Quantifying the Effects of Winter Weather and Road Maintenance on Emissions and Fuel Consumptions

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Winter road maintenance (WRM) has significant benefits including improving road safety and reducing traffic delay caused by adverse weather conditions. It has also been suggested that WRM is beneficial in terms of reducing vehicular air emissions and fuel consumption because snow and ice on the road surface often cause drivers to reduce their vehicle speeds or to switch to high gears, thus decreasing fuel combustion efficiency of engines. However, there has been very limited information about the underlying relationship, which requires to quantify this particular benefit through a winter road maintenance program. This research is focused on establishing a quantitative relationship between winter road maintenance and vehicular air emissions.

Most studies related RSC, fuel consumption and vehicular emission used either lab collected or real-world collected sample data at several specific sites and hours, which usually have small sample sizes. Speed distribution models were developed for the selected highways using data from 22 road sites across the province of Ontario, Canada.

Through an intermediate variable – vehicle speed, a quantitative relationship was established between winter road surface condition and vehicular emissions including GHG, harmful gases and PM, and energy consumption. Using multiply linear regression, a speed distribution model, including hourly average speed model and speed variation model, established as a function of various winter weather factors and a measure of road surface condition under the assumption of normal distribution. The vehicular air emissions under different road surface conditions were calculated by coupling the speed models with the engine emission models integrated in the emission estimation model - MOVES.

It is found that, on the average, 10% improvement in road surface condition could result in approximately 2% reduction in air emissions. Application of the proposed methodology is demonstrated through a case study to analyse the air emission and energy consumption effects under specific weather events. The results show that better road surface condition (RSC) can reduce both the vehicular air emissions and energy consumption, and the effects of an earlier WRM operation would last longer and affect more during a snow event.

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LIST OF ABBREVIATIONS

CO	Carbon Monoxide
CV	Coefficient of Variation
EC	Environment Canada
EPA	Environmental Protection Agency
FFS	Free Flow Speed
GHG	Greenhouse Gases
HC	Hydrocarbons
HCM	Highway Capacity Manual
IEA	International Energy Agency
LOS	Levels of Service
MOVES	Motor Vehicle Emission Simulator
MTO	Ministry of Transportation, Ontario
NO_2	Nitrogen dioxide
NOx	Nitrogen Oxides
OTAQ	Office of Transportation and Air Quality
PDCS	Permanent Count Stations
PM	Particulate Matter
RCWIS	Road Condition and Weather Information System
RSC	Road Surface Condition
RSI	Road surface index
RWIS	Road Weather Information System
SO_2	Sulphur Dioxide
VOCs	Volatile Organic Compounds
VSP	Vehicle Specific Power
WPI	Winter Performance Index
WRM	Winter Road Maintenance

CHAPTER 1
INTRODUCTION

1.1 Background

Canada is among countries with long winter seasons lasting for approximately seven months. Snow and ice on roads during snow storms result in poor road surface conditions (RSC) which lead to increase a risk of collisions and reduced mobility. Moreover, poor RSC also causes vehicular air emissions and fuel consumptions to increase because the drivers have to either reduce their vehicle speeds or switch to high gears, thus decreasing fuel combustion efficiency. Only favourable RSC can support smooth and efficient transportation, which is essential to both economy and safety as it ensures the timely displacement of passengers and freights, mitigation adverse environmental impacts and, adverse environmental impacts.

The negative impacts of snow storms are mitigated through different winter road maintenance (WRM) operations. WRM operations ensure the provision of essentially bare road surface conditions, thereby reducing the negative impacts associated with poor RSC. However, WRM operations are costly; Canada spend over $1 billion every year on WRM operations to keep roads, sidewalks, and parking lots clear of ice and snow. As a result, around five million tons of salt or sand are applied on Canadian roads and other ground surfaces (Transport Association of Canada, 2013).

Impacts of adverse storms (e.g. mobility, safety and environment) and their mitigation measures (WRM operations) are costly, therefore, there is a trade-off between WRM activities and the required level of service. In terms of quantification of the benefits of WRM activities, most of the current research is related to quantifying the safety and mobility benefits of WRM (Usman et al., 2012; Donaher, 2014) ignoring the environmental and health benefits associated with WRM operations.

Motor vehicles are a major source of air pollution in Canada. Traffic-related air pollution is the major cause of a number of health issues such as respiratory, cardiovascular and neuro-developmental effects. (HEI, 2010). Reduction in traffic related air emissions is beneficial to the environment and human health. Besides reduction in vehicular air emissions, other benefits such as reduction in fuel consumption can also be realized through effective WRM activities. Moreover, from a performance measurement perspective, inclusion of environmental and fuel consumption also benefits informed decision making.

1.2 Research Objectives

The main purpose of this research is to evaluate the impacts of WRM on vehicular air emissions and fuel consumption. To achieve this goal, the following tasks were carried out.

- To summarize the previous research on vehicular air emissions and WRM;
- To review existing speed based emission models;
- To estimate vehicular speed distribution under various road surface conditions by developing speed distribution models;
- To investigate the relationship between RSC and vehicular air emission and energy consumption; and
- To quantify the benefits of WRM in terms of emission and energy consumption, and give some recommendations.

1.3 Thesis Organization

This thesis consists of six chapters:

Chapter 1 introduces the research background, problem and objectives. Chapter 2 gives a state-of-the-art literature review for vehicular air emissions and road surface. It also reviews previous studies on existing models of fuel consumption and vehicular air emission related weather, road surface and traffic condition. Chapter 3 shows the data source, introduces the methodology of this thesis work. Chapter 4 presents exploratory analysis of different variables in the data set, calibration of the speed distribution models, and interpretation of the modelling results in terms of the impact of winter weather and RSC on the highway speed distribution; Chapter 5 shows two case studies to quantify the effects of RSC and WRM on vehicular emissions under typical scenarios. Chapter 6 contains the concluding remarks and directions for future work.

CHAPTER 2
LITERATURE REVIEW

Many previous studies have been carried out on the direct or indirect effects of WRM. This chapter contains a review of WRM benefits with a focus on environmental impacts. Additionally, existing models for both speed distribution, vehicular air emissions and fuel consumption are reviewed and summarized. Finally, the knowledge gap and problem definition are presented.

2.1 Winter Road Maintenance

WRM consists of different types of operations such as plowing, sanding, salting etc., conducted by governments, institutions and individuals to remove or control the amount of ice and snow brought by snow events on roadway surface. It aims to make travel easier and to reduce the risk of accidents. WRM activities keep our roadways in safe and reliable driving condition by minimizing weather-induced disruptions to our daily lives. It also ensures that emergency services are continually delivered where and when needed. Moreover, they enable sustained health of our modern society and productivity of our economy through continued mobility.

Effective WRM performance measures are important to both the government and maintenance contractors. On one hand, by measuring maintenance performance and benchmarking outcomes, the government is able to tell how well the job is done by the maintenance contractors. On the other hand, maintenance contractors can make more informed decisions, and conduct better planned maintenance operations toward specific objectives (Qiu, 2008).

2.1.1 Current WRM performance measurements

The CTC & Associates LLC of Wisconsin DOT Research & Library Unit conducted a survey in 2009, which showed that around 70% of transportation agencies use bare pavement regain time or similar measures as the main indicator of WRM performance. One major problem of bare pavement regain time is that it is usually reported by maintenance or quality assurance personnel based on periodic visual inspection during and after snow events. As such, it lacks of objectivity and repeatability (Feng et al., 2010).

Therefore, many transportation agencies around the world including US, Canada, Japan and Europe (especially Finland and Norway) started considering the friction level correlates to collision risk, traffic speed and volume as an indicator so that it can be used as an acceptable measure for snow and ice control operations. Some studies have been conducted regarding using friction level as WRM performance measurement. For example, Jensen et al. (2013) from Idaho DOT describes how two key performance measures for winter maintenance were developed and implemented, outlined some of the immediate and potential benefits of the performance measures and proposed Winter Performance Index (WPI).

2.1.2 Benefits of winter road maintenance

Several studies have been conducted to investigate benefits of winter maintenance in the past two decades.

Haber and Limaye (1990) used stochastic simulation to quantify the benefits of reducing the delay time. Using this method, if the mean and standard deviation of speed in two levels of service (LOS) is known (e.g., an old treatment LOS versus an upgraded LOS), random normal variables can be calculated to represent the two speeds. If the average trip length is also known the time saved or lost under a specific maintenance LOS could be calculated and converted to the corresponding value of the dollar.

Hayashiyama et al. (2000) used contingent value method to quantify indirect benefits of the winter maintenance. Contingent value method useed an interviewer who asked respondents how much they would pay to reach a certain improvement (WTP) or how much compensation they would need if conditions deteriorate to a specified point (willingness to accept). The researchers noted that the contingent value method is not suitable for the cost-benefit analysis, winter maintenance activities, because it does not include travel time and cost indicators. However, it does provide a method to estimate the value of winter maintenance operations for indirect benefits, despite the requirements of a large sample of respondents interviewed (100+ for each category).

Adams et al. (2006) used regression tree model to predict winter storms maintenance costs in Wisconsin, USA. To account for different variables of winter maintenance operations, such as service level, size, overtime costs, and so on, regression tree modeling method is chosen. While focused on assessing this application in maintenance resources required for each storm, the regression tree method may also provide an adaptable method to estimate the advantages of operating different level of maintenance and transportation of inputs. However, no such application has been developed to date, which would require more detailed investigation.

Ye et al. (2009) determined the cost benefits of weather information for WRM. A two-step methodology was used to estimate the benefit of weather information. Sensitivity analysis was used to explore the effects of input variables on maintenance costs. Then, neural networks were used to model winter maintenance costs and evaluate the impacts of weather information. To determine the benefits of weather information, the maintenance costs of a base case were compared with those of alternative scenarios in which different levels of weather information were used. The difference between the costs from each scenario and the base case was the benefit to winter maintenance. Although the approach appears at first glance to focus on cost information, it ultimately generates estimates of the value of winter maintenance benefits.

Fu et al. (2006) examined the effects of winter weather and maintenance treatments on safety. It was found that the anti-icing and pre-wetting improved safety (anti-ice use only one route), and sanding operations produce a positive impact on safety on the two routes. The researchers noted that plowing and salt operation cannot be confirmed significantly in the research, noting that there could be an interdependency between maintenance operations and snow conditions, with more maintenance operations dispatched during more severe weather conditions. Thus, one under the given weather conditions change in these operations may be small.

Usman et al. (2010) quantified the safety benefits of winter maintenance by investigating the relationship between accident frequency s and road surface conditions, visibility, and other influencing factors (controlling for traffic exposure) during snow event. The research did not consider specific maintenance operations directly in the models that were developed, because it was assumed that these operations were reflected in the measurements of road surface conditions. Exploratory analysis indicated that maintenance activities were correlated to RSI and were not statistically significant once road surface conditions were accounted for.

In 2012, Usman et al. (2012) presented a disaggregated modeling approach to investigate the relationship between winter road crashes, weather, RSI, traffic exposure, temporal trends, and site-specific effects at an operational level. RSI was found to have a great impact on the variation of collisions within and between individual storms and maintenance routes. Moreover, some influcing factors such as air temperature, visibility, precipitation intensity, wind speed, exposure, length of winter seasons, and storm hour have statistically significant effects on winter road safety.

2.1.3 Using traffic emission and energy consumption as WRM performance measures

Air pollution is a major risk to human health and the environment. Outdoor air pollution is estimated to cause 1.3 million annual deaths worldwide (WHO, 2011). Among different kinds of pollution sources, road transport often is considered as the single most important source of urban air pollution in source apportionment studies (Maykut et al., 2003; Querol et al., 2007). The International Energy Agency (IEA) estimated that the transportation sector accounted for approximately 19% of global energy consumption and 23% of energy-related emissions (IEA, 2012), and global transportation energy use and emissions will increase by approximately 50% by 2030 and by over 80% 2050 (IEA, 2009). Particular matters (PM) emissions from road vehicles, include emissions from the tailpipe (exhaust emissions) and those due to wear and tear of vehicle parts such as brake, tyre and clutch and re-suspension of dust; exposure to PM from vehicular emissions has been demonstrated to have detrimental impacts on human health (Mauderly,1994; Buckeridge et al., 2002; Fan et al., 2006; HEI, 2010; Masiol et al., 2012; Rissler et al., 2012). For this reason, major efforts are being made to reduce air polluting emissions from road transport. Moreover, it has been suggested that WRM is beneficial in terms of reducing vehicular air emissions and fuel consumptions because snow and ice on road surface often cause the drivers to reduce their vehicle speeds or to switch to high gears, thus decreasing fuel combustion efficiency.

2.2. Vehicular Air Emissions

Road transportation is one of the major contributors to energy consumption, air pollution, and emission of greenhouse gases (WBCSD, 2001). This section reviews the principal air pollutants and the major influencing factors of vehicular air emissions.

2.2.1 Principal vehicular emissions

A variety of atmospheric pollutants are emitted from road vehicles as results of combustion and other process. The main sources of emissions, and the pollutants concerned are summarised in Table 1, including exhaust emissions of carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide(SO_2), volatile organic compounds(VOCs), particulate matter (PM) the greenhouse gases.

Table 1 Vehicular air emission sources and pollutants

Source/Process	Pollutant(s) emitted
Hot and cold start exhaust emissions	CO
	VOCs
	NO_x
	SO_2
	Exhaust PM 2.5/10
Evaporative emissions	VOCs
Tyre and break wear	Non-exhaust PM 2.5/10
Road surface wear	
Resuspension	

The transportation sector in Canada is a significant emitter of GHGs. According to Environment Canada, in 2013 transportation was responsible for 27% (200,000 kt of CO_2 eq) of the total GHG emissions (747,000 kt of CO_2 eq). Road transportation accounted for 69% (137,000 kt of CO_2 eq) of the GHG emissions within the sector. Greenhouse gas emissions from transportation primarily come from burning fossil fuel for our cars, trucks, ships, trains, and planes. Over 90% of the fuel used for transportation is petroleum based, which includes gasoline and diesel

Carbon monoxide is a byproduct of incomplete combustion. CO is colorless, odorless, but poisonous. High concentrations of CO can increase the risk of cardiovascular problems and impede the psychomotor functions. Infants, the elderly, and people with cardiovascular diseases and respiratory problems are more at risk. Also, CO indirectly contributes to the buildup of ground-level ozone and methane. 51% of CO emissions in the US come from on-road mobile sources, and in cities the proportion can be much higher (EPA, 2001c)

Nitrogen oxides is the generic term for a group of highly reactive gases. They form when fuel is burned at high pressure and temperature conditions, which induce the dissociation and subsequent recombination of atmospheric N_2 and O_2 that generate NO_x. Many of the nitrogen oxides are colorless and odorless. However, nitrogen dioxide (NO_2) can be seen in the air as a reddish-brown layer over many urban areas. When the fuel consumption rate is low, very little NOx is emitted. It reacts with ammonia, moisture, and other compounds to form nitric acid that may cause serious respiratory problems. It also contributes with SO2 to the formation of acid rain and of particulate matter. The EPA estimates that on-road mobile sources contribute 34% of the total NOx emitted in the US. 42% of this is produced by diesel vehicles (EPA, 2001c).

Sulphur dioxide is generated when sulphur-containing fossil fuels or ores are burned. Much of this eventually turns into sulphate in the atmosphere as a secondary pollutant. Industry accounts for over 80% of all SO_2 produced in Ontario (Clean Air Hamilton). Ontario Hydro and ore smelting processes alone produce over half of the total SO_2. Non-industrial, area sources of SO_2 emissions include transportation and residential heating.

Volatile organic compounds are produced by vehicle emissions, chemical manufacturing, the evaporation of automotive fuels and other petroleum-based products, and chemical solvents. VOCs form particulate matter and react with nitrogen oxides to form ground-level ozone that forms smog.

According to Environment Canada, the sources and percentage amounts of man-made volatile organic compounds generated in 2013were as follows: (1) Transportation - 45.0%;(2) Petroleum and petrochemical industry - 26.0%;(3) Solvents, coatings and miscellaneous sources - 19.0%;(4) Fuel marketing (gasoline transfers from refinery to bulk stations, bulk stations to gas stations, gas stations to vehicles) - 6.0%;(5) Electrical power generation - 0.3%;(6) All other - 3.7%. This accounted for 229.2 kilotons of volatile organic compounds. Volatile organic compound emissions from natural sources (mainly trees) were estimated to be 890 kilotons.

Motor vehicles are a major emission source of particles, especially in urban areas. Mobile sources such as cars, trucks, trains, ships, and airplanes contribute to PM2.5 pollution by direct emissions (primary PM2.5) as well as emissions of precursor pollutants like sulfur dioxide, nitrogen oxides, and hydrocarbons, which undergo chemical transformations to form secondary PM2.5.In the US, approximately 30% of primary PM2.5 emissions and 60% of NOx emissions can be attributed to mobile sources (US EPA, 1999c).

Traffic related particles can be distinguished into: exhaust traffic related particles, which are emitted as a result of incomplete fuel combustion and lubricant volatilization during the combustion procedure, and non-exhaust traffic related particles, which are either generated brake, tyre, clutch and road surface wear or already exist in the environment as deposited material and become suspended due to traffic induced turbulence. It is estimated that exhaust and non-exhaust sources contribute almost equally to total traffic-related PM10 emissions

2.2.2 Effects of vehicle operation on vehicular emissions

Operation of vehicle is one of the main factors of traffic emission and energy use, and thus vehicle speed profile, which can reflect road surface and driving conditions. It is an important indicator of vehicular air emissions. Much work has been done on the modelling of vehicular air emission. This section will review previous efforts on exploring the relationship between vehicular speed and environmental impacts (vehicular air emissions and fuel consumption) and some existing emission models based on speed.

2.2.2.1. Effects of speed distribution on vehicular emissions

Vehicle speed distribution, including average speed and speed variation, is closely linked to fuel consumption and air emission rates, and speed profile is an important indicator to capture vehicular emissions and fuel consumption.

Mainly, there are three types of speed-based models: instantaneous models, average speed based models, and power demand based models.

- Instantaneous Models

Microscopic models are mainly applied to estimate small-scale traffic emissions due to substantial amount of input data. They use vehicle activity (second-by-second speed trace) and fleet composition of traffic being modeled as inputs, estimate second-by-second tailpipe emissions and fuel consumption. This type of modes decomposed the physical emission generation process into modular components corresponding to physical phenomena: engine power, engine speed, air-to-fuel rate, fuel use, engine-out emission, and catalyst pass fraction. They calculated emission levels under stoichiometric, cold-start, enrichment, and enplanement conditions. (e.g. CMEM (2000), EMIT(2002),VT-Micro(2004))

- Average Speed Based Models

Under the assumption that average emission factors for a given pollutant and vehicle type vary according to the average speed during the trip, they were widely applied to regional and national emissions inventories in the world. Many commonly used emission models are based on average speed:

a. MOBILE (U.S. EPA, 2003): Vehicle emission estimates produced by MOBILE use average link speeds as a key input to determine the emission factors. The output from the model is in the form of emission factors (in grams per mile), which are then multiplied by vehicle miles traveled (VMT) to estimate total emissions.
b. COPERT (Gkatzoflias et al., 2007) is based on the driving cycle named NEDC (New European Driving Cycle) and the calculation of emission factors depends on the application of formula, which is similar to MOBILE to some extent.
c. Other models: EMFAC(2002)

- Power Demand Based Models

They apply the relationship between vehicle specific power (VSP) and air emissions, and then establish the emission rates database based on VSP and use the distribution of VSP to describe vehicle operating modes . It is more flexible than those models based on fixed driving cycles. (e.g. MOVES (U.S. EPA, 2010), IVE (International Sustainable Systems Research Center, accessed July 8, 2013))

Motor Vehicle Emission Simulator (MOVES) is the official highway vehicle emission model developed by the U.S. Environmental Protection Agency (EPA) and can calculate vehicle fuel consumption and pollutant emissions (including GHGs) based on emission factors and traffic fleet composition. MOVES uses VSP as an indicator of the engine running status. VSP is the engine power per unit vehicle mass and it represents the power demand placed on a vehicle when the vehicle operates at various conditions and at various speeds. It is calculated based on the vehicle’s instantaneous speed and the forces that an engine needs to overcome during normal running, including aerodynamic drag rolling resistance, engine inertial drag, and gradient force. Thus VSP can incorporate the effect from rolling resistance on fuel consumption and air emissions. In each model running instance, MOVES calculates the second-by-second VSP of a vehicle to derive the emission factors. MOVES’s estimation of VSP includes typical speed fluctuations in congested traffic based on measured driving behavior under specific conditions.

Vehicle speed distribution on highways can be influenced by many factors, such as time of the day, driving habits, the vehicle model, traffic volume, highway class and design. During winter seasons, both weather and road surface condition play important roles in traffic speed change on highways.

Winter weather events could slow down traffic, causing delay in traffic. The magnitude of the effect is expected to depend on many factors such as precipitation, visibility, road surface conditions, and road characteristics. Much research work has been carried out to address the impact of adverse weather on traffic speed. HCM (2010) provides information about the impact of weather condition on traffic speed on freeways. Two precipitation categories are considered: light and heavy snow. Accordingly, there is a drop of 8-10 percent in free flow speed (FFS) due to light snow while heavy snow can reduce the FFS between 30–40 percent compared with normal conditions.

Agarwal et al. (2005) investigated the impact of weather type and intensity on urban freeway traffic flow characteristics using traffic and weather data collected in the Twin Cities, Minnesota, USA. Rain, snow, temperature, wind speed and visibility were considered, and each of these variables was categorized into 3 to 5 categories by intensity ranges. Average traffic speeds were calculated for different weather types and weather intensities. The research finally suggests that light and moderate snow show similar speed reductions with the HCM 2000 while heavy snow has significantly lower impact on speed reduction than those recommended by the manual. In addition, it was found that lower visibility caused 6% to 12% reductions in speed while temperature and wind speed had almost no significant impact on the average traffic speed. Table 2 shows the comparison between the model results and those values suggested on HCM 2000.

Table 2 comparison between the model results

Source: Agarwal et al. (2005)

Variable	Range	Assumed corresponding categories from the Highway Capacity Manual (2000)	Capacities (percentage reductions)		Average Operating Speeds (percentage reduction)	
			Highway Capacity Manual (2000)	Agarwal’s study	HCM	Agarwal’s study
Rain	0-0.01 inch/hour	Light	0	1-3	2-14	1-2.5
	0.01-0.25 inch/hour	Light	0	5-10	2-14	2-5
	>0.25 inch/hour	Heavy	14-15	10-17	5-17	4-7
Snow	<= 0.5 inch/hour	Light	5-10	3-5	8-10	3-5
	0.06-0.1 inch/hour	Light	5-10	5-12	8-10	7-9
	0.11-0.5 inch/hour	Light	5-10	7-13	8-10	8-10
	>0.5 inch/hour	Heavy	25-30	19-28	30-40	11-15
Temperature	10-1 ℃	-	N/A	1	N/A	1-1.5
	0-(-20) ℃	-	N/A	1.5	N/A	1-2
	<-20℃	-	N/A	6-10	N/A	0-3.6
Wind Speed	16-32 km/hr	-	N/A	1-1.5	N/A	1
	>32 km/hr	-	N/A	1-2	N/A	1-1.5
visibility	1-0.51 mile	-	N/A	9	N/A	6
	0.5-0.25 mile	-	N/A	11	N/A	7
	<0.25 mile	-	N/A	10.5	N/A	11

Zhao et al. (2011) proposed a new weather indexing framework for weather factors. Instead of using sensor data directly, the framework transformed the data into weather indices. These indices are Visibility, Weather Type, Temperature, Wind Speed and Precipitation. The average speed is then determined using model is shown in the following equation:

$$Avg\ Speed = 7.23 + 0.770 * Visibility + 0.358 * WeatherType + 0.132 * Temperature - 0.0469 * WindSpeed - 1.92 * CumuPrecip\ (Update12am) + 0.853 * Norm\_Hr\_Speed - 0.935 * Day\_Index \quad (1)$$

The calibrated regression model suggests that an increase in the visibility index (better visibility) leads to higher speeds, with the speed increasing by about 2 km/h for each 1 km increase in visibility. The coefficient of Weather Type indicates that the more severe the weather type, the slower the traffic speed. Moreover, a temperature above the freezing point results in a 1.58 km/h higher travelling speed compared to a temperature below freezing. High wind speed has a negative impact on traffic speed, with the speed decreasing by about 1.3 km/h for each 10 km/h increase in wind speed. The report mentioned that to ensure a proper match between weather (hourly data) and traffic data (10-minute interval data), traffic data observed during the last 10 minute interval of every hour was used to match the weather data (e.g. 0:50 – 1:00am, 1:50-2:00pm). This indicates that the traffic data (average traffic speed, volume) may not be representative of that hour. Moreover, RSC was not used in the weather indexing framework so that the relationship between traffic speed and RSC cannot be revealed by the model.

A research project conducted by FHWA (1977) showed that the freeway speed reduction caused by adverse road conditions was 13% for wet and snowing, 22% for wet and slushy, 30% for slushy in wheel paths, 35% for snowy and sticking and 42% for snowing and packed.

An empirical study has shown that the underlying relationship can be captured by Equation 6 (Fu et al., 2012).

$$S = 69.082 + 0.089 * T - 0.078 * W + 0.310 * V - 1.258 * \mathrm{H}P + 16.974 * RSI - 4.325 * x + PSL + \Phi \tag{2}$$

where,

S = Average speed over the duration of the event (km/hr)

T = Average temperature during the event (C)

W = Average wind speed during the event (km/hr)

V = Average visibility during the event (km)

HP = Average precipitation intensity (cm/hr)

RSI = Road surface index

x = Volume to capacity ratio

PSL = Posted speed limit (0 if PSL 80 km/hr; 1.95 if 90 km/hr and 12.62 if 100 km/hr)

Φ = Indicator for site

RSI has a positive correlation with traffic speed and Road Class 1 is expected to have higher RSI value than in Class 2. This results in comparatively higher travel speed in Class1 highways. The speed in this model is average speed, which means more information is needed to generate speed distribution during the event.

Kwon et al. (2013) examined the relationship between freeway traffic capacity, FFS and various weather and RSC factors. Traffic, weather and RSC data were used to calibrate multiple linear regression models for estimating capacity and FFS as a function of several weather-related variables, such as snow intensity, visibility, air temperature, road surface index (RSI) and wind speed. As shown in Table 3, it was found that snow intensity is highly correlated with visibility while both can statistically significant affect FFS. Hourly snow intensity rates of 2.0 mm/h and 15.0 mm/h would cause p reductions of 1.8% and 13.5% in FFS, respectively. As visibility increases, FFS also increases. Visibility greater than 1.0 km had less than 5% reductions in FFS. Increased RSI (i.e., better road conditions) are correlated with increased FFS. For example, under the given snow intensity of 5 mm/h, at RSI = 0.2 (snow covered), FFS is reduced by 17.01%, whereas at RSI = 0.8 (bare wet), FFS is reduced about 11.01%.

Table 3 Capacity Models

Source: Kwon et al. (2013)

Predictor	Coefficient	SE	t	Sig.	95% confidence Interval	
					Lower bound	Upper Bound
1st Capacity Model: Calibrated Using All Variables (R^2=91%)						
(Constant)	814.27	62.25	13.08	7.46 E-12	685.17	943.36
RSI	463.41	71.71	6.46	1.68 E-06	314.69	612.14
ln(visibility)	226.51	24.69	9.17	5.67 E-09	175.3	277.72
2nd Capacity Model: Calibrated Using All Variables Except ln (visibility (R^2=76%)						
(Constant)	1222.89	103.71	11.79	5.57 E-11	1007.8	1437.98
Snow(mm/h)	-31.97	7.37	-4.34	2.66 E-04	-47.26	-16.68
RSI	619.06	108.52	5.7	9.75 E-06	394	844.12
1st FFS Model: Calibrated Using All Variables (R^2=84%)						
(Constant)	75.33	1.77	42.6	7.10 E-22	71.65	79
RSI	5.15	2.09	2.47	2.23 E-02	0.81	9.49
ln(visibility)	5.84	0.73	8.02	7.86 E-08	4.32	7.35
2nd Capacity Model: Calibrated Using All Variables Except ln (visibility (R^2=69%)						
(Constant)	85.81	2.57	33.4	1.09 E-19	80.47	91.15
Snow(mm/h)	-0.86	0.18	-4.7	1.21 E-04	-1.24	-0.48
RSI	9.54	2.7	3.53	1.98 E-03	3.92	15.16

Danaher (2012) investigated six years' data collected from 21 sites in Ontario, Canada. The author developed two types of regression models, namely, hourly based and event based. For hourly based models, to isolate the effect of volumes approaching capacity on speed on non-rural freeways, the traffic data was divided into "rural" and "urban" highways. Each event hour was paired with typical median speed established based on non-event data. The difference between the observed median speed and the typical median speed was used as the dependent variable for regression modelling. Weather factors and RSI were used as independent variables. For event based models, each storm event was summarized in terms of weather and RSC factors over the duration of the event. Each event is also compared with average conditions of a clear weather period in the week before or after of the same duration. A sample of the event model is shown in Table 4:

Table 4 Speed modelling results

Source: Danaher (2012)

Variable	Coef.	Sig	Std. Err	z	Elasticity
Constant	69.082	0.000	0.787	87.79	-
Temperature	0.089	0.000	0.022	3.98	-0.004
Wind Speed	-0.078	0.000	0.013	-6.06	-0.01
Visibility	0.31	0.000	0.019	16.38	0.034
Hourly Precipitation	-1.258	0.000	0.14	-8.96	-0.007
RSI	16.974	0.000	0.708	23.97	0.133
Volume to Capacity Ratio (V/C)	-4.325	0.004	2.966	-2.92	-0…4
Posted Speed Limit (80km/h)	-	0.007	0.718		
Posted Speed Limit (90km/h)	1.951	0.000	0.818	2.72	0.02
Posted Speed Limit (100km/h)	12.621	0.000		15.43	0.13
Site 1	-	-	-	-	
Site 2	-4.521	0.000	0.807	-5.6	-0.047
Site 3	7.644	0.000	0.664	11.53	0.079
Site4	12.023	0.000	0.704	17.08	0.124
Site5	12.459	0.000	0.658	18.92	0.129
Site6	12.812	0.000	0.718	17.85	0.132
Site7	7.825	0.000	0.857	9.13	0.081
Site8	10.295	0.000	0.791	13.01	0.106
Site9	17.189	0.000	0.716	24.01	0.178
Site10	11.38	0.000	0.69	16.5	0.118
Site11	10.031	0.000	0.672	14.93	0.104
Site12	7.244	0.000	0.662	10.95	0.075
Site13	-	0.000	-	-	-
Site14	8.408	0.000	0.6	14.01	0.087
Site15	9.897	0.000	0.807	12.27	0.102
Site16	8.411	0.000	0.817	10.3	0.087
Site17	15.273	0.000	0.926	16.4	0.158
Site18	0.74	0.276	0.679	1.09	0.008
Site19	13.331	0.000	0.676	19.72	0.138
Site20	8.23	0.000	0.72	11.43	0.085
Site 21	-	-	-	-	-
Observations	4822				
R^2	0.5879				
Adj R^2	0.5857				

The hourly model for rural sites is:

$$\Delta V = -15.287 - 0.033 * WindSpeed + 0.246 * Visibility - 0.472 * Precipitation + 10.887 * RSI + 4.378 * V/C + 2.903 * Daylight \tag{3}$$

The hourly model for urban sites is:

$$\Delta V = -22.192 + 0.420 * Temperature - 0.048 * WindSpeed + 0.527 * Visibility - 0.938 * Precipitation + 17.143 * RSI - 4.472 * V/C + 2.364 * Daylight \tag{4}$$

While differing in research objectives, circumstances and data used, previous studies have all confirmed that adverse winter weather has a negative effect on vehicle speed.

2.2.3 The effects of acceleration and starts on air emissions

Joumard et al (1994) made a conclusion that for a given engine input, a slow moving vehicle will accelerate at a considerably higher rate than a fast moving vehicle. Thus, a better indication of the demand on the engine, which ultimately determines the rate of emission, is given by the product of the vehicle speed and acceleration. The emission data were therefore analysed with respect to the vehicle speed and the product of speed and acceleration, as instantaneous parameters. Therefore, the starts and acceleration profile also has significant impact on vehicular emission, the operation of a vehicle's engine that is necessary to achieve a certain rate of acceleration depends also on the vehicle's speed.

For start emission, cars with catalysts show a significant increase in exhaust emissions at engine start. These extra emissions are expressed as the difference, over a particular driving cycle, between emissions generated when the vehicle is started and when the engine or the catalyst are stably warm (Favez et al. 2008).

2.3 Effects of Weather Condition on Vehicular Emissions

Weather condition such as temperature and wind resistance would have impact on engine load directly and affect vehicle operation.

Ostrouchov (1978) conducted a lab test on the effect of cold weather on emissions and energy consumption and found that regulated emissions including hydrocarbons (HC), CO, and NO_x were 250%-820%, 140%-540%, 10-40% higher at -30°C than at 20°C, respectively. Fuel consumption was found to be 20%-80% higher.

2. 4 Effects of Road Condition on Vehicular Emissions

Road surface friction, vehicle acceleration, roadway grade and engine friction would affect engine load directly. These sources of engine load are in turn determined by a combination of vehicle attributes and vehicle operating conditions.

Hu et al. (2012) conducted a real-world vehicle emission measurement in 6 urban zones with different road pavement types in Macao. They identified a similar pattern for fuel consumption and three gaseous pollutants (HC, CO and NO_x) emissions and showed that air emissions would be lower when the vehicles were driving on the higher level roads with good pavement surface and less congested congestion.

Wang et al. (2012) conducted four case studies on four rural highway segments in California, USA to evaluate the effect of rolling resistance on the life cycle performance of pavements. Results from these studies show that when a life cycle scope is considered, rehabilitating a rough pavement segment with high traffic volume has a great potential to reduce fuel consumption and greenhouse gas (GHG) emissions. This research considered the air emission variation in relation to pavement structural conditions under normal weather conditions only and the results can’t be applied to road surface conditions affected by snow and ice formation in winter seasons.

2. 5 Summary

In summary, although the evaluation of WRM performance has gradually gained attention, most of the previous research is focused on evaluating the impacts of pavement structural conditions or cold weather on vehicular air emissions and fuel consumption. Little to no research is available on the relationship between winter road surface conditions, WRM activities, vehicular air emissions and fuel consumption. Since air pollution is highly related to human health and living environment and it has been demonstrated that traffic emission and energy use would be affected by road condition, traffic emission and energy consumption can be considered as a potential alternative WRM performance indicator. To improve the emission control technologies of individual vehicles, current efforts should be directed toward strengthening road condition management to reduce vehicular emissions and fuel consumption. . Many studies have been done to model the road mobility by weather and RSC, and the significant impact of traffic mobility characteristics on emission is also be identified. Therefore, estimating the effect of WRM on traffic emission is feasible by linking the weather impacted model and emission models.

CHAPTER 3
METHODOLOGY

3.1 Overall Approach

Poor RSC in winter weather not only increase fuel consumption of vehicles but also increase vehicular air emission increase because the drivers have to either reduce their vehicle speeds or switch to high gears, thus decreasing fuel combustion efficiency. In order to investigate the relationship between vehicular air emission and fuel consumption and RSC in winter, data is needed for different variables related to weather condition, road surface and traffic conditions in winter. A statistical modelling approach is developed here for the relationship between vehicular speed distribution and weather and road surface conditions. The proposed modelling approach consists of the following steps:

- Site selection: 22 highway sites throughout Ontario
- Data collection, integration and processing
- Extraction of hourly snow storm events
- Exploratory data analysis: including correlation analysis and single variable analysis
- Model development: Both average speed and model speed variation model were developed using multiple linear regression. The model for multiple linear regression, given n observations, is:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots \beta_p x_{ip} + \varepsilon_i \qquad \text{(for i = 1,2, ... n.)} \qquad (5)$$

- Application of the developed models to MOVES: Total emissions and energy consumption were estimated under different RSC in first application; vehicular air emission and energy consumption with different WRM timing were compared with each other in the second application.

In order to model the effect of winter weather and RSC on vehicular emission and fuel consumption on a highway, an intermediate variable - vehicle speed is introduced as a bridge between the two. It is assumed that adverse weather conditions would induce variation in vehicle speeds, including reduced average speed and increased speed variability, which in turn would lead to increased emission and fuel consumption. As a result, the overall approach contains two main components, as shown in Figure 1. The first component attempts to quantify the effect of adverse weather and RSC on the distribution of traffic speeds on a highway (including mean and standard deviation) while the second component focuses on modeling the emissions and fuel consumption based on changes in traffic speed distribution. For the second component, using speed distribution along with other required inputs, the well-known emission estimation model MOVES developed by US EPA was used to estimate the vehicular air emission and energy consumption. As shown in Figure 1, the data in shade are obtained from other sources.

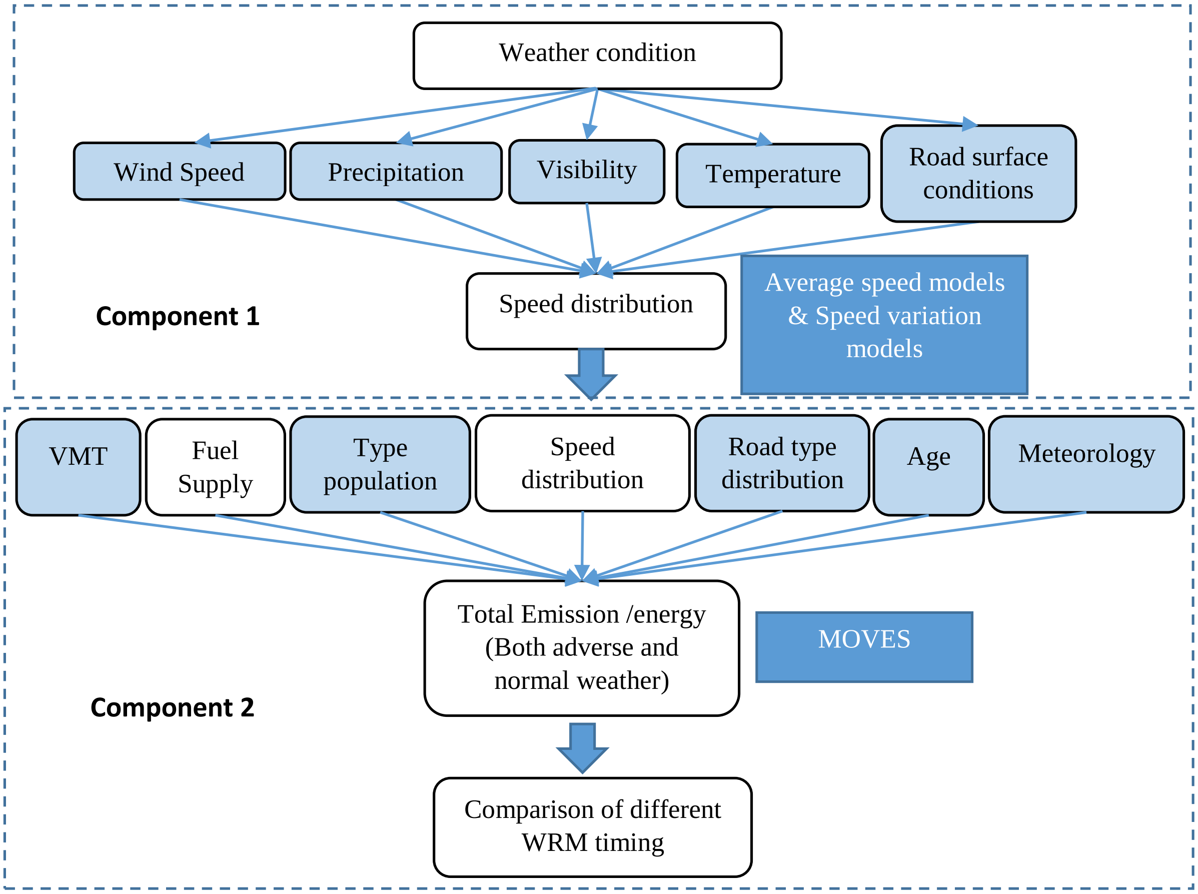

Figure 1. Research Methodology

3.2 Study Sites

Twenty-two maintenance patrol routes were selected from different regions of Ontario, as shown in Figure 2 (different line colours serve only to facilitate differentiation of patrol routes). These sites were selected based on the availability of traffic, weather and RSC data. The selected road sections belong to different highway classes, ranging from low volume rural two lane sections to high volume multi-lane urban freeways.

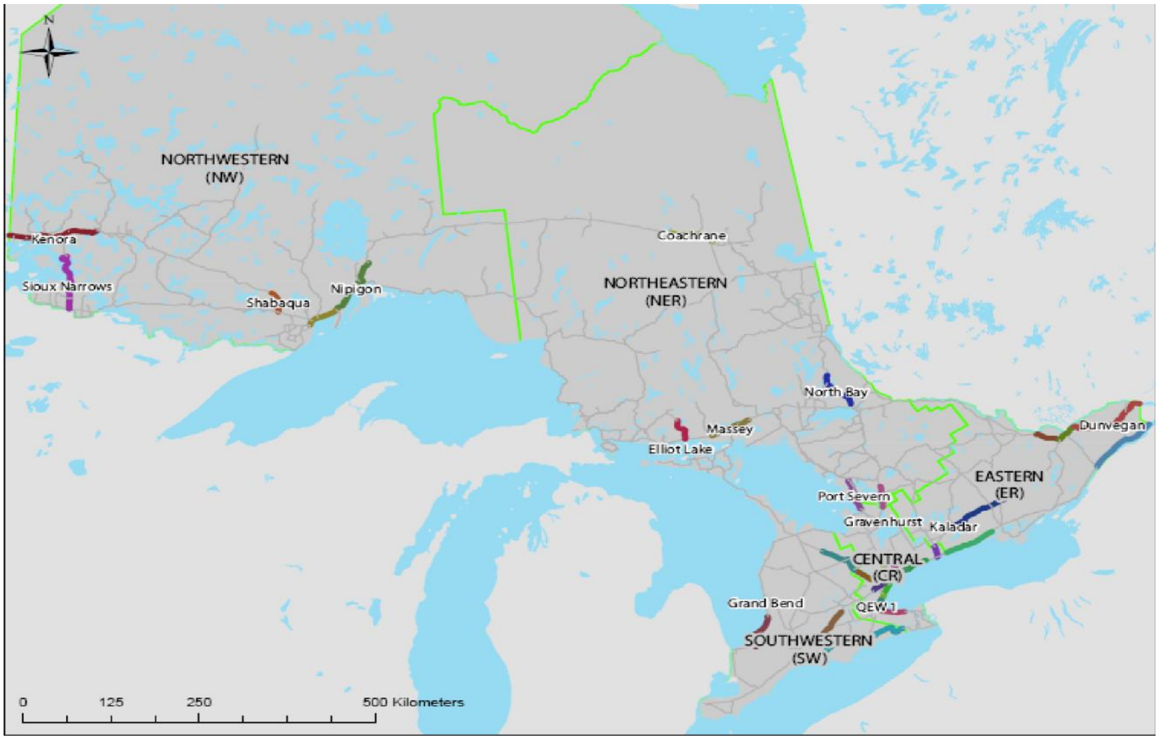

Figure 2. Selected study sites

3.3 Data Source

Due to varying data availability, 22 sites were grouped to create a data subset spanning six winter seasons (2000 – 2006) with available event based information. For the hourly evaluation, 22 sites had complete data spanning three winter seasons (from 2003 – 2006). All data were compiled from several different sources. A description of each data source is given below. The analyses were performed using three types of data: weather, road surface condition and traffic.

3.3.1 Weather information data

The weather information for each site is obtained from two sources, road weather information system (RWIS) and Environment Canada (EC). RWIS stations are installed along the study routes to collect real-time climatic data such as temperature, precipitation type, visibility, wind speed and road surface condition. Weather data from Environment Canada includes temperature, precipitation type and intensity, visibility and wind speed. RWIS stations record data every 20 minutes. Data from 45 RWIS stations were used in this research. In the case that multiple stations covered a maintenance route, average values from all the stations were used. Hourly precipitations from RWIS sensors were either not available or unreliable. As a result, this information was derived from the daily precipitation amount reported by EC.

Weather data from Environment Canada includes temperature, precipitation type and intensity, visibility and wind speed. With the exception of precipitation intensity, all data given are in an hourly format. Data from most single EC stations were incomplete; for this reason, EC data were obtained from 217 stations for the study routes. This data set was processed in three steps. In the first step, a 60 km arbitrary buffer zone was assumed around each route and all stations within this boundary were assigned to the particular route. In the next step, EC stations near the routes were identified and filtered based on a t-test to remove EC stations that showed significantly different weather. In the last step, data from different EC stations around a route were converted into a single dataset by taking their arithmetic mean.

3.3.2 Road condition data

Data on road surface conditions and maintenance activities were obtained from Ministry of Transportation, Ontario (MTO)'s road condition and weather information system (RCWIS). RCWIS data is collected by MTO maintenance personnel, who patrol the maintenance routes during storm events 3 to 4 times on the average. Information from all patrol routes are conveyed to a central system six times a day. Instead of stations, this data is collected for road sections. It contains information about RSC, maintenance operations, precipitation type, accumulation, visibility and temperature. Information from all patrol routes is conveyed to a central system six times a day. One of the most important pieces of information in this data source is the description of the overall RSC of the highway section at the time of observation. This description is used as a basis for determining a scalar variable called road surface index (RSI).

3.3.3 Traffic information data

Traffic volume and speed were obtained from MTO's permanent count stations (PDCS). The original hourly PDCS data included traffic counts and binned speed measurements for each lane. The binned speed measurements cannot be used to obtain good estimate on the average hourly speed because of the large bin size at the low speed range (e.g., the lowest speed bin is from 0 to

60 km/h). For this reason, the sample median speed is estimated from the binned speed measurements and is used as the response variable for evaluating the effect on speed in the subsequent analysis. As a result, we follow the normal distribution assumption, which means the sample mean is the same as the sample median and the sample standard deviation can be derived from the 85th percentile.

3.4 Data Processing

3.4.1 Road Surface Index

The major classes of road surface conditions, defined in RCWIS, were first arranged according to their severity in an ascending order as follows: Bare and Dry < Bare and Wet < Slushy < Partly snow covered < Snow Covered < Snow Packed < Icy.

Considering binary variables would mean loss of information in the ordering, road surface condition index was first defined in Usman's (2010) work. They used a friction surrogate because there have been a number of field studies available on the relationship between descriptive road surface conditions and friction (Wallman et al 1997; Wallman and Astrom 2001; NCHRP web document # 53, 2002; Transportation Association of Canada 2008; Feng et al 2010), which provided the basis to determine boundary friction values for each category. Each major class of road surface state was defined in the previous step as a range of values based on the literature in road surface condition discrimination using friction measurements. For the convenience of interpretation, RSI is assumed to be similar to road surface friction values and thus varies from 0.05 (poorest, e.g., ice covered) to 1.0 (best, e.g., bare and dry).

Each category in the major classes is assigned a specific RSI value.

The RSI values for major road surface classed are given in Figure 3 below. As Figure 3 shown, when road surface condition changes from "Icy" to "Partly Snow Covered", the RSI values increase sharply, while the slope becomes gentler after RSC is better than slushy. This means snow and ice have greater impact on road surface friction than water.

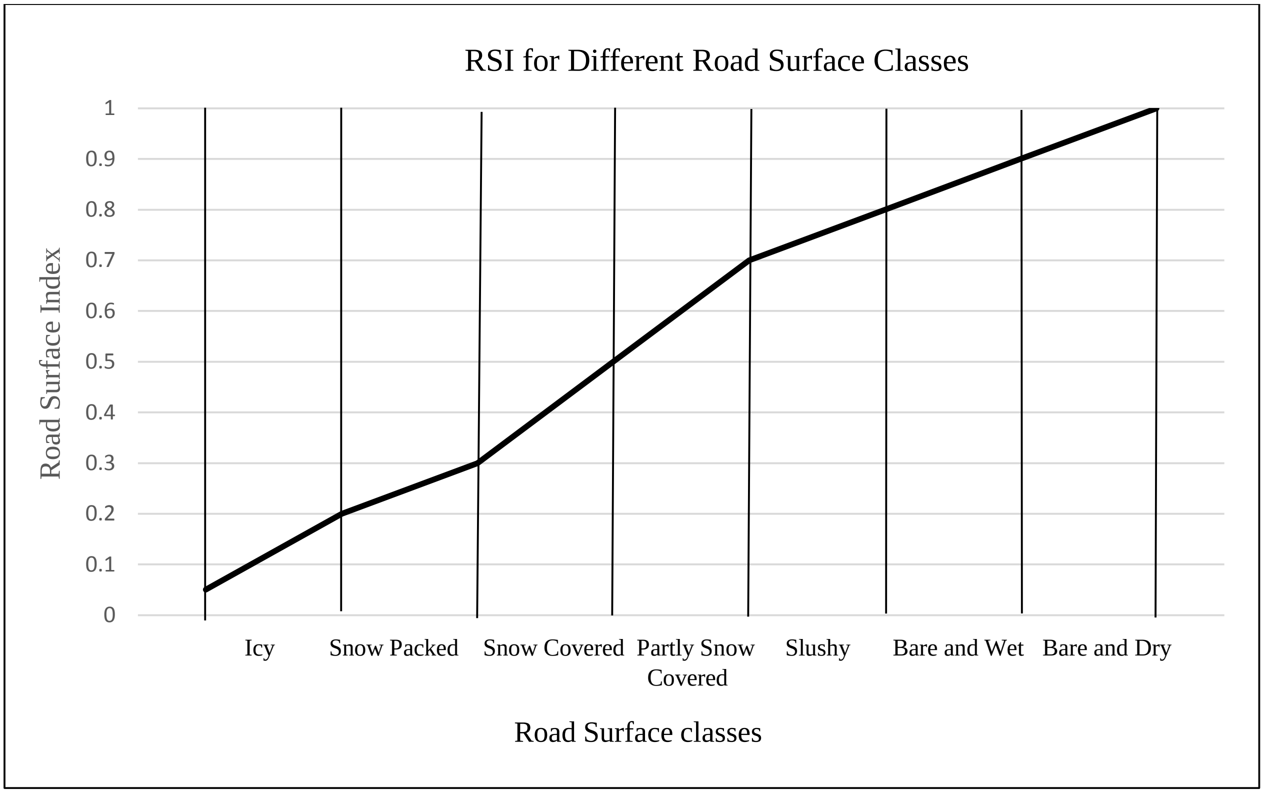

Figure 3 RSI for different road surface classes

(Source: Taimur Usman 2011)

3.4.2 Hourly data set

To develop speed distribution models for both individual sites and combined sites, two kinds of datasets were prepared for the subsequent analyse. In the first set, all the data sources from one site were combined to form an integrated data set, date and time as the common basis for each site. For the second set, data from all the sites were pooled into a single dataset with each site assigned a unique identification (site ID) and four site-specific variables, including region ID, road type, road class and climate zone, to retain its identity. Table 5 shows the descriptive statistics of weather and road condition variables, and each variable dataset contains a large range of values, and many data under extreme conditions are also included. Table 6 shows the observation distribution for each site, and the distributions of observation among the 22 sites were almost even.

Table 5 Descriptive Statistics

Variables	Minimum	Maximum	Average	Standard Deviation
Temperature(℃)	-42.15	28.35	-0.338	8.895
Wind Speed (km/h)	0	69	10.881	8.650
Visibility(km)	0	40.2	17.912	7.508
Hourly Precipitation(cm)	0	13.8	0.041	0.215
Traffic	1	24482	1786.755	3342.093
Road Surface Index (RSI)	0.05	1	0.898	0.158

Table 6 SITE Data Distribution

Site 1	3.38%	Site 9	4.82%	Site 17	5.36%
Site 2	4.76%	Site 10	4.84%	Site 18	4.25%
Site 3	4.85%	Site 11	2.33%	Site 19	4.85%
Site 4	5.13%	Site 12	5.66%	Site 20	4.72%
Site 5	5.20%	Site 13	5.21%	Site 21	5.42%
Site 6	4.71%	Site 14	5.88%	Site 22	5.34%
Site 7	6.22%	Site 15	4.83%		
Site 8	5.37%	Site 16	5.02%		

The dataset contains binned speed (the speed was binned every 5 km/h except the speed below 60 km/h and beyond 125 km/h), which may not obtain good estimation on the average hourly speed because of the large bin size at the first and last speed bins. To use the sample median speed estimated from the binned speed measurements as the independent variable for evaluating the effect on speed in the subsequent analysis, the speed were assumed to follows the normal distribution, which means the sample mean is the same as the sample median and the sample standard deviation can be derived from the 85th percentile. Based on this, Table 8 shows the average speed and CV of speed we calculated.

Table 7 Summary Statistics of CV and Average speed

	Coefficient of Variation				Average speed			
Site ID	Min	Max	Average	St.Dev	Min	Max	Average	St.Dev
1	0	0.962	0.101	0.069	30	112.5	73.311	22.744
2	0	0.762	0.118	0.104	30	122.5	73.609	19.719
3	0	0.706	0.099	0.040	30	110	92.275	4.983
4	0	0.447	0.076	0.032	30	184.5	39.822	25.669
5	0	0.561	0.079	0.030	30	110	100.421	4.713
6	0	0.481	0.073	0.024	50	110	101.286	3.368
7	0	0.513	0.123	0.052	30	112.5	94.220	6.754
8	0	0.412	0.095	0.026	60	120	107.905	6.963
9	0.022	0.423	0.093	0.023	60	115	104.877	5.973
10	0	0.372	0.070	0.024	35	107.5	98.807	4.089
11	0	0.462	0.093	0.035	42.5	110	97.695	4.178
12	0	0.249	0.094	0.022	60	100	93.278	4.063
13	0	0.423	0.094	0.033	47.5	115	87.371	4.758
14	0.025	0.407	0.096	0.024	60	100	93.515	4.963
15	0.019	0.437	0.085	0.024	45	125	110.427	5.764
16	0	0.299	0.092	0.020	60	122.5	111.173	5.540
17	0.019	0.434	0.085	0.028	42.5	127.5	117.396	7.694
18	0	0.722	0.110	0.028	30	112.5	103.257	9.255
19	0	0.424	0.101	0.024	60	120	113.618	6.441
20	0.04	0.385	0.108	0.023	60	120	107.364	7.882
21	0	0.722	0.124	0.039	30	115	79.480	26.067
22	0	0.802	0.117	0.064	30	122.5	87.174	29.230
Total	0	0.962	0.097	0.043	30	127.5	97.844	15.758

3.5 Motor Vehicle Emission Simulator

EPA's Office of Transportation and Air Quality (OTAQ) has developed the MOVES. This emission modeling system estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis. MOVES provide total air emission estimation that previous models (etc. MOBILE 2003; COPERT 2007) do not, which is more suitable for event based simulation in this research. It has a base emission rate reflecting fuel consumption and emission measurements gathered in a laboratory setting using pre-defined test drive cycles. This base rate is then modified to account for differences in speed distribution between the laboratory and real world cycles, and the differences in temperature, fleet composition, mileage of vehicles, type of fuel used, and other vehicle operating conditions. (Vallamsundar et al. 2011).

Some key distinctive features of MOVES that presumably make it superior to others in some aspects are: a modal-based approach to emission factor estimation; availability of MySQL database management versus external Excel spreadsheet type of data management scheme; and more sophisticated GHG estimation mechanisms and total energy consumption estimation available. MOVES 2014 version was used in this study.

This chapter introduced the overall research process, study sites, dataset information and models used in the subsequent analysis. Using vehicle speed distribution as a bridge, winter RSC and vehicular air emissions are linked.

CHAPTER 4

CALIBRATION OF SPEED DISTRIBUTION MODELS

As Chapter 3 introduced, speed distribution was used as the bridge of RSC and vehicular air emissions, so speed distribution is necessary for the subsequent analyses. To investigate and quantify the relationship between vehicle speed distribution and various influencing factors, especially those related to adverse winter weather conditions, we developed a speed distribution model. Multiple linear regression is applied to explore quantitative relationships between winter road condition and speed distribution parameters.

4.1 Modelling Assumption and Influencing Factors

An empirical process is adopted using winter traffic and weather data from Ontario highways. According to literature, In general, with almost homogeneous traffic conditions, the speed of vehicles on a straight road follows a normal distribution (Helbing, 1996, 1997A, 1997B; McLean, 1978):

$$P_G(v;x,t) = \frac{1}{\sqrt{2\pi\sigma(x,t)}}\exp\left(\frac{(v-V(x,t))^2}{2\sigma(x,t)}\right) \tag{6}$$

Where V (x, t) = Δ v, Δ denotes the average velocity and σ (x, t) = Δ (v−V (x, t))^2 ,Δ represents the velocity variance. This assumption is supported by many experimental works.

Therefore, it is assumed that the speeds of vehicles over a particular period (e.g., one hour) follow a normal distribution and its distribution parameters (average and coefficient of variation) can be modeled as a function of independent variables.

According to the literature, factors influencing speed can intuitively be grouped into two categories: first, the vehicle and driver; second, the highway facility itself.

The performance characteristics of each vehicle will obviously play a role in how fast that vehicle can travel. More important to this research is the behaviour of the driver. How a driver reacts to the other vehicles on the highway and how the driver reacts to adverse conditions are key to determining whether or not a driver will choose a different speed in response to poor RSC.

Several aspects of the highway facility design will influence how comfortable it is to travel at any given speed. For example, wider lanes shoulder curves, appropriate super elevation and long sight distances all allow, and to some extent encourage, higher travel speeds. A smooth flat surface also makes travelling at higher speeds more comfortable. It seems likely that the converse of this is also true: that poor surface conditions lead to lower speeds.

Six influencing factors were considered in the individual speed distribution model: temperature (°C), wind speed (km/h), visibility (km), hourly precipitation over the event (cm), traffic volume (per hour) and RSI. All of them are hourly data.

Both individual models and pooled models were tested because the variation may vary among different road types, climate zones and regions. For pooled models, five kinds of location features were assigned to each site, including site ID, road type, road classes, climate zone and region. The road type and region information are shown in Table 8 and 9 below.

Table 8 Road type

No.	Road Type
1	Freeway - 13 to 15 lane divided - Core/Collector
2	Freeway - 10 to 6 lanes divided
3	Freeway - 8 lane divided
4	Freeway - 6 lane divided
5	Freeway - 4 lane divided
7	Kings - 4 lane divided
8	Kings - 4 lane undivided
9	Kings - 2 lane undivided

Table 9 Region Code

Region	Code 1
CR	1
ER	2
NER	3
NW	4
SW	5

The SPSS 19 software package was used to perform the statistical analyses in this thesis work. All research questions surrounding highway speed were tested using multiple linear regressions. This approach allowed a wide variety of available independent variables to be tested for significance within the context of predicting traffic volume and speed. Datla and Sharma (2010) found statistically significant second order effects in estimating highway speeds in adverse weather.

4.2 Average Speed Models

Following the multiple linear regression technique, the average speed is assumed to be a linear function of various influencing factors (Equation 5), such as, temperature (°C), wind speed (km/h), visibility (km), hourly precipitation over the event (cm), traffic volume (per hour) and RSI for each site (highway). Because of the availability of data from multiple sites, two approaches were taken: one is developing separate models for individual sites, and the other pooling the data from all sites and developing a single unified model.

4.2.1 Qualitative analysis of average speed model

The qualitative analyses of hourly average speed factors are as follows in Table 10.

Table 10 Qualitative Analyses of Average Speed

Variable	Analysis	Effects on Average Speed
Temperature	Only considering temperature intuitively, there is no obvious relationship between temperature and speed dispersion, unless low temperature comes with snow storm or other adverse weather condition.	Uncertain
Wind Speed	Under strong wind, drivers are tend to slow down their speed since it is relatively hard to control the vehicles in the desire direction for safety. Lower average speed may be expected under higher wind speed.	Negative effect
Visibility	With poor visibility, drivers cannot see traffic and roads clearly, and they would drive with a lower speed for safety, so lower visibility may cause lower average speed.	Positive effect
Precipitation	Similar to visibility, higher precipitation leads to poorer visibility and RSC, drivers would slow down when there is more snow around the roads.	Negative effect
Traffic Volume	With heavy traffic on road, especially in a congestion, all the vehicles are moving in a similar speed with the leading one, which usually have lower speed than free flow speed. As a results, average speed would decrease with increasing traffic volume.	Negative effect
RSI	It is difficult to control the vehicle when road surface condition is uncomfortable. When drivers are suffering from bad road surface condition, such as icy or snow covered, drivers would decrease the speed for safety. As a results, average speed would increase with greater RSI value.	Negative effect

4.2.2 Exploratory data analysis

4.2.2.1 Correlation analysis

To test the independence among the aforementioned six variables, Pearson Coefficient was used as an indicator of correlation. The Pearson correlation coefficient is a measure of the strength of the linear relationship between two variables. It is referred to as Pearson's correlation or simply as the correlation coefficient. Pearson's coefficient can range from -1 to 1. A value of -1 indicates a perfect negative linear relationship between variables, a value of 0 indicates no linear relationship between variables, and a value of 1 indicates a perfect positive linear relationship between variables. Table 11 below shows the Pearson correlation among each two of these variables.

Table 11 Pearson Correlation Matrix

	Temperature	Wind Speed	Visibility	Precipitation	Traffic Volume	RSI
Temperature	-	0.101**	-0.033**	-0.092**	0.156**	0.170**
Wind Speed	0.101**	-	-0.010**	0.077**	0.090**	-0.139**
Visibility	-0.033**	-0.010**	-	-0.232**	0.034**	0.339**
Precipitation	-0.092**	0.077**	-0.232**	-	-0.032**	-0.260**
Traffic Volume	0.156**	0.090**	0.034**	-0.032**	-	0.060**
RSI	0.170**	-0.139**	0.339**	-0.260**	0.060**	-

** Correlation is significant at the 0.01 level.

Although all the coefficients are statistically significant, and the absolute values are all less than 0.35, which means the correlation is weak. These six variables are considered to be independent with each other in the subsequent analysis.

4.2.2.2 Singe variable analysis

For average speed model, the dependant variable is taken as the hourly average speed on a highway. Each of the six independent variables being tested was plotted against hourly average speed below. In each of these exploratory plots only the effects of a single variable; as such any interaction between effects is masked. The data for hourly average speed is originally binned in 5km/hr increments. These increments show up in the plots below as the areas of concentrated data.

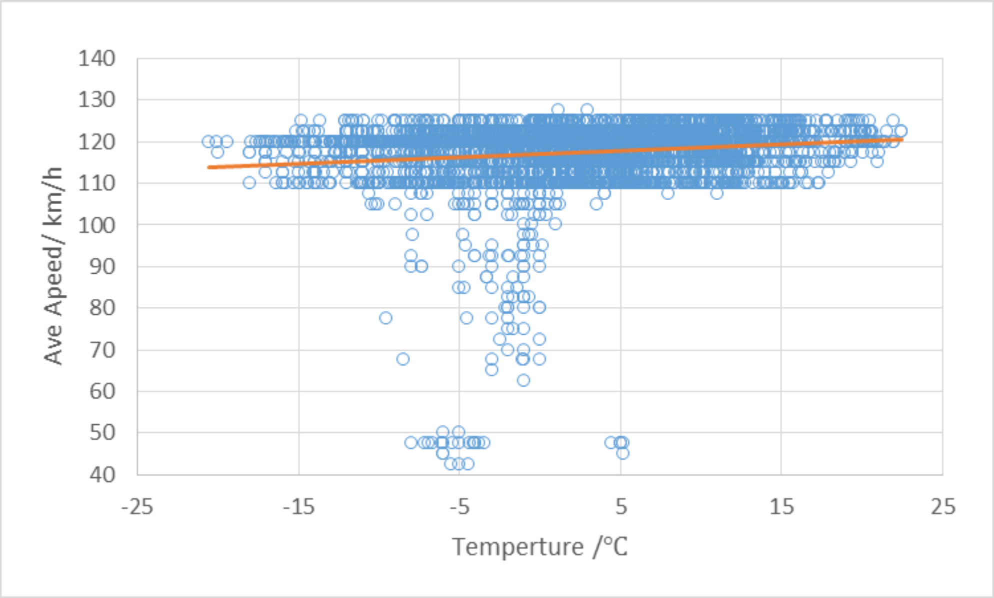

Figure 4 Average Speed vs. Temperature

When hourly average speed change is plotted against temperature in Figure 4. A linear trend shows only a small effect though it does demonstrate that average speed change, in general is positive in the temperature data set. The considerable noise within the data is also evident in the plot, which may result from some extreme conditions. Most data points with lower speed are corresponding to the temperatures between -10 ℃ and 0 ℃, which may indicate that the driving conditions under these temperatures are the worst.

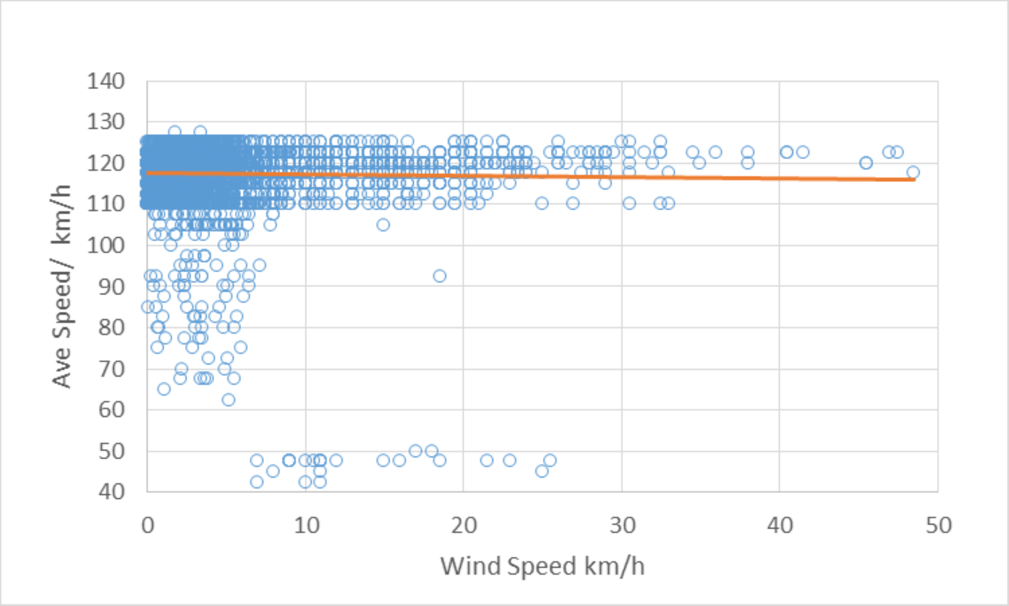

Figure 5 Wind speed vs. Average Speed

As seen in Figure 5, a linear trend line suggests that higher wind speeds is correlated with lower average speed during storms. Except for some extremely low data, most data with speed lower than 100 km/h happened at relatively low wind speeds.

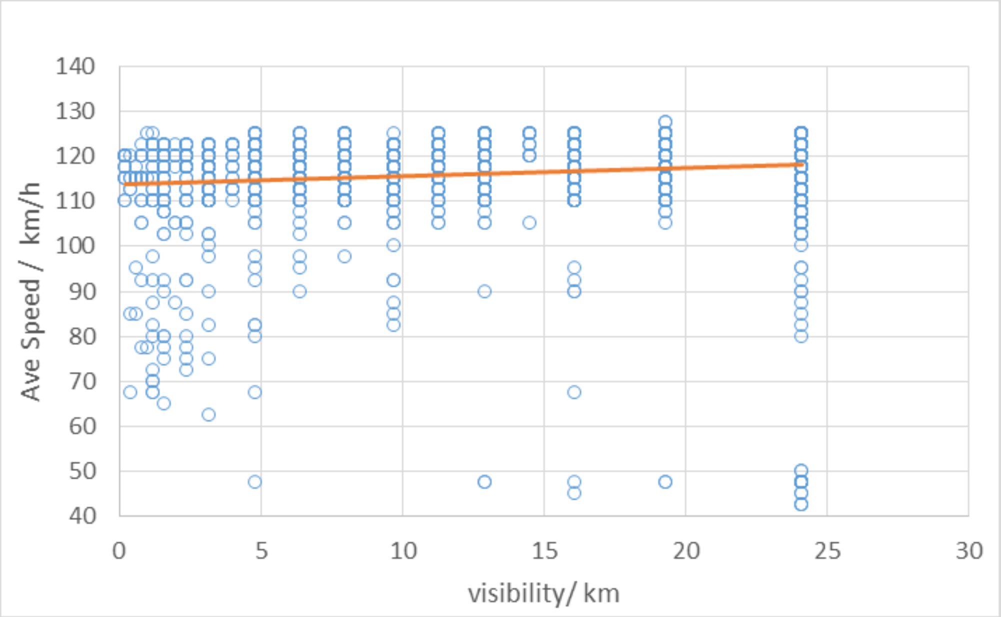

Figure 6 Visibility vs. Average Speed

The linear trend in Figure 6 suggests that low visibilities are correlated with lower hourly average speed. As we could see from the figure, among the points with lower average speed, most of them have poor visibility less than 5 km. It indicates that poor visibility would greatly affect the average speed in storms.

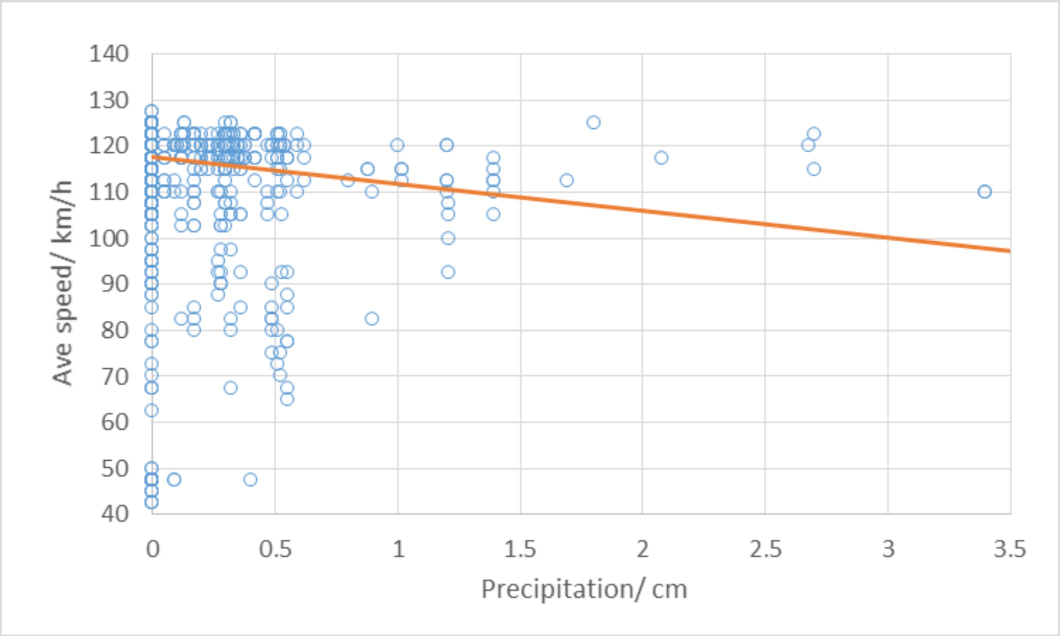

Figure 7 Hourly precipitation vs. Average Speed

On the other hand, the data is quite noisy in the linear trend appears to indicate a relationship between vehicle speed and precipitation. However, a relationship between the intensity of precipitation and hourly average speed is not obvious.

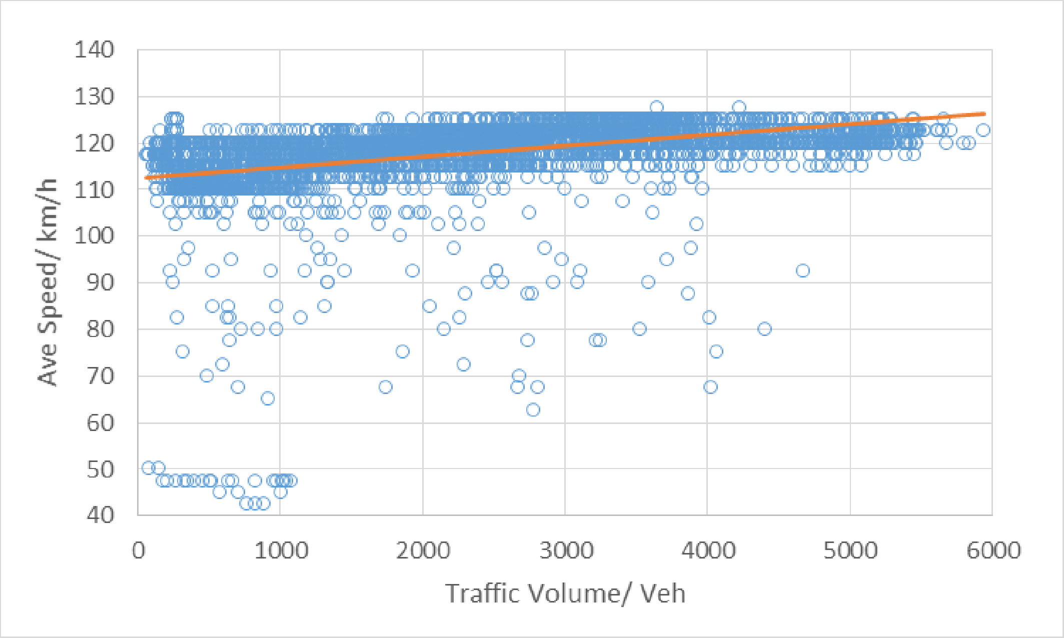

Figure 8 Traffic Volume vs. Average Speed

Figure 8 shows that an increase in traffic volume appears to be correlated with an obvious increase in hourly average speed. However, the data points with lower speed seem to be distributed randomly along the traffic volume axis which means low average speed has little relationship with traffic volume change.

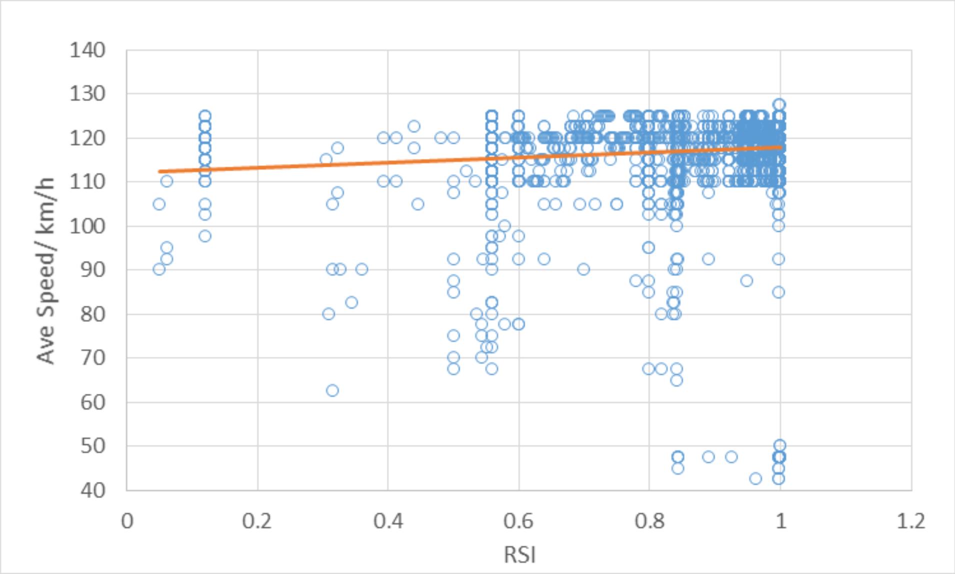

Figure 9 RSI vs. Average Speed

RSI is the primary factor of interest in this research. When comparing RSI to average speed reduction the linear trend clearly indicates a strong correlation between lower RSI and lower volume. This is also visible by observing the in data shifting away from the horizontal axis with lower RSI. However, the noise in the data masks this trend to some degree.

4.2.3 Modeling results and interpretation

A step-wise regression process was followed, each testing the significance of a variable based on a level of significance of 5%. The results are shown in Table 12. Both magnitude and the positive or negative effects for the average value of each variable coefficient in the modeling results were found to be similar to those from Donaher's (2012).

Table 12 Modeling Results for Individual Average Speed Model

Site ID	Temp	Wind Speed	Visibility	Precipitation	Traffic	RSI	Constant	R^2
1	0.106	-0.19	-0.11	-	0.48	-4.269	11.16	0.908
2	0.059	-	0.162	-4.378	0.005	10.473	95.340	0.408
3	0.142	-0.073	0.273	2.065	0.913	12.661	51.21	0.227
4	0.01	-0.072	0.139	-1.55	0.003	19.028	84.95	0.503
5	0.018	-0.022	0.094	-3.946	-0.004	13.931	83.80	0.242
6	0.101	0.102	0.333	-5.345	-	9.183	93.32	0.255
7	0.009	-	0.081	-1.59	0.005	7.741	91.79	0.288
8	0.058	-0.215	0.091	-2.554	0.004	11.807	97.28	0.249
9	0.02	-0.017	0.137	-1.557	0.01	10.368	87.62	0.39
10	0.193	-0.061	0.185	-5.326	-0.001	28.245	78.54	0.304
11	0.065	-	0.154	-4.635	0.002	2.52	107.41	0.218
12	0.009	-	-	-2.611	0.009	18.937	88.49	0.411
13	0.037	-0.037	0.129	-2.678	0.003	8.747	81.76	0.363
14	0.037	-0.034	0.084	-4.599	-	7.37	85.37	0.196
15	0.054	-0.049	0.205	-3.601	0.003	5.386	91.11	0.327
16	0.017	-0.014	-	-1.715	0.016	15.055	78.66	0.196
17	0.057	-0.053	0.238	-3.834	0.003	7.294	83.62	0.394
18	0.049	-0.034	0.089	-3.923	-0.002	16.905	71.30	0.388
19	-0.086	1.216	0.371	-1.625	0.397	6.913	36.99	0.4
20	0.095	-0.066	0.222	-8.131	0.0003	7.212	104.05	0.211
21	0.472	-0.734	0.279	-	-	-	39.87	0.133
22	-0.168	1.246	0.185	-15.622	-0.001	5.37	60.23	0.255

One location feature was added as a nominal variable at one time, along with all the scale variables used in the individual models. As shown in Table 13, the six columns from left to the right represented the results of pooled models without location feature, site ID, region, road type, road class and climate zone respectively. The results show that none of the R^2 of pooled models is greater than those in the individual models, separate models for each highway routes therefore performed better than the pooled models, the individual models were therefore chosen to estimate the average speed in the following analysis.

Table 13 Pooled Modeling Results for Average Speed Model

	No location feature added	Add site ID	Add region	Add road type	Add class	Add climate
Temperature	0.121	0.087	0.113	0.111	0.101	0.087
Wind Speed	-0.054		-0.04	-0.025	0.032	-0.085
Visibility	0.323	0.312	0.248	0.313	0.238	0.357
Precipitation	-1.826	-1.942	-2.32	-1.986	-2.367	-1.751
Traffic		-0.001	-0.001	-0.001	-0.001	
RSI	8.042	8.132	7.302	7.778	8.109	7.714
Constant		77.088	97.281	99.627	110.097	91.141
Site ID		0.575				
Region			-3.233			
Road type				-2.036		
Class					-13.514	
climate						-2.088
R^2	0.047	0.117	0.102	0.087	0.146	0.066

In order to have a better understanding of the coefficients, the coefficients for all sites were plotted below in Figure 10, and from the individual modelling results, following interpretation can be obtained:

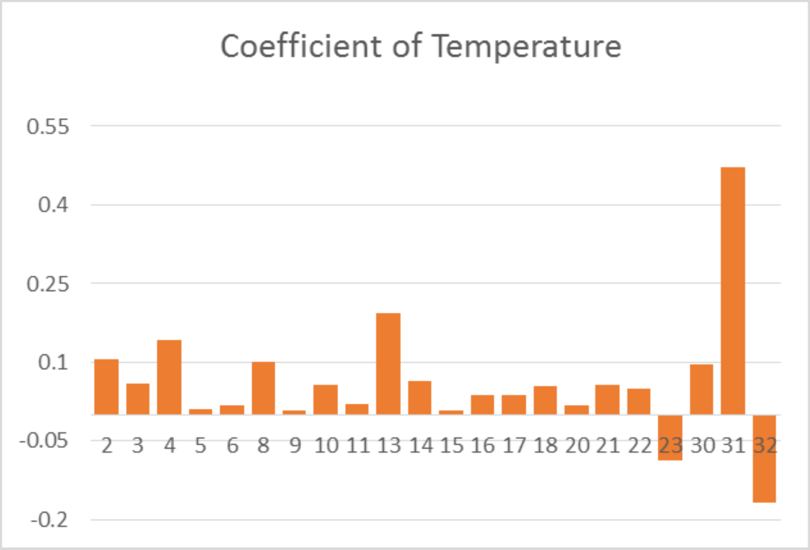

Figure 10 Coefficient of Temperature in Average Speed Model

- Temperature: As figure 10 shown, the average temperature during an event had little impact on average speed indicating that driving speed in winter conditions is only influenced by temperature slightly, and the relationship is mostly positive. As qualitative analysis shown, temperature does not have direct impact on average speed, but cold weather would be related with snow storm which would result in adverse RSC. Therefore, the drop of temperature may correlated with lower average speed.

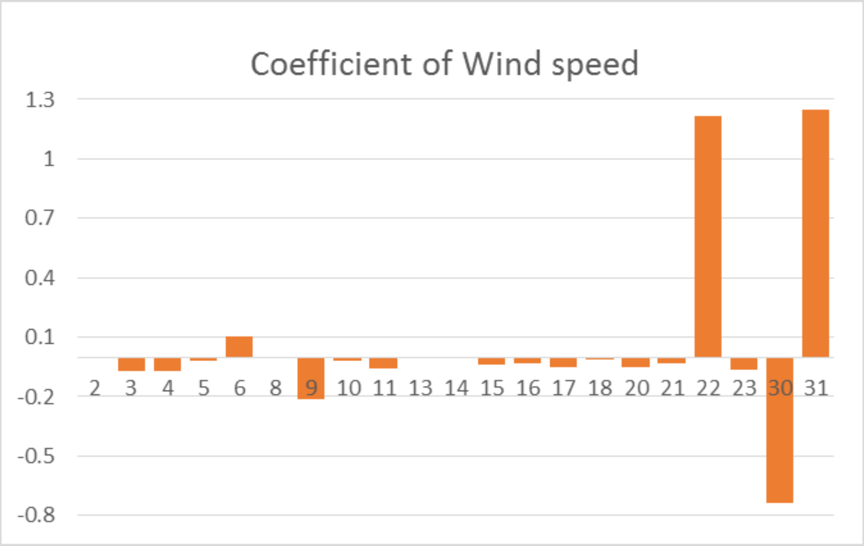

Figure 11 Coefficient of Wind Speed in Average Speed Model

- Wind Speed: Wind speed was found to be significant although the effect on traffic speed is relatively small. Each 10km/h increase in wind speed is correlated with a 0.8km/h drop in average vehicle speed. This relatively little impact on vehicle speed consistent with literature findings that wind speed was only a strong factor when very high wind speeds were reached. Despite the small coefficient value, strong winds could still result in large traffic volume and median speed reductions.

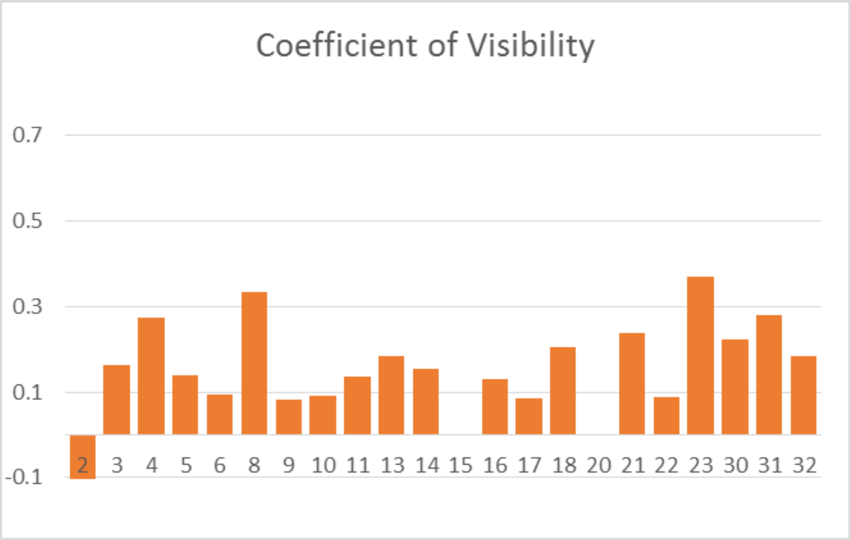

Figure 12 Coefficient of Visibility in Average Speed Model

- Visibility: Visibility had a strong effect on median vehicle speed. On average, each 10km drop in visibility could lead to a 3.1km/h drop in average speed. This results are also supported by the quantitative test for visibility in Table 11.

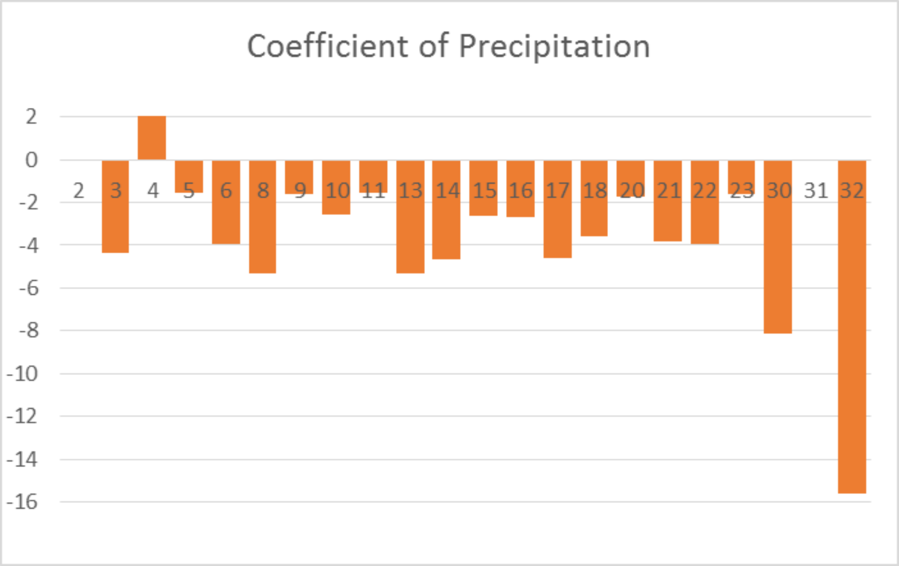

Figure 13 Coefficient of Precipitation in Average Speed Model

- Precipitation: Precipitation has the anticipated impact on average vehicular speed. Each additional centimeter of precipitation is expected to result in a 1.3 km/h drop in average speed. Similar effects of precipitation are well documented in the literature (Rakha et al. 2007; Cao et al. 2013).

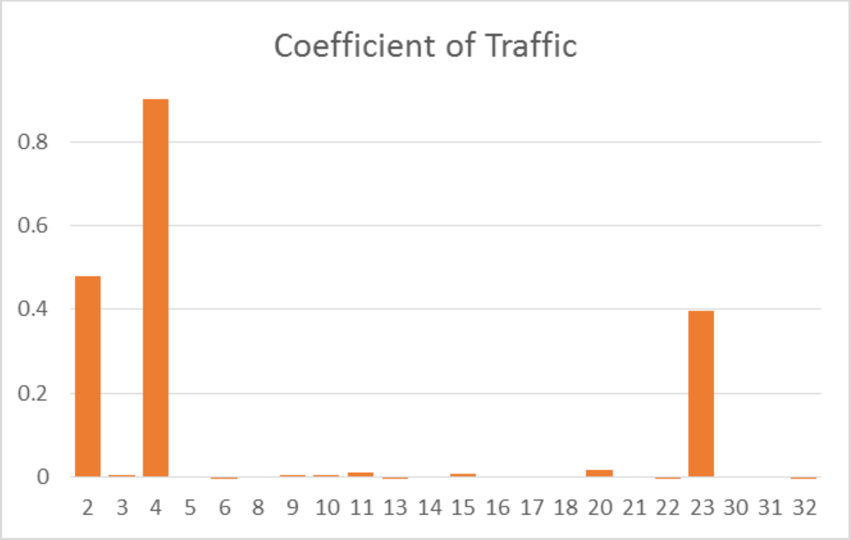

Figure 14 Coefficient of Traffic Volume in Average Speed Model

- Volume: The impact of average volume (or volume to capacity ratio) on average speed was found to be relatively little, which is consistent with the general traffic stream patterns. A 0.1 increase in volume to capacity ratio would lead to 0.4 km/h reduction in median speed.

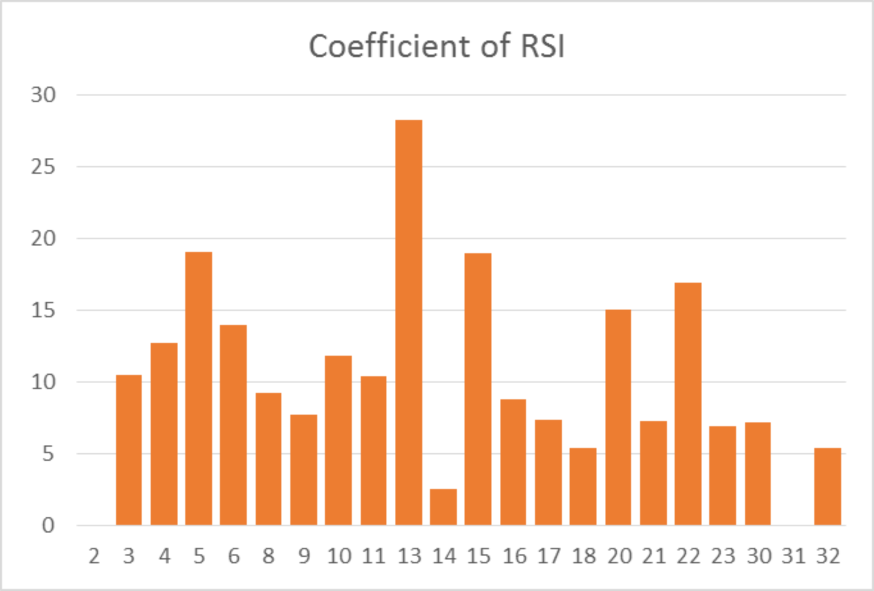

Figure 15 Coefficient of RSI in Average Speed Model

- Road surface index was shown to be a significant factor in median speed models. In Figure 15, each drop of 0.1 in RSI is correlated with a 1.05 km/h drop in average speed.

4.3 Speed Variation Model

Speed variation could lead to recurring patterns of decelerations and accelerations as well as lane changes when individual vehicles travel at different speeds in a freeway section. It is assumed here in that the second by second speed distribution on highways follows a normal distribution, and coefficient of variation is the indicator of speed distribution. Based on the normal distribution assumption, the variability of speed can be captured completely by its standard deviation. Following the common approaches adopted in traffic engineering, the coefficient of variation (CV) of speed, which is defined as the ratio of standard deviation to the mean, is considered as the direct modelling target. Note that the standard deviation can be determined as the product of the mean and CV.

In probability theory and statistics, the coefficient of variation (CV) is a standardized measure of dispersion of a probability distribution or frequency distribution. The coefficient of variation (CV) is defined as the ratio of the standard deviation σ to the mean μ:

$$c_v = \frac{\sigma}{\mu} \tag{7}$$

Hourly CV is calculated by combining the information of median speed and the 85% lie speed in this research.

4.3.1 Qualitative analysis of vehicular speed variation

The results of qualitative of CV factors are summarized as follows in Table 14.

Table 14 Qualitative Test of speed variation model

Variables	Analyses	Effects on CV
Temperature	Temperature has no obvious direct impact on speed variation intuitively. However, If there are snow storm or poor RSC coming with low temperature, it may have adverse effect on speed variation.	Uncertain
Wind Speed	Only consider wind speed, it seems no fixed relationship between wind and speed variation. Strong wind may result uneven road surface with high precipitation.	Uncertain
Visibility	Similar to wind speed, under poor visibility, drivers cannot see traffic and roads clearly, which may results in more unexpected breaks and enlarge the speed dispersion, so lower visibility may cause higher value of CV.	Negative effects
Precipitation	As explained above, higher precipitation leads to poorer visibility and poor RSC, so CV would increase when there is more snow around the roads.	Positive Effects
Traffic Volume	With heavy traffic on road, especially in a congestion, drivers cannot drive in their desire speed, all the vehicles are driving in a similar speed with the leading one. CV would decrease with higher traffic volume.	Negative effects
RSI	When drivers are suffering from bad road surface condition, ice or snow is probably not evenly distributed, so they would change their speed more frequently than normal condition, and the speed dispersion tends to disperse and the CV would increase with lower RSI value.	Negative effects

4.3.2 Exploratory data analysis

For the speed variation model, we used same weather and road surface condition variables. The correlation among the six variables are therefore the same with that in the average speed model.

4.3.2.1 Single variable analysis

For speed variation model, the dependant variable is taken as CV of hourly average speed on a highway. Each of the six independent variables being tested was plotted against CV below in Figures. Only the effect of a single variable is presented in each of these exploratory plots; as such any interaction between effects is masked. These increments show up in the plots below as the areas of concentrated data.

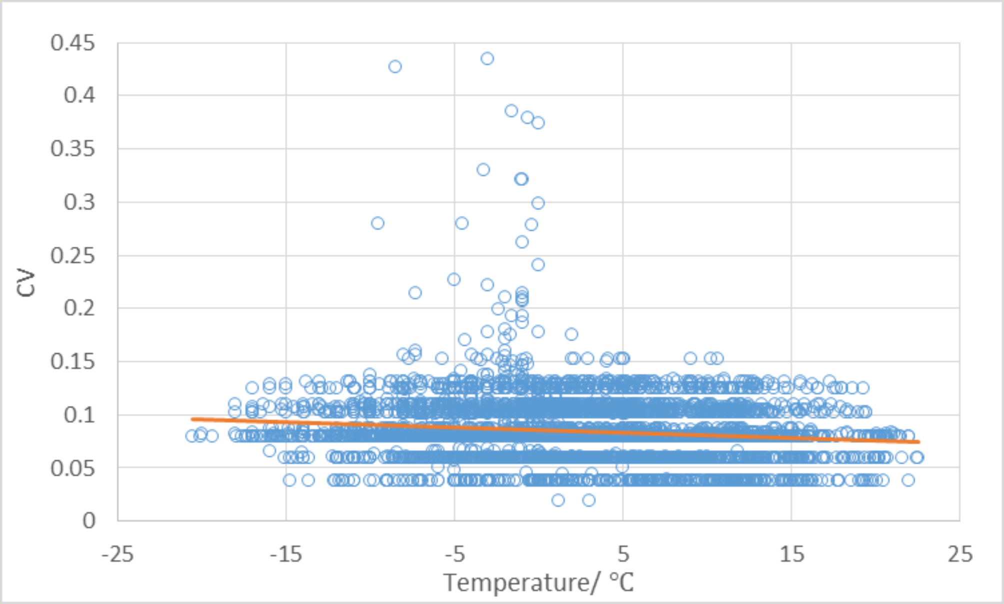

Figure 16 Temperature vs. CV

As with the exploratory analysis of average change, there is not really an obvious trend in the relationship between temperature and CV. A linear trend shows only a small effect though it does demonstrate that CV change, in general is negative in the temperature dataset. As shown

Figure 16, most data points with higher CV value are within the range between -10 ℃ and 0 ℃, which may indicate that the speed variation under this temperature range is most unstable.

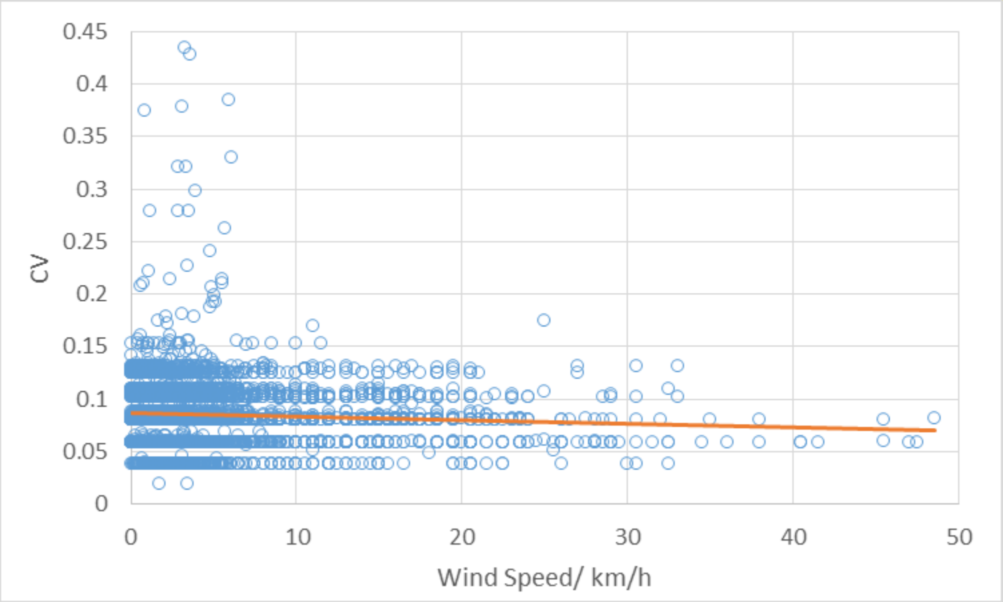

Figure 17 Wind Speed vs. CV

Wind speed does appear to be correlated with CV based on this linear trend line. Little trend is obvious when comparing wind speed to CV value change. A linear trend line does suggest that higher wind speeds is correlated with lower CV during storms. As shown in Figure 17, most data with CV larger than 0.2 happened at relatively low wind speed.

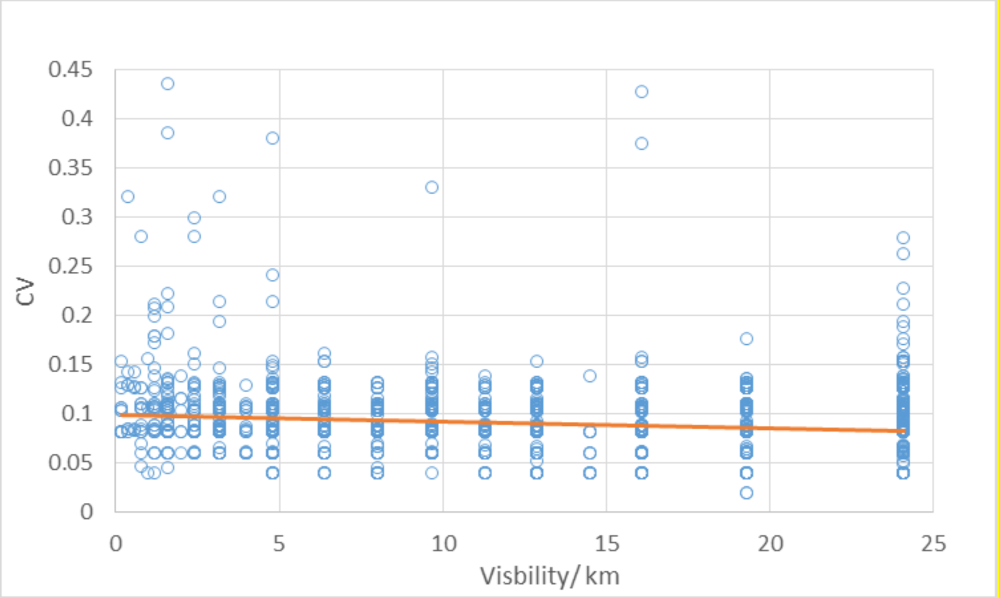

Figure 18 visibility vs. CV

Again, a lower visibility appears to be correlated with lower visibility. As seen from Figure 18, among the points with CV value higher than 0.2, most of them have poor visibility less than 5 km. It can be indicated that poor visibility would significantly affect the speed variation in storms.

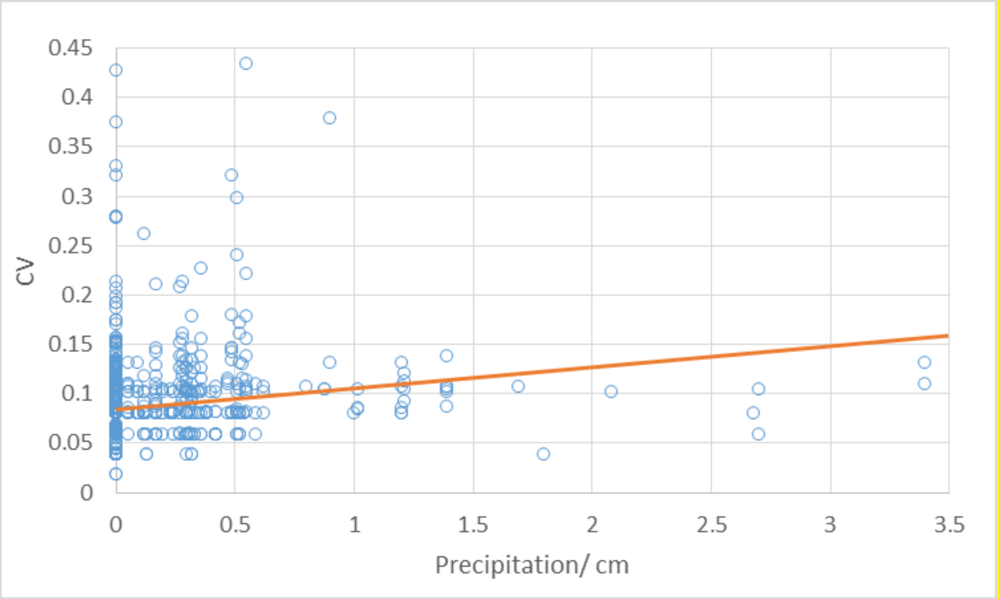

Figure 19 Hourly Precipitation vs. CV

While the data is quite noisy, the linear trend appears to indicate a relationship between CV and precipitation in Figure 19. However, a relationship between the intensity of precipitation and speed variation is less obvious since the data during that range.

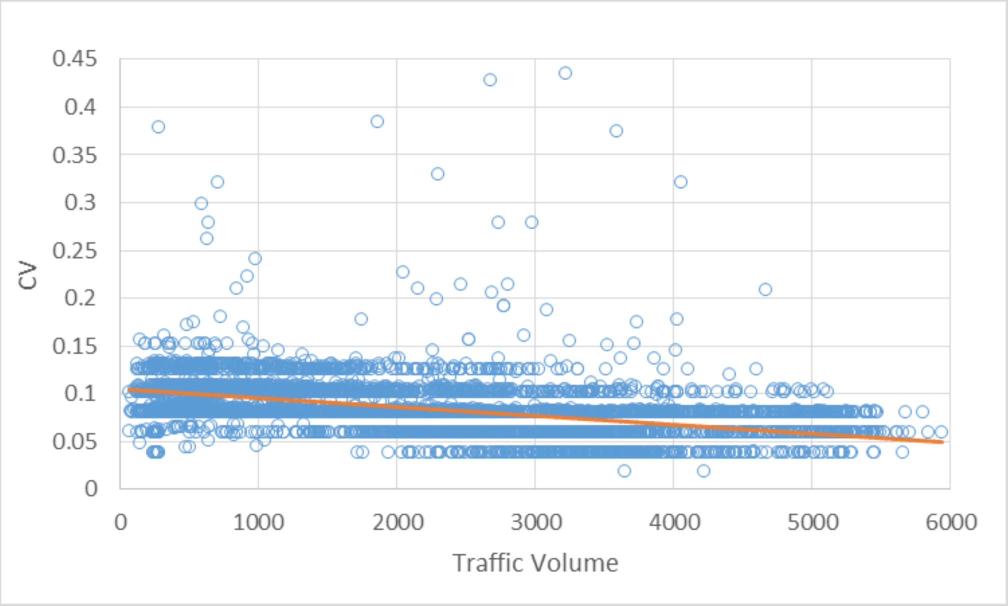

Figure 20 Traffic Volume vs. CV

Figure 20 shows an increase in traffic volume appears to be correlated with a decrease in CV. However, the data points with higher CV value seem to be distributed randomly along the traffic volume axis and not correlated with traffic volume.

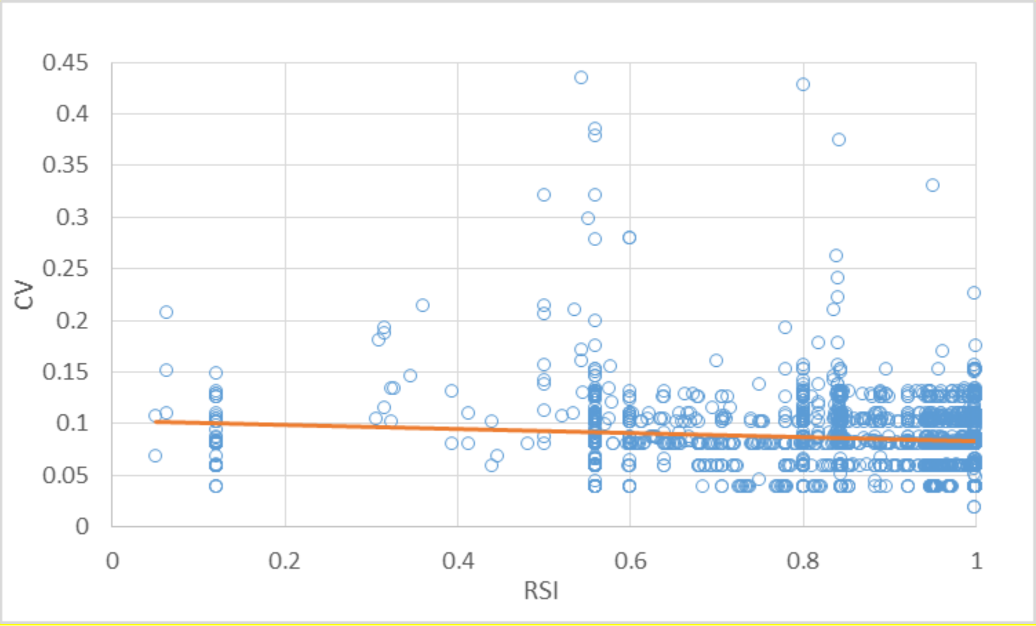

Figure 21 RSI vs. CV

RSI is the primary factor of interest in this research. Figure 21 shows when comparing RSI to CV reduction the linear trend clearly indicates a strong correlation between higher RSI and lower CV. This is also visible by observing the shift in data away from the horizontal axis with lower RSI. However, the noise in the data masks this trend to some degree.

4.3.3 Modeling results

Based on the normal distribution assumption, the variability of speed can be captured completely by its standard deviation. Following the common approached adopted in traffic engineering, the coefficient of variation (CV) of speed, which is defined as the ratio of standard deviation to the mean, is considered as the direct modelling target. Note that the standard deviation can be determined as the product of the mean and CV.

The raw traffic data contains binned speed counts, which can be used to derive the sample standard deviation of speed. Independent variables tested for significance include temperature (°C), wind speed (km/h), visibility (km), hourly precipitation over the event (cm), volume (per hour) and RSI (dimensionless) for each site. Models were developed for the individual sites. Backward elimination process was used for all the models, eliminating all non-significant variables based on a level of significance of 5%. The modelling results are shown in Table 15 and Table 16 below.

Table 15 Modeling Result for Speed Variation Models

Site	Temp	Wind Speed	Visibility	Precipitation	Traffic	RSI	Constant	R^2
1	-0.143	-	-0.55	6.31	-0.001	-9.873	110.249	0.216
2	-	-0.12	-0.23	3.532	-0.14	-15.249	72.187	0.297
3	-	-0.191	0.828	7.413	0.323	-14.549	91.456	0.082
4	-	-	-0.086	3.418	-0.003	-48.99	139.52	0.146
5	-0.085	-	0.091	8.795	-0.029	-20.974	14.122	0.019
6	-0.467	-0.045	-0.519	7.936	-0.001	-9.845	130.426	0.089
7	-0.155	-0.1	-	3.568	0.022	-22.912	98.762	0.044
8	-	0.338	-	5.866	0.009	-21.25	96.699	0.054
9	-	0.052	0.259	3.765	-0.03	-30.704	114.835	0.065
10	-0.267	-0.106	-0.165	7.766	0.002	-36.787	136.281	0.104
11	-0.105	-	-0.502	17.486	-0.009	-8.338	121.124	0.247
12	0.108	-0.108	-	3.61	-0.016	-29.567	126.291	0.075
13	-	0.091	-0.32	4.605	-0.013	-18.785	124.27	0.109
14	-0.163	-0.084	0.178	9.384	-0.076	-14.513	121.992	0.07
15	-0.046	0.192	-0.537	11.366	-0.016	-17.891	94.688	0.081
16	0.677	-2.085	-	8.219	-0.101	-37.937	190.031	0.157
17	-0.114	0.164	-0.623	10.314	-0.012	-13.881	118.78	0.112
18	-0.211	0.171	-0.122	7.024	-0.05	-44.271	145.703	0.12
19	-	-0.234	-0.517	-	-0.122	-23.772	138.029	0.012
20	-0.158	0.101	-0.245	11.596	-	-10.394	116.748	0.033
21	-0.333	0.292	-0.113	-	0.004	-23.261	107.711	0.073
22	0.093	0.274	-	8.074	0.002	-12.178	111.546	0.072

Table 16 Modeling results of pooled speed variation model

	+ Nothing	+Site ID	+Region	+Road type	+Class	+climate
Temp	-0.063	-0.066	-0.063	-0.071	-0.069	-0.102
Wind S	0.109	0.113	0.11	0.13	0.134	0.075
Visibility	-0.341	-0.342	-0.348	-0.349	-0.367	-0.341
Ppt	5.19	5.178	5.14	5.502	5.018	4.991
Traffic	0.003	0.003	0.003	0.002	0.003	0.003
RSI	-20.509	-20.5	-20.584	-20.689	-20.481	-21.09
Constant	112.811	112.088	113.997	123.526	120.334	119.674
Site ID	-	0.05	-	-	-	-
Region	-	-	-0.326	-	-	-
Road type	-	-	-	-1.542	-	-
Class	-	-	-	-	-4.129	-
climate	-	-	-	-	-	-2.349
R2	0.071	0.071	0.071	0.074	0.072	0.077

Similar to the hourly average speed model, the results showed that separate models for each highway routes performed better than the pooled models, the individual models were therefore chosen to estimate the average speed in the following analysis.

In order to have a better understanding of the coefficients, all the coefficients for each sites were plotted below, and base on the modeling results in Table 4, the following interpretations can be made on the effect of the significant factors:

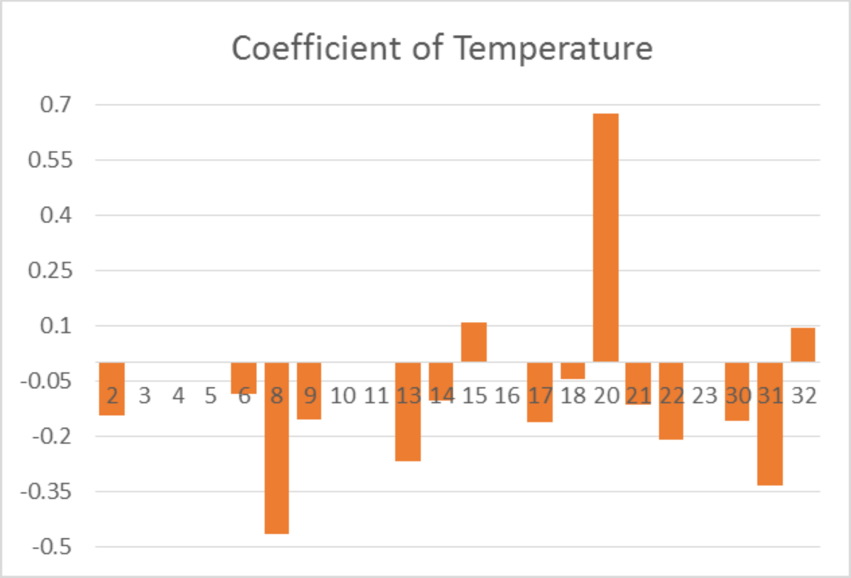

Figure 22 Coefficients of Temperature in Speed Variation Model

- Temperature: As shown in Figure 22, results indicates that increase in temperature will lead to decrease in speed variation. One reason for this is that with increase in temperature, variation in RSC will decrease leading to more uniform RSC. One degree drop in temperature can cause 0.9% increase in speed variation, on the average.

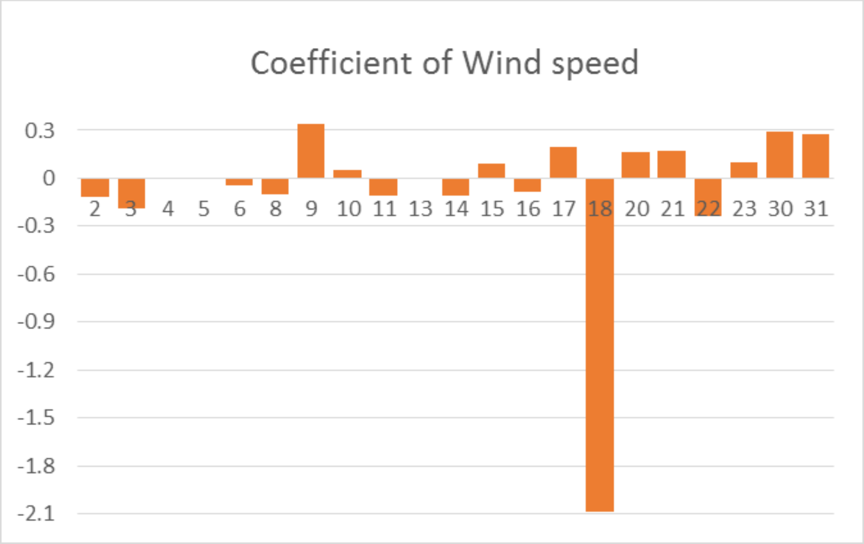

Figure 23 Coefficients of Wind Speed in Speed Variation Model

- Wind speed: As shown in Figure 23, mixed results were obtained in case of impacts of wind speed on speed variation. Depending on the terrain, wind speed could cause drifting leading to hazardous conditions and thus forcing drivers to reduce speed resulting in less speed variation.

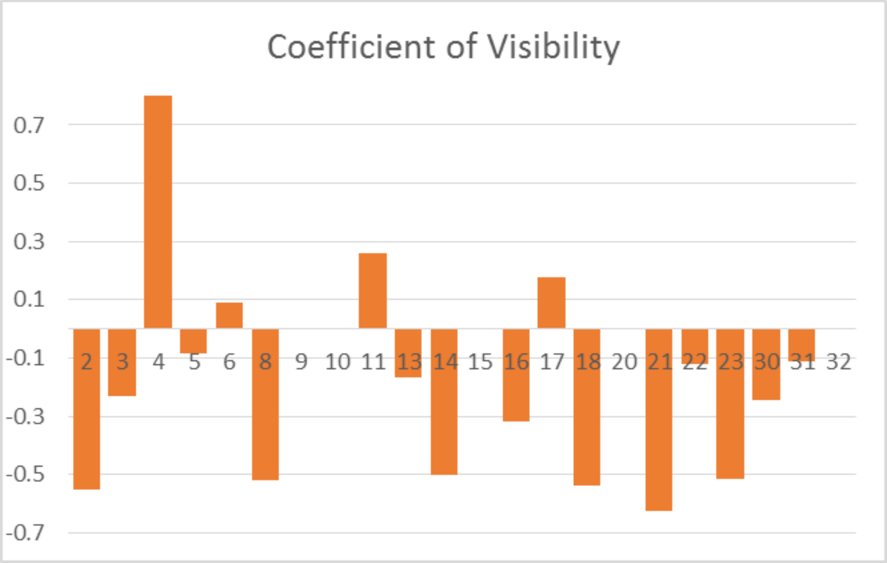

Figure 24 Coefficients of Visibility in Speed Variation Model

- Visibility: Modeling results in Figure 24 shows that an increase in visibility could lead to a decrease in speed variation. Poor visibility can result in more unexpected accelerations and decelerations and thus leading to more speed variation compared to good visibility. A 10% drop in visibility can increase speed variation by 1.6%, on the average.

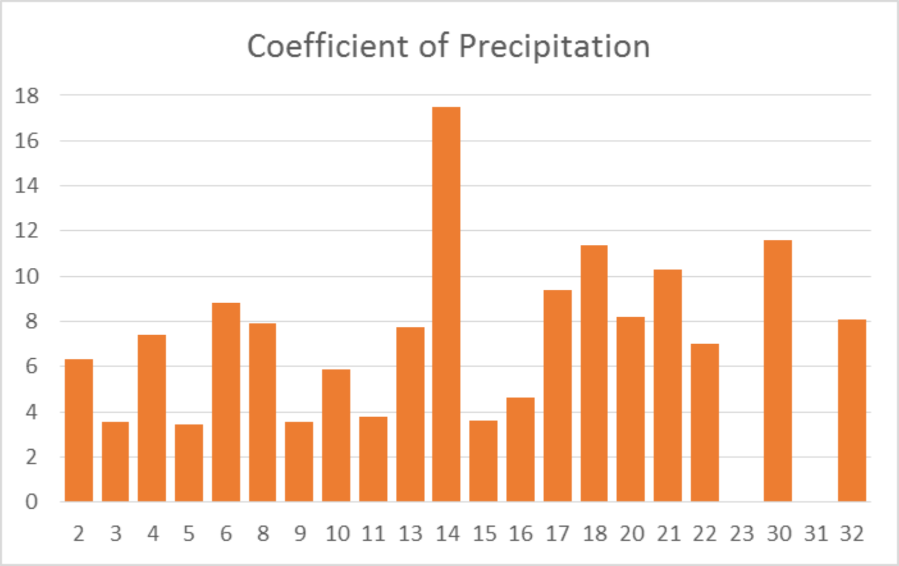

Figure 25 Coefficients of Precipitation in Speed Variation Model

- Precipitation: Precipitation was found to be a significant factor with positive impact on speed variation in Figure 25. High precipitation can not only cause visibility problems but also lead to deteriorated RSC which can result in more speed variation. One centimetre drop in precipitation can cause speed variation to reduce by 7.5%, on the average.

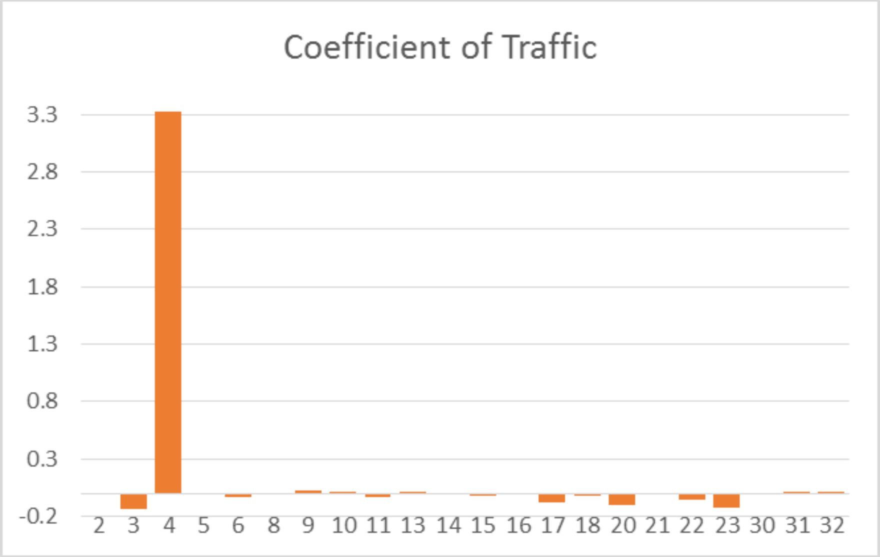

Figure 26 Coefficients of Traffic Volume in Speed Variation Model

- Traffic volume: As shown in Figure 26, modeling results indicates that higher traffic volume would decrease speed variation. High traffic volume will result in less gaps between vehicles and thus forcing them to reduce speed to maintain safe gap between vehicles. Speed variation would decrease by 0.1% with10% higher traffic volume.

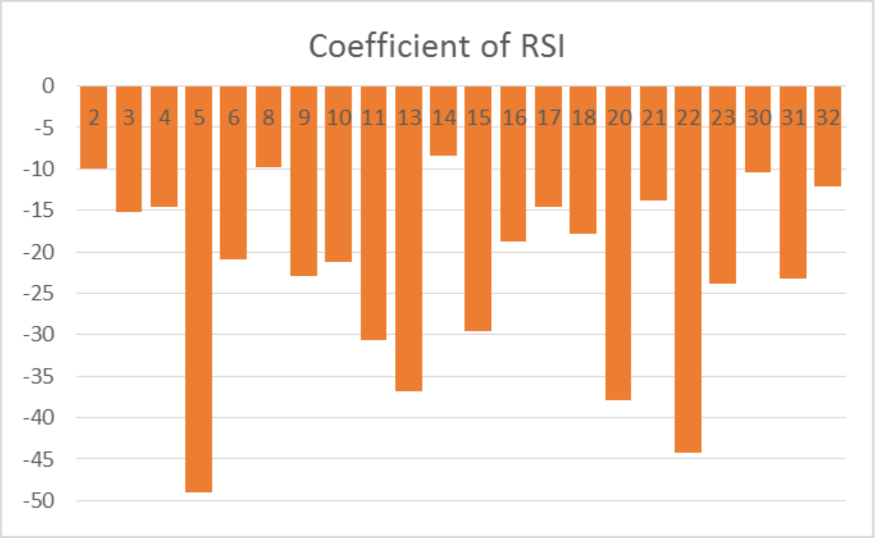

Figure 27 Coefficients of RSI in Speed Variation Model

- RSI: RSI was found to be a significant factor affecting speed variation in Figure 27. Results indicate that with improvement in RSC, speed variation will decrease. Poor RSC condition could result in different speed profiles for different vehicles based on their braking capabilities and the required stopping site distance thus leading to an increase in speed variation. Every 0.1 decrease in RSI would lead to 2.2 increase of speed variation.

All the values of variable coefficients are supported by the previous qualitative test in Table 13. Applying this speed distribution model results to the input of the emission simulator, we could estimate the vehicular air emissions with RSC. This will be introduced in the next chapter.

CHAPTER 5

APPLICATIONS TO THE ESTIMATION OF AIR EMISSION AND ENERGY CONSUMPTION

By combining the average speed model and speed variation model developed in Chapter 4, speed distribution can be estimated according to weather, road surface and traffic conditions. The effects of adverse weather and RSC on the distribution of vehicle speed on a highway is quantified, which is the first component of this research. This section shows two applications of the developed models, including quantifying the effects of RSC on vehicular emissions and evaluating the environmental benefits of WRM.

5.1 Effect of Road Surface Condition

The change of road surface condition directly affects WRM, one needs to explore the relationship between RSC and vehicular air emission before evaluating the environmental benefits of WRM. To quantify how vehicular air emissions and energy consumption would change with WRM activities, a case study was conducted to simulate emissions and energy consumed under different RSC. RSI is used as the indicator of RSC in this study.

Model using data from Site 11, which was randomly chosen, was used to explore the relationship between Road Surface Condition and traffic emission in this case study. Hourly vehicular air emissions under different road surface index (RSI from 0.05 to 1) were estimated through the speed distribution and air emission models.

In this case study, I randomly chose a weekday of 2005 in February, which usually contains a lot of snow event, as study date, and the time spans was 8:00 am to 9:00 am. The weather condition (hourly average temperature and humidity) and the traffic volume were obtained from the site #11. The following four types of air pollutants and total energy consumption were estimated within the hour:

- Greenhouse Gases (/g)
- Harmful Gases (CO, NO, NO_2, SO_2, Volatile organic compounds/g)

- PM 2.5 (Total and non-exhaust/g)
- PM 10 (Total and non-exhaust/g)
- Total energy(/J)

Results were plot are summarized in figures below:

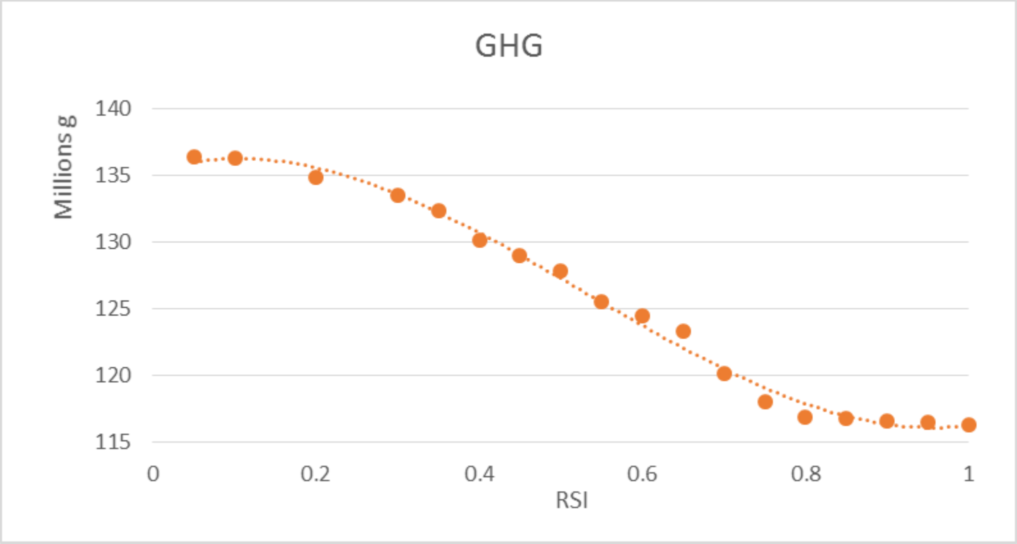

Figure 28 Greenhouse Gases vs RSI

Figure 28 shows that Greenhouse Gases decreased with increasing RSI. It implies that better RSC can reduce GHG emissions. GHG emissions drops rapidly when RSI is between 0.2 to 0.8, while there is relatively low reduction or little increase when the RSI is lower than 0.2 and between 0.8 and 1. According to the classification of RSI, when RSI is less than 0.2, the RSC can be described as icy. It indicated that the volume of ice on the road surface would not make too much differences of average speed when the road is icy; while when RSI value is larger than 0.8, the road surface is basically bare. Wet surface would not have much adverse impact on driving condition, because as the RSI definition shows, water has much less negative impacts on road surface friction than snow or ice;

On the other hand, when RSI reached 0.8 and above, there is no further reduction in GHG emission reduction. This is reasonable because when road condition is good enough, traffic condition and engine combustion both become stable regardless of the extra improvement in road condition.

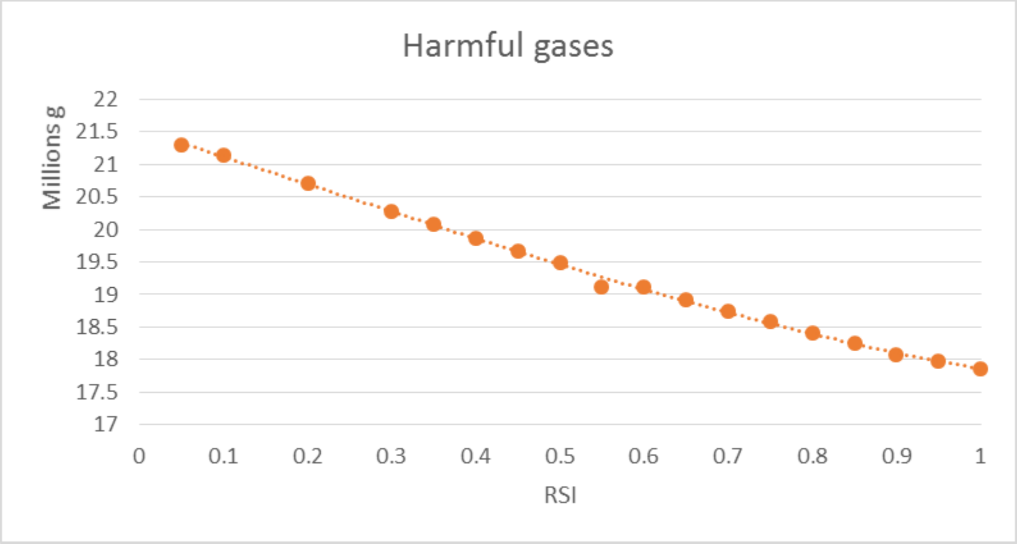

Figure 29 Harmful Gases Emissions vs. RSI

As seen in Figure 29, the mass of harmful gases (CO, NO, NO_2, SO_2 and Volatile organic compounds) was found to decrease almost linearly when RSI changed from 0.05 to 0.7, and when RSI is greater than 0.7, the reduction rate is getting small. It implies that a 10% improvement of RSC can result 350 kg reduction of harmful gas emissions.

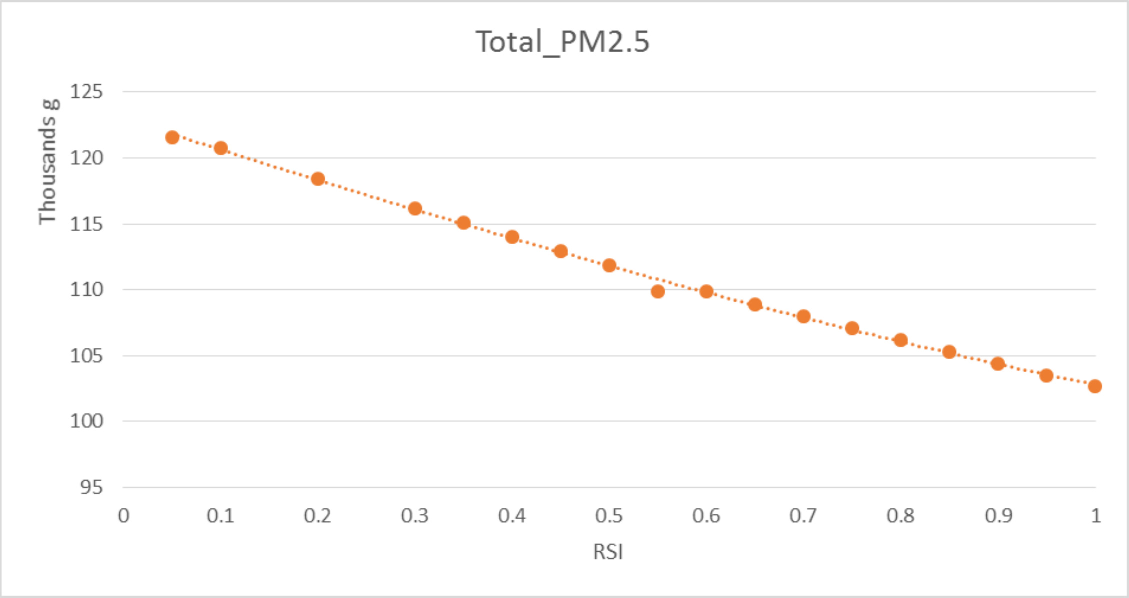

Figure 30 Total PM 2.5 vs. RSI

In Figure 30, linear trend is obvious when correlating RSI value with total PM 2.5 emission, and it has a similar patter with harmful gas. When the RSC is getting better, total PM2.5 emission is decreasing. Again, the slope for relatively low RSI value (less than 0.55) is slightly greater than that for high RSI. 10% drop of RSI value results in 2 kg reduction of total PM 2.5 on average during this one hour.

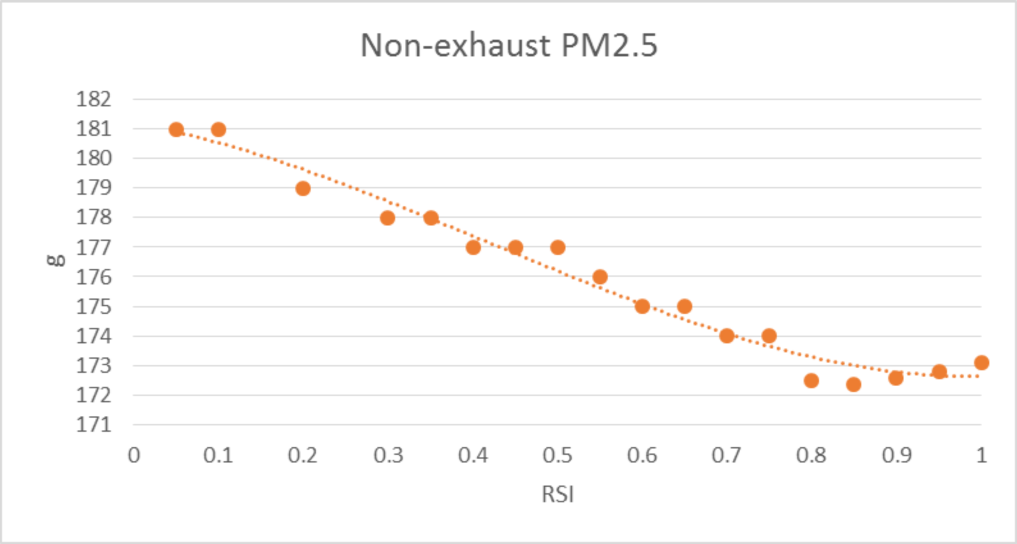

Figure 31 Non-exhaust PM 2.5 vs. RSI

Figure 31 presents a negative relationship between non-exhaust PM 2.5 emission and RSI. Again, the slope with relatively low RSI value (less than 0.8) is slightly greater than that for high RSI (0.8-1). It indicated that as long as the road surface is bare, wet condition would not have much adverse impact on driving condition or non-exhaust PM 2.5 emission. The pattern of non-exhaust PM 2.5 seems to fluctuate than other pollutants presented above. In total, 10% drop of RSI value resulted in 0.2 g reduction of Non-exhaust PM 2.5 on average during this one hour.

Figure 32 Total PM 10 vs. RSI

The mass of total PM 10 emission in Figure 31 was found to decrease almost linearly when RSI changed from 0.05 to 1. It implies that a 10% improvement of RSC can result in around 2 kg reduction of harmful gas emissions on average.

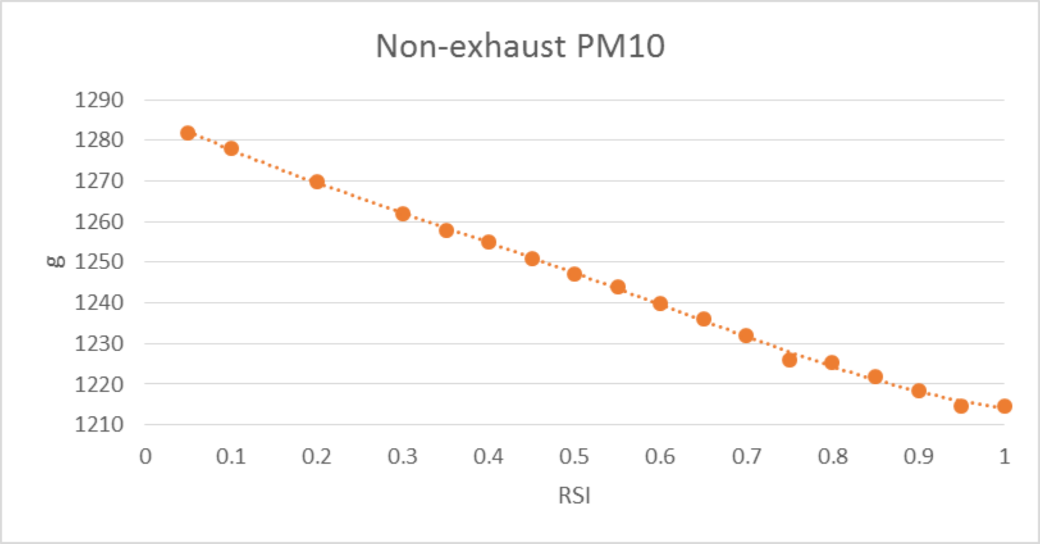

Figure 33 Non-exhaust PM 10 vs. RSI

The Figure 33 presents a negative relationship between non-exhaust PM 10 emission and RSI, which means non-exhaust PM 10 emission would be reduced when RSC is getting better. Similar to the results of GHG, non-exhaust PM 10 emission dropped more sharply when RSI is less than 0.25 than RSI is greater than 0.8. It is reasonable because when RSI value is less than 0.8, road surface would be fully or partly covered with snow or ice according to the classification of RSI; when the RSI value exceeds 0.8, it means that road surface is mainly bare. Around 6 g reduction of non-exhaust PM 10 emission was observed with RSI had 10% improvement on average in this study, which means there is only little impact of PSI on non-exhaust PM 10.

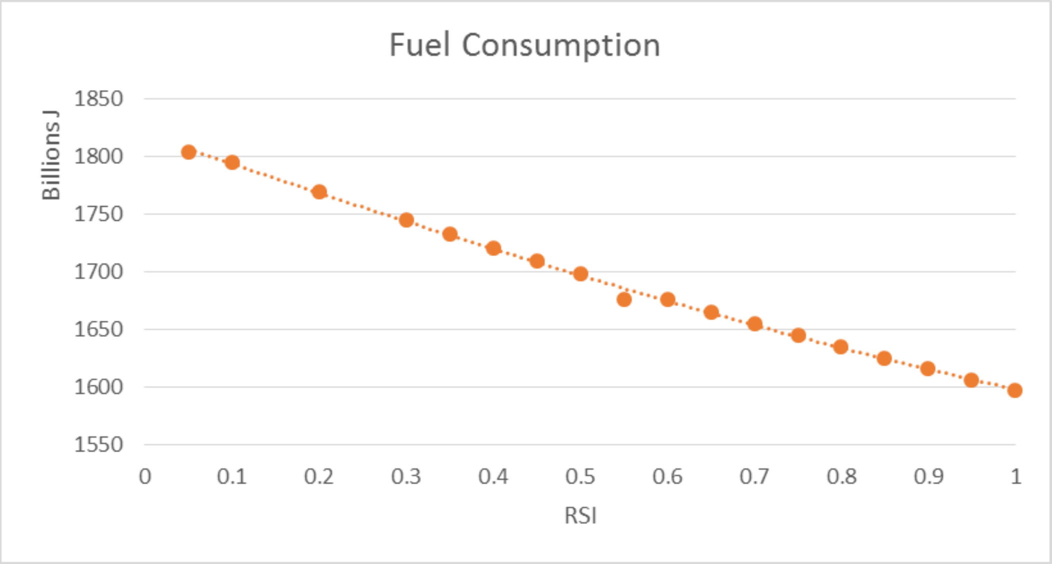

Figure 34 Total Fuel Consumption vs. RSI

Figure 34 shows that fuel consumed decreased with increasing RSI. It implies that better RSC can save the total energy consumed. The pattern showed above was similar to the pattern of harmful gas and demonstrated that there was a basic linear and negative relationship between total energy and RSI value. On average, 20 billion Joule could be saved when the RSI have 10% improvement, which equals to 252.92 L gasoline of #87 and 278.212 CAD Dollars based on current gas price.

On the other hand, the trend line shows a continuous drop in fuel consumption even when RSI reached a certain level of 0.8. This seems to be against common sense because when RSI reaches 0.8 and higher, the engine combustion efficiency and the traffic volume both become stable. As a result the GHG emission became stable as indicated in Figure 28. This contradictory results in Figure 28 and 34 deserve further investigation, and the models should be improved in the future.

5.2 Effect of Winter Road Maintenance

To demonstrate the application of the developed models, a particular patrol route – Site 11 was selected for a case study. The route is 78.2 km long and has an annual average daily traffic (AADT)of 17000. The case study is to quantify the implications of different maintenance schedule on total air emissions and energy consumption during a particular snowstorm.

Throughout this research events are identified based on the definition used in the database prepared by Taimur Usman (2010) as part of his review on the safety impact of winter maintenance. Each event spans a period from the time when precipitation is first observed and ends when road surface condition of bare has been recovered. In order to qualify as a winter event the temperature must also have been below 5°C and the road surface condition must drop below the level of bare surface.

The snowstorm is assumed to have the following characteristics (the average values for each variable in Site 11 were used in this case study):

- Duration = 8 hours
- Wind Speed = 4 km/h
- Temperature = -2℃
- Hourly precipitation = 2.75 cm
- Visibility = 10 km

The road surface condition of this route, as represented by RSI, is assumed to vary over the event as follows:

- At the beginning of the snow event, the RSI is 1.0 since the road surface is bare and dry.
- The road surface condition ends up with an RSI of 0.2 in the first hour, the road surface is snow packed with ice.
- In the first scenario, it is assumed that little maintenance work was done, and the road surface would remain at RSI=0.2 until the end of the event for 8 hours.
- For the cases with maintenance activities (Scenario 2-4), a combination of ploughing and salting operation is conducted at Hours 3, 4 and 6, and this would improve the road surface condition to a mixed state of slushy, wet, and partially snow covered with an RSI value of 0.8. It is assumed that the effect of salt would last for five hours, and the corresponding
- RSI would reduce linearly from 0.8 to 0.2.
- To demonstrate how the effect is quantified, the benefit of WRM on vehicular air emissions is defined as percentage of reduction in air emissions between the scenario that WRM is delivered at a particular hour and one without WRM. In the scenarios with WRM (scenario 2-4), we consider the aforementioned snow event with the maintenance operations (ploughing and salting) completed at the start of the third, fourth and sixth hour.

Table 17 below shows the hourly emissions and energy consumption of all kinds of pollutants.

Table 17 Hourly emission and energy consumption

		Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6	Hour 7	Hour 8
No WRM	GHG/g	7.43E+6	1.37E+6	1.72E+6	4.71E+6	9.37E+6	3.54E+6	7.86E+6	2.12E+8
	Total PM 10/g	11926	19029	1757	5264	11235	44083	99855	272380
	Total PM 2.5/g	10550	16833	1554	4657	9939	38996	88334	240952
	Energy/J	1.03E+11	1.9E+11	2.39E+10	6.55E+10	1.3E+11	4.92E+11	1.09E+12	2.94E+12
	Harmful Gases/g	2173115	3560567	445692	1178661	2018440	7685077	17088033	46493591
	Non-exhaust PM 10/g	16	12	11	11	15	31	63	90
WRM at Hour 3	GHG/g	7.43E+6	1.37E+6	1.56E+6	4.32E+6	8.75E+6	33609780	76941760	2.12E+08
	Total PM 10/g	11926	19029	1564	4805	10457	41844	97763	272380
	Total PM 2.5/g	10550	16833	1383	4251	9250	37016	86483	240952
	Energy/J	1.03E+11	1.9E+11	2.17E+10	6.01E+10	1.22E+11	4.68E+11	1.07E+12	2.94E+12
	Harmful Gases/g	2173115	3560567	398686	1077586	1879277	7294340	16728992	46493591
	Non-exhaust PM 10/g	16	12	10	10	15	31	63	90
WRM at Hour 4	GHG/g	7429322	13666446	1720731	4207391	8586190	32957210	74646248	2.07E+08
	Total PM 10/g	11926	19029	1757	4670	10254	41011	94781	266655
	Total PM 2.5/g	10550	16833	1554	4131	9071	36279	83845	235888
	Energy/J	1.03E+11	1.9E+11	2.39E+10	5.85E+10	1.19E+11	4.59E+11	1.04E+12	2.88E+12
	Harmful Gases/g	2173115	3560567	445748	1047879	1843077	7148995	16217379	45514707
	Non-exhaust PM 10/g	16	12	10	10	15	30	63	89
WRM at Hour 6	GHG/g	7429322	13666446	1719682	4705838	9371470	31439610	71798968	1.97E+08
	Total PM 10/g	11926	19029	1757	5264	11235	39074	91083	253335
	Total PM 2.5/g	10550	16833	1554	4657	9939	34566	80574	224105
	Energy/J	1.03E+11	1.9E+11	2.39E+10	6.55E+10	1.3E+11	4.37E+11	9.99E+11	2.74E+12
	Harmful Gases/g	2173115	3560567	445692	1178661	2018440	6810993	15582790	43237106
	Non-exhaust PM 10/g	16	12	11	11	15	30	62	88

To make it more clearly, the hourly reduction percentage for each pollutants and energy were calculated and plotted below. As shown in Figures, the vertical axis represents the hourly reduction percentage of a given air pollutant or total energy consumption by proper maintenance. The solid lines represent the emission reduction change when WRM happen at 3rd hour; the squat dot lines represent the emission reduction change when WRM happen at 4th hour; and the long dash dot lines represent the emission reduction change when WRM happen at 6th hour. It was assumed that if there is no WRM during this event, the reduction emission reduction would be zero throughout the event. Each points represents hourly reduction percentage.

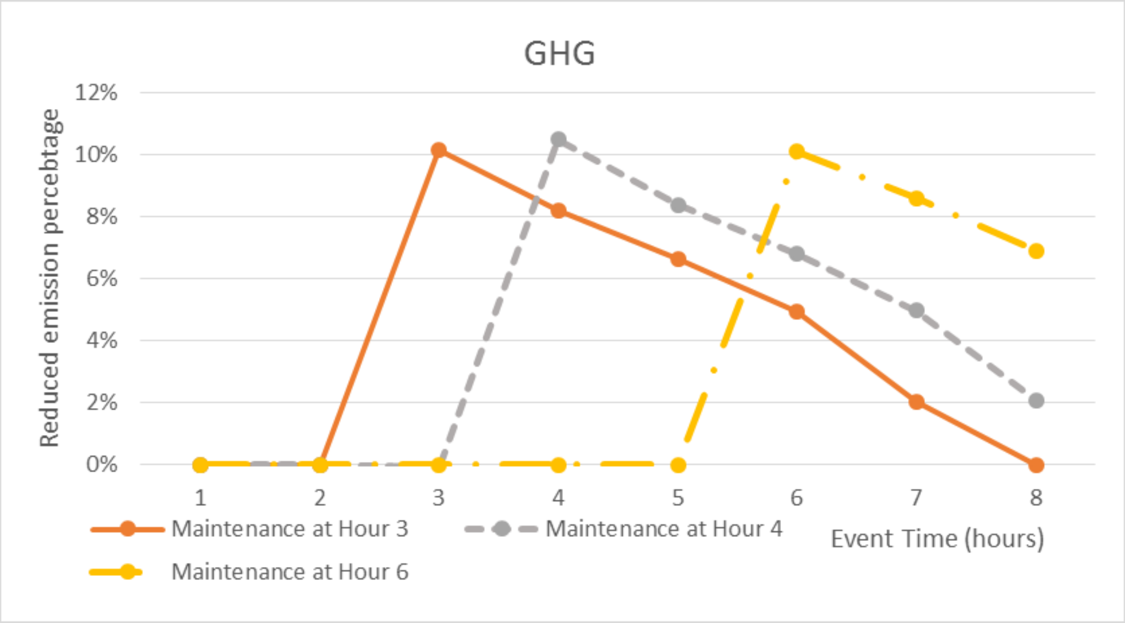

Figure 35 GHG Emission Reduction vs. Maintenance Timing

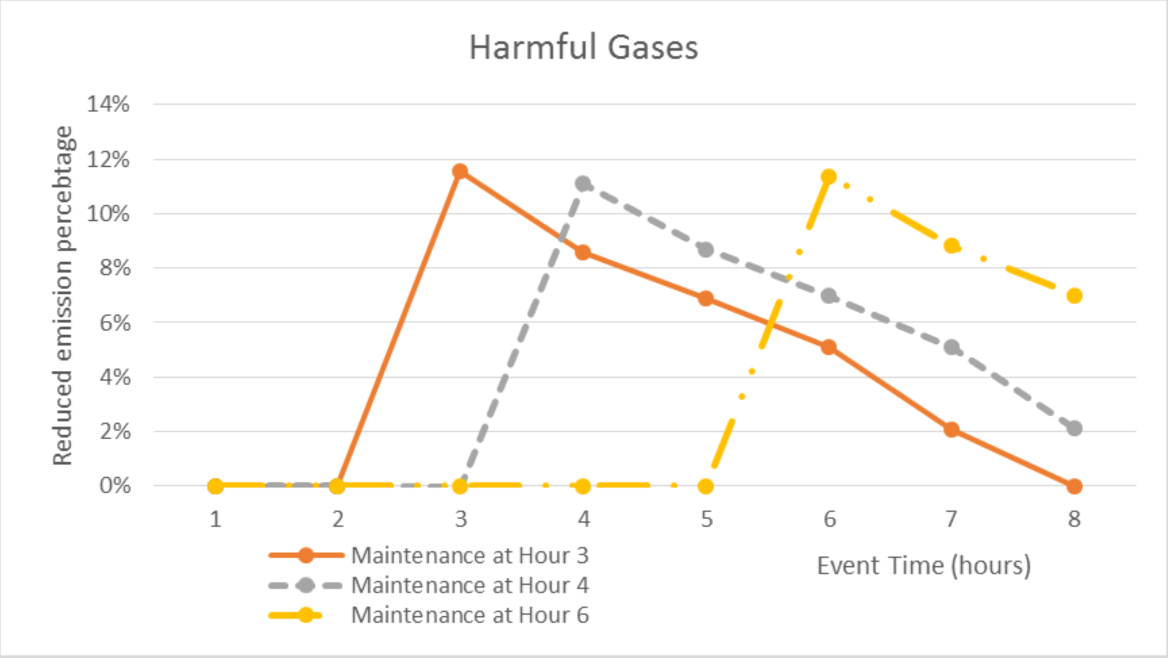

Figure 36 Harmful Gases Emission Reduction vs. Maintenance Timing

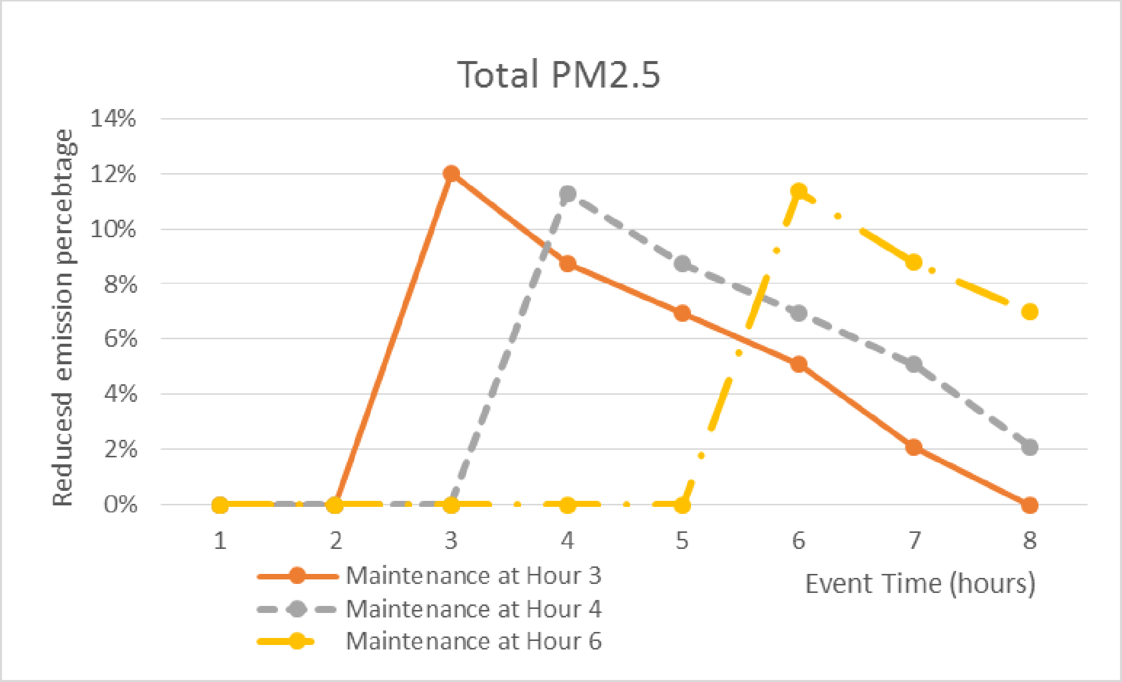

Figure 37 Total PM 2.5 Emission Reduction vs. Maintenance Timing

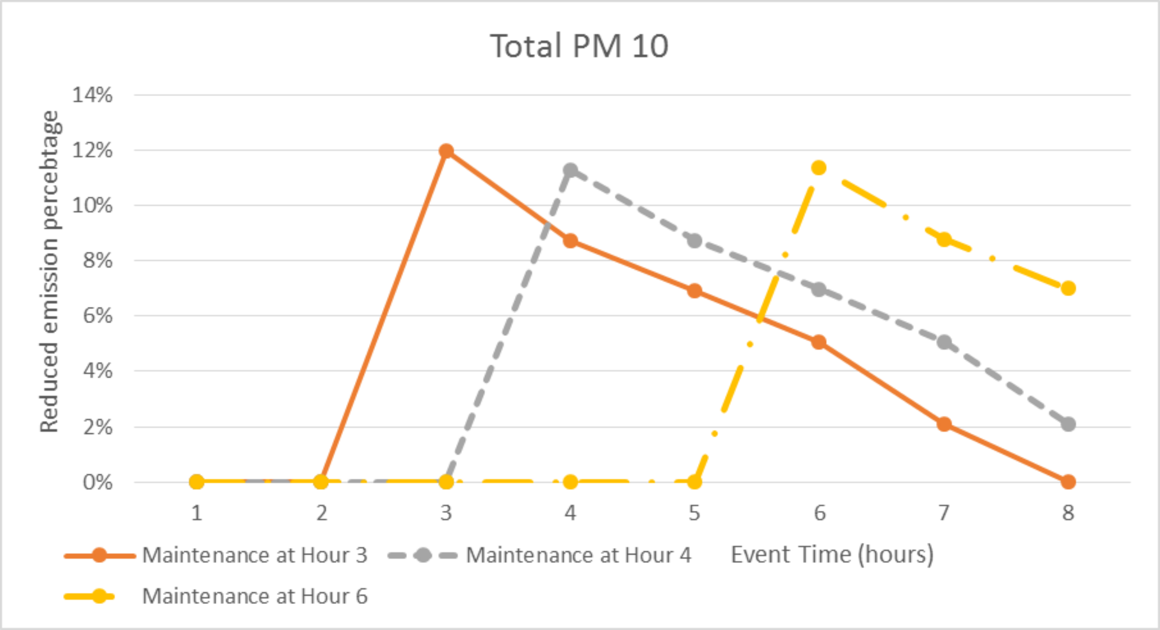

Figure 38 GHG Emission Reduction vs. Maintenance Timing

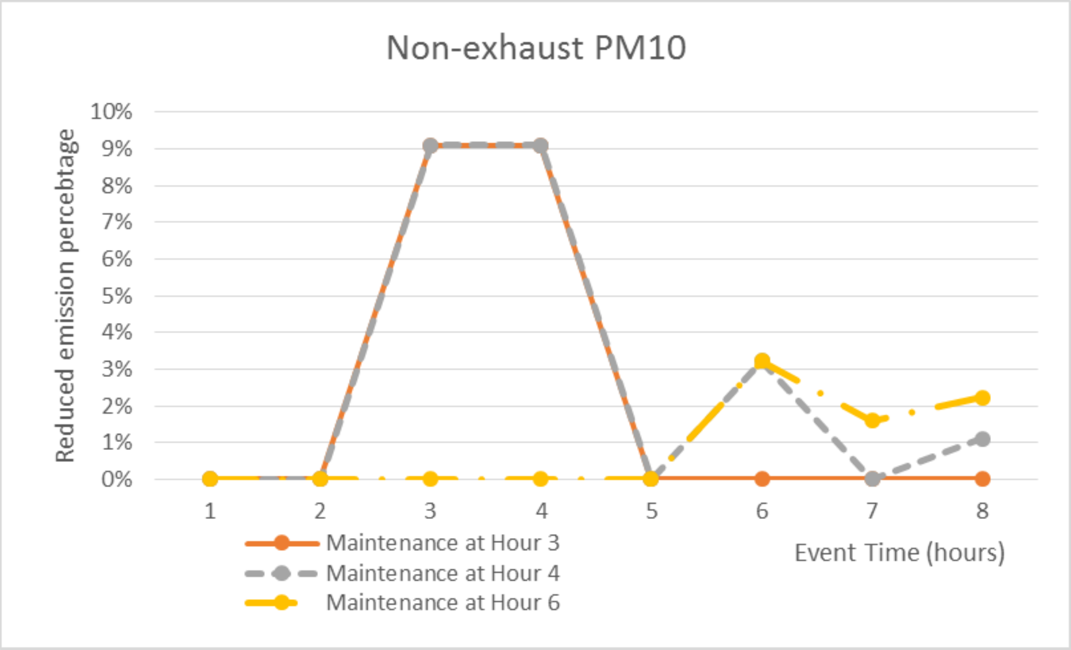

Figure 39 Non-exhaust PM 10 Emission Reduction vs. Maintenance Timing

All the patterns except non-exhaust PM 10 emission are found to be similar to each other. There was a continuous reduction in emission right after road maintenance, regardless of the starting time. As shown in Figure 39, the results non-exhaust PM 10 seems to be more fractured than other pollutants. One reason could be that the total volume of non-exhaust PM 10 is negligible compared to others and the simulation outputs are all integers, so the results of small value may not be accurate as expected.

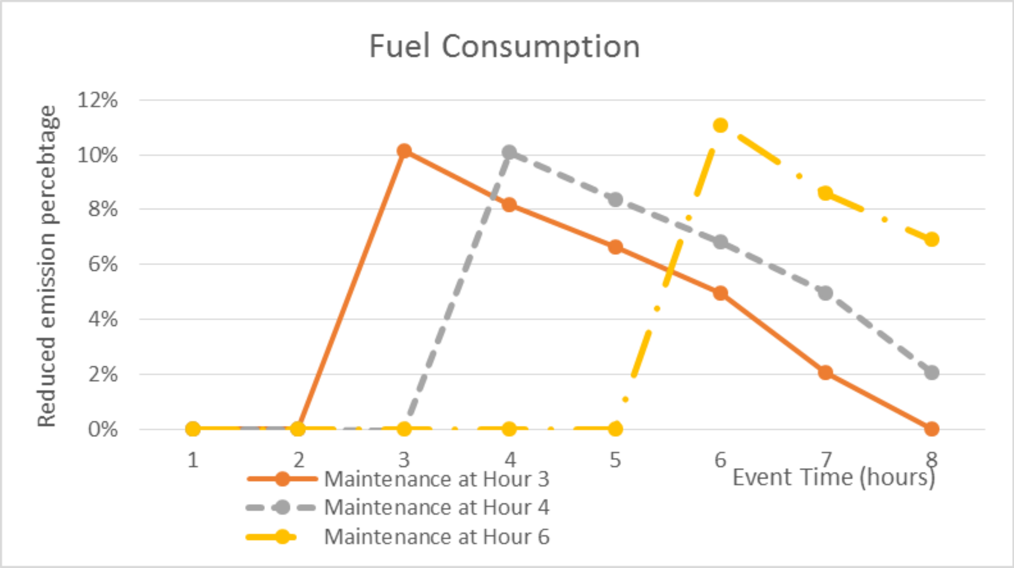

Figure 40 Fuel Consumption Saved vs. Maintenance Timing

To quantify the average benefit for each scenario, the hourly emission reduction of WRM over the entire snow event is summarized in Table 18.

Table 18 Effects on WRM over the event

	WRM at Hour 3		WRM at Hour 4		WRM at Hour 6	
GHG/g	1.49E+7	4.10%	1.48E+7	4.08%	1.16E+7	3.20%
Total PM10 /g	20252	4.35%	19883	4.27%	15793	3.39%
Total PM2.5 /g	17928	4.35%	17594	4.27%	13969	3.39%
Total Energy /J	2.017E+11	4.00%	2.03E+11	4.03%	1.68E+11	3.33%
Harmful Gases/g	3447720	4.28%	3422037	4.24%	2740527	3.40%
Non-exhaust PM10/g	4	2.27%	4	2.81%	1	0.88%

Table 18 shows that when WRM was conducted at hour 3, the benefit could reach 4.3% per hour; there was a 2.8% to 4.2% reduction per hour in air emissions for the case, where maintenance starts at hour 4; 1.6% to 3.4% reduction was achieved when WRM took place at hour 6. Overall, conducting WRM at 3rd hour was found to be the most beneficial one during the event. It indicates that, in a snowstorm event, the effects of an earlier WRM activity would last longer and have a greater benefit than late ones. At hour 8, RSI value would become 0.8, 0.68 and 0.44 for WRM timing of 3rd, 4th, 6th hour, and all of them would increase slowly at the same speed. Therefore, the road surface under WRM at hour 3 would have the least negative impacts on driving condition

This methodology calculates environmental impact on WRM in first time, but it still has some limitations: (1) It is based on the assumption that the speed distribution is the only direct inflicting factor to capture the changes of WRM in emission models. However, in reality other factors may also affect emissions (e.g. the driving trajectory may be changed by different WRM activities); (2) car is consider to be the only kind of vehicle in this research, different composition of vehicle may change the emission pattern, too.

CHAPTER 6

CONCLUSION AND FUTURE WORK

According to the literature review, much work has been done to explore the relationship between weather and road condition and the benefits of WRM in terms of mobility and safety. Few researchers, however, were considering the environmental impacts (vehicular air emissions and fuel consumption). This study has attempted to develop a quantitative understanding of the relationship between winter road surface conditions (RSC) and vehicular air emission and energy consumption, which is critical to answer the question of how beneficial winter road maintenance is in terms of reducing fuel consumption and air emission.

Most studies related RSC, fuel consumption and vehicular emission used either lab collected or real-world collected sample data at several specific sites and hours, which usually have small sample sizes. In this research, a large data set from 22 highway routes through Ontario in Canada for six winters was used to calibrate the model. More than 250,000 hourly observations could support more convincing modelling results.

Through an intermediate variable – vehicle speed, we established a quantitative relationship between winter road surface condition and vehicular emissions including GHG, harmful gases and PM, and energy consumption. Many studies have been exploring the relationship between weather or road surface condition and average speed; however, most of them ignored the impact of speed validation. In this study, speed variation under different winter weather and road surface conditions were first investigated. Using multiply linear regression, a speed distribution model, including hourly average speed model and speed variation model, established as a function of various winter weather factors and a measure of road surface condition under the assumption of normal distribution. The speed distribution model was then coupled with US EPA's emission estimation model – MOVES to estimate the vehicular emission and energy consumption under different road surface conditions.

The results based on one specific site data showed that better RSC can reduce both the vehicular air emissions and energy consumption, and a 10% improvement in RSC would result in 0.6% to 2% reduction in vehicular air emissions. In terms of different pollutants, 10% increases of RSI value would lead to 1.91% reduction of GHG, 2.21% reduction of harmful gases, 2.04% decrease of total PM 2.5, 0.51% reduction of non-exhaust PM 2.5 emission, 2.05% for total PM 2.5 emission, 0.62% reduction of non-exhaust PM 10 emission, and 1.44% saving of energy consumption, respectively.

Another case study was conducted to evaluate the benefit of winter road maintenance under specific winter events. The results based on the specific site showed that the effects of an earlier WRM operation would last longer and have a greater benefit than late ones during a snow event.

Several research extension related to this study are possible, which could lead to better understand of the effects of WRM on vehicular air emissions and fuel consumption. In particular, the following extensions could be conducted to improve on the ability to practically apply the study findings to road surface or WRM management:

- In terms of the evaluation of the environmental impact, this study only used emission volume and total consumption of energy as indicators. A further improvement would be applying unit cost of different kinds of pollutants and the unit price of fuel on the benefits calculation, and use monetary indicators to evaluate the impacts of vehicular air emissions and the energy saving from the RSC change, which would be easier for decision makers and road user to understand the benefits.

- In this research, we calibrated Poisson and linear regression models only; however, other model structures such as time series cross section models and multilevel models could also be calibrated for this data.

- Only a one hour event (8:00am- 9:00am on a weekday) was considered in the case study to estimate the impact of WRM timing. The variance of traffic conditions between both peak hours and off peak hours and weekdays and weekends may also have impacts on the vehicular air emissions and energy consumption.

- In the second case study, there was only one type of maintenance approach (ploughing and salting). However, there are many other kinds of WRM actives, such as anti-icing, de-icing and sanding in reality. Apply more types of maintenance actives on the evaluation would make the results more specific for the practical application.

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