	0	0	0	1
	Euro IV		0.0024	-4.6E-05	0	0	0	0	5.59E-09	0	0	0	1
Diesel LG	Pre-Euro 1		0.553	-0.0066	0.00002				2.54E-07	-0.53	13		1
	Euro I		0.127		-3.8E-05				4.15E-07	0	0	0	1
	Euro II		0.127		-3.8E-05				4.15E-07	0	0	0	1
	Euro III		0.127		-3.8E-05				4.15E-07	0	0	0	0.8
	Euro IV		0.127		-3.8E-05				4.15E-07	0	0	0	0.49
HGVs	Pre-1988	rigids	0.174	0	0	0	0	0	1E-07	14.4	0	0	2.09
		artics	0.283	0	0	0	0	0	0	20.9	-13	0	1.14
	1988 - 19	rigids	0.174	0	0	0	0	0	1.00E-07	14.4	0	0	1
		artics	0.283	0	0	0	0	0	0	20.9	-13	0	1
	Euro I	rigids	0.0896	0	0				5.16E-08	7.43	0	0	1
		artics	0.236	0	0				1.36E-07	19.5	0	0	1
	Euro II	rigids	0.111	-0.0015	1.3E-05				0	4.05	-7	0	1
		artics	0.288	-0.0038	3.3E-05				0	10.6	-18	0	1
	Euro III	rigids	0.111	-0.0015	1.3E-05				0	4.05	-7	0	0.72
		artics	0.288	-0.0038	3.3E-05				0	10.6	-18	0	0.72
	Euro IV	rigids	0.111	-0.0015	1.3E-05				0	4.05	-7	0	0.15
		artics	0.288	-0.0038	3.3E-05				0	10.6	-18	0	0.15
	Euro IV+ (	rigids	0.111	-0.0015	1.3E-05				0	4.05	-7	0	0.15
		artics	0.288	-0.0038	3.3E-05				0	10.6	-18	0	0.15
Buses	Pre-1988 models		0.128	0	0	0	0	0	0	14.4	0	0	2.31
	1988 - 1993 models		0.128	0	0	0	0	0	0	14.4	0	0	1

	Euro I		0.0843	0	0				4.85E-08	6.98	0	0	1
	Euro II		0.104	-0.0014	1.2E-05				0	3.81	-6	0	1
	Euro III		0.104	-0.0014	1.2E-05				0	3.81	-6	0	0.72
	Euro IV		0.104	-0.0014	1.2E-05				0	3.81	-6	0	0.15
	Euro IV+ (2008)		0.104	-0.0014	1.2E-05				0	3.81	-6	0	0.15
Motorcyc	Pre-2000	moped (2-s	0.04	0	0	0	0	0	0	0	0	0	1
		<250cc 2-s	0.04	0	0	0	0	0	0	0	0	0	1
		<250cc 4-s	0.12	0	0	0	0	0	0	0	0	0	1
		250-750cc	0.12	0	0	0	0	0	0	0	0	0	1
		>750cc 4-s	0.12	0	0	0	0	0	0	0	0	0	1
	97/24/EC	moped (2-s	0.04	0	0	0	0	0	0	0	0	0	1
		<250cc 2-s	0.04	0	0	0	0	0	0	0	0	0	1
		<250cc 4-s	0.12	0	0	0	0	0	0	0	0	0	1
		250-750cc	0.12	0	0	0	0	0	0	0	0	0	1
		>750cc 4-s	0.12	0	0	0	0	0	0	0	0	0	1

Appendix D

Code

```
#include<iostream.h>
#include<fstream.h>
#include<string.h>
#include <math.h>
#include <iomanip.h>

using namespace std;
bool print_welcome_screen(ifstream& input, ofstream& output);
void compute (long double road_length,
                                int num_lanes, double distance,
                                long double arrival_rate,
                                long double frac_hd,
                                long double frac_ld,
                                long double frac_pc,
                                long double freeflow_speed,
                                double wind_speed, ofstream& output);

int main()
{

  int num_lanes;
  ifstream input;
  ofstream output;
  char ch, again, end;
  bool data_entry_method;

  double distance,wind_speed;
  long double freeflow_speed, arrival_rate,
                          frac_hd, frac_ld, frac_pc,
                          road_length, fraction_stagnat;

 do{
  data_entry_method=print_welcome_screen(input, output);
  if(data_entry_method){

         while(!input.eof()){
         input>>road_length>>ch>>num_lanes>>ch>>distance>>ch>>
                        arrival_rate>>ch>>frac_hd>>ch>>frac_ld>>ch>>
                        frac_pc>>ch>>freeflow_speed>>ch>>wind_speed;
                        compute (road_length, num_lanes, distance,
                                        arrival_rate, frac_hd, frac_ld,
                                        frac_pc, freeflow_speed,
                                        wind_speed, output);
                }

  }
  else{
          do{
                 cout<<"Enter the following variables-->"<<endl;
```

```
                    cout<<"Length of the road:";
                    cin>>road_length;
                    cout<<"Number of lanes:";
                    cin>>num_lanes;
                     cout<<"Enter distance from the road-->"<<endl;
                    cin>>distance;
                    cout<<"Arrival rate: "<<endl;
                    cin>>arrival_rate;
                cout<<"Fraction of heavy trucks:";
                    cin>>frac_hd;
                    cout<<"Fraction of light trucks:";
                    cin>>frac_ld;
                    cout<<"Fraction of personal cars:";
                    cin>>frac_pc;
                    cout<<"Free flow speed:";

                    cin>>freeflow_speed;

                    cout<<"Enter wind speed-->"<<endl;
                    cin>>wind_speed;

                   compute (road_length,  num_lanes, distance,
                                    arrival_rate, frac_hd, frac_ld,
                                    frac_pc, freeflow_speed, wind_speed, output);
                   cout<<"Do you want to do again with single input? (y or n)";
                   cin >> again;
                   }while(again=='Y' || again=='y');
  }

  input.close();
  output.close();
  cout<<"Do you want to do again with new data? (y or n)";
  cin>> end;
  }while(end=='y' || end=='Y');

  return 0;
}



//****************************************************************
bool print_welcome_screen(ifstream& input, ofstream& output){

cout<<"\t\t\t\t\tWELCOME\t\t\t\t\t"<<endl;
cout<<"Select data entry preference (1 or 2):"<<endl;
cout<<"\t\t1.File input/output"<<endl;
cout<<"\t\t2.Single data input/output"<<endl;

int preference;
char input_filename[50];
char output_filename[50];

cin>>preference;

switch(preference){
        case 1:
                cout<<"Enter input file name:";
                cin>> input_filename;
                input.open(input_filename);
                if(!input){
                        cerr<<"Input file: "<<input_filename
                                <<" can not be found!"<<endl;
                        break;
                }

                cout<<"Enter output file name:";
                cin>>output_filename;
                output.open(output_filename);

        break;
        case 2:
```

```
        break;

        default:
                cout<<"Wrong preference entry!"<<endl;
                //exit(1);
        break;
}

return preference==1;
}
//*************************************************************

void compute (long double road_length,
                                int num_lanes, double distance,
                                long double arrival_rate,
                                long double frac_hd,
                                long double frac_ld,
                                long double frac_pc,
                                long double freeflow_speed,
                                double wind_speed, ofstream& output){

 long double e;
 double dilution_factor, meteo_factor;
 long double y,z,c,x,w,t,a,p,q,s, f, ll, lp, aw,fr,gh,
                        l, third_moment, u,emission_factor,
                        capacity_per_lane, tt, cfd;
 int max_density, density;
 capacity_per_lane = 2300*(frac_ld+frac_hd);
 max_density = (4*capacity_per_lane/freeflow_speed)
                                *num_lanes*road_length;
 long double b, d;
  d=0;
  long double inf, old_t, old_a;
  inf=1.0/0.0;
  for(int i=1;i<max_density;i++)
  {
    a = pow(arrival_rate,i);
        if (a==inf)
        {
                a=old_a;
        }
        else
        {
                old_a=a;
        }
    t=1;
   for(int j=1; j<=i ;j++)
   {
         t = t*(freeflow_speed*j)*(1 - (j/max_density));
        if(t==inf)
        {
                t=old_t;
        }
        else
        {
                old_t=t;
        }
        d=d + (a/t);
   }
  b=1/d;

        l=0;u=0;e = 0;cfd=0;
        for(int k=1;k<max_density;k++)
  {
   a=pow(arrival_rate,k);
        //output<<"a="<<a<<endl;
        if (a==inf)
        {
                a=old_a;
        }
```

```
        else
        {
                old_a=a;
        }
    t=1;
   for(int m=1; m<=k ;m++)
   {
           t = t*(freeflow_speed*m)*(1 - (m/max_density));
           if (t==inf)
        {
                t=old_t;
        }
        else
        {
                old_t=t;
        }
   }
   p=b*(a/t);
   l=l+k*p;
   u=u+pow(k,2)*p;
   e=e+pow(k,3)*p;
  long double average_speed = freeflow_speed
                        *((max_density - l)/max_density);
   if(cfd > 1)
     break;
  }
        long double gf, hk, average_speed, total_emission;

        int g = ceil(l);
        long double yt, ut, tr,  second_moment, conc;
           average_speed = freeflow_speed*((max_density - l)/max_density);
    second_moment = pow(freeflow_speed,2)*
                                      (1 - 2*(u/pow(max_density,2)) +
                                      (e/pow(max_density,3)));

   third_moment = pow(freeflow_speed,3)*
                               (1 - 3*(l/max_density) +3*(u/pow(max_density,2))
                                - (e/pow(max_density,3)));

  dilution_factor = 0.725*pow(distance, -0.77*(distance + 2.7)
          /distance)*(-0.0011*distance + 1.2);

  meteo_factor = 5/wind_speed;

        emission_factor =
         frac_pc*(0.8*(0.00356  - 0.00013*average_speed +
         0.00000138*second_moment + 0.0024 - 0.000046*average_speed +
         5.59*pow(10,-9)*third_moment + 0.0024 - 0.00000164*second_moment +
         1.739*pow(10,-8)*third_moment    )+ 0.2*(0.35*(0.0722-0.000018*
        second_moment+ 0.000000151*third_moment) + 0.35*
        (0.113-0.0000224*second_moment+0.0000002*
         third_moment+30.4/third_moment)))+ frac_ld*(0.5*(0.0024-0.000046*
         average_speed +5.59*pow(10, -9)*third_moment) +
         0.5*0.49*(0.127 -0.000038*second_moment + 0.000000415*third_moment))+
         frac_hd*(0.5*0.15*(0.111-0.00145*average_speed +
         0.0000126*second_moment +4.05/average_speed - 6.7/second_moment)+
         0.5*0.15*(0.288-0.000379*average_speed +
         0.000033*second_moment +10.6/average_speed -17.5/second_moment));


    cout<<"The expected number of vehicles per hour is EL = "<<g<<endl<<endl;
         cout<<"The average speed of a vehicle is EV (km/hr)= "
         <<average_speed<<endl<<endl<<endl;
         cout<<"The third moment of speed of a vehicle is EV^3 ="<<third_moment<<endl;
         cout<<"Emission factor of a vehicle is (g/km)   "<<emission_factor<<endl<<endl;
         cout<<"The dilution factor is(s/m^2) =  "<<dilution_factor<<endl<<endl<<endl;
         total_emission = emission_factor*g*1000;
         cout<<"The total emission is (micro g/m/s)   "<<total_emission<<endl<<endl;
         conc = 0.62* total_emission*dilution_factor*meteo_factor;
         cout<<"Hourly total concentration is (micro gram /m^3)  "<<conc<<endl<<endl;
         output<<g<<'\t'<<average_speed<<'\t'<<third_moment<<'\t'<<emission_factor<<
```

```
        '\t'<<dilution_factor<<'\t'<<total_emission<<'\t'<<
        conc<<'\t'<<max_density<<'\t'<<arrival_rate<<endl;
}

//*******************************************
```

Listing D.1: The code used to implement the data of Rotterdam