Quantifying the Mobility Benefits of Winter Road Maintenance – A Simulation Based Approach

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.

I understand that my thesis may be made electronically available to the public.

Abstract

A good understanding of the relationship between highway performance, such as crash rates and travel delays, and winter road maintenance activities under different winter weather and traffic conditions is essential to the development of cost-effective winter road maintenance policies and standards, operation strategies and technologies. This research is specifically concerned about the mobility benefit of winter road maintenance. A microscopic traffic simulation model is used to investigate the traffic patterns under adverse weather and road surface conditions. A segment of the Queen Elizabeth Way (QEW) located in the Great Toronto Area, Ontario is used in the simulation study. Observed field traffic data from the study segment was used in the calibration of the simulation model. Different scenarios of traffic characteristics and road surface conditions as a result of weather events and maintenance operations are simulated and travel time is used as a performance measure for quantifying the effects of winter snow storms on the mobility of a highway section. The modeling results indicate that winter road maintenance aimed at achieving bare pavement conditions during heavy snowfall could reduce the total delay by 5 to 36 percent, depending on the level of congestion of the highway. The simulation results are then applied in a case study for assessing two maintenance policy decisions at a maintenance route level.

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Dedication

This thesis is dedicated to my parents, my wife Reem and my son Abdullah.

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Chapter 1
Introduction

1.1 Background

Adverse winter weather conditions such as winter snow storms have a significant impact on traffic operations of all highway classes. Snow and ice on road surface reduce pavement friction, and thus affect the driving conditions. Under these conditions drivers must reduce their speed and increase their following headways to maintain an acceptable level of safety (FHWA 2004). Past research indicates that heavy snow falls could reduce free flow speeds up to 40 percent and capacity up to 30 percent as compared to those during normal weather conditions (Ibrahim and Hall, 1994; HCM 2000). In addition, it has been found that travel time in adverse weather conditions such as fog, ice, snow storms increases up to 36 percent on major US highways (Han et al., 2003). According to FHWA (2008), adverse weather accounts for approximately 544 million vehicle-hours of delay per year or 23 percent of the total non-recurrent delay on the US highways.

Severe winter snow storms could also lead to increased traffic incidents and thus increased traffic delay. Past studies indicate that highway accident rates increase significantly during adverse weather conditions as compared to normal weather conditions. Andrey et al. (2003) found that traffic collisions increased by 75 percent and related injures increased by 45 percents due to adverse weather conditions (snowfall and rainfall). Moreover, 22percent of crashes in the US occurred under adverse weather conditions (Goodwin, 2003).

Furthermore, depending on their intensity and duration, winter snow storms could cause many trips being rescheduled or cancelled, leading to another form of productivity and economic losses. Past research indicates that winter storms could reduce traffic by over 50 percent (Hanbali and Kuemmel, 1993).

The safety and mobility impacts of snow storms could be reduced through effective winter road maintenance operations such as plowing, salting and sanding. Maintaining bare pavement enhances skidding resistance between vehicle tires and pavement surface and therefore increases safety and roadway capacity and reduces travel time and delay. Despite these safety and mobility benefits, winter maintenance operations are also costly, both economically and environmentally. Statistics Canada (2008) reported that the total budget allocated by Canadian government in 2006 for snow removal was about \$1.25 billion. Furthermore, approximately five million tonnes of sodium chloride were used on Canadian roads (Morin and Perchanok, 2003), which has already been designated as being detrimental to the environment by Environment Canada (2009). It is therefore paramount to develop a sustainable winter road maintenance program that minimizes maintenance costs and salt usage without compromising road safety and mobility.

A good understanding of the relationship between highway performance, such as crash rates and travel time delays, and winter storm characteristics and road surface conditions is essential to the development of cost-effective winter road maintenance policies and standards, operation strategies and techniques. This research is specifically concerned about the mobility benefit of winter road maintenance.

1.2 Research Problem

Winter snow storms have a significant impact on the mobility of highways due to reduced friction between vehicles tires and the pavement surface. Significant research efforts have been devoted to modelling of the quantitative relationship between highway mobility and various factors related to weather, maintenance operations, and traffic. On the mobility part of the problem, most past studies have focused on the link between different weather variables such as precipitation intensity and wind speed, and traffic characteristics such as speed, capacity, and volume (Hanbali and Kuemmel, 1993; Ibrahim and Hall, 1994; Kyte et al., 2000; Kyte et al., 2001; Knapp et al., 2000; FHWA 2006; Datla and Sharma, 2008). In addition, a few past studies have attempted to capture pavement surface conditions in the relationship between speed and weather conditions (Liang et al., 1998; Kyte et al., 2000; Kyte et al., 2001; Knapp et al., 2000; Kumar and Wang, 2006). However, none of these past studies have investigated the direct effects of road surface conditions on capacity. Some attempts have been made to investigate the effect of weather variables on travel time delay at a national level (Han et al., 2003; Chin et al., 2004), but these studies did not investigate the effect of pavement surface conditions. Stern et al. (2003) used travel time data from SmarTraveler website (http://www.smartraveler.com/) to study the effect of adverse weather conditions and pavement surface conditions on travel time on 33 bi-directional road segments in Washington, D.C. during peak and off-peak periods, but the developed models establishing relationship between travel time and weather variables have little explanatory power (coefficient of determination less than 0.05 percent for peak period model and 0.23 percent for off-peak periods).

Despite these significant past efforts, one important issue remains to be addressed: what is the magnitude of effect of winter road maintenance on improving traffic conditions? While it is generally known that winter road maintenance plays a critical role in maintaining safe and efficient travel conditions through timely snow and ice control; however, it is largely unknown what is the exact relationship between the amount of winter road maintenance (input) and the safety and mobility benefits (outcome). This research focuses on the mobility benefit of winter road maintenance with the specific objective of quantifying the travel time and delay of a typical highway under specific road weather and traffic conditions.

1.3 Research Objectives

The main goal of this research is to quantify the effects of winter snow storms on the mobility of Ontario highways under various traffic characteristics and road surface conditions as a result of maintenance operations. The research outcome is promised to help facilitate comprehensive and systematic cost-benefit analysis of various strategic and operational decisions arising in winter road maintenance management. The research has the following specific objectives:

1. Conduct a comprehensive review of past research on the impacts of adverse winter weather conditions and road maintenance activities on highway mobility;
2. Propose a methodology that can be used to model traffic flow under various winter weather and road surface conditions and thus expected mobility effects of winter maintenance operations.
3. Conduct a case study to illustrate the application of the proposed methodology for evaluating a typical set of maintenance policy and decisions such as bare pavement recovery time and maximum allowable snow accumulation.

1.4 Organization of Thesis

The rest of this thesis is organized in four chapters. Chapter 2 presents the literature review that covers past research on the effects of adverse weather conditions, such as precipitation intensity, wind speed, visibility, on traffic flow parameters and operations. Chapter 3 explains the INTEGRATION simulation model, the study network, the calibration process of the simulation network, and the modeling of snow storm effects and maintenance levels. Chapter 4 presents the analysis results from the simulation study in Chapter 3, and applications for the mobility benefit model. Chapter 5 summarizes the main conclusions of the research and recommendations for further studies.

Chapter 2
Literature Review

Adverse winter weather conditions have a negative impact on traffic operations of all highway classes on both demand and supply sides. Winter snow storms affect road environment by reducing visibility and pavement friction. As a result drivers need to reduce their speed and increase their following distance headways, causing reduction in capacity and increase in travel time. Furthermore, the adverse weather conditions contribute to increased traffic incidents and thus increased congestion and delay. Moreover, poor weather and road surface conditions could bring significant travel difficulties, causing trips rescheduling and cancellation. All these negative effects of winter weather coupled with the need to develop cost-effective winter road maintenance policies and strategies have stimulated a large number of past studies devoted to the problem of quantifying the specific impacts of winter weather on traffic conditions. This section attempts to summarize the findings of these studies with a specific focus on the effects of winter storms on traffic demand, speed, roadway capacity, and delay.

2.1 Effects of Adverse Weather Conditions on Traffic Flow Parameters

As mentioned earlier, poor visibility and road surface traction due to adverse winter weather require drivers to adjust their driving behavior such as reducing speed and increasing car-following distance. These changes in driving behavior could lead to changes in macroscopic traffic patterns as represented by the fundamental relationships between the three traffic stream variables, namely, speed, flow and density. Knowledge about the impact of weather on these relationships allows quantification of the overall impact of weather on mobility. Hence, a number of past studies have been devoted to this topic, especially, to the issue of how weather affects the four key parameters, including free flow speed, capacity, speed at capacity, and jam density, which characterizes the fundamental speed-flow relationship. Figure 2.1 shows one of the traffic stream models and the four key parameters. This section reviews the major findings of these studies.

2.1.1 Effects of Adverse Weather Conditions on Free Flow Speed

Free flow speed (*FFS*) is defined as the speed that occurs when density and flow rate approach zero (HCM 2000). According to Highway Capacity Manual (2000) the free flow speed is used to describe the average traffic speed that drivers would travel if there were no congestion; it is important for capacity analysis and for determining level of service for uninterrupted flow conditions. Free flow speed of a freeway can be affected by many factors such as lane width and lateral clearance, number of lanes, interchange density, and vertical and horizontal alignments. Moreover, adverse weather conditions can cause a significant reduction in free flow speed (HCM 2000). Ibrahim and Hall (1994) found that the free flow speed on the Queen Elizabeth Way (QEW) in Ontario decreased by 2 percent in light rain and 5-7 percent in heavy rain as compared to normal weather conditions. Moreover, they observed that free flow speed is reduced by 1 percent and 36~40 percent in light snow and heavy snow respectively. These results have been adopted by the Highway Capacity Manual (HCM 2000), as shown in Table 2.1.

Kyte et al. (2000) studied the effects of wind speed, precipitation intensity, pavement surface condition, and visibility on the free flow speed of rural freeways in the United States. The assumed normal baseline condition was one with no precipitation, dry pavement surface, visibility greater than 0.37 km, and wind speed less than 16 km/h (86 5-minutes data, from automatic traffic counters, was used to determine normal speed). The traffic characteristics during the normal conditions are shown in Table 2.2. The authors developed two linear relationships between the free flow speed and several weather related variable using data aggregated over 5-min interval (733 observations), as shown in Equations 2.1 and 2.2.

Table 2.1: Recommended Free Flow Speed for Freeways by HCM 2000

Weather condition	Recommended FFS (Km/h)
Clear and dry	120
Light rain and Light snow	110
Heavy rain	100
Heavy now	70

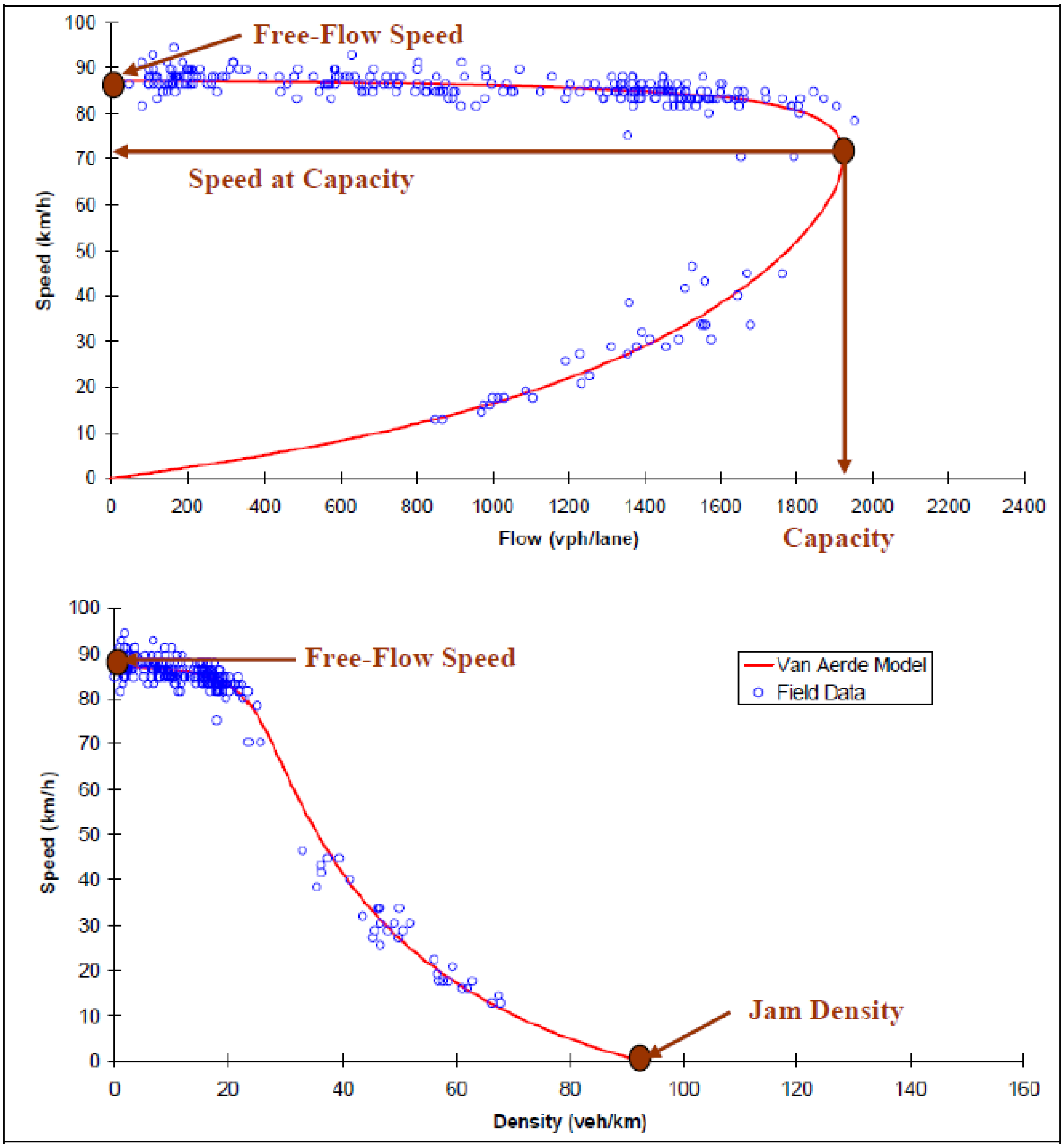

Figure 2.1: Van Aerde Traffic Stream Model for Data from I-4, Orland (Source: Rakha and Crowther, 2002)

Table 2.2: Traffic Characteristics during Normal Weather Conditions (Source: Kyte et al., 2000)

Vehicle type	Mean Speed (km/hr)	Flow Rate (vehicles per hour)		Traffic Composition
		Mean	Range	
Passenger car	117.10	269	12 to 636	52% trucks
Truck	98.80			

$$FFS = 115.82 - 0.34 \times Wind - 4.77 \times PR + 0.62 \times Vis - 4.54 \times SC \qquad (2.1)$$

$$FFS = 126.53 - 9.03 \times Wind - 8.74 \times PR - 5.43 \times SC \qquad (2.2)$$

where

FFS = the free flow speed in km/h,

$Wind$ = dummy variable that represents wind speed. *Wind* equals to 1, 2, 3, and 4 for wind speeds less than 16, 16 to 32, 32 to 48 , and greater than 48 km/h, respectively for Equation 2.1, and it equals 1 for wind speeds equal or less than 48 (km/h) and equals 2 when wind speed greater than 48 (km/h), respectively for Equation 2.2,

PR = dummy variable that represents precipitation intensity. *PR* equals 1, 2, 3, 4 for no precipitation, light precipitation, medium precipitation, and heavy precipitation, respectively,

Vis = dummy variable that represents visibility. *Vis* equals 1, 2, and 3 for visibilities equal or less than 0.16 kilometre, 0.16 to 0.37 kilometre, and equals or greater than 0.37, respectively, and

SC = dummy variable that represents pavement surface condition. *SC* equals 1, 2, 3 if the pavement is dry, wet, and snow or ice covered, respectively.

All variables in Equations 2.1 and 2.2 were statistically significant. For normal conditions, Equations 2.1 and 2.2 estimate the free flow speed as 108.03 (km/h) and 103.33 (km/h) respectively. The difference between the two models is that in the first model the wind speed was categorized into four categories (less than 16, 16 to 32, 32 to 48, and greater than 48 km/h) but in the second model it was categorized into two categories only (less than 48 km/h and greater than 48 km/h). Besides, the visibility is included as a variable in the first model only.

The authors (Kyte et. al., 2000) suggested that the second model was a better representation of the relationship between weather variables and driver speed. Some representative reduction values of free flow speed due to different weather conditions estimated from Equation 2.1 and Equation 2.2 are shown in Table 2.3.

Although Equations 2.1 and 2.2 yield little difference (1 to 2 percent) in terms of the reduction in free flow speed due to road surface condition, they provide different reduction factors for precipitation intensity (4 to 12 percent) and wind speed (8 to 16 percent). The reduction in the free flow speed estimated by Equation 2.2 is almost twice that by Equation 2.1, and the reduction due to wind speed greater than 48 km/h from Equation 2.2 is 9 times the corresponding value from Equation 2.1.

In another study, Kyte et al. (2001) investigated the effect of adverse weather conditions on passenger car free flow speed on a rural freeway (I-84) in Idaho using aggregated 5-minute traffic data (travel speed and traffic flow) and various weather variables (visibility, road conditions, wind speed, and precipitation). The normal condition was defined as dry pavement, visibility greater than 0.28 kilometers, and wind speed less than 24 km/h. They developed a regression relationship between free flow speed and pavement surface condition (wet or snow covered), visibility, and wind speed, using 5-minutes traffic data. The developed model is shown as Equation 2.3.

$$FFS = 100.2 - 16.40 \times Snow - 9.50 \times Wet + 77.30 \times Vis - 11.70 \times Wind \tag{2.3}$$

where

FFS = the free flow speed for passenger car in km/h (base *FFS* = 121.844 km/h),

Snow = dummy variable indicating the presence of snow on the roadway. It equals 0 if pavement is dry and 1 if snow there is on the pavement, *Wet* =dummy variable indicating whether the pavement is wet or not. It equals 0 if pavement is dry and 1 if pavement is wet,

Vis = visibility in kilometers. *Vis* equals 0.28 when the visibility exceeds 0.28 km and equals the value of the visibility when the visibility is less than 0.28 km, and

Wind = dummy variable indicating whether the wind speed exceeds 24 km/h or not. *Wind* equals 0 if wind speed is less than 24 km/h and *Wind* equals 1 if wind speed is greater than 24 km/h.

All coefficients in Equation 2.3 were statistically significant at 0.95 confidence level with *R-Squared* equal to 0.34 and standard error equal to 12.6 km/h. The base free flow speed during the normal weather conditions from the regression model in Equation 2.3 is 121.8 km/h. The reductions in free flow speed due to effects of adverse weather conditions are 8 percent when the pavement surface is wet, 13 percent when the pavement surface is snow-covered, 10 percent when wind speed exceeds 24 km/h, and reduced by about 0.63 percent for every 0.01 kilometers below the critical visibility of 0.28 kilometers.

Table 2.3: Reduction in Free Flow Speed as a Function of Some Weather Factors

<table>
<tr><th rowspan="2">Weather Variable</th><th rowspan="2">Intensity</th><th colspan="2">% Reduction in FFS</th></tr>
<tr><th>Equation 2.1</th><th>Equation 2.2</th></tr>
<tr><td rowspan="4">Wind Speed (Km/h)</td><td>≤ 16</td><td>0.31</td><td rowspan="3">8.74</td></tr>
<tr><td>16 - 32</td><td>0.63</td></tr>
<tr><td>32 - 48</td><td>0.95</td></tr>
<tr><td>> 48</td><td>1.26</td><td>17.48</td></tr>
<tr><td rowspan="3">Precipitation</td><td>Light</td><td>4.42</td><td>8.46</td></tr>
<tr><td>Medium</td><td>8.83</td><td>16.92</td></tr>
<tr><td>Heavy</td><td>13.24</td><td>25.38</td></tr>
<tr><td rowspan="2">Visibility (km/h)</td><td>≤ 0.16</td><td>1.15</td><td>*</td></tr>
<tr><td>0.16 - 0.37</td><td>0.57</td><td>*</td></tr>
<tr><td rowspan="2">Pavement Surface Condition</td><td>Wet</td><td>4.20</td><td>5.26</td></tr>
<tr><td>Snow-covered</td><td>8.41</td><td>10.51</td></tr>
</table>

* Visibility was not significant in Equation 2.2.

Knapp et al. (2000) showed that severe winter storms reduce free flow speed by about 11 percent compared with normal weather conditions at a road section in Iowa. Knapp et al. (2000) considered only winter storms with duration of four hours or more and precipitation intensity of 0.20 inches per hour or more. Knapp's finding is consistent with the reduction in free flow speed obtained from Kyte et. al (2000) model for heavy precipitation given by Equation 2.1.

The Federal Highway Administrations (FHWA, 2006) conducted a study in three metropolitan areas in the USA, namely Baltimore, Maryland, Twin Cities, Minnesota, Seattle, Washington. The reduction in free flow speed is shown in Table 2.4 which shows that the reduction in free flow speed due to light snow with intensity less than 0.01 centimeters per hour (0.0039 inches per hour) was between 5 percent and 16 percent, and between 5 percent and 19 percent for snowfall intensity of about 0.30 centimeters per hour (0.12 inches per hour). Moreover, a regression model between the reduction in free flow speed and precipitation intensity and visibility was built for snow as shown in Equation 2.4.

Table 2.4: Reduction in Free Flow Speed Suggested by FHWA (2006)

Weather condition	Range of impact
Light rain (<0.01 cm/h or 0.0039in/h)	-2% to -3.6%
Rain(~ 1.6 cm/h or 0.63 in/h)	-6% to -9%
Light snow (<0.01 cm/h or 0.0039in/h)	-5% to -16%
Snow(~ 0.3 cm/h or 0.12 in/h)	-5% to -19%

For snow events:

$$R = 1 - \left(0.838 - 0.0908 \times PR + 0.00597 \times (Vis)^2\right) \tag{2.4}$$

where

R = the percentage reduction in the free flow speed,

PR = the precipitation intensity in centimetres per hour, and

Vis = visibility in kilometres.

The adjusted R^2 is 0.824 for Equation 2.4 and the number of observations used to calibrate Equation 2.4 was 40. The authors found that the interaction term between precipitation intensity and visibility was not significant, so Equation 2.4 did not include the interaction term.

2.1.2 Effects of adverse Weather Conditions on Speed at Capacity

According to HCM (2000) the reduction in speed at flow rate of 2400 vehicles per hour was 8 to 14 percent due to light rain and 15 to 20 percent due to heavy rain. Maze et al. (2006) studied the relationship between the reduction in the traffic speed and adverse weather conditions. Their study was conducted on a congested freeway, which assumed that the operating speed is the speed at capacity, in the metropolitan area of Twin Cities, Minneapolis, USA. The reductions in the speed at capacity due to rainfall, snowfall, air temperature, wind speed, and visibility compared with normal weather conditions are shown in Table 2.5, which shows that the highest reduction in speed is 13 percent due to heavy snow precipitation with intensity greater than 0.50 inches per hour, followed by a reduction of 12 percent when the visibility is less than 0.25 miles (0.40 kilometers). It should be noted that the number of observations corresponding to the estimation of these effects was limited because the study area does not experience many foggy days. In general, snowfall had the greatest impact on the speed reduction followed by the visibility.

Federal Highway Administrations study (FHWA 2006) recently conducted a study on the impact of winter weather on speed and the results are summarized in Table 2.6 , It can be seen that the reduction in the speed at capacity is between 5 and 16 percent due to light snow (intensity < 0.01 centimeter per hour), which is equal to the reduction of the free flow speed under the same condition, and between 5 and 19 percent for snowfall intensity of about 0.30 centimeters per hour. Moreover, a regression model between the reduction in speed at capacity and visibility was built for snow conditions as shown in Equation 2.5.

For snow events:

$$A = 0.816 + 0.0308 \times Vis \tag{2.5}$$

where

A = the adjustment factor of the speed at capacity in percent ($A = 1 - Reduction\ \ Factor$), and

Vis = visibility in kilometers.

The number of observations used to develop Equations 2.5 was 47 observations, the $Adjusted - R^2$ associated with Equation 2.5 is 0.362. The authors found that the interaction term between precipitation intensity and visibility was not significant. In addition, visibility was the sole significant variable in the snowfall's model, Equation 2.5.

Table 2.5: The Average Reduction in Speed and Capacity in Twin City Base Under Different Weather Conditions (Source: Maze et al., 2006)

Weather Variable	Intensity	% Speed Reduction	%Capacity Reduction
Rainfall (Inches per Hour)	Less than 0.01	2	2
	From 0.01 to 0.25	4	7
	Greater Than 0.25*	6	14
Snowfall(Inches per Hour)	Less than 0.05	4	4
	From 0.06 to 0.10	8	9
	From 0.11 to 0.50	9	11
	Greater than 0.50	13	22
Temperature (degree Celsius)	From 10 to 1	1	1
	From 0 to -20	1	1
	Less than -20	2	8
Wind Speed (km/h)	From 16 to 32	1	1
	Greater than 32	1	1
Visibility (Miles)**	From 1 to 0.51	7	10
	From 0.50 to 0.25	7	12
	Less than 0.25	12	11

* The very heavy rainfalls are uncommon in Twin Cities

** The data set used to estimate the impact of visibility was limited.

Table 2.6: Reduction in Speed at Capacity (Source: FHWA, 2006)

Weather condition	Range of impact
Light rain (<0.01 cm/h or 0.0039in/h)	-8% to -10%
Rain(~ 1.6 cm/h or 0.63 in/h)	-8% to -14%
Light snow (<0.01 cm/h or 0.0039in/h)	-5% to -16%
Snow(~ 0.3 cm/h or 0.12 in/h)	-5% to -19%

Table 2.7: Reduction in Capacity Due To Rainfall and Snowfall

Weather condition	Capacity reduction (Percent)
Light rain	No Effect
Light snow	From 5 to 10
Heavy rain	From 14 to 15
Heavy now	30

2.1.3 Effect of Adverse Weather Conditions on Roadway Capacity

Capacity can be defined as "the maximum flow rate that can be accommodated by a given traffic facility under prevailing conditions" (HCM, 2000). Roadway capacity could be reduced due to work zones, construction and maintenance activities, incidents, and adverse weather conditions (HCM 2000). The Highway Capacity Manual (HCM, 2000) states that light rain has no effect on capacity unless the visibility is affected and the pavement surface becomes wet. However, heavy rain could reduce freeway capacity by 14 to 15 percent. In addition, capacity could decrease by 5 to 10 percent due to light snow and 30 percent due to heavy snow precipitation, as shown in Table 2.7.

Smith et al. (2004) found that freeway capacity was reduced by 4 to 10 percent due to light rain (0.01 inches per hour to 0.25 inches per hour), and by 25 to 30 percent due to heavy rain (greater than 0.25 inches per hour) respectively, on Hampton Roads, Region of Virginia, USA, using 15-minutes aggregated traffic data. Although, the HCM's capacity reduction is different from those reported by Smiths et al., it is consistent with the capacity reduction factors suggested by Agarwal et al. (2005). Agrawal et al. (2005) proposed a number of capacity reductions factors in terms of different weather conditions, as shown in Table 2.8. The authors obtained these factors using 10-minute aggregated traffic data from an urban freeway in Twin Cities, Minneapolis.

In the same study that was described in Section 2.1.2, Maze et al. (2006) reported the capacity reduction factors due to different weather conditions, as shown in Table 2.5. The researchers found that the highest reduction in capacity of 22 percent is due to heavy snow precipitation with intensity greater than 0.50 inches per hour, followed by a reduction of 14 percent due to rainfall of intensity greater than 0.25 inches per hour. The reduction in capacity associated with visibility was counter intuitive as it was 11 percent when visibility was less than 0.25 miles, and 12 percent when visibility was between 0.25 and 0.50 miles, This might be because of the limited sample size used to calculate the effects of visibility as mentioned by the authors.

Table 2.8: Impacts of Rainfall and Snowfall on Speed and Capacity on an Urban Freeway (Source: Agarwal et al., 2005)

Weather Variable	Intensity in Inches per Hour	% Capacity Reduction	% Speed reduction
Rainfall	Trace, less than 0.01	1 – 3*	1 – 2
	Light, from 0.01 to 0.25	5 – 10	2 – 4*
	Heavy, greater than 0.25	10 – 17	4 – 7*
Snowfall	Trace, less than 0.05	3 – 5	3 – 5
	Light, from 0.06 to 0.10	6 – 11	7 – 9
	Moderate, from 0.11 to 0.50	7 – 13	8 – 10
	Heavy, greater than 0.50	19 – 27	11 – 15

* The values are not statistically significant when compared with no precipitation conditions.

The Federal Highway Administrations study (FHWA, 2006), discussed in the previous section, also investigated the effects of adverse weather conditions on capacity. They found that the reduction in capacity remains constant (10 to 11 percent) and was not affected by the rainfall intensity less than 1.70 centimeters per hour. In addition, the reduction in roadway capacity remains constant for all snowfall intensities for individual sites with a reduction factor between 12 percent and 20 percent across different sites. Moreover, visibility associated with snowfall had a larger effect on traffic stream parameters than rainfall. The average reduction corresponding to visibility reduction of 4.8 kilometres was 10 percent. Moreover, two separate regression models were calibrated to estimate the reduction in capacity in rain and snow events as shown in Equation 2.6 and Equation 2.7.

For rain events:

$$A = 0.892 \tag{2.6}$$

For snow events:

$$A = 0.792 + 0.0048 \times (Vis)^2 \tag{2.7}$$

where

A = the adjustment factor of the speed at capacity in percent ($A = 1 - Reduction\ \ Factor$) and

Vis = visibility in kilometers.

The $Adjusted - R^2$ associated with Equation 2.7 is 0.503 and the number of observations used to develop Equations 2.6 and 2.7 were 173 and 45, respectively, Equation 2.6 shows a constant reduction (10.80 percent) in capacity regardless of rainfall intensity or visibility. Furthermore, the authors found that the interaction term between precipitation intensity and visibility was not significant, so both equations did not include the interaction term. In addition, the squared visibility was the sole significant variable in the snowfall model (Equation 2.7).

2.1.4 Effects of Adverse Weather Conditions on Jam Density

Traffic density is defined as "the number of vehicles occupying a given length of a lane or roadway at a particular instant, usually expressed as vehicles per kilometer" (HCM, 2000). Jam density is the highest density which occurs when all vehicles are stopped and have occupied all the roadway spaces. Obviously, this situation is associated with speed and flow rate of zero. The Federal Highway

Administrations study (FHWA, 2006) shows that the jam density is not affected by adverse weather conditions, which makes intuitive sense.

2.2 Effects of Adverse Weather Conditions on Traffic Volume

Traffic volume, expressed as vehicles per hour, is defined as “the total number of vehicles that pass over a given point or section of a lane or roadway during a given time interval” (HCM, 2000). Moreover, traffic volume represents the actual number of vehicles observed at a given location at a given time period, which usually varies by time. Adverse weather conditions have a great impact on the traffic volume. In the following section, such effects are discussed.

Hanbali and Kuemmel (1993) studied the effects of winter snow storms on traffic volume using data from 11 highways in rural and suburban areas of the United States. They categorized the traffic volume data into three categories. Firstly, according to the average daily traffic volume, they classify it to “from 11,000 to 20,000 vehicles” and “from 21,000 to 30,000 vehicles” for rural and suburban freeways, and “from 3,000 to 6,000 vehicles” and “from 7,000 to 10,000 vehicles” for rural and suburban highways; secondly, according to weekday or weekend; and finally, according to snowfall intensity, to less than 25 millimetres, from 25 to 75 millimetres, from 75 to 150 millimetres, from 150 to 225 millimetres, and from 225 to 375 millimeters. In addition, they divided the snow storm events into hourly periods, peak-hour periods and off-peak-hour periods. For each winter snow storm event, the hourly traffic volume was measured and compared with hourly traffic volume during normal weather conditions for the same hour, day, month, and year, then the reduction in traffic volume associated with every snow event was calculated using Equation 2.8.

$$Snow\,redaction\ factor = \frac{Traffic\ volume\ during\ snow\ event}{Traffic\ volume\ during\ normal\ weather\ conditions} \qquad (2.8)$$

The average reductions in hourly traffic volume due to winter snow storms are shown in Table 2.9, Table 2.10, and Table 2.11 as suggested by Hanbali and Kuemmel’s study (1993).

Table 2.9: Average Traffic Volume Reductions during Weekdays and Weekends (Source: Hanbali and Kuemmel, 1993)

Snowfall (millimeters)	Weekdays average traffic volume reduction %	Weekends average traffic volume reduction %
< 25	7 – 17	19 – 31
25 – 75	11 – 25	30 – 41
75 – 150	18 – 43	39 – 47
150 – 225	35 – 49	41 – 51
225 – 375	41 – 53	44 – 56

Table 2.10: Average Traffic Volume Reductions during Weekdays: Peak hours Versus Off-Peak Hours (Source: Hanbali and Kuemmel, 1993)

Snowfall (millimeters)	Weekdays average traffic volume reduction %	
	Peak hours	Off-peak hours
< 25	7 – 11	8 – 17
25 – 75	11 – 18	13 – 31
75 – 150	18 – 25	28 – 43
150 – 225	35 – 40	42 – 49
225 – 375	41 – 44	47 – 53

Table 2.11: Average Traffic Volume Reductions during Weekends: Peak hours Versus Off-Peak Hours (Source: Hanbali and Kuemmel, 1993)

Snowfall (millimeters)	Weekends average traffic volume reduction %	
	Peak hours	Off-peak hours
< 25	19 – 23	27 – 31
25 – 75	30 – 36	32 – 41
75 – 150	39 – 42	42 – 47
150 – 225	41 – 46	49 – 51
225 – 375	44 – 50	55 – 56

Knapp et al. (2000) studied the effect of winter snow storms on traffic volumes in a number of interstates freeways in Iowa. They only considered the snow storms with the following characteristics:

1. Snow storms that had intensity of more than 0.20 inch per hour and duration of more than hours.

2. Snow storms that occurred during working days (the snow storms that occurred on holidays or near holidays were excluded).

The reduction in traffic volumes was about 29 percent in average, ranging from 16 percent to 47 percent, compared with non-storm traffic volumes. The authors developed a regression model using 15-minutes aggregated traffic data to estimate reductions in traffic volume in terms of snowfall intensity and maximum wind gust speed as shown in Equation 2.9.

$$\%Traffic\ volume\ reduction = -1.583 + 2.289 \times PR + 0.0296 \times (Wind)^2 \tag{2.9}$$

where

PR = total snowfall intensity in inches, and

$Wind$ = Maximum wind gust speed in miles per hour (mph).

PR in the above equation varies between 1.05 inches and 10.83 inches with a mean of 3.764 inches and standard deviation of 2.377 inches. The range of the $(Wind)^2$ variable was from 36 $(mph)^2$ to 2,916 $(mph)^2$ with mean of 742.70 $(mph)^2$ and standard deviation of 584.10 $(mph)^2$. The number of observations used to develop the model was 64; the associated $Adjusted-R^2$ was 0.544. Equation 2.9suggests that the traffic volume would be reduced by about 2.30 percent for every total snowfall of 1 inch, and by 0.03 percent for every 1 $(mph)^2$ increase in the maximum wind gust speed. Moreover, the model suggests an increase of 1.58 percent in traffic volume when there is no precipitation and wind speed equals to zero; the authors suggested that using the data in the same range for the developed model would be more appropriate.

Kumar and Wang (2006) studied the traffic volume reductions due to adverse weather events at two sites in Oregon, USA. One of the sites was a two lane undivided rural highway and the other was a four lane undivided rural highway. The traffic volume during adverse weather events was compared to the normal traffic volumes during the normal weather events. The normal traffic volume during weather events was calculated using Autoregressive Integrated Moving Average (ARIMA) time series model. The reduction in traffic volume was then calculated using Equation 2.10.

$$\%Traffic\ volume\ reduction = \frac{(Adverse\ weather\ traffic\ volume - Normal\ traffic\ volume)}{Normal\ traffic\ volume} \qquad (2.10)$$

Kumar and Wang (2006) found that the traffic volume reduced on average by about 2 to 7 percent with standard deviations of 14 to 44 percent, due to rain and snow events.

In a recent study, Datla and Sharma (2008) used 11 years of data from1995 to 2005 in the Province of Alberta and found that the reduction in winter daily traffic volume was about 7 to 17 percent due to a total snowfall of 10 centimetres and from 21 to 51 percent in the event of severe snow storms with a total snowfall of 30 centimeters or above. These results are consistent with those of Hanbali and Kuemmel (1993) and Knapp et al. (2000).

2.3 Effects of Adverse Weather Conditions on Average Speed

Average speed is a measure of the quality of travel over a certain road section. It is also used as a measure of effectiveness for calculation of the level of service for many roads such as rural two-lane highways (HCM 2000). In general, road users are more concerned about average speed rather than the free flow speed or the speed at capacity, since the former is a direct indication of travel time. This section reviews the effects of adverse weather conditions on average speed.

Liang et al. (1998) studied the effects of fog and snow events on a section of a rural interstate freeway in Idaho using data from December 1995 to April 1996. They found that the reductions in average speed were 7.6 and 18.13 percent for fog and snow events respectively in comparison with the normal sunny clear days without wind and with visibility greater than 1.6 kilometers. Their findings are summarized in Table 2.12.

Liang et al. (1998) in the same study developed a multiple regression analysis using 16 observations for normal weather conditions, fog events, and snow events using 5-minutes aggregated traffic data to quantify the effects of visibility, wind speed, air temperature, time of day, and the road surface conditions on the average speed. The developed models are shown as Equations 2.11 and Equation 2.12 for fog events and snow events respectively; the coefficient of determination (R^2) associated with Equation 2.11 and Equation 2.12 were 0.52 and 0.384, respectively.

Table 2.12: Speed Variability during Different Fog and Snow Weather Conditions (Source: Liang et al., 1998)

Weather condition	Number of events evaluated	All vehicles		Passenger cars only		Trucks only	
		Mean speed (km/h)	Standard deviation (km/h)	Mean speed (km/h)	Standard deviation (km/h)	Mean speed (km/h)	Standard deviation (km/h)
Base conditions	3	105.9	3.7	110.1	5.8	102.2	4.2
Fog events	2	97.9	7.4	104.3	11.6	95.3	7.1
Snow events	11	86.7	10.1	89.0	12.2	84.5	10.3

During fog events:

$$Speed = 98.72 + 2.55 \times Log(Vis) + 2.12 \times Dtime + 2.83 \times Temp \tag{2.11}$$

During snow events:

$$Speed = 89.13 + 4.61 \times Log(Vis) + 2.58 \times Dtime + 2.58 \times Temp - 3.49 \times SC - 1.09 \times Wind \tag{2.12}$$

where

Speed = Average vehicles speed in km/h,

Vis = visibility in km,

SC = dummy variable representing road surface condition. *SC* equals 0 when the roadway is dry and 1 when it is snow-covered,

Dtime = dummy variable representing time of the day. *Dtime* equals 0 during night time and equals 1 during day time,

Temp =dummy variable representing temperature. *Temp* equals 0 when the temperature is below 0 degree, and equals 1 when the temperature is above 0 degree,

Wind = dummy variable representing wind speed. *Wind* equals 0 when the wind speed is less than 40 km/h and *Wind* equals - 40 when the wind speed exceeds 40 km/h, and

Log = logarithm with base 10.

Table 2.13: Recommended Operating Speed during Snow Event (Source: Liang et al., 1998)

Visibility (km)	Nighttime speed						Daytime speed					
	Dry surface			Snow surface			Dry floor			Snow floor		
	Wind speed (km/h)			Wind speed (km/h)			Wind speed (km/h)			Wind speed (km/h)		
	<40	40-55	>55	<40	40-55	>55	<40	40-55	>55	<40	40-55	>55
0-1.6	87	80	69	80	76	64	89	84	72	84	77	66
>1.6	95	89	77	89	84	72	97	92	80	92	85	74

In the regression models given by Equations 2.13 and 2.14, visibility affects speed according to a logarithmic relationship. In addition, the reduction in average speed associated with snowfall due to the presence of snow on pavement surface was found to be 3.49 km/h or 3.66 percent compared with the day time average speed during normal weather conditions, which is 95.23 km/h, but the reduction in speed that has been observed at the study site was 5.6 km/h. Liang et al's (1998) recommended values of operating speed (operating speed may be defined as the actual speed of a group of vehicles within a certain roadway segment (NCHRP, 2003)) during snowy weather conditions are shown in Table 2.13.

Knapp et al. (2000) stated that the average speed on a road section in Iowa reduced by 16 percent due to severe winter storms. The authors used 15-minute aggregated traffic data that was collected by mobile video cameras; the data collected included traffic volumes, vehicle gaps and headways, visibility, and the percentage of the roadway cross section covered by snow. Total snowfall and gust wind speed were not collected in this study. In addition, a linear regression model for off-peak hour and no low-volume time period was developed using 83 observations. The model is shown in Equation 2.13.

$$Speed = 55.7 + 0.00002 \times (V)^2 - 3.88 \times Vis - 7.23 \times SC \qquad (2.13)$$

where

Speed = average vehicle speed in mile per hour,

V = traffic volume in vehicle per hour (V^2 has a mean value of 327,980 and standard deviation of 214,125 with range between 15,376 and 788,544),

Vis = dummy variable that represents visibility. *Vis* equals 1 and 0 for visibility less than 0.25 mile and visibility greater than 0.25 mile, respectively, and

SC = dummy variable that represents pavement surface condition. *SC* equals 1 when snow is present on traffic lanes and equals 0 otherwise.

The regression model given by Equation 2.13 has a Mean Square Error of 21.85, Coefficient of Multiple Determination (R^2) value of 0.618, and Adjusted $-R^2$ value of 0.603. The average speed and volume during normal conditions were 71.50 mph and 1037 vph respectively; the average speed during winter storm events was 59.9 mph within a range of 51.3 to 69.7 mph. This shows a 16 percent reduction in average vehicle speed between normal and winter storm conditions. In addition, the model shows a positive relationship between average vehicle speed and the square of traffic volume during winter storm event, which shows that the more vehicles on the road during the adverse weather conditions the more confident the drivers are to increase their driving speed (Kumar and Wang, 2006). Moreover, the reduction in average speed due to visibility less than 0.25 mile is 3.88 mph or 5.43 percent. The reduction due to the snow-covered pavement is 7.23 mph or 10.11percent; the combined reduction when pavement was both snow-covered and visibility was low is 11.11 mph or 15.54 percent compared with normal weather conditions. Furthermore, Knapp et al. (2000) found that the variability in average speed associated with snow events (standard deviation = 7.57 mph) is higher than the variability during normal weather conditions (standard deviation = 1.86 mph).

Smith et al. (2004) found that the operating speed on urban freeway in Virginia was reduced by 3-5 percent in the presence of rain (from 0 to more than 0.25 inches per hour) regardless of rainfall intensity, using 15-minte aggregated traffic data. But, Agrawal et al. (2005) found that the speed reduction associated with rainfall of less than 0.01 inches per hour, 0.10-0.25 inches per hour, and more than 0.25 inches per hour was between 1 to 2 percent, 2 to 4 percent, and 4 to 7 percent respectively. In addition, Agrawal et al. (2005) found that heavy snowfall with intensity more than 0.50 inches per hour reduced speed by 11-15 percent. The effect of snowfall intensities on speed are shown in Table 2.8.

Kumar and Wang (2006) found that the average speed from 3 sites on rural roads in Montana between 2001 and 2003 was reduced by 6 to 11 percent with a standard deviation ranging from 6.30 to 8.80 percent due to snow events compared with the annual average travel speed during the corresponding years. The reduction in speed is site specific and affected by the wind speed and the pavement surface temperature. A linear regression model showing the relationship between the percentages of average speed reduction during snow events, wind speed, snowfall intensity and duration, and pavement surface temperature was developed and is presented in Equation 2.14. The regression model has an Adjusted $-R^2$ of 0.15 for 250 observations. Furthermore, the overall regression model and coefficients are statistically significant.

$$R = -8.387 + 0.23 \times Wind - 0.048 \times D - 0.016 \times PR + 0.004 \times PT \tag{2.14}$$

where:

R = the percentage change in the average hourly travel speed,

$Wind$ = average wind speed in mph,

D = duration of snow event in hours,

PR = precipitation rate in inches per hour, and

PT = pavement surface temperature in degrees.

2.4 Effect of Adverse Weather Conditions on Delay

Delay can be defined as "additional travel time experienced by a driver, passenger, or pedestrian beyond what would reasonably be desired for a given trip" (HCM, 2000). The average travel delay can be calculated based on the difference between the average travel time and the free flow travel time. The reductions in speed and capacity at the same volume increase travel delay and hence increase the operation cost. Adverse weather conditions can dramatically affect both speed and capacity, which will increase the travel time delay. The increase of travel time delay during peak hours will be higher than during off peak hours. The following section covers findings of existing studies on the increase in travel time delay as a consequence of adverse weather conditions.

According to FHWA Road Weather Management Program Website (FHWA, 2008), adverse weather counts for about 544 million vehicle-hours of delay per year on the US highways, which represents 23percent of non-recurrent delay. Using the Highway Capacity Manual procedure, GIS and database tools, Han et al. (2003) estimated that the total travel time delay on major US highways in 1999 increased by 7 to 36 percent due to adverse weather conditions (fog, ice, and snow storms). In addition, the American drivers on major U.S. highways faced about 46 million hours of traffic delay due to adverse weather conditions. These findings were based on the assumptions that the reduction in capacity would be 30 percent for both ice and snow storm events and 20 percent due to dense fog, and the safe operating speed during dense fog would be 80 km/h.

Stern et al. (2003) used 5-minute aggregated travel time data from SmarTraveler website (www.SmarTraveler.com) to study the effect of adverse weather conditions on travel time on 33 bi-directional road segments totaling 711.80 miles in Washington, D.C. The study period was between December 1999 and May 2001, Monday to Friday from 6:30 AM to 6:30 PM. A linear regression model was developed between the actual travel time and weather condition variables as shown in Equation 2.15 for peak hours and off-peak hours for each road segment, which can be used to predict travel time during adverse weather condition. The travel time delay is then calculated as the difference between TT and TT_{Base}, and the percentage increase in travel time is then calculated by dividing the difference between TT and TT_{Base} by TT_{Base}. The peak hours used in this study was defined as the 2 hours with historically highest travel time, and the off-peak hours are the 2 hours of the lowest historical travel time.

$$TT = TT_{Base} + b_1 \times (SC)^2 + b_2 \times Wind + b_3 \times Vis + b_4 \times PR \tag{2.15}$$

where

TT = Travel time in minutes,

TT_{Base} = the intercept, base travel time associated with normal weather conditions in minutes,

PR = dummy variable that describes precipitation type and intensity. It equals 0, 1, 2, and 3 for no precipitation, light rain or snow, heavy rain, and heavy snow or sleet respectively,

SC = dummy variable that represents the pavement surface condition. It equals 0, 1, 2, 3 when the pavement surface is dry, wet, snow or ice covered, black ice covered respectively,

$Wind$ = dummy variable that represents wind speed. It equals 0 when wind speed is less than 30 mph, and equals 1 when wind speed greater than or equals 30 mph, and

Vis = dummy variable that represents the visibility distance. It equals 0 when visibility is greater than or equal to 0.25 miles, and equals 1 when visibility is less than 0.25 miles.

The R^2 values associated with peak period models were between 0.005 and 0.05, which means that less than 5 percent of the variability on travel time can be explained by the model, and the average R^2 value associated with the off-peak period models is 0.23. These results suggest that the peak period model is meaningless and the model can only be used to predict travel time during off-peak period.

Stern et al. (2003) found that the average increase in travel time during off-peak periods is 14 percent due to the combined effect of weather conditions; the cases with adverse weather conditions represent 13 percent of all cases. Moreover, during peak period, travel time increased by at least 11 percent due to precipitation. The authors also used the analysis of means (ANOVA) method to estimate the increase of travel time caused by precipitation only and found that the travel time during peak period increased by about 25 percent, which is more than double of the increase using the regression analysis. Furthermore, the travel time increased by only 3.5 percent during off-peak period.

Chin et al. (2004) studied the aggregate effect of adverse weathers conditions (rain, snow, fog, and ice) on capacity and delay along several US highways during 1999. The speed and capacity reduction factors that have been used in their study are shown in Table 2.14 for different types of highways. The total travel time (TTT) based on the traffic volume in normal conditions days had been calculated based on the average travel time for normal conditions and adverse weather conditions.

Table 2.14: Speed and Capacity Reduction Factors

Weather condition	Highway type							
	Urban freeway		Rural freeway		Urban arterials		Rural arterials	
	Capacity	Speed	Capacity	Speed	Capacity	Speed	Capacity	Speed
Light rain	4%	10%	4%	10%	6%	10%	6%	10%
Heavy rain	8%	16%	8%	16%	6%	10%	6%	10%
Light snow	7.50%	15%	7.50%	15%	11%	13%	11%	13%
Heavy snow	27.50%	38%	27.50%	38%	18%	25%	18%	25%
Fog	6%	13%	6%	13%	6%	13%	6%	13%
Ice	27.50%	38%	27.50%	38%	18%	25%	18%	25%

Chin et al. (2004) calculated the average travel time based on the Highway Capacity manual (HCM 2000) by converting the HCM 2000 curves, speed-flow curves, for different highway types into numerical values using polynomial equations connecting the average speed with the volume by capacity (v/c) ratio. For the freeways, they convert the speed-flow curve shown in Figure 2.3 into the following equations:

$$Avg\,Speed\,(mph)_{FFS=75mph} = -46.79\left(\frac{v}{c}\right)^4 + 22.72\left(\frac{v}{c}\right)^3 + 5.0909\left(\frac{v}{c}\right)^2 - 2.1844\left(\frac{v}{c}\right) + 74.6 \tag{2.16}$$

$$Avg\,Speed(mph)_{FFS=75mph} = -87.69\left(\frac{v}{c}\right)^4 + 107.92\left(\frac{v}{c}\right)^3 - 40.719\left(\frac{v}{c}\right)^2 + 4.5651\left(\frac{v}{c}\right) + 68.345 \tag{2.17}$$

$$Avg\,Speed(mph)_{FFS=75mph} = -111.01\left(\frac{v}{c}\right)^4 + 164.11\left(\frac{v}{c}\right)^3 - 74.212\left(\frac{v}{c}\right)^2 - 9.9859\left(\frac{v}{c}\right) + 60.091 \tag{2.18}$$

$$Avg\,Speed(mph)_{FFS=75mph} = -79.645\left(\frac{v}{c}\right)^4 + 127.36\left(\frac{v}{c}\right)^3 - 62.256\left(\frac{v}{c}\right)^2 - 9.0488\left(\frac{v}{c}\right) + 55.87 \tag{2.19}$$

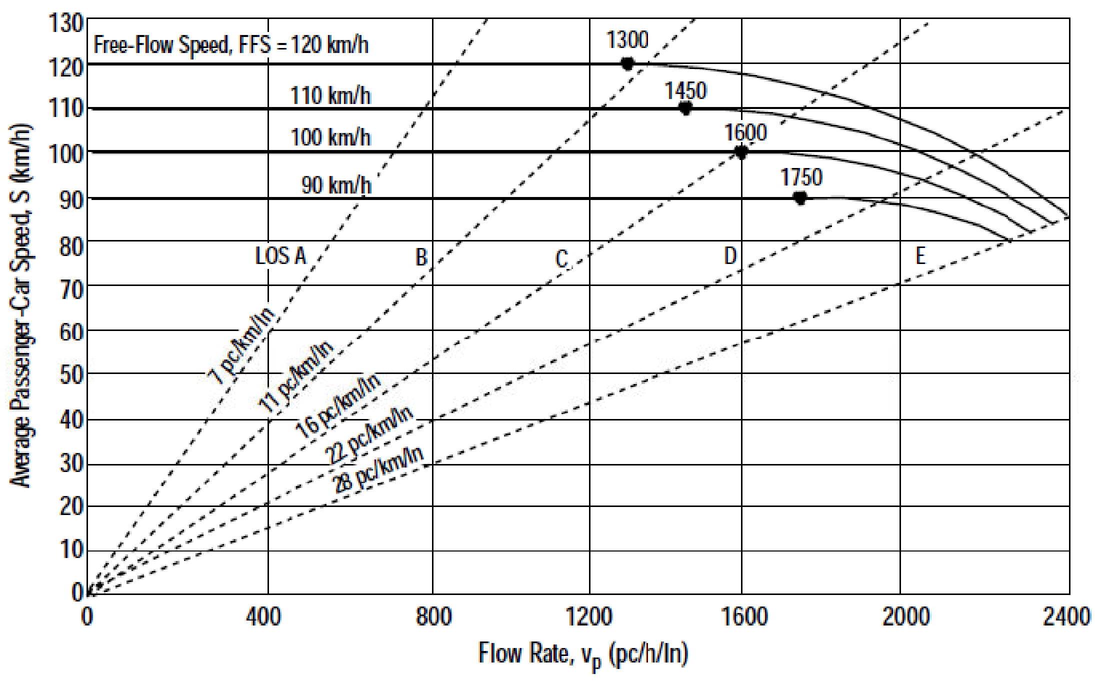

Figure 2.2: Speed-Flow Curves for Basic Freeway Segment (Source: HCM 2000)

The resulting speed versus (v/c) ratio curves for basic freeways segment based on the previous equations are shown in Figure 2.3. The travel time has been calculated based on the average speed from corresponding equations for the highway type. For the case when (v/c) ratio is greater than 1, they tracked the queue to calculate the queue length and the queue delay. This delay was then added to the travel time that was calculated using the average travel time from the previous equations.

Chin et al. (2004) found that adverse weather (rain, fog, snow, and icy) conditions reduced capacity by about 21 billion vehicles and caused about 330 million vehicles-hours of delay. The delay caused by rain had the highest portion of delay which is 71percent, followed by ice (14percent), snow (13percent), and fog (2percent). Adverse weather conditions affected mostly the urban areas which experienced about 92percent of delay as shown in Figure 2.4.

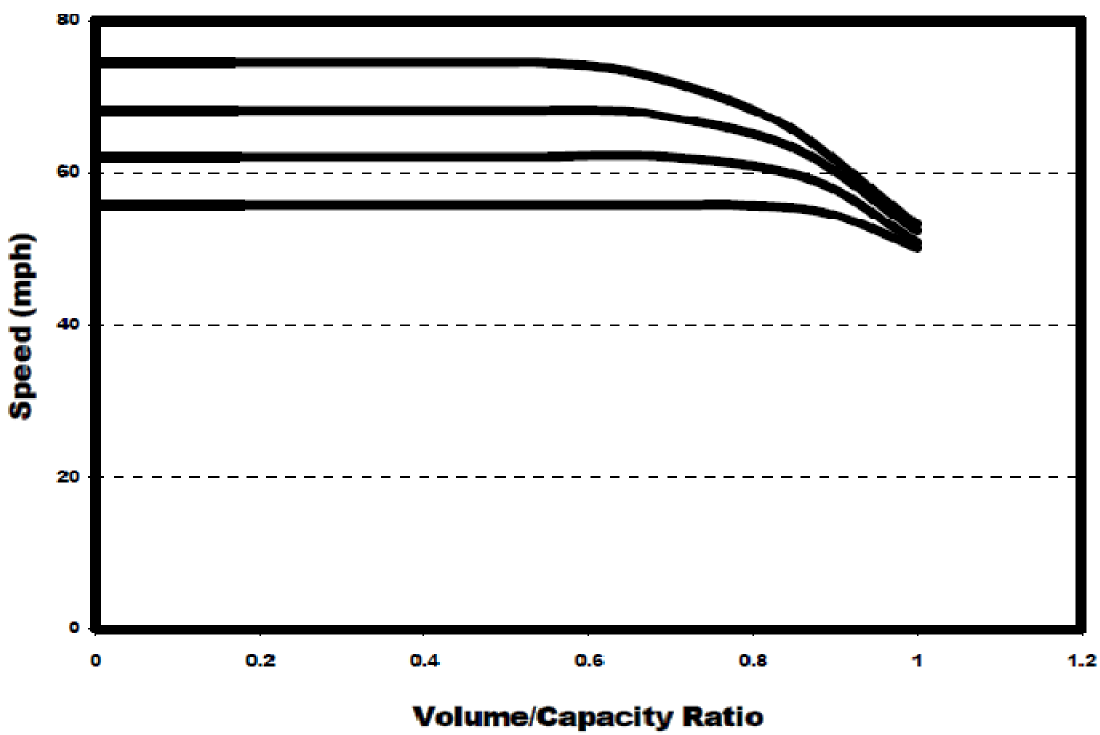

Figure 2.3: Speed versus (v/c) ratio for Basic Freeway Segment (Source: Chin et al., 2004)

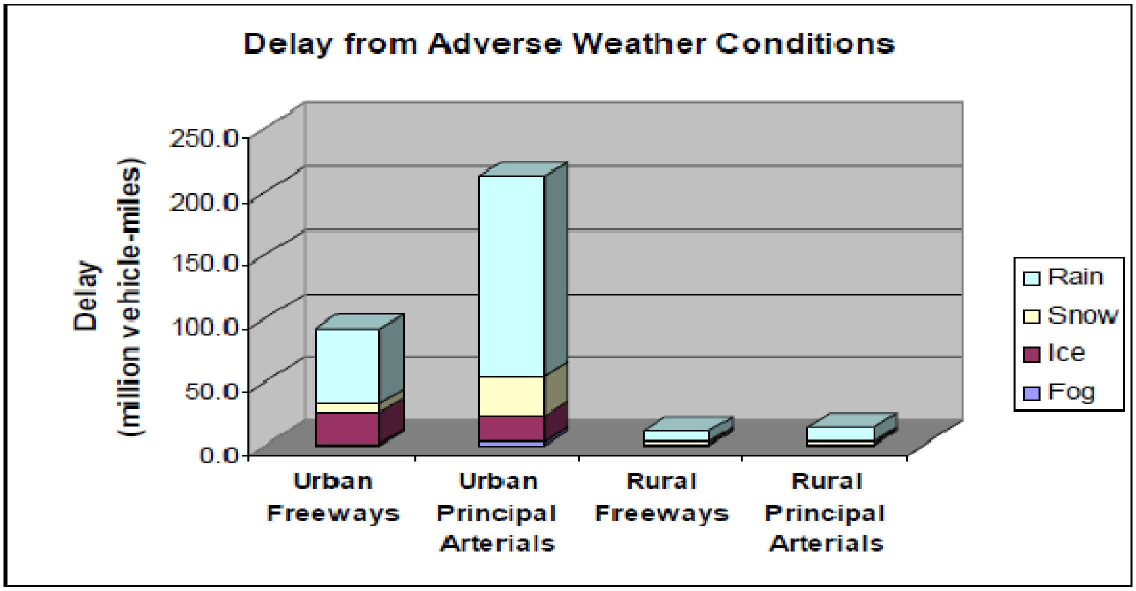

Figure 2.4: Weather-Related Delay for Different Highways (Source: Chin et al., 2004)

2.5 Summary

This chapter reviewed the literature on research related to the effects of adverse weather conditions on traffic flow characteristics, travel demand and travel time. Past research has shown that adverse weather conditions could have a significant effect on traffic parameters. For example, some studies have found that free flow speed could reduce by up to 40 percent due to heavy snowfall and by 13 percent when the pavement surface is snow-covered and that capacity could reduce by over 30 percent. In addition, it has be found that the reduction in speed at capacity is in general close to the reduction in free flow speed under the same weather conditions and that adverse weather conditions have little effect on the jam density. Furthermore, adverse weather conditions could reduce traffic volume or demand by more than 50 percent; this reduction was found to be higher during off-peak periods as compared to peak periods. Moreover, the reduction in both speed and capacity due to adverse weather conditions directly affects the average travel speed and hence the travel time or delays; the increase in travel time was found to be up to 36 percent.

Despite these significant past efforts, one important issue remains to be addressed, namely, what is the magnitude of effect of winter road maintenance on improving traffic conditions? While it is generally known that winter road maintenance plays a critical role in maintaining safe and efficient travel conditions through timely snow and ice control; however, it is largely unknown what is the exact relationship between the amount of winter road maintenance (input) and the safety and mobility benefits (outcome). This research focuses on the mobility benefit of winter road maintenance with the specific objective of quantifying the travel time and delay of a typical highway under specific road weather and traffic conditions.

Chapter 3
Simulation Modeling of Winter Traffic

This chapter presents the steps taken to develop the simulation model that used to evaluate traffic conditions under adverse weather conditions. It describes the simulation model, the study network, the calibration process of the simulation model, and the modeling of various snow storm and maintenance levels.

3.1 Simulation Model

The INTEGRATION simulation model (M. Van Aerde &Assoc. Ltd., 2005a and b), was chosen to model traffic under adverse weather conditions because of its flexibility in representing the effects of weather and road surface conditions on traffic through macroscopic parameters, such as free flow speed, capacity, and jam density. As discussed in Chapter 2, most studies conducted in the past have focused on the effects of weather and winter maintenance on macroscopic traffic parameters measures such as roadway capacity and free-flow speed. Hence the INTEGRATION model allow for use of this rich source of past experience for realistic simulation of traffic under various road weather conditions.

The INTEGRATION simulation model is a fully microscopic simulation model developed by the late Professor Van Aerde and his students (Van Aerde, 2005a and b). The model is designed to trace individual vehicle movements from its origin to destination with a resolution of 0.10 second (deci-second). The microscopic characteristics of the model have been calibrated in a way that it can represent the same aimed macroscopic traffic features such as speed-flow relationships for the links, different types of delay (uniform, random, and over-saturation), merging/diverging and weaving capacities, and traffic assignment (Van Aerde, 2005a). Appendix A presents an overview on the traffic simulation features of the INTEGRATION simulation model.

3.2 Modeling of Winter Traffic Behavior

Because the INTEGRATION model does not have a mechanism to reflect driver behavior under specific weather and road surface conditions, the winter traffic behavior is modeled indirectly by adjusting the macroscopic traffic parameters that are used by the INTEGRATION model. INTEGRATION uses four link-specific macroscopic traffic parameters to capture driver behavior under specific road, traffic, and environmental conditions, namely, free flow speed, speed at capacity, capacity, and jam density. The general form for Van Aerde Model is shown in Equation 3.1(Van Aerde, 1995). The parameters ($k,\ c_1,\ c_2,\ and\ c_3$) in the Van Aerde model can be calculated using Equations 3.2-3.5 (Van Aerde and Rakha, 1995).

$$D = \frac{1}{c_1 + \frac{c_2}{S_f - S} + c_3 \cdot S} \tag{3.1}$$

$$k = \frac{2S_c - S_f}{(S_f - S_c)^2} \tag{3.2}$$

$$c_2 = \frac{1}{D_j \cdot (k + 1/S_f)} \tag{3.3}$$

$$c_1 = k \cdot c_2 \tag{3.4}$$

$$c_3 = \frac{1}{S_c}\left(-c_1 + \frac{S_c}{V_c} - \frac{c_2}{S_f - S_c}\right) \tag{3.5}$$

where:

D = density (veh/km) or the inverse of the vehicle headway (km/veh)

D_j = density (veh/km) or the inverse of the vehicle headway (km/veh)

S =speed (km/h)

S_f =frees-flow speed (km/h)

V_c = flow at capacity (veh/h)

c_1 = fixed distance headway constant (km)

c_2 = first variable headway constant (km^2/h)

c_3 = second variable distance headway constant (h)

k= is a constant used to solve for the three headway constants (h/km)

By systematically adjusting these four parameters, the effects of different road weather and surface conditions on traffic could be simulated. Figure 3.1, Figure 3.2, Figure 3.3, and Figure 3.4 illustrate the modeling idea using the fundamental speed-flow-density diagrams during normal weather conditions and adverse weather conditions using Van Aerde's macroscopic single regime model (Equation 3.1). For this example the traffic parameters during normal weather condition are assumed to be 110 km/h, 90 km/h, 2200 veh/h/lane, and 120 veh/km/lane for the free-flow speed, speed at capacity, capacity, and jam density, respectively. Furthermore, the traffic parameters during adverse weather conditions are assumed to be reduced by 11percent for both free-flow speed and speed at capacity, and by 15percent for capacity of normal weather conditions parameters.

As shown in Figure 3.4, according to INTEGRATION model drivers would respond to a reduction in capacity or free-flow speed by adopting a reduced car-following speed under a given distance headway. Under the same logic, a large distance headway would be maintained by drivers under a given speed. The INTEGRATION's car-following model is a function of the distance headway (as discussed in Appendix A). During adverse weather conditions, drivers choose to keep larger distance headways with the vehicles in front of them. This may also lead to different lane changing behavior as they may found more suitable gaps in the adjacent lanes to their current lane. Furthermore, because drivers aim to attain larger distance headway with the leading vehicles that may change the criteria for the accepted gap in the target lane.

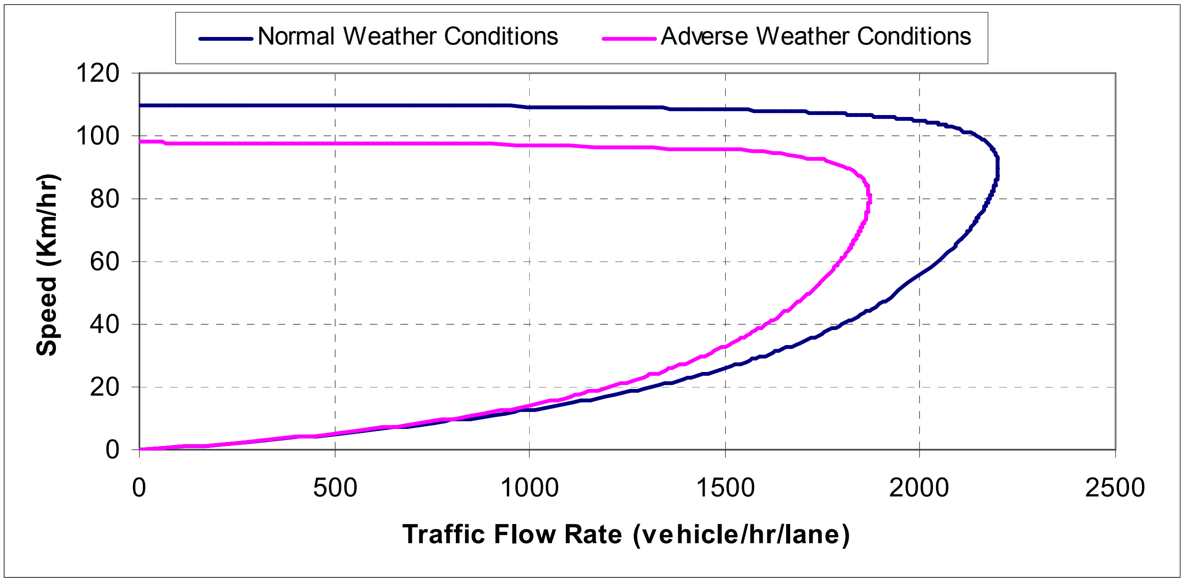

Figure 3.1: Traffic Flow Rate Vs. Speed Under Two Different Weather conditions

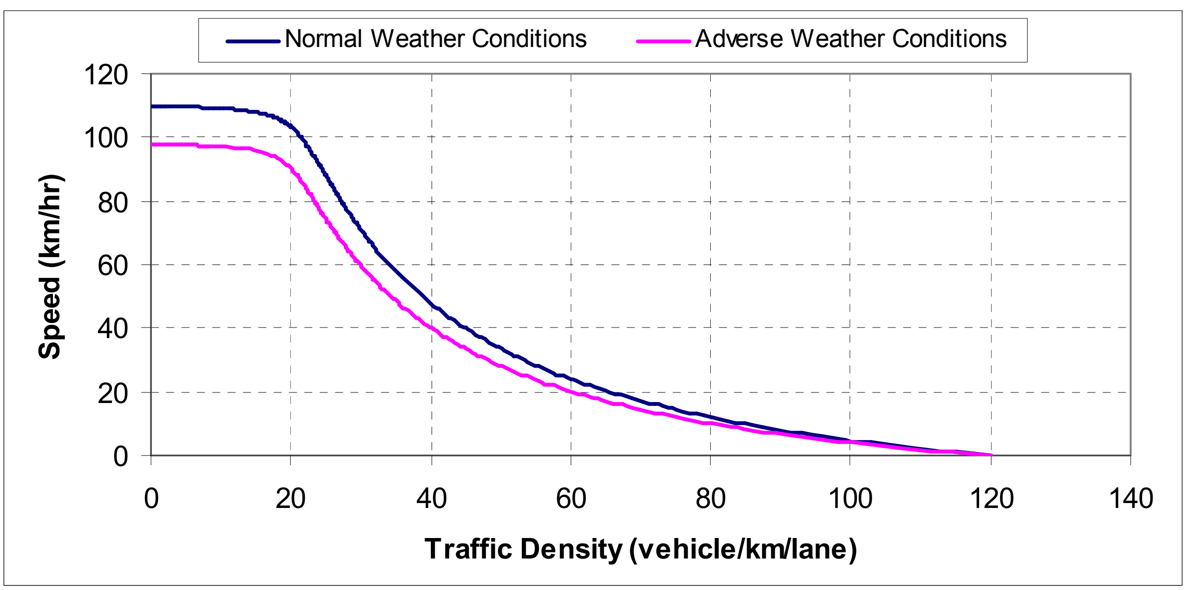

Figure 3.2: Traffic Density Vs. Speed under Two Different Weather conditions

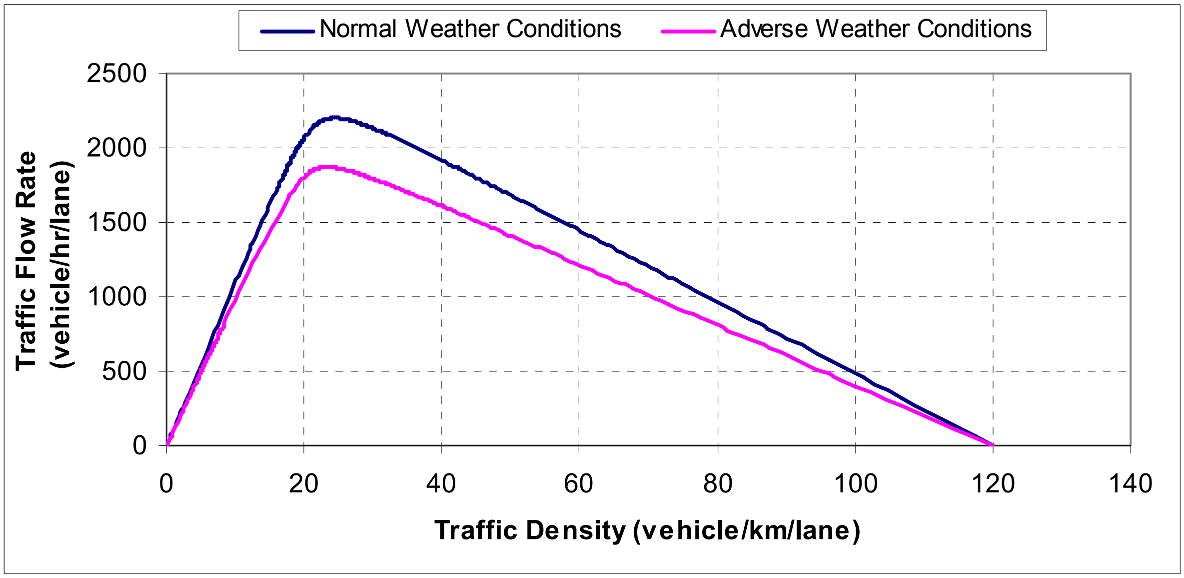

Figure 3.3: Traffic Flow Rate Vs. Density Under Two Different Weather conditions

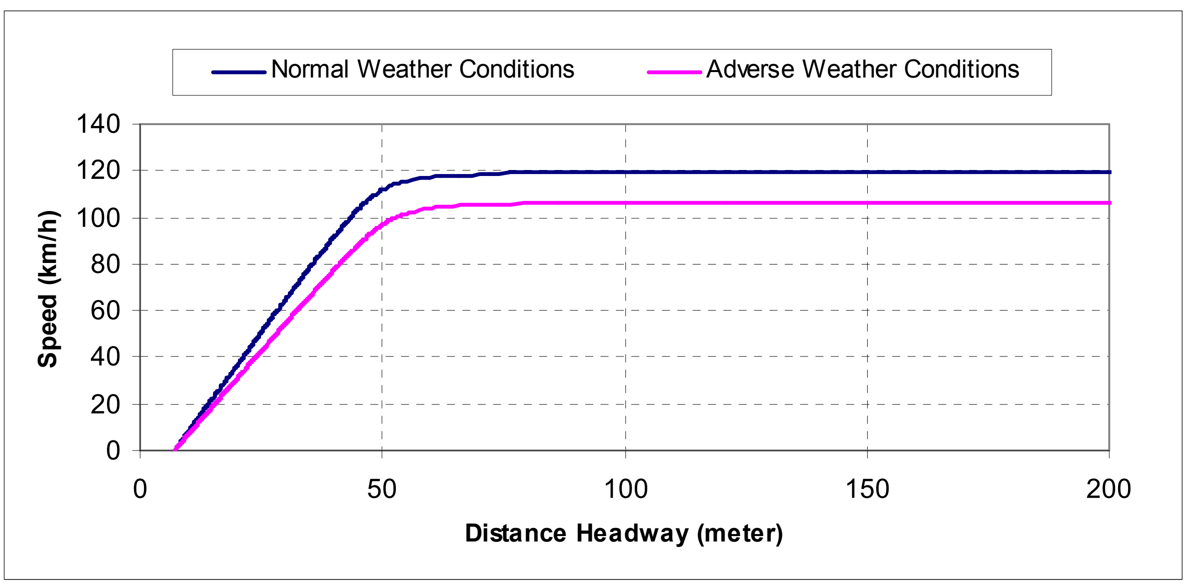

Figure 3.4: Distance Headway Vs. Speed Under Two Different Weather Conditions

The following section details the reduction models that are used to determine the values for macroscopic traffic parameters as a function of various road weather and surface condition factors.

Modeling of Free-flow Speed Reduction

From the literature review described in Chapter 2, the most reasonable impact model that addresses the effect of both road surface conditions and snowfall precipitation on the free flow speed is the statistical model developed by Kyte et al. (2000), shown as Equation 3.6.

$$FFS = 115.82 - 0.34 \times Wind - 4.77 \times PR + 0.62 \times Vis - 4.54 \times SC \tag{3.6}$$

where

FFS = free flow speed in km/h,

$Wind$ = dummy variable representing wind speed. *Wind* equals to 1, 2, 3, and 4 for wind speeds less than 16, 16 to 32, 32 to 48, and greater than 48 km/h respectively,

PR = dummy variable representing precipitation intensity. *PR* equals 1, 2, 3, 4 for no precipitation, light precipitation, medium precipitation, and heavy precipitation, respectively,

Vis = dummy variable representing visibility. *Vis* equals 1, 2, and 3 for visibilities equal to or less than 0.16 kilometre, 0.16 to 0.37 kilometre, and equal to or greater than 0.37 kilometre, respectively, and

SC = dummy variable representing road surface condition. *SC* equals 1, 2, 3 if the road is dry, wet, and snow or ice covered, respectively.

The baseline condition that was assumed in developing Equation 3.6 is one with no precipitation, dry road surface, visibility greater than 0.37 km, and wind speed less than 16 km/h. The resulting free-flow speed under this baseline condition is 108.03 km/h.

According to Equation 3.6, about 1 percent reduction in free flow speed would result when wind speed is greater than 48 km/h; 4 percent and 9 percent when road is wet and covered by snow or ice, respectively; 4 percent, 9 percent, and 13 percent due to light precipitation, medium precipitation, and high precipitation, respectively; less than 1 percent for visibility between 0.16 to 0.37 kilometers and about 1 percent for visibility less than 0.16 kilometers.

According to Equation 3.6 and the free-flow speed at normal weather conditions (108.03 km/h), a reduction model for the free-flow speed under different weather conditions can be constructed as shown in Equation 3.7.

$$R = \left(108.03 - \left(115.82 - 0.34 \times Wind - 4.77 \times PR + 0.62 \times Vis - 4.54 \times SC\right)\right)/108.03 \qquad (3.7)$$

where

R = Percentage reduction in free flow speed from the normal free-flow speed (108.03 km/h),

Figure 3.5 presents a plot for the four main factors (wind speed, precipitation intensity, visibility, and road surface condition) versus the reduction in free-flow speed (in percentage), obtained from Equation 3.6. Figure 3.5 shows that the snowfall intensity and road surface condition represent the main effects on the free flow speed. As a result, the reduction in free flow speed is suggested to be the combined effect of the main effects (snowfall intensity and road surface conditions) with the average effects of other factors (wind speed and visibility).

To generalize the impact model so that it can be applied to other highways with different base conditions an impact model can be introduced. This model takes into account the relative impact of weather and other factors and is based on Equation 3.7 assuming a mean value for wind speed and visibility. This proposed impact model is presented in Equation 3.8.

$$R = -0.0577 + 0.0442 \times PR + 0.0420 \times SC \qquad (3.8)$$

where

R = percentage reduction in free flow speed from the normal free-flow speed,

PR = dummy variable representing precipitation intensity. *PR* equals 1, 2, 3, 4 for no precipitation, light precipitation, medium precipitation, and heavy precipitation, respectively,

SC = dummy variable representing road surface condition. *SC* equals 1, 2, 3 if the road is dry, wet, and snow or ice covered, respectively.

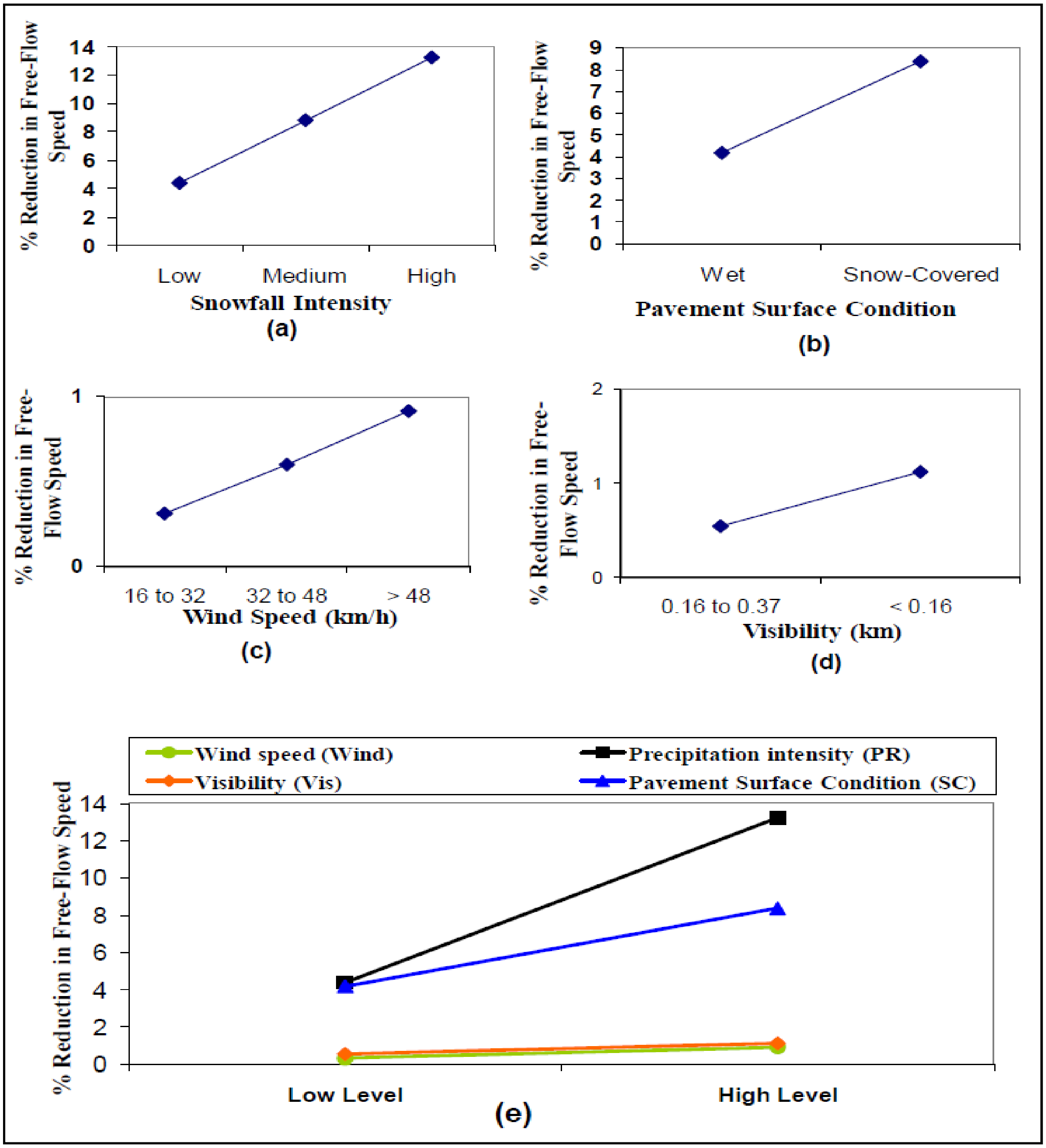

Figure 3.5: The Main Effects Plots for Equation 3.7. (a) Snowfall Intensity. (b) Road Surface Conditions. (c) Wind Speed. (d) Visibility. (e) Snowfall Intensity-Road Surface Condition-Wind Speed-Visibility

The number of observations used to develop Equation 3.8 is 12 (4 levels for snowfall intensity and 3 levels for road surface condition). The overall model is statistically significant. Both explanatory variables (PR and SC) are statistically significant as well. Moreover, the adjusted R^2 associated with the model equals 1.

Results of Equation 3.8 in terms of free flow speed reduction factors for different snowfall intensity levels (low, medium, and high) and different road surface conditions (wet, snow-covered) are presented in Table 3.1.

Table 3.1: Free Flow Speed Reduction Factors

Precipitation Intensity Level	Road Surface Condition	
	Wet	Snow-Covered
Low	11%	16%
Medium	15%	21%
High	20%	25%

Modeling of Reduction in Speed at Capacity

According to FHWA (2006), the reduction in speed at capacity due to snowfall conditions is generally similar to the reduction in free flow speed. Accordingly, this research assumes that the relative reduction factor in speed at capacity as a result of snowfall and road surface condition is the same as those for the free-flow speed. Therefore, the reduction factor model for speed at capacity is also given by Equation 3.8.

Modeling of Capacity Reduction

In Kyte et al. (2000), the effect of road surface conditions on free flow speed is explicitly accounted for, as shown in Equation 3.6. However, their research did not provide any equation for quantifying the effect of road surface conditions on capacity. Besides, as discussed in Chapter 2, there is no literature dealing specifically with this effect. Hence this study proposes an indirect approach to quantify the capacity effect of weather and road surface conditions. The idea is to identify the relationship between the reduction in free-flow speed and reduction in roadway capacity based on the study by FHWA (2006). In the FHWA (2006) study, regression models for the reduction factors for both free-flow speed and capacity during different weather conditions (snowfall intensity and visibility) were developed as shown in Equation 3.9 and Equation 3.10. Figure 3.6 and Figure 3.7 show the relationship between the reduction in free-flow speed (Equation 3.9) and roadway capacity (Equation 3.10), respectively, under different weather conditions (snowfall intensity and visibility). It may be noted that the reduction factors developed by the FHWA study did not include a road surface condition factor. However, based on Equations 3.9 and 3.10, reduction in capacity could be related to reduction in free flow speed which is a function of road surface conditions as given by Equation 3.11.

$$R_{FFS} = 1 - \left(0.838 - 0.0908 \times PR + 0.00597 \times (Vis)^2\right) \tag{3.9}$$

$$R_{Capacity} = 1 - \left(0.792 + 0.0048 \times (Vis)^2\right) \tag{3.10}$$

where

R_{FFS} = reduction factor in free flow speed,

$R_{Capacity}$ = reduction factor in capacity,

PR = precipitation intensity in centimeters per hour, and

Vis = visibility in kilometers.

The relationship between the reduction in capacity (Equation 3.10) and the reduction in free-flow speed (Equation 3.9) is developed by first generating a set of snowfall intensities based on the different values of visibility and the reduction in free-flow speed (in Equation 3.9). A number of observations were generated for different snowfall intensities (0 – 0.50 cm/h) and visibility (0 – 5 km). Then the values of the generated snowfall intensities and the corresponding visibility values are used to generate the reductions in free-flow speed (Equation 3.9) and roadway capacity (Equation 3.10). The relationship between the generated reductions in capacity versus the reduction in free-flow speed was developed by a regression analysis, as shown in Equation 3.11.

$$R_{Capacity} = 3.8857 + 0.98 \times R_{FFS} \tag{3.11}$$

where

$R_{Capacity}$ = the percentage reduction in roadway capacity, and

R_{FFS} = the percentage reduction in free-flow speed.

The adjusted R^2 associated with the model equals 0.951. In addition, the overall model and R_{FFS} are statistically significant. Figure 3.8 shows the relationship between the capacity reduction and the free-flow speed reduction as suggested by the model in Equation 3.11.

Table 3.2 shows the capacity reduction factors used in this study for different snowfall intensities (low, medium, and high) and different road surface conditions (wet, snow-covered) based on Equation 3.11 and Table 3.1. The relative effect of weather and road surface conditions on capacity is slightly higher than that on free-flow speed. For example, the model would predict 21percent reduction in free-flow speed but 24percent in capacity under medium precipitation and snow-covered condition.

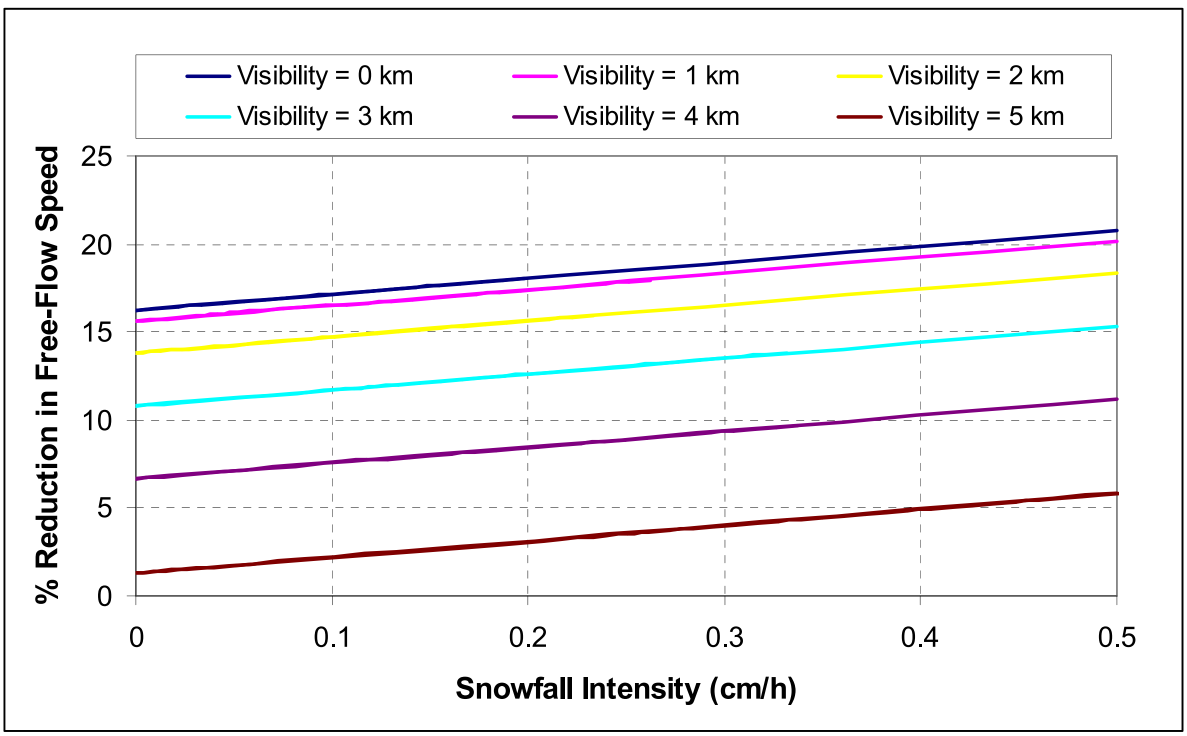

Figure 3.6: Relationship between the Reductions in Free-Flow Speed and Both Snowfall and Visibility Based on FHWA (2006) Model

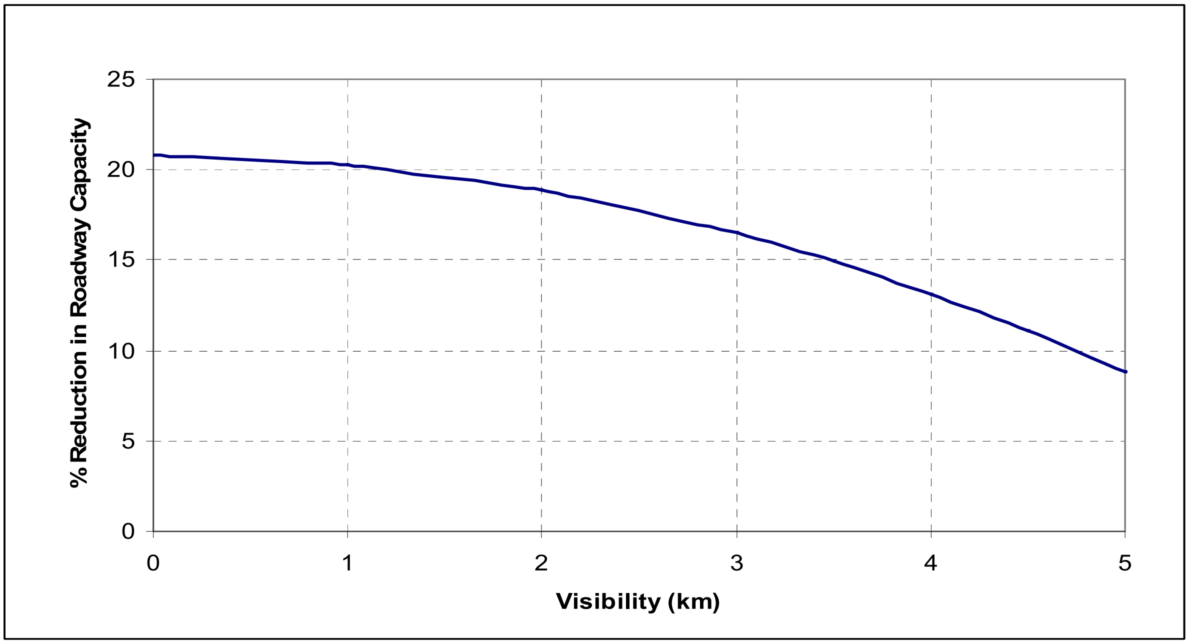

Figure 3.7: Relationship between the Reductions in Roadway Capacity and Visibility Based on FHWA (2006) Model

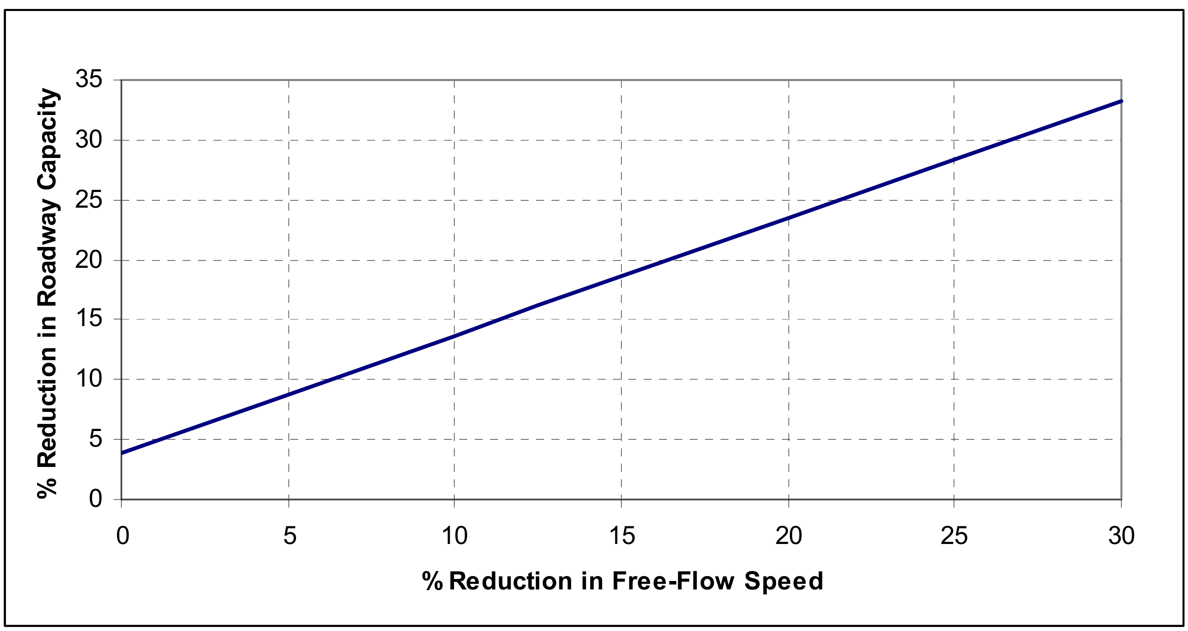

Figure 3.8: Relationship between Capacity Reduction and Free-Flow Speed Reduction

Table 3.2: Average Capacity Reduction Factors

Precipitation Intensity Level	Road Surface Condition	
	Wet	Snow-Covered
Low	15%	20%
Medium	19%	24%
High	23%	28%

Modeling of Jam Density

Jam density is the highest density which occurs when all vehicles are stopped and have occupied all the roadway spaces. Obviously, this situation is associated with speed and flow rate of zero. As a result, it can be reasonably expected that the jam density is not affected by weather conditions. This is confirmed by the FHWA (2006) study. As a result, this research assumes that the effect of weather conditions on the jam density is negligible.

3.3 Case Study Description

The following section presents the application of the proposed methodology to quantify the mobility benefits of achieving bare pavement on a highway segment from Ontario under different traffic characteristics, winter snow storms intensities, and road surface conditions as a result of maintenance operations.

3.3.1 Study Network

A section of the Queen Elizabeth Way (QEW) was chosen and modeled using the INTEGRATION simulation model (Van Aerde, 2005a and b). The section starts East of Guelph Line to West of Bronte Road with a total length of about 8.60 km, as shown in Figure 3.9. The motivation for using this section is because it had been used in another recent study (Allaby, 2006).

This QEW freeway segment consists of a three-lane mainline section, four one-lane on-ramps, and three two-lane off-ramps. The QEW mainline is instrumented with thirteen dual loop detector stations, with a single loop station on each on and off-ramp section. A modified AutoCAD drawing for the study section had been drawn based on an AutoCAD file by MTO for the QEW highway where the locations of loop stations are shown in Figure 3.10. In addition, Table 3.3 shows the loop station identification numbers and descriptions designated by MTO and the abbreviation codes used in Figure 3.10.

3.3.2 Traffic Data

The aggregated 5-minute loop detector data (traffic volume and speed) from the Ministry of Transportation of Ontario (MTO) for April 14, 2005 has been used for the calibration of the simulation model (Appendix B). The AM peak period starts around 6:15 AM to 9:30 AM as shown in Figure 3.11. In addition, the congestion started from downstream of the QEW section and moves upstream as time progresses. Furthermore, the weather during that day is mainly clear with visibility equals to 24.10 km, air temperature ranging from 3.7 °C to 12 °C, and wind speeds between 9 km/h to 33 km/h during the whole day, as shown in Appendix C (Environment Canada, 2008).

Figure 3.9: Study Network (© Google, 2007)

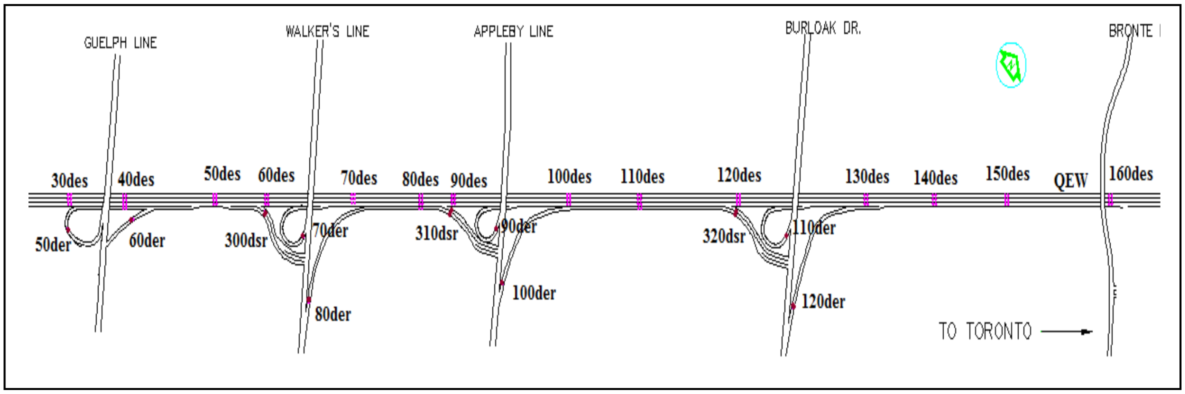

Figure 3.10: Loop Stations \ Locations

Table 3.3: Loop Stations \ Locations

Location	Loop Station ID	Abbreviation	Description
QEW Mainline	QEWDE0030DES	30des	Guelph Line
	QEWDE0040DES	40des	East of Guelph Line
	QEWDE0050DES	50des	East of Guelph Line
	QEWDE0060DES	60des	At Walker's Line
	QEWDE0070DES	70des	East of Walker's Line
	QEWDE0080DES	80des	East of Walker's Line
	QEWDE0090DES	90des	Appleby Line
	QEWDE0100DES	100des	East of Appleby Line
	QEWDE0110DES	110des	East of Appleby Line
	QEWDE0120DES	120des	Burloak Drive
	QEWDE0130DES	130des	East of Burloak Drive
	QEWDE0140DES	140des	East of Burloak Drive
	QEWDE0150DES	150des	East of Burloak Drive
	QEWDE0160DES	160des	Bronte Rd.
On Ramps	QEWDE0050DER	50der	SB Guelph Line -EB QEW
	QEWDE0060DER	60der	NB Guelph Line -EB QEW
	QEWDE0070DER	70der	SB Walker's Line -EB QEW
	QEWDE0080DER	80der	NB Walker's Line -EB QEW
	QEWDE0090DER	90der	SB Appleby Line -EB QEW
	QEWDE0100DER	100der	NB Appleby Line -EB QEW
	QEWDE0110DER	110der	SB Burloak Drive -EB QEW
	QEWDE0120DER	120der	NB Burloak Drive -EB QEW
Off Ramps	QEWDE0300DSR	300dsr	EB QEW - Walker's Line
	QEWDE0310DSR	310dsr	EB QEW- Appleby Line
	QEWDE0320DSR	320dsr	EB QEW- Burloak Drive

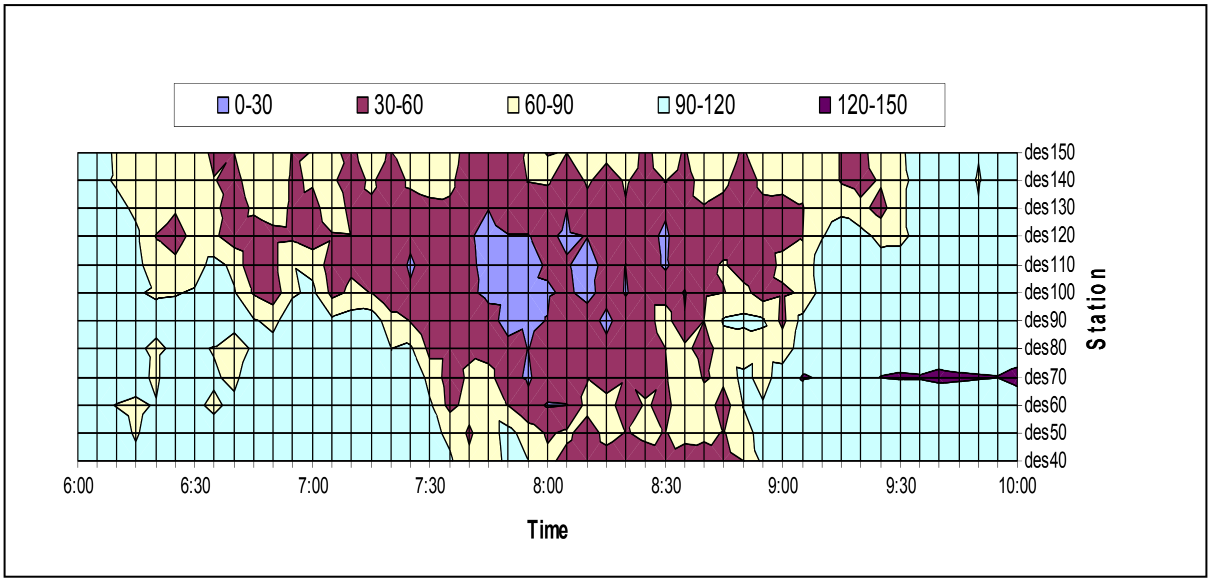

Figure 3.11: Contour Map for the Observed Speed (5-minute aggregated data)

3.3.3 Simulated Network

Figure 3.12 shows the study network in the INTEGRATION simulation model. Appendix F summarizes the INTEGRATION input values for the nodes, links, OD matrix, etc. used in this research. Based on the observed traffic volume and speed at all mainline loop stations, the traffic parameters that have been used for the simulation network can be shown in Table 3.4. The traffic parameters in Table 3.4 obtained by running the simulation model several times in order to get a similar traffic parameters to those observed from loop detectors stations.

Table 3.4: Traffic Parameters for the Simulated Network

Section	Free Flow Speed, km/h	Basic Capacity, veh/h/lane	Speed at Capacity, km/h	Jam Density, veh/km/lane
Basic Highway Section	125	2300	110	140
Merging Section	125	2400	110	140
Diverging Section	125	2400	110	140

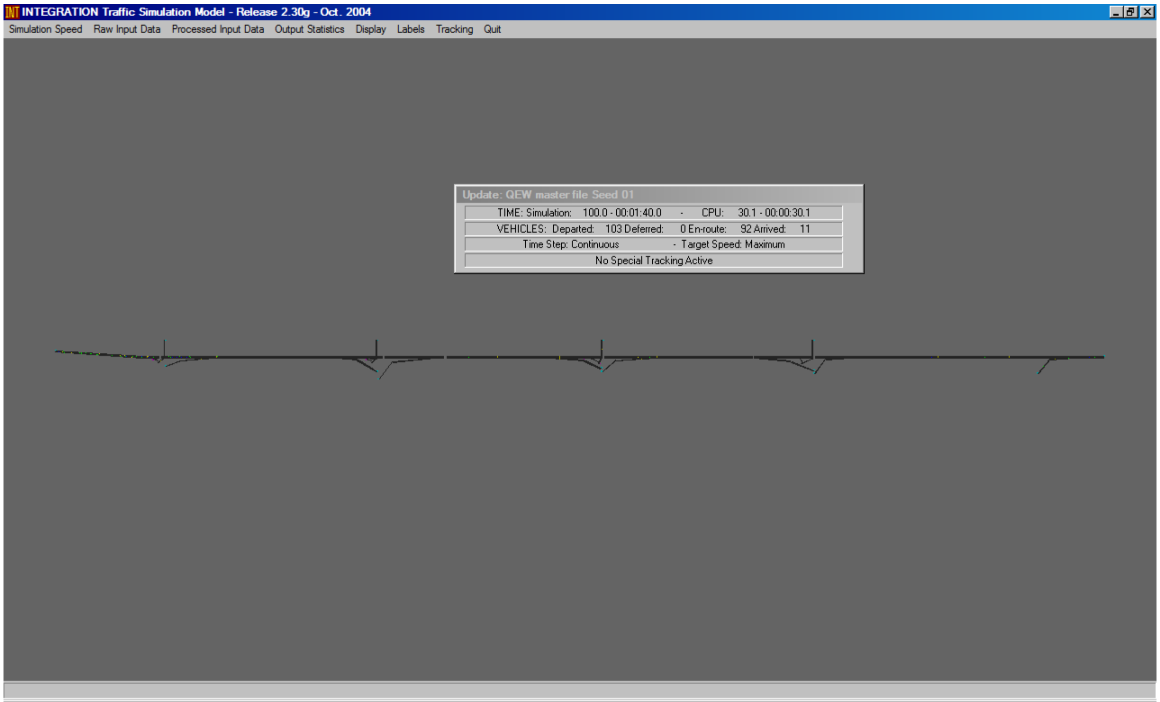

Figure 3.12: The Study Network From INTEGRATION Microsimulation Software

3.3.4 Model Calibration

The main objective of the calibration is to ensure that the simulated traffic volume and speed profiles obtained from the INTEGRATION simulation model at all the loop-detector stations match those observed in the field. For this purpose the origin-destination matrix (OD) is required. The first 5-minute OD matrix based on the observed traffic volume from loop detectors stations has been used as the first OD matrix for the period from 5:30 AM to 10:00 AM. The first 30 minutes (from 5:30 AM to 6:00 AM) was used as a warming up period. Then by comparing the simulated volume/speed profiles at all the mainline loop stations with the observed volume/speed profiles based on the confidence limits, which can be considered as the 95percent Confidence Interval ($Z_{\alpha/2} \times \sigma$). Where $Z_{\alpha/2}$ is the standardized normal distribution factor, which equals 1.96 at the 95% confidence interval and σ is the standard deviation of the observations. Furthermore, the overall accuracy is measured by the root mean square error (*RMSE*) as defined in Equation 3.12.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i}^{N}(O_i - S_i)^2} \qquad (3.12)$$

where

Si = the simulated traffic parameter (speed or volume) for observation i,

Oi = the Observed traffic parameter (speed or volume) for observation i, and

N = the number of observation.

The demand OD matrix between zones was adjusted to minimize the RMSE function and ensure that the simulated volume/speed profiles match well with those observed. The final OD matrix is shown in Table 3.5. The detailed 5-minutes OD matrix is in Appendix F.

Based on the OD matrix from Table 3.5 and by using 10 different random number seeds, the average traffic volume and traffic speed between 6:00 AM and 10:00 AM for all the loop detectors along the mainline were calculated. Comparing the simulated volumes/speeds with the observed volumes/speeds, the RMSE equals to 776.61 vehicles/hour and 24.106 km/h for volume and speed respectively. The speed profile for all loop stations for the period from 6:00 AM to 10:00 AM are shown in Figure 3.13. In addition, the individual speed and volume profiles for station 70des are shown in Figure 3.14 and Figure 3.15 respectively. Furthermore, Appendices C and D provide the complete individual speed and volume profiles. The model was reasonably calibrated as shown from Figure 3.14, Figure 3.15, Appendix D, and Appendix E.

Table 3.5: Demand OD Matrix from 5:30AM to 10:00 AM

Origin	Destination				Total (vehicles)
	Walker's Line	Appleby Line	Burloak Drive	Mainline Downstream	
Mainline Upstream	3245	3776	961	15447	23428
Guelph Line N	0	0	0	0	0
Guelph Line S	0	0	0	0	0
Walker's Line N	0	0	171	1193	1364
Walker's Line S	0	0	151	1063	1214
Appleby Line N	0	0	0	642	642
Appleby Line S	0	0	0	396	396
Burloak Dr. N	0	0	0	2846	2846
Burloak Dr. S	0	0	0	2510	2510
Total (vehicles)	3245	3776	1283	24096	32399

* The values in the table represent the total traffic volume in vehicles

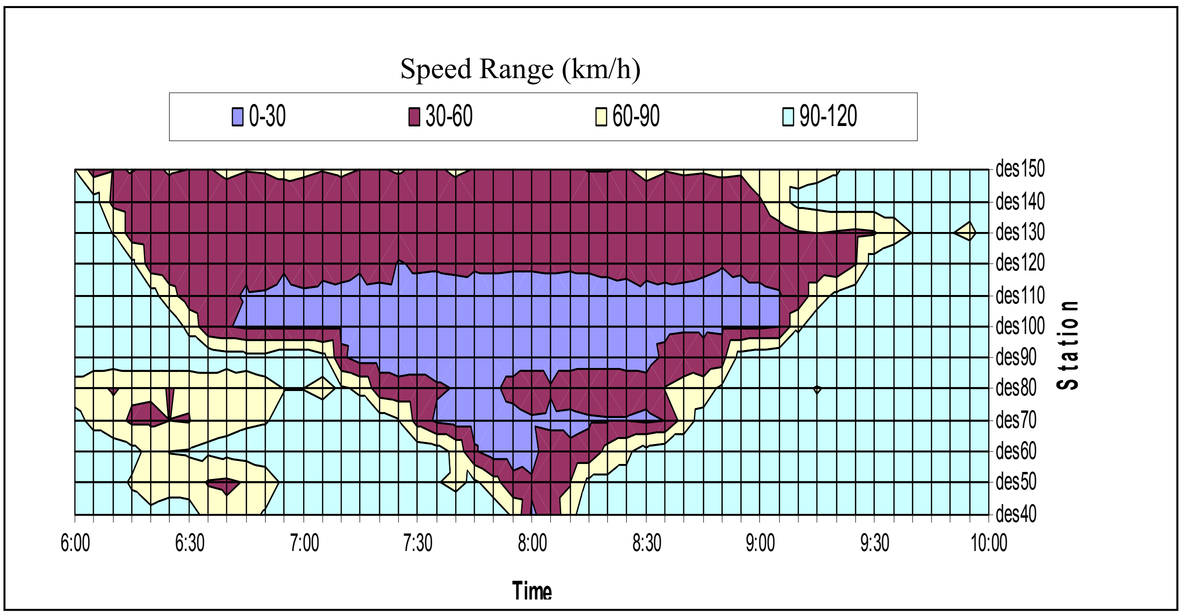

Figure 3.13: Contour Map for Aggregated 5-minute Simulated Speed

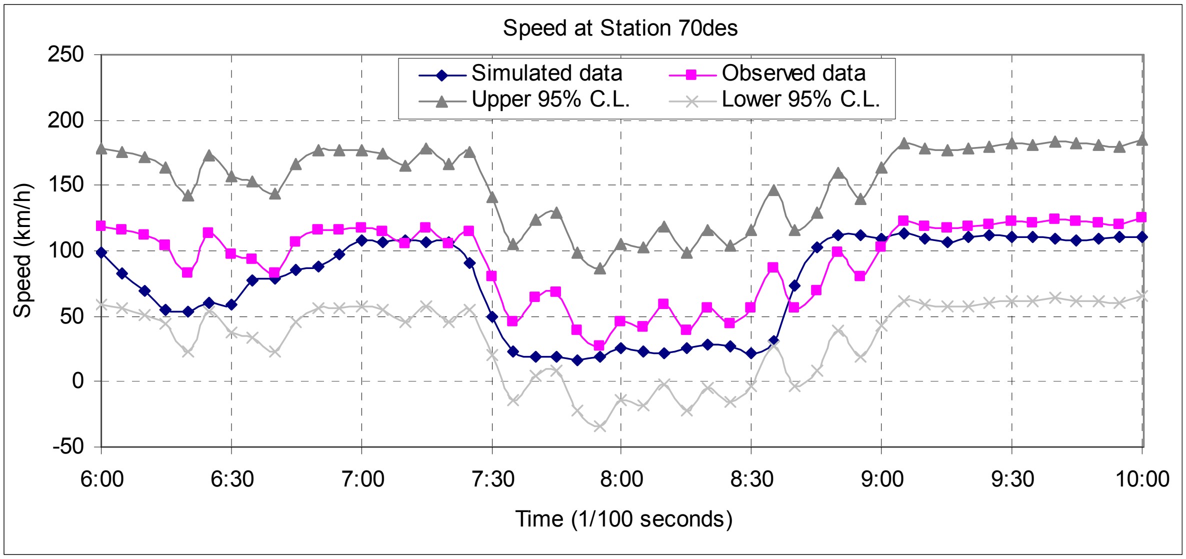

Figure 3.14: Aggregated 5-Minute Speed at Station No. 70des

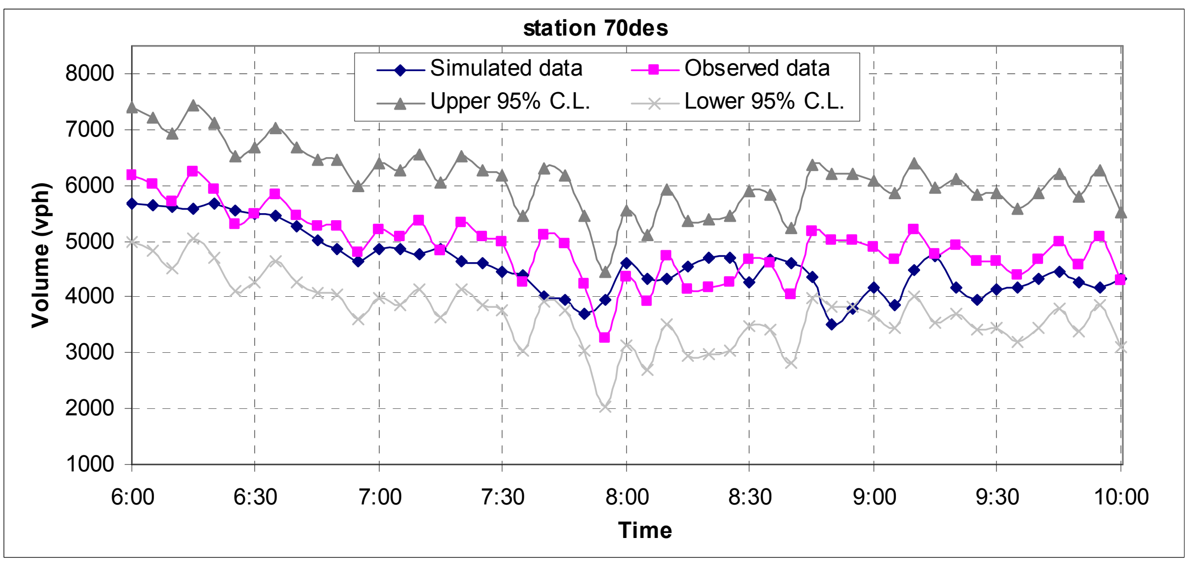

Figure 3.15: Aggregated 5-Minute Traffic Volume at Station 70des

3.3.5 Traffic Conditions Scenarios

To estimate the mobility benefits under different traffic conditions (congestion levels), different traffic scenarios were generated based on the AM peak demand. Based on the ratio between traffic volume and capacity (*V/C*) for the bottle neck section, which is at the end of the study network east to loop station (150 des) as can be shown from Figure 3.11, five demand scenarios were generated to represent different traffic conditions in addition to the base scenario which represent the AM peak scenario. The six demand levels (in terms of percent of the AM peak demand) and V/C ratios for the scenarios are shown in Table 3.6.

Table 3.6: Different Demand Scenarios for Simulation Analysis

Scenario	Percentage of Base Scenario Demand	V/C Ratio
Scenario 1 (Base Case)	100%	0.91
Scenario 2	40%	0.37
Scenario 3	65%	0.59
Scenario 4	75%	0.69
Scenario 5	80%	0.73
Scenario 6	110%	1

Chapter 4
Analysis of Results

This chapter discusses the results of the simulation study that was designed to model the mobility benefit of achieving the bare pavement under different traffic and road surface conditions, a result of weather events and maintenance operations. Total travel time (TTT) was used as a performance measure for quantifying the effects of winter snow storms on the mobility. In addition, a case study is undertaken to illustrate that the mobility benefit models can be applied to evaluate alternative maintenance policies.

4.1 Introduction

The INTEGRATION simulation model has been used to evaluate the mobility benefit under different traffic and road surface conditions as discussed in Chapter 3. 4.50 hours that represents the AM peak period, on a road segment with a length of 8.60 kilometers from QEW, was simulated using the INTEGRATION simulation model. A warming-up period of 0.50-hour was considered in this study. Furthermore, a uniform effect of both snowfall intensity and road surface condition has been assumed in this study during the 4-hour period.

The INTEGRATION simulation model outputs the link travel time of every vehicle traversing each link. Upon entering a link each vehicle is provided with a time card which is retrieved when it leaves the link. The link travel time for each vehicle is computed as the difference between the exit and entry times. The total link travel time of all vehicles is determined as the summation of the travel time for all vehicles that traverse the link. Furthermore, the INTEGRATION simulation model estimates vehicle delay every 0.10 seconds as the difference in travel time between a vehicle's travel time under its current speed and the travel time achievable at free flow speed (M. Van Aerde &Assoc. Ltd., 2005a).

In this study, the total travel time includes only the portion of travel time on the QEW mainline links (East of Guelph Line to West of Bronte Road with total length of 8.60 km) in addition to the travel time for vehicles that did not have the opportunity to enter the simulated network during the simulation period, and the vehicles that are left on the network at the end of the simulation model. The following sections present the results of the simulation modeling of the QEW under different scenarios of traffic characteristics, and road surface conditions as a result of weather events and maintenance operations.

The total travel time under both bare wet pavement and snow-covered road surface conditions (RSC) for different snow storm intensities and traffic congestion levels were compared. The relative mobility benefit of achieving the bare wet pavement condition is evaluated using the following two measures:

$$MB_1 = \frac{TTT_{Snow-Covered} - TTT_{Wet}}{TTT_{Snow-Covered}} \times 100 \tag{5.1}$$

$$MB_2 = \frac{TTT_{Snow-Covered} - TTT_{Wet}}{TTT_{Dry}} \times 100 \tag{5.2}$$

where

MB_1 = Relative Mobility Benefit of achieving bare pavement,

MB_2 = Mobility Benefit of achieving bare pavement relative to No-Precipitation and dry case,

$TTT_{Snow-Covered}$ = Total travel time associated with snow-covered pavement case in vehicle-hours,

TTT_{Wet} = Total travel time associated with wet pavement case in vehicle-hours,

TTT_{Dry} = Total Travel Time associated with no-precipitation and dry pavement case in vehicle-hours.

Note that Equation 5.1 is defined to show the relative benefit of winter road maintenance using the ratio of the total travel time savings to the total travel time without winter road maintenance. On the other hand, Equation 5.2, which uses the total travel time under normal road weather and surface conditions (TTT_{dry}) as a comparison basis, is proposed for the sake of application as it can be conveniently applied for estimating the mobility benefit of maintenance without conducting an extensive simulation.

It should be noted that the V/C ratio used in all discussion in this chapter is associated with the no-precipitation and dry surface scenarios. It represents the level of demand that will occur with different time of day, and it is not the actual V/C ratio at particular weather conditions. Furthermore, the capacity (no precipitation and dry surface) that used is fixed which represents the maximum capacity that can be reached during different weather conditions. Moreover, traffic demand was assumed to be the same during different precipitation intensities and road surface conditions within the same scenario.

4.2 Effect of RSC on Traffic under No-Precipitation

Under the no-precipitation case, the modeling results show that for different road surface conditions (dry surface, wet surface, and snow-covered surface) the total travel time increases as traffic congestion level increases (V/C ratio), as shown from Table 4.1 and Figure 4.1. In addition, the total travel time associated with snow-covered surface has the highest values in comparison with dry surface and wet surface conditions for different traffic conditions. As expected the reduction in the traffic parameters (free-flow speed, speed at capacity, and capacity) due to snow-covered conditions is higher than those for dry surface (up to 1336 veh.hr) and wet surface (up to 663) conditions.

Under no-precipitation, the modeling results show that the mobility benefit (travel time saving) of achieving wet bare pavement increases as traffic congestion level increases, as shown from Table 4.2 and Figure 4.2. In addition, Table 4.2 and Figure 4.3 show that the mobility benefit, as a percentage of travel time associated with both snow-covered and dry conditions, increases as congestion level increases until the V/C ratio reaches the near-saturation region (V/C around 0.73). After that it decreases (4 to 5 percent) as the V/C increases. Furthermore, it is noted that the relative increase in travel time as percentage of travel time associated with dry surface condition is greater than that associated with snow-covered condition, as shown from Table 4.2 and Figure 4.3.

Table 4.1: Total Travel Time Associated With No-Precipitation Scenario

Road Surface Condition	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Dry Surface	595	1003	1192	1315	4573	7038
Wet Surface	616	1044	1252	1447	6231	7711
Snow-Covered Surface	645	1095	1337	1636	6686	8374

Table 4.2: Mobility Benefit of Achieving Bare Pavement associated with No Precipitation

Mobility Benefit (Travel Time Saving)	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Vehicle-hours	29	51	86	190	455	663
% From Snow-Covered Case	5	5	6	12	7	8
% From Dry Case	5	5	7	14	10	9

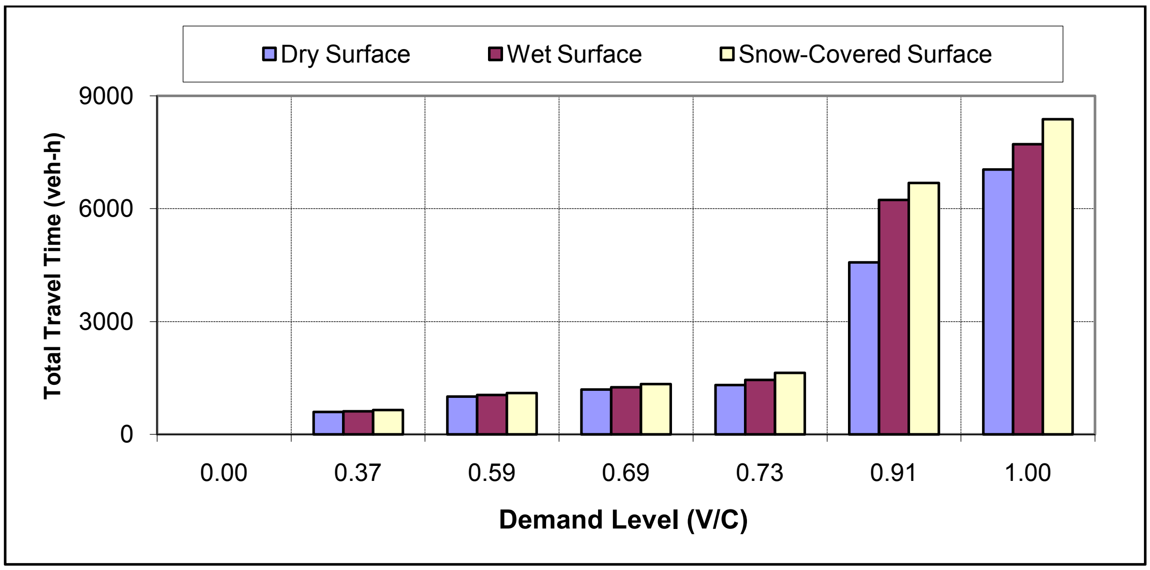

Figure 4.1: Total Travel Time Under No-Precipitation

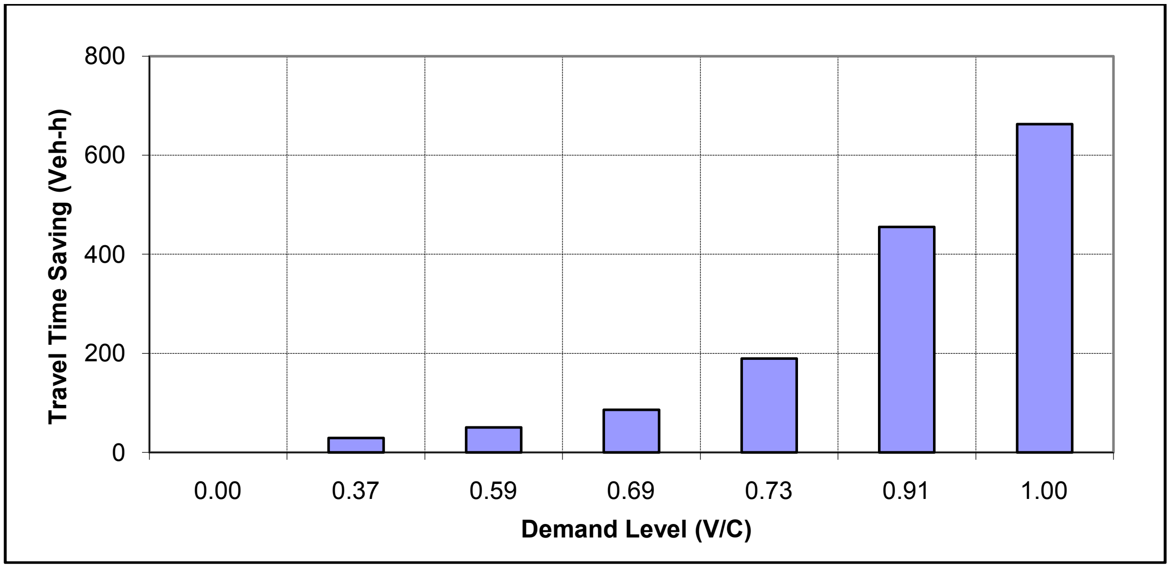

Figure 4.2: Travel Time Saving of Achieving Bare Pavement under No Precipitation

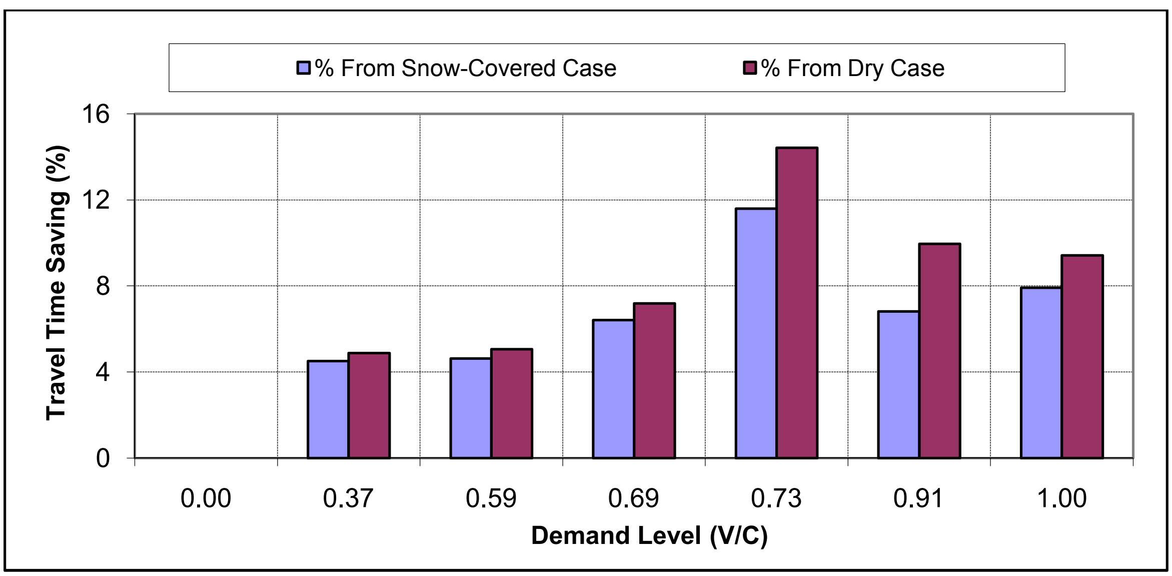

Figure 4.3: Relative Travel Time Saving of Achieving Bare Pavement under No Precipitation

4.3 Effect of RSC on Traffic under Low Snowfall Intensity

In the same fashion, under low-precipitation, the modeling results show that for different road surface conditions (wet surface, and snow-covered surface) the total travel time increases as traffic congestion level increases (V/C ratio) as shown from Table 4.3 and Figure 4.4. In addition, the total travel time associated with snow-covered surface has the highest values in compared with wet surface conditions for different traffic conditions, which is expected as the reduction in traffic parameters (free-flow speed, speed at capacity, and capacity) associated with the snow-covered condition is higher than for wet surface conditions.

Under Low-precipitation, the modeling results show that the mobility benefit (travel time saving) of achieving wet bare pavement increases as traffic congestion level increases as shown from Table 4.4 and Figure 4.5. In addition, Table 4.4 and Figure 4.6 show that the mobility benefit, as a percentage of travel time associated with snow-covered and dry conditions, increases as congestion level increases until the V/C ratio reaches the near-saturation region (V/C around 0.73). After that it decreases as V/C increases. Furthermore, it is noted that the relative increase in travel time as percentage of travel time associated with dry surface condition is greater that that associated with snow-covered condition as shown from Table 4.4 and Figure 4.6.

Table 4.3: Total Travel Time Associated under Low-Precipitation Scenario

Road Surface Condition	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Wet Surface	677	1157	1346	2029	7261	9288
Snow-Covered Surface	721	1238	1813	2764	8066	10411

Table 4.4: Mobility Benefit of Achieving Bare Pavement under Low-Precipitation

Mobility Benefit	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Vehicle-hours	43	81	468	735	804	1122
% From Snow-Covered Case	6	7	26	27	10	11
% From No-Prec. & Dry Case	7	8	39	56	18	16

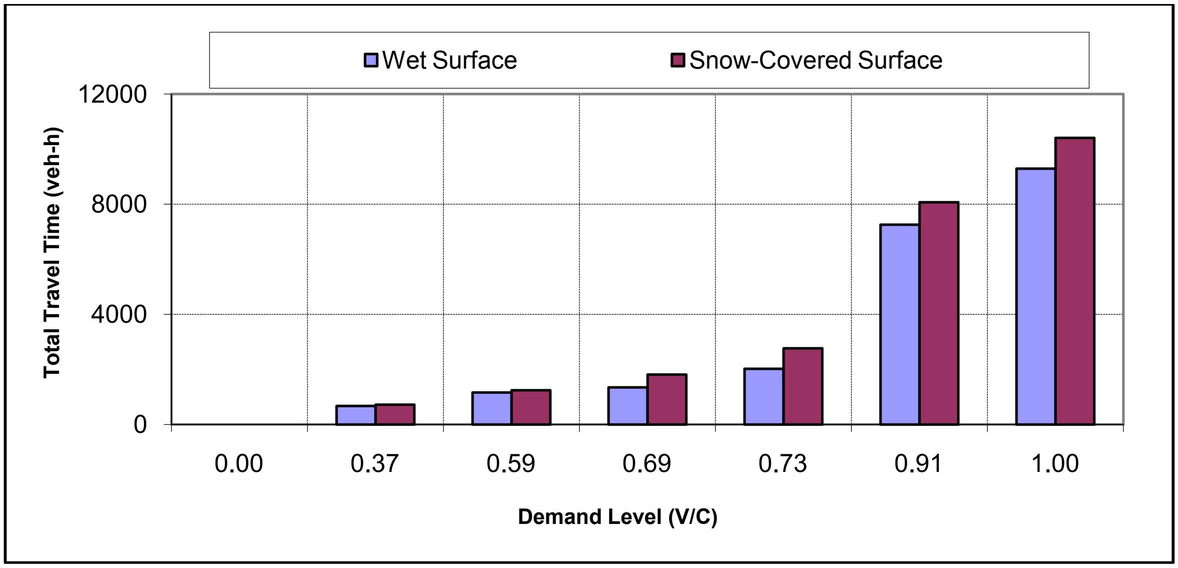

Figure 4.4: Total Travel Time During Low-Precipitation Scenario

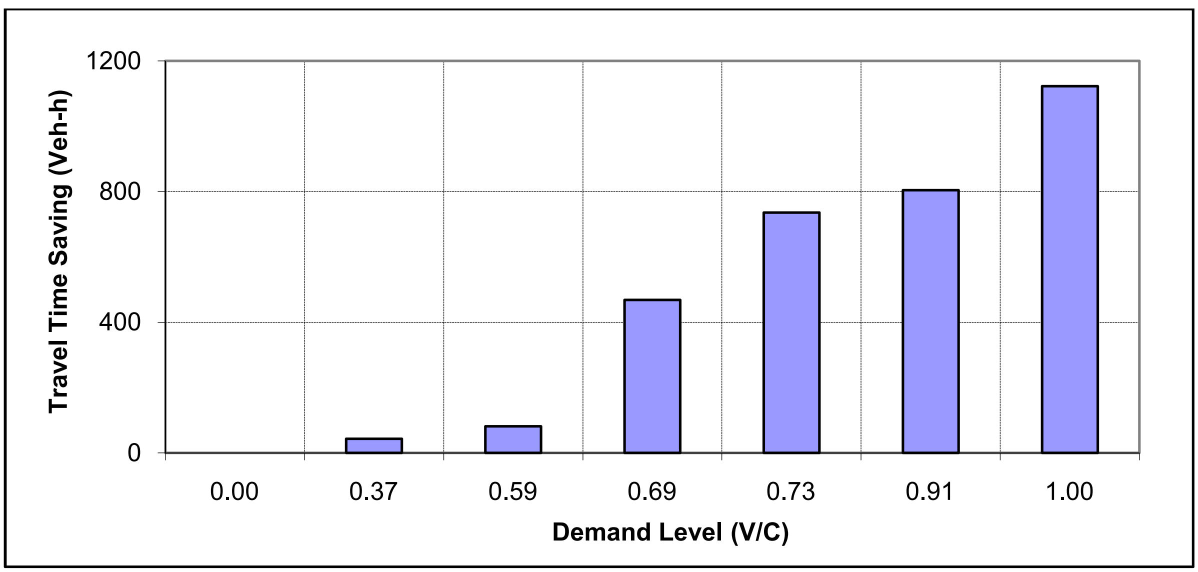

Figure 4.5: Travel Time Saving of Achieving Bare Pavement during Low-Precipitation

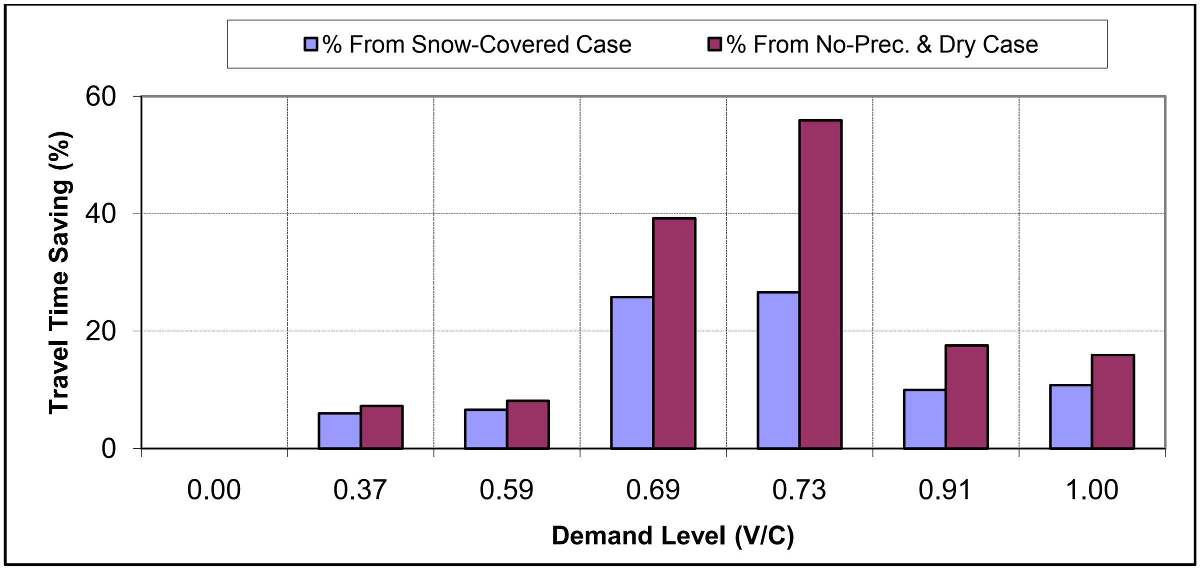

Figure 4.6: Relative Travel Time Saving of Achieving Bare Pavement during Low-Precipitation

4.4 Effect of RSC on Traffic under Medium Snowfall Intensity

In the same fashion, under medium-precipitation, the modeling results show that for different road surface conditions (wet surface, and snow-covered surface) the total travel time increases as traffic congestion level increases (V/C ratio) as shown from Table 4.5 and Figure 4.7. In addition, the total travel time associated with snow-covered surface has the highest values in compared with wet surface conditions for different traffic conditions, which is expected as the reduction in traffic parameters (free-flow speed, speed at capacity, and capacity) associated with the snow-covered condition is higher than for wet surface conditions.

Under medium-precipitation, the modeling results show that the mobility benefit (travel time saving) of achieving wet bare pavement increases as traffic congestion level increases (up to 1468 veh-hr) until it reaches V/C of 0.73, then mobility benefit decreases (by about 500 veh-hr) as V/C increases till V/C of 0.91, then it increases again as V/C increases as shown from Table 4.6 and Figure 4.8. In addition, Table 4.6 and Figure 4.9 show that the mobility benefit, as a percentage of travel time associated with snow-covered and dry conditions, increases as congestion level increases until the V/C ratio reaches the near-saturation region (V/C around 0.73). After that it decreases as V/C increases. There is slight increase (1percent) in mobility benefit for V/C greater than 0.91 than for V/C of 0.91. Furthermore, it is noted that the relative increase in travel time as percentage of travel time associated with dry surface condition is greater than that associated with snow-covered condition as shown from Table 4.6 and Figure 4.9.

The higher values of mobility benefit associated with traffic conditions near-saturation (V/C around 0.73) because travel time is very sensitive to the change in both capacity and free flow speed. The reduction in capacity, at the same demand, will move the traffic congestion level from lower V/C ratio to higher V/C ratio.

Table 4.5: Total Travel Time Associated During Medium-Precipitation Scenario

Road Surface Condition	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Wet Surface	716	1230	1763	2593	7981	10213
Snow-Covered Surface	764	1333	2329	4061	8950	11663

Table 4.6: Mobility Benefit of Achieving Bare Pavement During Medium-Precipitation

Mobility Benefit	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Vehicle-hours	48	104	566	1468	969	1451
% From Snow-Covered Case	6	8	24	36	11	12
% From No-Prec. & Dry Case	8	10	47	112	21	21

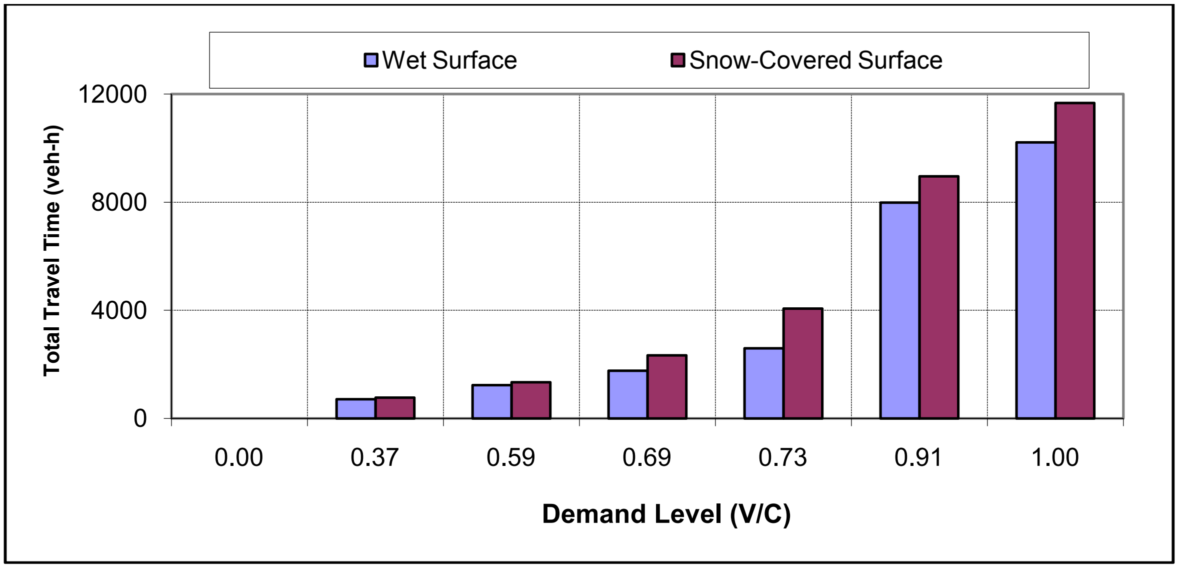

Figure 4.7: Total Travel Time during Medium-Precipitation Scenario

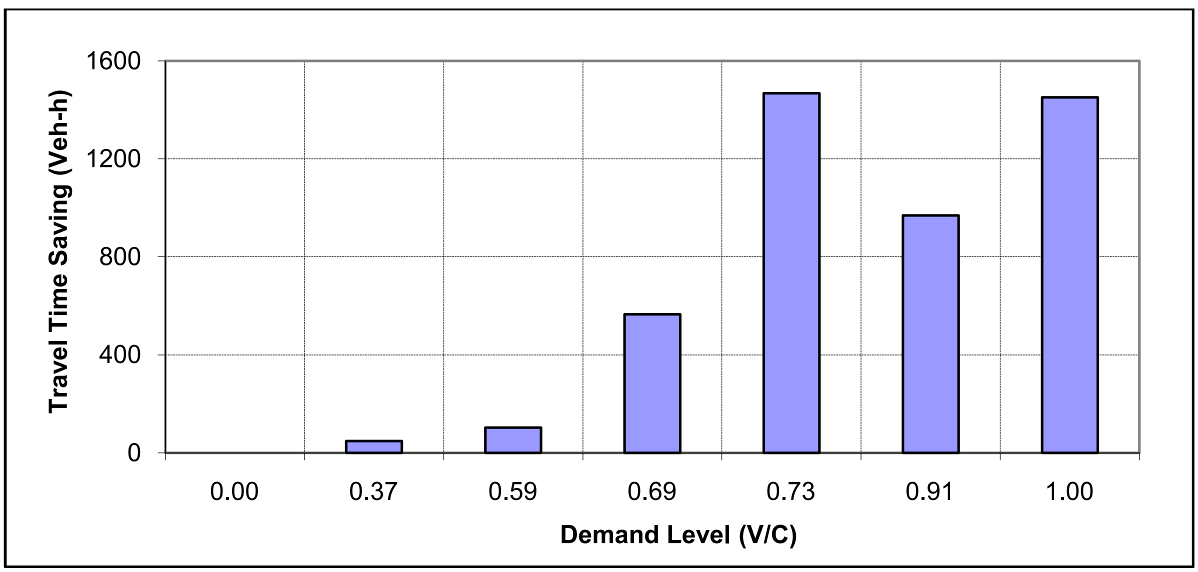

Figure 4.8: Travel Time Saving of Achieving Bare Pavement During Medium-Precipitation

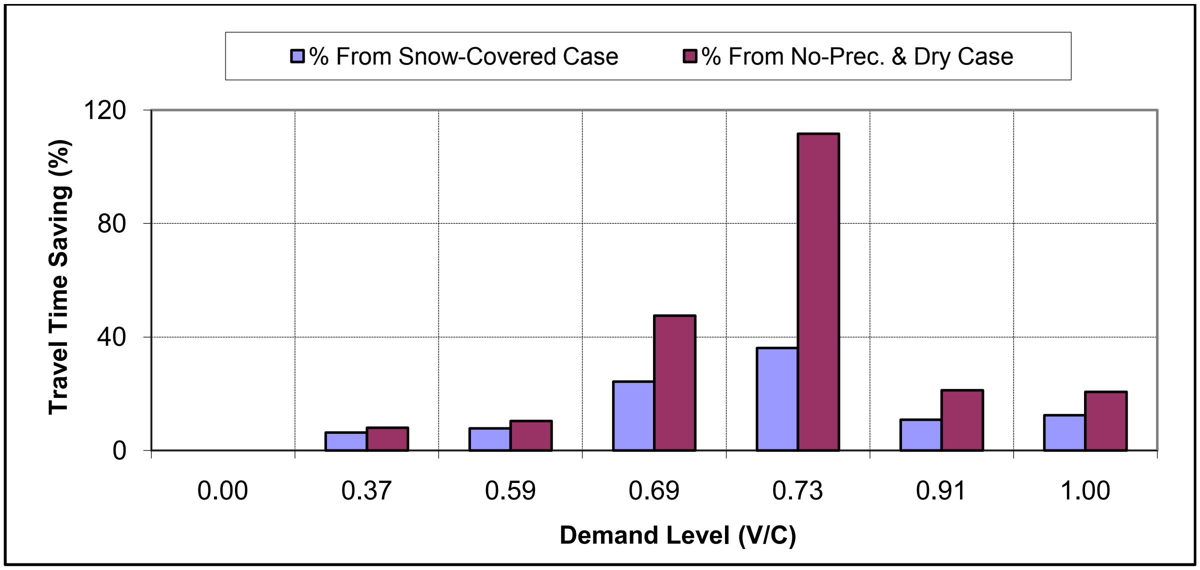

Figure 4.9: Relative Travel Time Saving of Achieving Bare Pavement During Medium-Precipitation

4.5 Effect of RSC on Traffic under High Snowfall Intensity

Under High-precipitation, the modeling results show that for different road surface conditions (wet surface, and snow-covered surface) the total travel time increases as traffic congestion level increases (V/C ratio), as shown from Table 4.7 and Figure 4.10. In addition, the total travel time associated with snow-covered surface has the highest values as compared with wet surface conditions for different traffic conditions, which is expected as the reduction in traffic parameters (free-flow speed, speed at capacity, and capacity) associated with the snow-covered condition is higher than for wet surface conditions.

Under High-precipitation, the modeling results show that the mobility benefit (travel time saving) of achieving wet bare pavement increases as traffic congestion level increases until it reaches V/C of 0.73 , then mobility benefit decreases as V/C increases till V/C of 1.0, as shown from Table 4.8 and Figure 4.11. In addition, Table 4.8 and Figure 4.12 show that the mobility benefit, as a percentage of travel time associated with snow-covered and dry conditions, increases as congestion level increases until the V/C ratio reaches the near-saturation region (V/C around 0.73). After that it decreases as V/C increases to 1.0. Furthermore, it is noted that the relative increase in travel time as percentage of travel time associated with dry surface condition is greater than that associated with snow-covered condition as shown from Table 4.8 and Figure 4.12.

It is noted that the total travel time associated with snow-covered surface during snowfall of low intensity is greater than that associated with wet surface during snowfall of medium intensity. In addition, the total travel time associated with snow-covered surface during snowfall of medium intensity is greater than that total travel time associated with wet surface during snowfall of high intensity.

Table 4.7: Total Travel Time Associated During High-Precipitation Scenario

Road Surface Condition	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Wet Surface	759	1318	2227	3781	8801	11372
Snow-Covered Surface	814	1481	3135	5914	10032	11947

Table 4.8: Mobility Benefit of Achieving Bare Pavement During High-Precipitation

Mobility Benefit	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
Vehicle-hours	55	163	908	2133	1231	575
% From Snow-Covered Case	7	11	29	36	12	5
% From No-Prec. & Dry Case	9	16	76	162	27	8

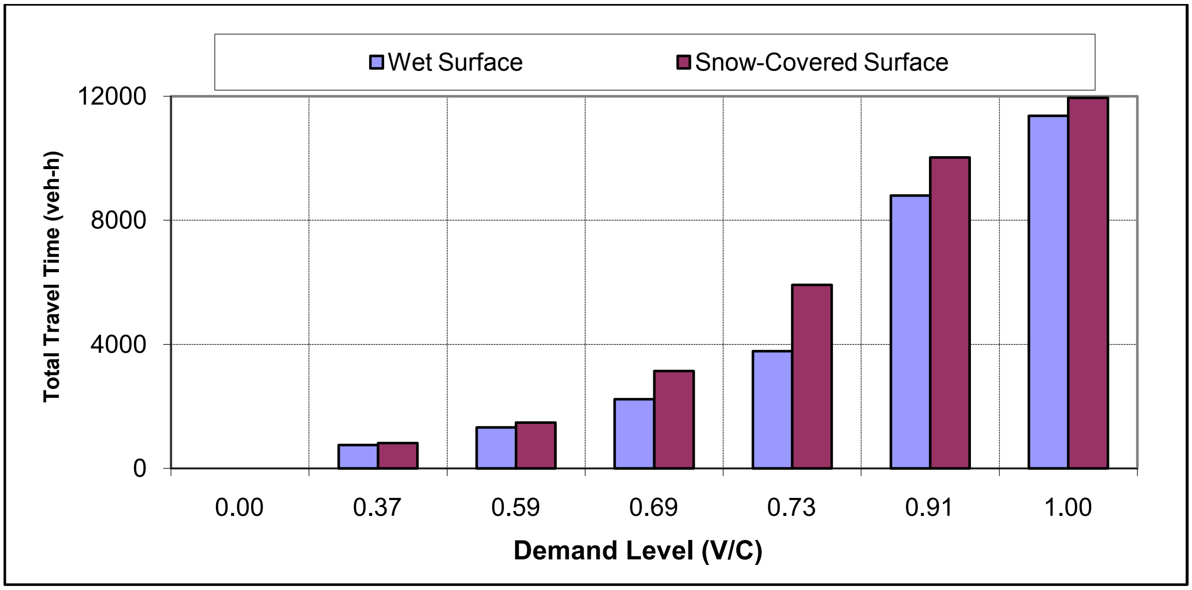

Figure 4.10: Total Travel Time During High-Precipitation Scenario

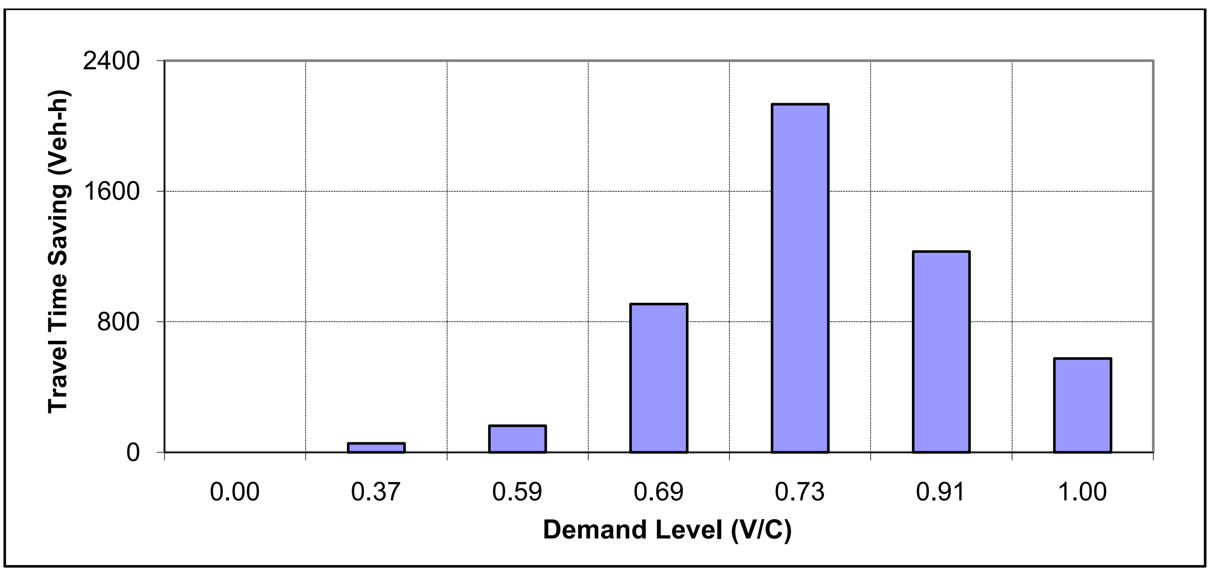

Figure 4.11: Travel Time Saving of Achieving Bare Pavement During High-Precipitation

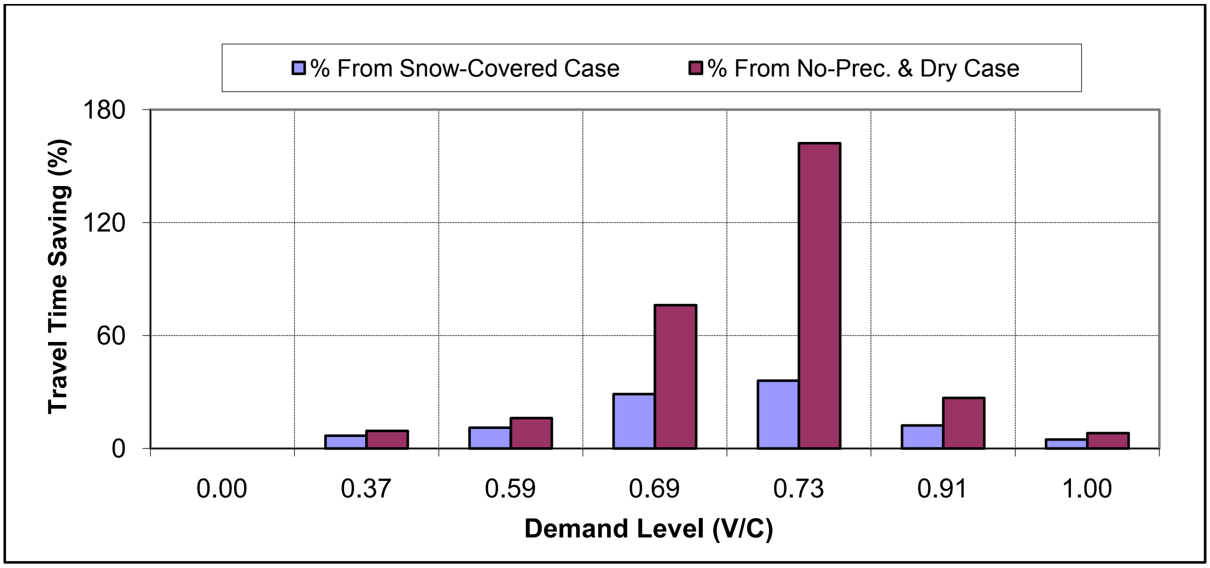

Figure 4.12: Relative Travel Time Saving of Achieving Bare Pavement During High-Precipitation

4.6 Mobility Benefit of Achieving Bare Pavement

By comparing total travel times between snow-covered surface scenarios (without maintenance) and bare wet surface scenarios (with maintenance) for different snowfall intensities (no, low, medium, and high precipitations) and different traffic conditions (V/C ratio), it was found that a slight increase in travel time saving, from 51 to 163 vehicle-hours, was observed for V/C up to 0.60, which represents undersaturated traffic conditions. It is noted that the travel time saving with a V/C between 0.60 and 0.73 during medium and high snowfall intensities is significantly higher than those during no-precipitation and low precipitation. Moreover, under medium-precipitation, the travel time saving starts to decrease as V/C increases from 0.73 to 0.91, and then increases again as V/C increases further. For snowfall of high intensity, travel time saving decreases for values of V/C greater than 0.73. In contrary, for no-precipitation and low-precipitation scenarios, travel time saving increases (by about 387 to 473 veh-hr than at V/C of 0.73) as V/C increases, as can be seen from Table 4.9 and Figure 4.13.

On the other hand, by comparing relative travel times between snow-covered surface scenarios (without maintenance) and bare wet surface scenarios (with maintenance) for different snowfall intensities (no, low, medium, and high precipitations) and different traffic conditions (V/C ratio), the relative travel time saving for V/C from 0.0 to 0.60 is found to fall between 5 and 11 percent. Relative saving in travel time, for V/C greater than 0.60, significantly increases till V/C of around 0.70 for different snowfall intensities (low, medium, and high). But for no-precipitation scenario, there is a slight increase when V/C increases from 0.60 to 0.70. Furthermore, relative saving in travel time decreases for V/C greater than 0.70 until V/C reaches 0.91. For V/C greater than 0.91, relative travel time saving slightly increases except for snowfalls of high intensity. For snowfall of high intensity, the saving in travel time decreased for V/C greater 0.70, as shown from Table 4.10 and Figure 4.14.

In the same fashion, relative travel time as a percentage of total travel time during no-precipitation and dry surface scenarios have the same trend as for relative travel time as a percentage of total travel time during snow-covered scenarios. The difference between the two cases is that the relative saving in travel time with the former case is much higher than for the latter case, especially for V/C greater than 0.60 as shown from Table 4.10, Table 4.11, Figure 4.14, and Figure 4.15.

The low values of mobility benefit for over saturated traffic conditions (V/C greater than 0.90) may be interpreted as when the traffic congestion level is high the total travel time is insensitive to the change in the road surface conditions (from snow-covered pavement to wet pavement), which have a direct effect on traffic parameters (capacity, free-flow speed, and the speed at capacity). The change in the pavement condition has an effect on the total travel time during the under saturated traffic conditions; however, because of the low V/C value, the reduction in the total travel time becomes less significant overall.

During the near-saturation traffic condition period, the total travel time is very sensitive to the change in the capacity, the free flow speed, and speed at capacity as a result of the pavement surface condition. Because of the reduction in capacity the congestion level could move from near-saturated regime to the saturated regime.

Table 4.9: Mobility Benefit of Achieving Bare Pavement as Total Travel Time Saving

Snowfall Intensity	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
No Prec.	29	51	86	190	455	663
Low Prec.	43	81	468	735	804	1122
Medium Prec.	48	104	566	1468	969	1451
High Prec.	55	163	908	2133	1231	575

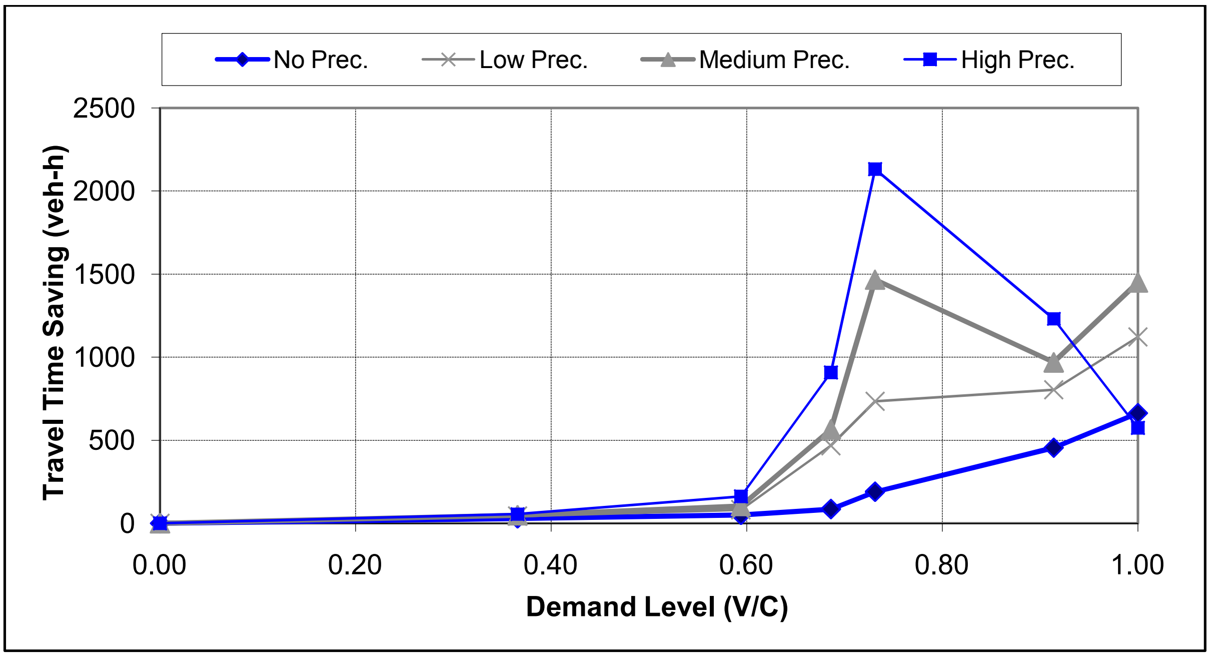

Figure 4.13: Mobility Benefit of Achieving Bare Pavement

Table 4.10: Mobility Benefit of Achieving Bare Pavement as a Percentage of Travel Time of Snow-Covered scenario

Snowfall Intensity	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
No Prec.	5%	5%	6%	12%	7%	8%
Low Prec.	6%	7%	26%	27%	10%	11%
Medium Prec.	6%	8%	24%	36%	11%	12%
High Prec.	7%	11%	29%	36%	12%	5%

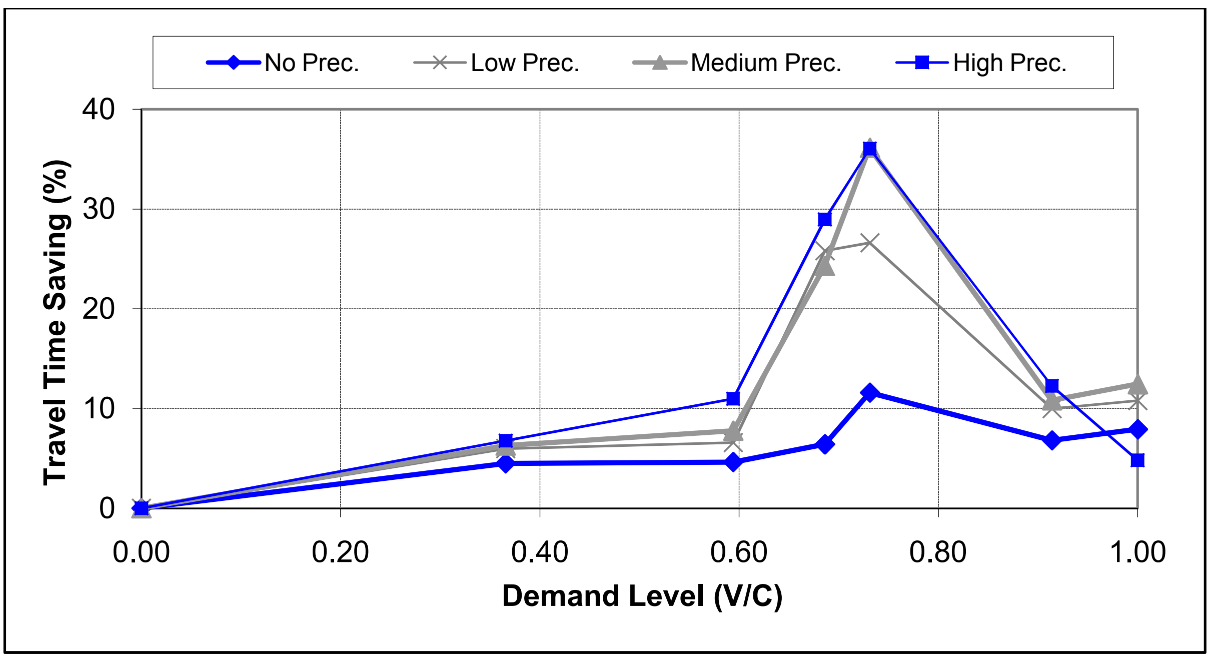

Figure 4.14: Mobility Benefit of Achieving Bare Pavement as a Percentage of Travel Time of Snow-Covered scenario

Table 4.11: Mobility Benefit of Achieving Bare Pavement as a Percentage of Travel Time of No-Precipitation and Dry-Surface scenario

Snowfall Intensity	Demand Level (V/C)					
	0.37	0.59	0.69	0.73	0.91	1.00
No Prec.	5%	5%	7%	14%	10%	9%
Low Prec.	7%	8%	39%	56%	18%	16%
Medium Prec.	8%	10%	47%	112%	21%	21%
High Prec.	9%	16%	76%	162%	27%	8%

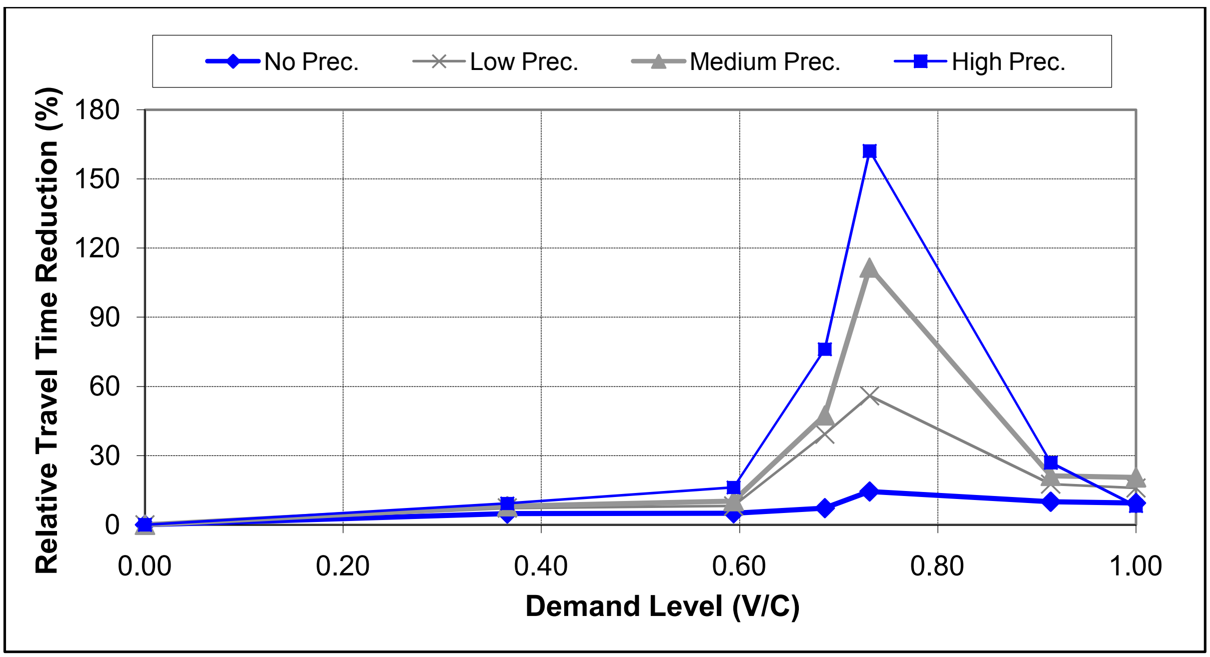

Figure 4.15: Mobility Benefit of Achieving Bare Pavement as a Percentage of Travel Time of No-Precipitation and Dry-Surface scenario

4.7 Applications of the Mobility Benefit Model

This section introduces a procedure to demonstrate how the mobility benefit factors derived from the simulation study in the previous section could be applied to estimate the benefit of two maintenance decision scenarios without conducting a time consuming simulation analysis. The analyses consider a particular maintenance route that is similar to the one modeled in our simulation. In the first analysis, we show how the upper bound of the overall benefit of maintaining bare pavement conditions for a given winter season can be estimated. In the second scenario, we examine the relationship between the mobility benefit of winter road maintenance and bare pavement recovery time - an important winter road maintenance policy variable.

4.7.1 Benefits of Maintaining Bare Pavement

Figure 4.16 shows the steps involved to estimate the mobility benefit of maintaining bare pavement. The fundamental assumption behind this procedure is that the mobility benefits models (or factors) obtained in the previous section could be applied to other similar highways. Furthermore, some basic information related the highway and weather, such as traffic demand and snow storms, is assumed to be available. This proposed procedure is demonstrated using a case study with the following data:

- Highway Length = 100 kilometer
- 3-lanes in each direction
- FFS = 110 km/h and average speed under normal weather conditions over the day
- Capacity = 2,200 vehicle/hour/lane
- Average annual daily traffic (AADT) = 160,000 vehicle/day (assumed to be the average along the whole segment)
- The hourly variation of traffic (assumed as shown in Table 4.12 to be the average along the whole segment)
- 50/50 directional split
- Details on snow storms, including frequency, intensity and duration

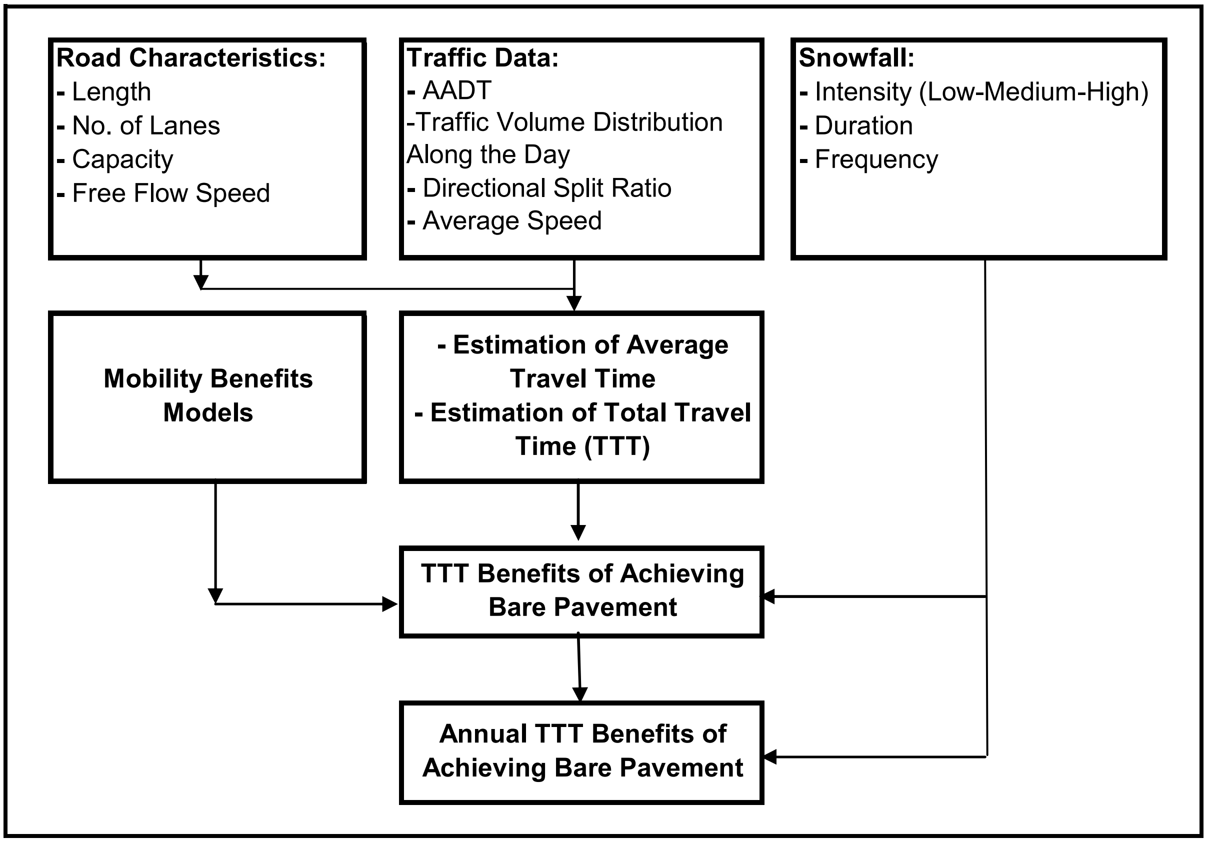

Figure 4.16: Flow Chart for Estimating of the Annual Mobility Benefits

The procedure for estimating the annual mobility benefit of achieving bare pavement is summarized in the following steps:

Step 1: Estimate Hourly Traffic Volume and Congestion Level

The first step of the procedure is to estimate hourly traffic volume based on AADT and historical traffic variation pattern. In this example, we assume that the traffic is distributed by time of day, with its distribution given in Table 4.12. It is further assumed that traffic is uniformly distributed within each time period as shown in Figure 4.17. Based on hourly traffic volume, roadway capacity, number of lanes, and directional split, the volume/capacity (V/C) ratio can be estimated for each period, as shown in Figure 4.18.

Table 4.12: Demand Distribution along the Day

Time of day	% Daily Traffic Volume
12:00 AM - 6:00 AM	10
6.01 AM - 10:00 AM	25
10:01 AM - 3:00 PM	20
3:01 PM - 7:00 PM	30
7:01 PM - 11:59 PM	15

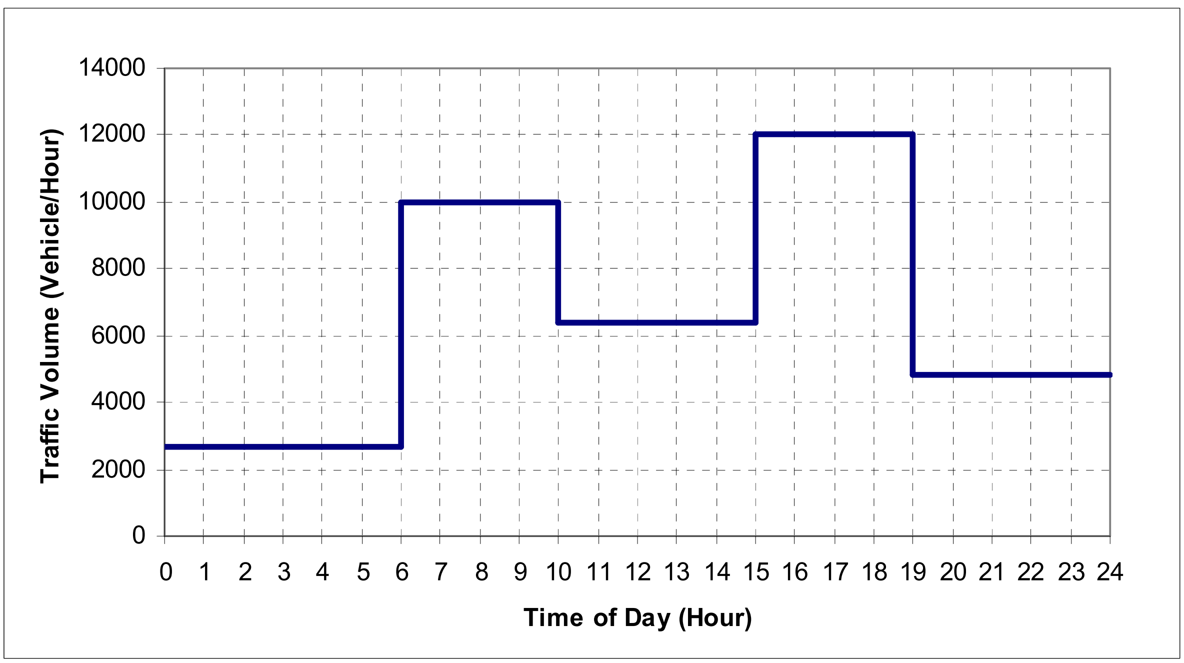

Figure 4.17: Demand Distribution along the Day

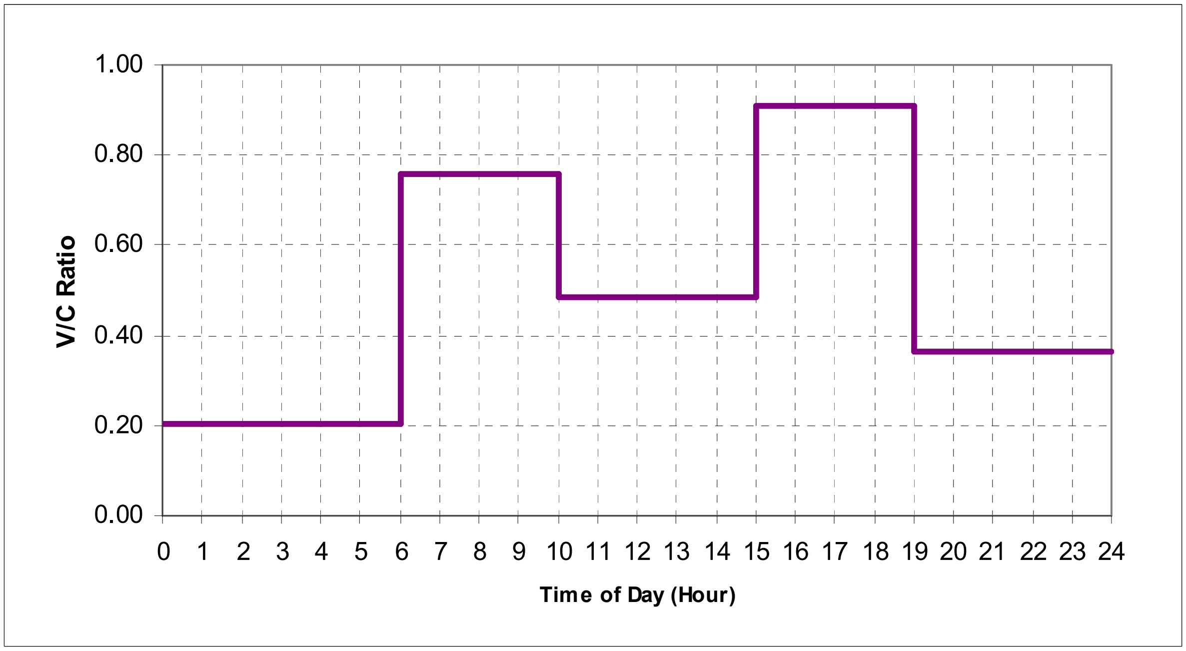

Figure 4.18: V/C Ratio

Step 2: Estimate Average Travel Speed and Travel Time under Normal Weather Conditions (No-precipitation and dry surface)

It is also assumed that the average speeds for individual time periods under normal weather conditions are known or can be estimated approximately using a simple traffic stream model based on traffic flow rate and capacity. For this example, the average speed over the day is distributed according to Figure 4.19. With the given speed distribution, the average travel time for each period can be estimated. Figure 4.20 shows the average travel time for each period of the day.

Step 3: Estimate Total Travel Time under Base Condition

The hourly total travel time can be estimated based on the average travel time obtained in Step (2) and the hourly traffic volume from Step (1). Figure 4.21 shows the hourly total travel time by time of day.

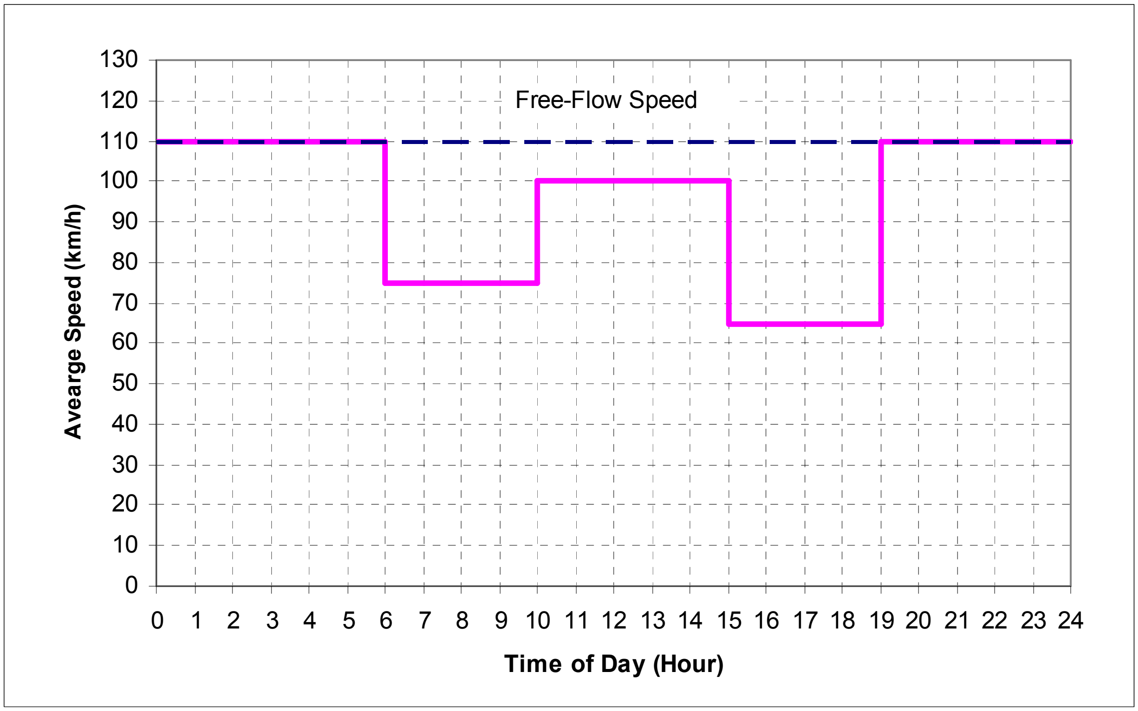

Figure 4.19: Average Traffic Speed during the Day

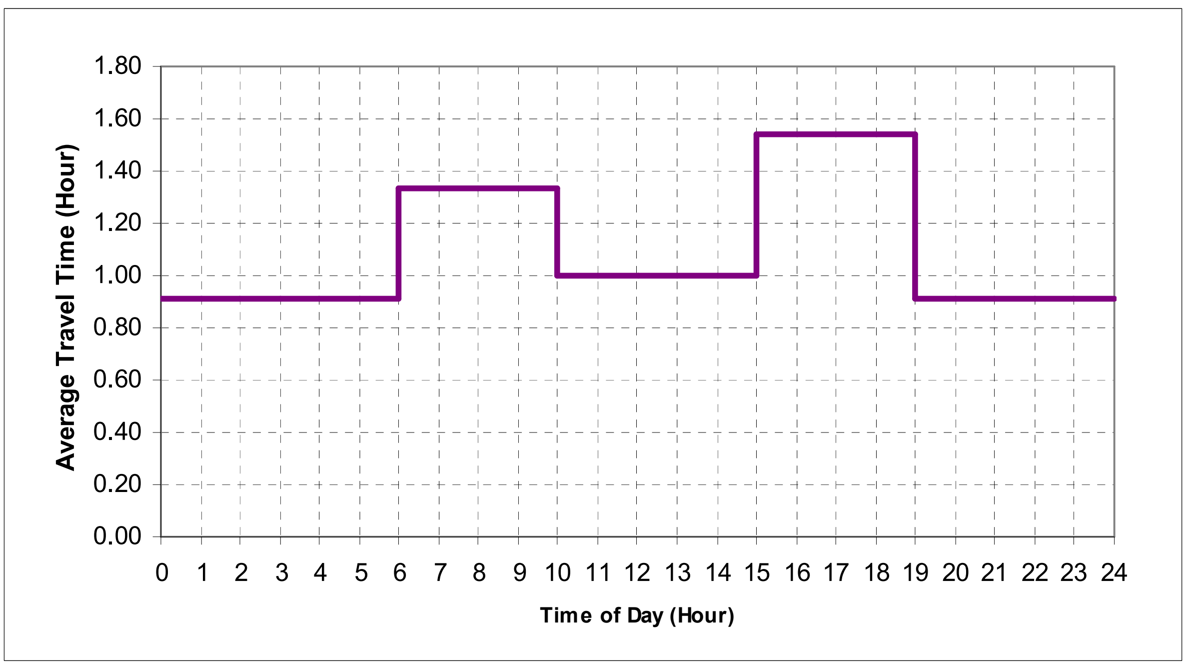

Figure 4.20: Average Travel Time during Different Traffic Conditions

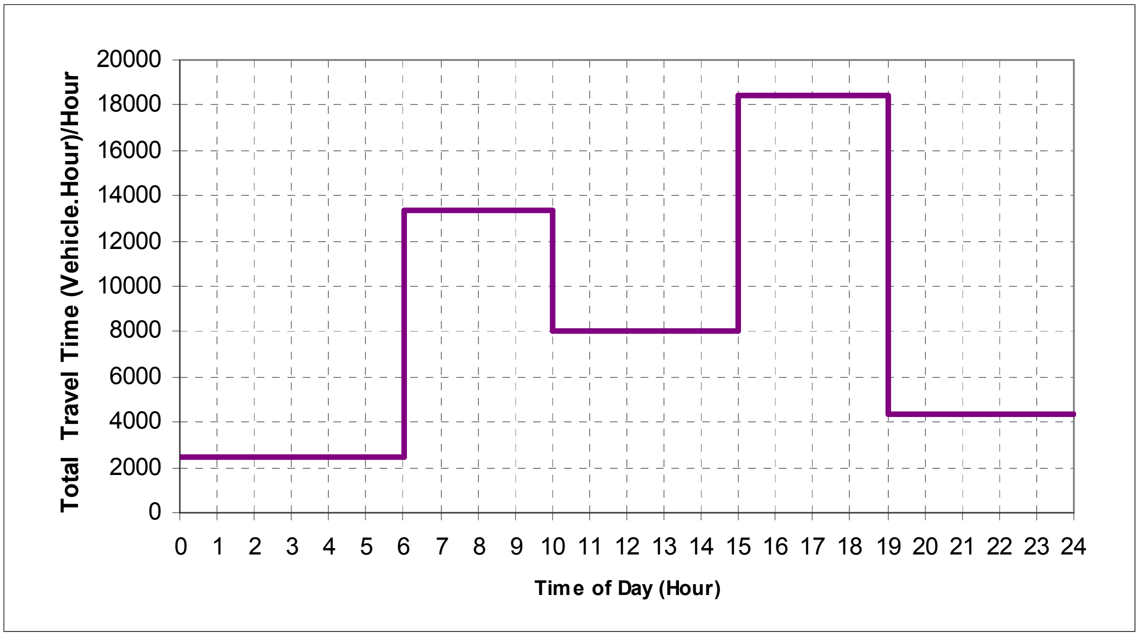

Figure 4.21: Hourly Total Travel Time over the Day

Step 4: Generate Snow Storms for a Given Season

This step is to generate snow storms based on historical weather data. To generate snow storms, information about the intensity (low, medium, and high), frequency of different snow storms, duration of each snow storm and occurrence time are required. Furthermore, a statistical distribution for frequency, duration, and time of occurrence is needed. In our example, snow storm data from the Ministry of Transportation Ontario (MTO) for the winter season 2003/2004 near QEW highway is available and thus used in this analysis. The characteristics of snow storms during 2003/2004 are shown in Appendix G. Based on the data in Appendix G, the characteristics of the snow storms are summarized as follows:

1. Number of snow storms with low intensity (less than 1.27 cm/h) = 26 (Assumed to follow Poisson Distribution),
2. Number of snow storms with medium intensity (1.27 to 3.81cm/h) = 26 (Assumed to follow Poisson Distribution),
3. Number of snow storms with high intensity (greater than 3.81 cm/h) = 10 (Assumed to follow Poisson Distribution),

4. Average Duration = 7.25 hours (the Negative Exponential distribution is a good fit for the data with a scale factor of 0.138 (1/average duration) as shown in Appendix G), and
5. Occurrence start time is assumed to follow a uniform distribution over the 24 hour period with a probability density function of 1/24.

An Excel (Microsoft ® Office Excel 2003) sheet was created to generate snow storms for a given winter season. It should be noted that Excel (2003) does not include the inverse function for Poisson distribution. As a result, the SIMTOOLS.XLA (Myerson © 2009) has been used to generate the inverse for Poisson distribution.

Step 5: Estimate Mobility Benefit of Achieving Bare Pavement

The Mobility benefit of achieving bare pavement during different snowfall conditions are calculated by multiplying the estimated total travel time in step (3) by the mobility benefits factors from Table 4.11. Based on snow storm intensity, the mobility benefit of achieving bare pavement during different traffic conditions (V/C ratio) can be estimated. For our example, the hourly mobility benefit of achieving bare pavement for each hour under different snow storms and traffic conditions is shown in Table 4.13.

Table 4.13: Hourly Total Travel Time Reduction

V/C Ratio	Snowfall Intensity		
	Low	Medium	High
0.20	95	106	121
0.36	316	352	405
0.48	491	587	811
0.76	4291	5187	8013
0.91	3247	3912	4970

Step 6: Estimate Mobility Benefit of Achieving Bare Pavement for a Given Snow Storm

The hourly benefit of achieving bare pavement for a specific snow storm (with certain intensity, duration) can be estimated by multiplying the duration of the snow storm by the corresponding hourly total travel time benefits from Table 4.13 and the time period that the storm is likely to happen. If the snow storm duration is extended to different traffic regimes, each time period corresponding to a certain traffic condition can be assumed as a separate storm. Then the cumulative benefits can be calculated as the sum of all benefits associated with different traffic conditions. For example if there a snow storm with low intensity and duration of 6 hours (2 during V/C = 0.91 and 4 during V/C =0.36), the Mobility benefit of achieving the bare pavement can be calculated as following:

$$Mobility\ \ Benefit = 2 \times 3247\ +\ 4 \times 316 = 7758\ Vehicle - Hour$$

Step 7: Estimate Annual Mobility Benefit of Achieving Bare Pavement

Based on the historical data on the frequencies and durations of different snow storms (with low intensity, medium intensity, and high intensity), the annual mobility benefits of achieving the bare pavement can be calculated as the sum of the total travel time savings associated with all generated snow storms. In this example, a macro was developed in Excel using Visual Basic for Applications (VBA) in order to generate snowstorms based on data from Step (4), as shown in Appendix G. the Mobility Benefit of our example is shown in Table 4.14. The average reduction in the total travel time is 1402836 (vehicle-hours/direction). It should noted that the values in Table 4.14 is the average of 10 simulation runs, and each run is the average of 1000 trials.

Table 4.14: Annual Mobility Benefit of Achieving Bare Pavement for Application Example

Statistic Measure	Annual Total Travel Time Reduction (veh-h/direction)
Average	1402836
Standard deviation	272936
Maximum	2388007
Minimum	665606
Range	1722401

If the monetary equivalent of saving one-vehicle-hour of travel equals $15 (an assumption), the annual mobility benefit of achieving bare pavement in this example ranges from $20 million to $72 million, with an average of $42 million. Note that this estimate should be considered as the upper bound of the benefit of maintaining bare pavement as in reality it is impossible to maintain bare pavement at all the time during a snow storm.

4.7.2 Mobility Benefit of Shortening Bare Pavement Recovery Time

According to Ministry of Transportation Ontario (MTO)'s maintenance policy, the bare pavement recovery time for Class 1 highways is 8-hours (MTO, 2003). In this section, we conduct an analysis on the potential mobility benefit of reducing this bare pavement recovery time using the same case scenario as the one used in the previous section.

As described previously, the hourly mobility benefit during no precipitation can be estimated as shown in Table 4.15. Moreover, using the same weather conditions as in the previous example, the annual mobility benefit of achieving bare pavement can be calculated as the sum of the total travel time savings associated with each snow storm event. In this example, the same macro that was used in the previous example is used in order to generate snowstorms (as shown in Appendix G). The difference here is that mobility benefit is calculated based on the recovery time after the end of each weather event with no precipitation. The mobility benefits under different recovery times are calculated by changing the recovery time (from 0 to 8 hours) in the excel sheet (as shown in Appendix G).

Table 4.15: Hourly Mobility Benefit during No-Precipitation

V/C Ratio	Mobility Benefit (veh-h)
0.20	64
0.36	213
0.48	318
0.76	1826
0.91	1838

Table 4.16 shows the summary statistics of the increase in total travel time (vehicles-hour) as a result of the bare pavement (BP) recovery time over an 8-hour period after the storm ends. It should noted that the values in Table 4.16 is the average of 10 simulation runs, and each run is the average of 1000 trials.

As a result of the simulation modeling, the mobility benefit of shortening bare pavement recovery time for this particular case is shown in Figure 4.22. As expected, the amount of travel time savings is a linearly decreasing function of bare pavement recovered time. The annual average saving in total travel time for one hour reduction in bare pavement recovered time is approximately 90000 vehicle-hours for the highway, which could be transferred into a total annual saving of $1.35 million.

Table 4.16: Summary statistics of the increase in total Travel Time as a result of Bare Pavement Recovery Time

BP Recovery Time (Hour)	Total Travel Time Increase in Over 8 -hours				
	Average	Standard deviation	Maximum	Minimum	Range
8	367686	65455	603504	195544	407960
7	319730	57598	506835	160223	346612
6	276425	53094	437292	125868	311424
5	228448	43944	377205	108285	268920
4	183014	33869	294212	99568	194644
3	137455	25720	237984	52284	185700
2	90693	17265	154934	39926	115008
1	45717	8418	73600	25302	48298
0	0	0	0	0	0

Figure 4.22: Total Travel Time Saving versus the Amount of Bare Recovery Pavement Time Reduced

Chapter 5
Conclusions and Recommendations

This research conducted a simulation study to understand the relationship between highway mobility and winter road maintenance under varying winter weather and traffic conditions. A good understanding of this relationship is essential to the development of cost-effective winter road maintenance policies and standards, operation strategies and technologies. A microscopic traffic simulation model was used to investigate the traffic patterns under adverse weather and road surface conditions. A segment of the Queen Elizabeth Way (QEW) located in the Great Toronto Area, Ontario was used in the simulation study and field traffic data were obtained and used in calibrating the simulation model. Different scenarios of traffic characteristics and road surface conditions as a result of weather events and maintenance operations were simulated and travel time was used as a performance measure for quantifying the effects of winter snow storms on the mobility. This chapter summarizes the major conclusions and findings from this thesis research, followed by recommendations for future work.

5.1 Conclusions

This research conducted a simulation study on the effects of winter snow storms on traffic mobility on a road segment with a length of 8.60 kilometers from QEW. The INTEGRATION model was used to simulate the traffic operations under a set of assumed snow storm events and maintenance scenarios. The simulated snow storms represent three different levels of snowfall intensities, including low snowfall, medium snowfall, and heavy snowfall. For each snow storm event, two types of road surface conditions are assumed: one is snow-covered representing the extreme scenario of having no winter road maintenance and the other is bare wet road surface representing the scenario of having perfect road maintenance. In addition, six levels of travel demand, representing traffic conditions with V/C of 0.37, 0.59, 0.69, 0.73, 0.91, and 1.00 respectively, were considered as an attempt to capture the effect of the variation in congestion level.

The modeling results indicate that winter road maintenance aiming at achieving bare pavement conditions during low snowfall events could save the total travel time (compared with snow-covered scenario) by about 6-7percent for V/C of from 0.35-to 0.60, 26-27 percent for V/C from 0.70 to 0.75, and 10-11percent for V/C between 0.90 and 1.00. It was also found the relative travel time saving increases as the snowfall intensity increases. The total travel time saving under heavy snowfall storms could increase to 7-11 percent for V/C of 0.35 to 0.60, 29-36 percent for V/C from 0.70 to 0.75 and 5-12percent for V/C between 0.90 and 1.00 respectively.

The modeling results also show that winter road maintenance is most beneficial for periods that experience moderate demand and congestion, such as those in the near-saturation periods. Our simulation concluded that the potential reduction in total travel time due to maintenance could reach as high as 36 percent. This result makes intuitive sense as traffic congestion or delay is highly sensitive to any change in capacity when the demand is near the capacity. In the contrary, maintaining bare surface during the over-saturation-period and under-saturation-period is least effective, reducing the total delay by only 6 – 12percent. This finding is important as it has significant implications for resource planning and allocation over a roadway network.

Based on the simulation results, this research also proposed and demonstrated a systematic framework and method for estimating the mobility benefit of winter road maintenance at an analysis scale comparable to a normal maintenance route. While the model inputs need to be further refined with more extensive case studies, this proposed framework has the potential to become an integral part of a comprehensive cost-benefit analysis tool for winter road maintenance management.

5.2 Recommendations for Future Work

This research represents the initial research effort toward the goal of developing a systematic and rigorous platform for cost-benefit analyses of various maintenance policies, methods and decision. Further research is need in many aspects to achieve this goal. Specifically, the following research directions are recommended for future work:

1. Adverse winter weather could significantly deteriorate road traveling conditions and thus increase road accidents. Increased road accidents will not only result in increased direct costs such as losses of human life and property damages, but also cause significant traffic delay. In this study, travel time loss due to increased traffic accidents induced by adverse winter weather was not considered. Traffic accidents are more likely to occur during winter snow storms, so considering traffic accidents when studying the mobility benefit of winter road maintenance will provide a more complete account of the benefits of winter road maintenance.
2. The simulation study conducted in this study is also limited in several levels. First of all only six levels of congestion with V/C of 0.37, 0.59, 0.69, 0.73, 0.91, and 1.00 were considered.

Also, the simulation study was performed on a freeway network with a simple network configuration and road classes. Furthermore, the types of weather events considered were also limited. In order to generalize the results of the simulation study and develop a mobility benefit model that can be applied all kinds of scenarios, it is important to cover a wider range of conditions related road network and weather conditions.

3. In this study, the mobility benefits of achieving bare pavement was estimated based on comparing simulation results at different snowfall intensities and traffic congestion levels. In order to validate the model estimates, it is necessary to collect real traffic data under different snow storms, traffic conditions, and pavement surface conditions as a result of maintenance operations.

4. In this study, traffic demand under adverse weather conditions was assumed to be the same as that in normal weather conditions. Under adverse weather conditions, some drivers may cancel their trips (based on the importance of the trip) which will affect the traffic demand and thus the mobility benefits. As a result, possible change in traffic demand due to adverse weather conditions should be taken into account in mobility benefit modeling.

5. In this study, the INTEGRATION simulation model was used to model traffic conditions under different weather conditions. The modeling of the effects of adverse weather and road surface conditions is done in an indirect way by modifying some macroscopic traffic stream parameters. It is expected that a direct approach of representing driver behavior under adverse weather could lead to more realistic modeling of the overall traffic and thus the effects. This could be accomplished through some simulation models such as Vissim and Paramics. It would be interesting to investigate the application of these simulation models for the purpose of this study and compare the results from these different models. Furthermore, modeling how drivers' behavior is by itself a fundamental and challenging problem in traffic engineering.

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Appendix A
INTEGRATION Micro-simulation Model

Car Following Behavior

The model simulates the departures of vehicles according to a time-varying OD matrix. Every vehicle departures its origin labeled with the following: vehicle's desired departure time, trip origin and trip destination, and a unique number, which allows the model to trace vehicle along the network from vehicle's origin to its final destination. Every vehicle enters the simulated network based on its scheduled departure time starting from its origin zone by selecting the lane with the largest available distance headway and then continues towards its destination zone. Each vehicle is tracked by modeling vehicle car-following, lane-changing, and gap acceptance behavior by computing its desired speed based on the distance headway (the inverse of traffic density) between it and the vehicle in front of it within the same lane. For a specific link, the desired speed for each vehicle within the link is computed based on Van Aerde macroscopic single regime model (Van Aerde, 1995; Van Aerde and Rakha, 1995) which can be calibrated using field data. Upon calibrating the macroscopic traffic parameters (free-flow speed, speed at capacity, capacity, jam density), the distance headway at different speed is calculated. Figure A.1 shows the relation between the macroscopic traffic parameters (speed-flow relationship and speed-density relationship) and the microscopic traffic parameters (speed-space headway relationship) for uncongested traffic conditions (point a), capacity flow (point b), and uncongested traffic conditions (point c). Point a and point c have the same traffic flow but different speeds and densities, and as a result they have different space headway. That assures that traffic conditions with different speeds can be identified. From the speed-space headway relationship in Figure A.1, it can be noted that vehicles will keep their desired free flow speeds when the distance headway in front of them is very large (low traffic density). In contrary, when distance headway move towards the link's jam density headway, vehicles will decelerate until they come to a complete stop (M. Van Aerde &Assoc. Ltd., 2005a).

INTEGRATION model has separate deceleration and acceleration logic which allow the transition of vehicles between traffic density regimes. The deceleration logic identifies the speed difference between response vehicle (vehicle that is making desired speed decisions), and the vehicle ahead of it (leading vehicle). In this case, the response vehicle first estimate the residual headway (the difference between the current available headway and the minimum headway) with the leading vehicle and then compute the time it needs to gradually reduce its current speed to the speed of the leading vehicle. For constant deceleration rates, the deceleration time equals to the residual headway divided by the average speed of the response the leading vehicles. This time is updated (each 0.10 second) as the positions of both vehicles is changes with time which will result in a asymptotic deceleration of the response vehicle rather than constant deceleration based on the leading vehicle's speed. On the other hand, if the leading vehicle is accelerating, the response vehicle will continue to decelerate only until it reaches the same speed as the leading vehicle. After that the response vehicle will start to accelerate in order to reach its desired speed as the gap between it and the leading vehicle increased. The acceleration rate of vehicles is governed by their maximum acceleration. This maximum possible rate of acceleration is computed based on the power vehicle dynamics model. This model considers the resultant force between the vehicle's tractive effort and resistance forces (the aerodynamic resistance, the rolling resistance, and the grade resistance) based on vehicle dynamics model by Rakha et al. (2001) (M. Van Aerde &Assoc. Ltd., 2005a).

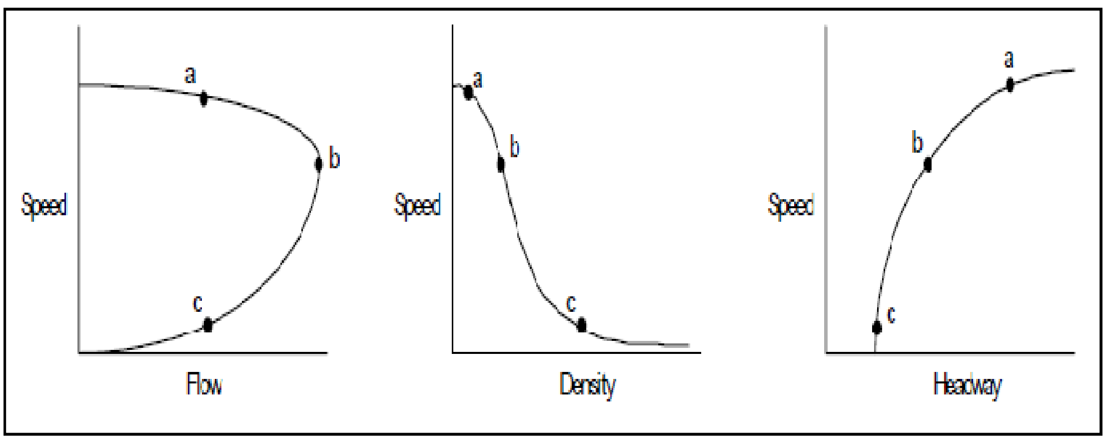


Figure A.1: Determination of Microscopic Speed from Corresponding Macroscopic Relationships (Source: M. Van Aerde &Assoc. Ltd., 2005a)

Lane Changing Logic

Vehicles during traversing a certain link may choose to make: discretionary lane changes, mandatory lane changes, or both. Discretionary lane changes are subject to the availability of an adequate gap in the lane into which the vehicle wishes to move. The main aim of vehicles to make discretionary lane changes is to maximize their speed which is selected base on the computation of three speed alternatives every 0.10 second. The first alternative represents the speed that the vehicle could continue to travel in the current lane while the second and the third alternatives represent the speed that the vehicle could travel with to the adjacent lanes to the current lane. These speed comparisons are made based on the available headway in each lane, and pre-specified biases for the vehicle to remain in the current or to move to the shoulder lane (e.g., heavy trucks). On the other hand, Vehicles make mandatory lane changes in order to maintain lane connectivity between the end of the current lane and the beginning of the next lane in onto which the vehicle anticipated turning. To do that every vehicle must change its current lane to be in one of the lanes that are directly connected to the relevant downstream link. The lane change model in INTEGRATION computes internally the lane connectivity at any diverge or merge. When a lane-changing maneuver has been initiated, a following lane change is not allowed until a pre-specified minimum amount of time has elapsed (M. Van Aerde &Assoc. Ltd., 2005a).

The mandatory lane changing logic guarantees that vehicles will automatically change their current lane into the lanes that have direct access to the next preferred link. Then vehicle will be automatically considered for entry into the suitable lane onto the next link. The vehicle will enter to the downstream link according to the availability of a minimum distance headway that can absorb the new vehicle without violating the specified jam density of the downstream link. If there is no such an accepted headway, the vehicle will be retained on the current link until the availability of an accepted headway. In addition, if the vehicle has to cross opposing flow, it will wait for an accepted gap in the opposing traffic stream. The vehicles will continue in the previous fashion from link to link and their positions (longitudinal and lateral positions) will be updated every 0.10 second until their destination. The vehicles are deciding the following links to take based on the INTEGRATION's internal routing logic by Rilett and Van Aerde (1991a and b). It should be noted that for each vehicle there is a vehicle-specific array that contain the entire sequence of links from the vehicle origin to its destination (M. Van Aerde &Assoc. Ltd., 2005a).

Modeling of Freeway Sections

In addition to car-following and lane changing, INTEGRATION has unique ways of dealing with the three fundamental traffic operations that occur on a freeway section, namely, merging, diverging, and weaving. For merging operations, the model calculates the merge capacity dynamically based on the queue forming location. Queues may form downstream/upstream the ramp, on the on-ramp, or on both, depending on traffic demands on the mainline and the on-ramp. In the case of an acceleration lane after the ramp merge, the queue will automatically be modeled to occur upstream of the lane drop. If the queue filled the entire merge area, the queue may spill back further onto the on-ramp and onto the upstream of the mainline based on vehicles arrival rate in both the on-ramp and the mainline. In the case that an acceleration lane is not present, the queue was modeled to form upstream of the on-ramp merge. After the model determines the merge flow rate, it computes the suitable shock waves upstream either the mainline or the on-ramp or both. In addition, the model is able to analyze the queues over very short time interval (30 to 60 seconds) and/or long time intervals (15 minute to several hours) (M. Van Aerde &Assoc. Ltd., 2005a).

For diverges operations, queues may form on the off-ramp or upstream the diverge area (due to congestion of the mainline downstream the diverge area). Due to insufficient capacity of any of the diverge arms, vehicles will face a bottleneck and will start to queue upstream the diverge area that may constrain the flow of through vehicles. The queue spill-back is calculated in the INTEGRATION simulation model as a function of both the existing off-ramp over-saturation and the number of vehicles that are trying to change lane to the closest lane to the off-ramp (M. Van Aerde &Assoc. Ltd., 2005a).

For weaving operations, the weaving capacity is automatically calculated according to the duration of lane change and the portion of vehicles making lane change. The model assumes that the vehicle engaging in lane-changing will occupy space in both lanes (the current lane and the aimed lane) and consumes capacity in both lanes. In this case the vehicle that is making lane-change is assumed to be equivalent to two vehicles (M. Van Aerde &Assoc. Ltd., 2005a). The INTEGRATION modeling of weaving section is based on the interaction between the prevailing car-following and lane-changing behavior (Van Aerde et. al., 1996; Stewart et. al., 1996).

Appendix B

Traffic Data: April 14, 2005 from 5:30 AM till 10:00 AM

- The data below represents the 5-minute aggregated data period leading up to the time displayed.
- Volume represents the sum of all vehicles crossing the station over the 5-minutes interval.
- Speed represents the average station speed for the 5-minute interval in km/hr.

1. Loop Detectors in the Mainline

Station	Time	Volume	Speed
010des	05:35	337	106.47
010des	05:40	392	105.93
010des	05:45	421	103.60
010des	05:50	476	105.07
010des	05:55	438	103.40
010des	06:00	456	103.87
010des	06:05	480	103.33
010des	06:10	498	98.60
010des	06:15	478	98.40
010des	06:20	476	94.33
010des	06:25	479	86.86
010des	06:30	458	96.43
010des	06:35	523	94.33
010des	06:40	491	95.29
010des	06:45	521	96.47
010des	06:50	463	101.00
010des	06:55	501	97.27
010des	07:00	459	101.60
010des	07:05	457	102.00
010des	07:10	447	99.80
010des	07:15	409	102.07
010des	07:20	412	103.80
010des	07:25	448	99.33
010des	07:30	530	89.93
010des	07:35	478	76.33
010des	07:40	495	69.80
010des	07:45	454	67.00
010des	07:50	510	78.47
010des	07:55	534	75.80
010des	08:00	519	67.53
010des	08:05	472	92.60
010des	08:10	472	97.40
010des	08:15	476	88.00
010des	08:20	476	71.87
010des	08:25	503	84.40
010des	08:30	494	78.87
010des	08:35	447	91.40
010des	08:40	445	106.53
010des	08:45	474	100.13
010des	08:50	430	101.00
010des	08:55	445	104.20
010des	09:00	427	103.27
010des	09:05	448	101.13
010des	09:10	473	98.40
010des	09:15	408	106.80
010des	09:20	406	103.40
010des	09:25	379	104.47
010des	09:30	413	98.73
010des	09:35	373	106.87
010des	09:40	358	105.07
010des	09:45	413	105.93
010des	09:50	398	106.20
010des	09:55	389	105.07
010des	10:00	359	105.14
020des	05:35	339	92.50
020des	05:40	426	94.33
020des	05:45	489	92.13
020des	05:50	497	94.40
020des	05:55	457	94.86
020des	06:00	505	96.60
020des	06:05	547	91.60
020des	06:10	519	90.07
020des	06:15	537	88.40
020des	06:20	517	88.60

Station	Time	Volume	Speed
020des	06:25	567	82.67
020des	06:30	565	88.53
020des	06:35	579	83.47
020des	06:40	564	88.87
020des	06:45	568	88.27
020des	06:50	530	93.07
020des	06:55	543	88.20
020des	07:00	547	91.60
020des	07:05	510	91.60
020des	07:10	514	91.80
020des	07:15	472	91.47
020des	07:20	472	91.50
020des	07:25	513	91.13
020des	07:30	557	82.86
020des	07:35	566	80.80
020des	07:40	569	76.80
020des	07:45	522	72.93
020des	07:50	586	71.33
020des	07:55	609	77.27
020des	08:00	587	75.60
020des	08:05	532	80.33
020des	08:10	547	74.80
020des	08:15	538	56.00
020des	08:20	569	69.47
020des	08:25	568	66.80
020des	08:30	550	51.27
020des	08:35	545	65.27
020des	08:40	477	91.50
020des	08:45	584	84.20
020des	08:50	506	63.93
020des	08:55	545	91.80
020des	09:00	501	92.87
020des	09:05	493	92.73
020des	09:10	559	88.13
020des	09:15	464	92.13
020des	09:20	474	93.73
020des	09:25	443	93.20
020des	09:30	483	90.20
020des	09:35	448	94.93
020des	09:40	452	95.80
020des	09:45	495	92.60
020des	09:50	452	97.00
020des	09:55	472	92.20
020des	10:00	446	93.60
030des	05:35	354	142.33

Station	Time	Volume	Speed
030des	05:40	382	140.67
030des	05:45	404	138.92
030des	05:50	469	139.13
030des	05:55	471	138.47
030des	06:00	477	140.73
030des	06:05	476	136.40
030des	06:10	493	136.00
030des	06:15	510	133.53
030des	06:20	453	137.67
030des	06:25	488	131.07
030des	06:30	496	132.00
030des	06:35	518	128.93
030des	06:40	476	137.80
030des	06:45	485	135.47
030des	06:50	447	138.67
030des	06:55	468	132.80
030des	07:00	469	136.80
030des	07:05	440	134.87
030des	07:10	452	135.13
030des	07:15	408	135.93
030des	07:20	435	135.80
030des	07:25	444	135.47
030des	07:30	485	127.27
030des	07:35	478	128.07
030des	07:40	448	104.33
030des	07:45	432	97.27
030des	07:50	434	128.13
030des	07:55	488	124.40
030des	08:00	433	118.40
030des	08:05	396	70.20
030des	08:10	382	52.93
030des	08:15	432	64.33
030des	08:20	443	68.07
030des	08:25	402	54.80
030des	08:30	422	72.00
030des	08:35	407	56.80
030des	08:40	416	65.67
030des	08:45	422	79.87
030des	08:50	362	69.36
030des	08:55	441	134.60
030des	09:00	414	135.53
030des	09:05	403	138.67
030des	09:10	475	134.67
030des	09:15	394	139.60
030des	09:20	395	136.27

Station	Time	Volume	Speed
030des	09:25	394	141.47
030des	09:30	393	137.13
030des	09:35	405	138.40
030des	09:40	383	142.87
030des	09:45	420	141.27
030des	09:50	381	136.47
030des	09:55	403	140.87
030des	10:00	370	141.53
040des	05:35	358	105.67
040des	05:40	395	106.67
040des	05:45	468	102.80
040des	05:50	494	104.53
040des	05:55	451	95.47
040des	06:00	469	101.73
040des	06:05	488	100.93
040des	06:10	508	99.67
040des	06:15	514	96.00
040des	06:20	449	101.60
040des	06:25	496	96.73
040des	06:30	503	96.80
040des	06:35	537	95.07
040des	06:40	476	99.93
040des	06:45	477	92.07
040des	06:50	455	102.33
040des	06:55	480	99.60
040des	07:00	475	102.53
040des	07:05	448	103.33
040des	07:10	465	98.13
040des	07:15	411	101.53
040des	07:20	449	102.27
040des	07:25	450	98.20
040des	07:30	493	94.73
040des	07:35	488	94.73
040des	07:40	430	67.07
040des	07:45	454	74.87
040des	07:50	438	97.13
040des	07:55	495	90.67
040des	08:00	425	67.73
040des	08:05	426	49.73
040des	08:10	388	41.60
040des	08:15	440	48.93
040des	08:20	440	44.07
040des	08:25	412	48.87
040des	08:30	436	54.67
040des	08:35	418	48.93

Station	Time	Volume	Speed
040des	08:40	414	41.87
040des	08:45	400	48.93
040des	08:50	435	58.93
040des	08:55	459	97.87
040des	09:00	416	103.13
040des	09:05	420	102.20
040des	09:10	488	99.13
040des	09:15	400	103.53
040des	09:20	412	102.60
040des	09:25	404	103.73
040des	09:30	405	102.13
040des	09:35	413	103.53
040des	09:40	397	106.80
040des	09:45	374	105.36
040des	09:50	405	100.73
040des	09:55	425	104.73
040des	10:00	375	105.73
050des	05:35	360	115.20
050des	05:40	420	113.73
050des	05:45	432	113.43
050des	05:50	517	107.20
050des	05:55	511	108.87
050des	06:00	496	111.20
050des	06:05	493	99.43
050des	06:10	525	100.53
050des	06:15	538	87.47
050des	06:20	490	103.07
050des	06:25	485	104.13
050des	06:30	485	103.21
050des	06:35	536	99.07
050des	06:40	517	102.20
050des	06:45	527	103.67
050des	06:50	508	105.87
050des	06:55	476	107.80
050des	07:00	501	105.07
050des	07:05	458	108.33
050des	07:10	490	101.33
050des	07:15	452	107.13
050des	07:20	459	109.07
050des	07:25	490	102.53
050des	07:30	495	101.07
050des	07:35	515	82.67
050des	07:40	445	55.33
050des	07:45	527	78.00
050des	07:50	460	101.00

Station	Time	Volume	Speed
050des	07:55	472	75.07
050des	08:00	414	56.20
050des	08:05	449	65.60
050des	08:10	410	47.60
050des	08:15	469	67.60
050des	08:20	433	58.73
050des	08:25	449	64.27
050des	08:30	430	59.00
050des	08:35	431	65.53
050des	08:40	471	67.00
050des	08:45	412	58.33
050des	08:50	491	79.53
050des	08:55	494	101.07
050des	09:00	460	106.13
050des	09:05	443	110.67
050des	09:10	492	107.47
050des	09:15	436	109.13
050des	09:20	442	107.73
050des	09:25	428	107.07
050des	09:30	406	111.13
050des	09:35	458	104.73
050des	09:40	416	113.73
050des	09:45	447	111.47
050des	09:50	418	113.00
050des	09:55	446	109.73
050des	10:00	381	115.67
060des	05:35	320	105.07
060des	05:40	401	104.60
060des	05:45	437	104.60
060des	05:50	471	102.73
060des	05:55	447	102.40
060des	06:00	478	103.33
060des	06:05	484	97.53
060des	06:10	472	89.00
060des	06:15	489	83.40
060des	06:20	450	92.67
060des	06:25	433	97.60
060des	06:30	449	94.07
060des	06:35	460	85.33
060des	06:40	417	96.20
060des	06:45	425	99.67
060des	06:50	423	101.00
060des	06:55	374	101.80
060des	07:00	433	99.67
060des	07:05	394	101.47

Station	Time	Volume	Speed
060des	07:10	411	97.27
060des	07:15	377	100.13
060des	07:20	401	101.13
060des	07:25	416	98.53
060des	07:30	417	94.07
060des	07:35	341	51.33
060des	07:40	394	71.07
060des	07:45	436	76.80
060des	07:50	347	58.67
060des	07:55	317	37.67
060des	08:00	297	28.27
060des	08:05	280	29.47
060des	08:10	376	67.27
060des	08:15	379	77.87
060des	08:20	271	35.53
060des	08:25	396	65.07
060des	08:30	322	47.20
060des	08:35	351	84.93
060des	08:40	376	78.33
060des	08:45	341	42.73
060des	08:50	396	91.13
060des	08:55	403	92.27
060des	09:00	367	103.47
060des	09:05	376	105.40
060des	09:10	409	103.73
060des	09:15	366	102.53
060des	09:20	378	104.13
060des	09:25	382	101.13
060des	09:30	361	103.00
060des	09:35	389	102.00
060des	09:40	353	105.20
060des	09:45	380	104.87
060des	09:50	361	105.67
060des	09:55	394	103.40
060des	10:00	336	108.27
070des	05:35	343	123.73
070des	05:40	408	121.73
070des	05:45	457	121.27
070des	05:50	467	119.93
070des	05:55	473	118.80
070des	06:00	516	118.33
070des	06:05	502	116.07
070des	06:10	476	111.53
070des	06:15	520	103.67
070des	06:20	493	82.87

Station	Time	Volume	Speed
070des	06:25	442	112.93
070des	06:30	456	97.40
070des	06:35	486	93.47
070des	06:40	455	83.20
070des	06:45	439	106.13
070des	06:50	438	116.47
070des	06:55	400	116.40
070des	07:00	433	117.07
070des	07:05	422	114.80
070des	07:10	446	105.67
070des	07:15	403	117.67
070des	07:20	444	105.93
070des	07:25	423	115.13
070des	07:30	415	80.67
070des	07:35	354	45.40
070des	07:40	426	64.00
070des	07:45	414	68.73
070des	07:50	353	38.33
070des	07:55	271	26.47
070des	08:00	362	45.67
070des	08:05	326	42.00
070des	08:10	394	58.20
070des	08:15	346	38.40
070des	08:20	348	55.67
070des	08:25	355	44.13
070des	08:30	390	56.00
070des	08:35	385	86.33
070des	08:40	336	55.80
070des	08:45	431	69.07
070des	08:50	418	99.27
070des	08:55	418	79.67
070des	09:00	407	103.13
070des	09:05	389	122.00
070des	09:10	434	118.33
070des	09:15	396	117.47
070des	09:20	409	118.07
070des	09:25	386	120.20
070des	09:30	387	122.13
070des	09:35	366	121.00
070des	09:40	389	123.87
070des	09:45	416	121.93
070des	09:50	382	120.87
070des	09:55	422	120.27
070des	10:00	359	125.40
080des	05:35	358	109.27

Station	Time	Volume	Speed
080des	05:40	402	111.07
080des	05:45	472	107.07
080des	05:50	478	106.13
080des	05:55	480	107.07
080des	06:00	542	103.27
080des	06:05	517	102.87
080des	06:10	495	102.33
080des	06:15	524	94.60
080des	06:20	501	84.33
080des	06:25	471	95.60
080des	06:30	474	93.13
080des	06:35	476	88.67
080des	06:40	465	75.93
080des	06:45	462	94.33
080des	06:50	454	101.93
080des	06:55	418	104.73
080des	07:00	451	103.13
080des	07:05	432	103.07
080des	07:10	470	97.67
080des	07:15	435	103.40
080des	07:20	453	89.80
080des	07:25	439	94.33
080des	07:30	382	50.20
080des	07:35	402	50.20
080des	07:40	438	55.80
080des	07:45	414	50.47
080des	07:50	349	40.53
080des	07:55	325	29.40
080des	08:00	364	39.40
080des	08:05	375	49.53
080des	08:10	407	48.07
080des	08:15	329	37.47
080des	08:20	422	58.80
080des	08:25	351	39.47
080des	08:30	437	59.53
080des	08:35	407	68.07
080des	08:40	349	47.93
080des	08:45	452	74.13
080des	08:50	453	70.13
080des	08:55	437	78.47
080des	09:00	445	74.60
080des	09:05	414	104.60
080des	09:10	427	106.53
080des	09:15	449	103.80
080des	09:20	439	104.53

Station	Time	Volume	Speed
080des	09:25	410	107.20
080des	09:30	413	107.87
080des	09:35	422	106.40
080des	09:40	408	109.47
080des	09:45	425	108.53
080des	09:50	407	109.53
080des	09:55	458	108.07
080des	10:00	371	109.73
090des	05:35	304	117.87
090des	05:40	349	117.27
090des	05:45	390	115.27
090des	05:50	401	113.80
090des	05:55	426	111.93
090des	06:00	481	107.60
090des	06:05	476	108.87
090des	06:10	461	108.60
090des	06:15	456	101.80
090des	06:20	442	98.07
090des	06:25	397	103.20
090des	06:30	397	103.27
090des	06:35	357	103.21
090des	06:40	375	100.47
090des	06:45	382	92.67
090des	06:50	348	80.80
090des	06:55	326	110.20
090des	07:00	371	109.53
090des	07:05	383	94.73
090des	07:10	387	105.60
090des	07:15	372	107.60
090des	07:20	316	72.71
090des	07:25	351	58.67
090des	07:30	283	31.53
090des	07:35	345	52.93
090des	07:40	375	59.53
090des	07:45	314	39.80
090des	07:50	220	18.73
090des	07:55	274	25.20
090des	08:00	261	30.53
090des	08:05	306	47.13
090des	08:10	307	42.73
090des	08:15	228	22.47
090des	08:20	323	44.87
090des	08:25	313	45.27
090des	08:30	339	75.60
090des	08:35	251	31.47

Station	Time	Volume	Speed
090des	08:40	340	60.00
090des	08:45	362	92.71
090des	08:50	394	96.40
090des	08:55	352	93.07
090des	09:00	334	53.27
090des	09:05	346	99.00
090des	09:10	354	114.47
090des	09:15	372	110.60
090des	09:20	373	112.47
090des	09:25	363	112.20
090des	09:30	347	113.87
090des	09:35	380	107.27
090des	09:40	353	115.47
090des	09:45	379	114.13
090des	09:50	357	115.73
090des	09:55	361	115.86
090des	10:00	350	115.87
100des	05:35	269	102.86
100des	05:40	341	103.07
100des	05:45	399	101.80
100des	05:50	400	100.53
100des	05:55	450	98.67
100des	06:00	476	90.40
100des	06:05	439	97.71
100des	06:10	483	91.80
100des	06:15	448	92.07
100des	06:20	450	87.33
100des	06:25	406	88.13
100des	06:30	381	93.33
100des	06:35	393	91.93
100des	06:40	381	91.87
100des	06:45	333	56.73
100des	06:50	373	42.53
100des	06:55	348	85.87
100des	07:00	373	95.67
100des	07:05	376	50.53
100des	07:10	407	65.53
100des	07:15	369	59.20
100des	07:20	333	32.00
100des	07:25	325	34.67
100des	07:30	329	40.40
100des	07:35	333	32.67
100des	07:40	370	35.13
100des	07:45	292	23.67
100des	07:50	244	23.20

Station	Time	Volume	Speed
100des	07:55	298	26.07
100des	08:00	292	27.27
100des	08:05	327	33.87
100des	08:10	232	21.93
100des	08:15	334	40.07
100des	08:20	282	28.27
100des	08:25	364	47.67
100des	08:30	333	48.40
100des	08:35	260	27.73
100des	08:40	364	55.67
100des	08:45	405	59.13
100des	08:50	397	68.67
100des	08:55	309	45.93
100des	09:00	384	54.33
100des	09:05	374	64.20
100des	09:10	323	100.29
100des	09:15	379	97.73
100des	09:20	369	97.67
100des	09:25	384	97.27
100des	09:30	327	99.67
100des	09:35	418	93.40
100des	09:40	362	99.67
100des	09:45	394	94.87
100des	09:50	385	99.73
100des	09:55	359	99.21
100des	10:00	373	100.27
110des	05:35	242	114.67
110des	05:40	276	116.27
110des	05:45	308	113.07
110des	05:50	330	111.87
110des	05:55	370	107.73
110des	06:00	360	103.93
110des	06:05	375	106.07
110des	06:10	375	103.07
110des	06:15	349	100.93
110des	06:20	320	67.40
110des	06:25	299	63.73
110des	06:30	298	76.07
110des	06:35	288	100.73
110des	06:40	280	83.27
110des	06:45	197	30.67
110des	06:50	274	51.53
110des	06:55	268	88.80
110des	07:00	283	81.87
110des	07:05	264	44.53

Station	Time	Volume	Speed
110des	07:10	298	55.80
110des	07:15	209	32.13
110des	07:20	282	54.73
110des	07:25	183	24.40
110des	07:30	253	48.13
110des	07:35	254	40.27
110des	07:40	236	33.00
110des	07:45	175	24.47
110des	07:50	161	20.07
110des	07:55	173	21.00
110des	08:00	251	33.40
110des	08:05	210	32.27
110des	08:10	138	15.93
110des	08:15	254	41.07
110des	08:20	211	29.60
110des	08:25	237	42.67
110des	08:30	186	25.93
110des	08:35	232	46.07
110des	08:40	225	53.87
110des	08:45	306	62.13
110des	08:50	258	45.80
110des	08:55	193	33.53
110des	09:00	267	71.33
110des	09:05	268	65.27
110des	09:10	284	106.93
110des	09:15	299	109.93
110des	09:20	262	110.20
110des	09:25	286	105.20
110des	09:30	253	106.60
110des	09:35	310	106.13
110des	09:40	283	112.07
110des	09:45	291	107.87
110des	09:50	301	111.67
110des	09:55	304	111.13
110des	10:00	299	112.80
120des	05:35	310	112.13
120des	05:40	352	111.87
120des	05:45	396	111.33
120des	05:50	414	107.67
120des	05:55	469	105.93
120des	06:00	468	104.07
120des	06:05	501	99.27
120des	06:10	521	97.67
120des	06:15	457	95.07
120des	06:20	440	59.13

Station	Time	Volume	Speed
120des	06:25	418	53.20
120des	06:30	404	65.33
120des	06:35	402	63.93
120des	06:40	313	43.60
120des	06:45	333	34.87
120des	06:50	414	50.80
120des	06:55	376	54.07
120des	07:00	320	41.87
120des	07:05	427	56.20
120des	07:10	432	58.13
120des	07:15	289	30.73
120des	07:20	357	43.67
120des	07:25	344	38.47
120des	07:30	334	33.80
120des	07:35	390	41.87
120des	07:40	336	32.60
120des	07:45	241	21.80
120des	07:50	320	28.80
120des	07:55	270	29.20
120des	08:00	366	34.40
120des	08:05	294	25.33
120des	08:10	296	30.93
120des	08:15	306	30.53
120des	08:20	367	42.33
120des	08:25	364	42.07
120des	08:30	218	22.73
120des	08:35	387	54.27
120des	08:40	308	35.33
120des	08:45	388	47.00
120des	08:50	336	49.80
120des	08:55	343	43.00
120des	09:00	350	46.87
120des	09:05	407	59.07
120des	09:10	392	87.40
120des	09:15	385	105.60
120des	09:20	360	99.93
120des	09:25	382	80.67
120des	09:30	306	81.14
120des	09:35	414	101.73
120des	09:40	400	102.93
120des	09:45	389	105.60
120des	09:50	417	104.00
120des	09:55	401	109.20
120des	10:00	403	106.53
130des	05:35	291	121.80

Station	Time	Volume	Speed
130des	05:40	382	120.13
130des	05:45	407	118.00
130des	05:50	430	115.13
130des	05:55	458	113.67
130des	06:00	491	109.27
130des	06:05	525	107.20
130des	06:10	546	98.00
130des	06:15	466	84.93
130des	06:20	470	68.40
130des	06:25	451	61.53
130des	06:30	439	61.80
130des	06:35	460	70.53
130des	06:40	303	32.60
130des	06:45	407	67.53
130des	06:50	442	73.33
130des	06:55	439	54.47
130des	07:00	356	47.27
130des	07:05	466	78.93
130des	07:10	410	49.60
130des	07:15	397	54.93
130des	07:20	369	43.67
130des	07:25	423	46.47
130des	07:30	426	53.67
130des	07:35	435	54.07
130des	07:40	394	40.40
130des	07:45	322	30.80
130des	07:50	404	43.07
130des	07:55	352	39.27
130des	08:00	428	45.33
130des	08:05	293	30.13
130des	08:10	434	53.13
130des	08:15	354	37.73
130des	08:20	448	58.47
130des	08:25	398	44.93
130des	08:30	327	35.00
130des	08:35	403	50.93
130des	08:40	411	58.20
130des	08:45	433	52.53
130des	08:50	356	39.67
130des	08:55	411	52.07
130des	09:00	395	49.27
130des	09:05	443	58.13
130des	09:10	449	75.20
130des	09:15	411	83.60
130des	09:20	371	67.67

Station	Time	Volume	Speed
130des	09:25	384	48.47
130des	09:30	383	82.53
130des	09:35	400	107.20
130des	09:40	442	105.47
130des	09:45	412	111.93
130des	09:50	456	91.67
130des	09:55	422	116.60
130des	10:00	414	115.73
140des	05:35	299	112.73
140des	05:40	410	110.47
140des	05:45	374	111.36
140des	05:50	417	107.86
140des	05:55	490	103.93
140des	06:00	501	101.67
140des	06:05	557	97.47
140des	06:10	565	86.40
140des	06:15	496	68.00
140des	06:20	503	74.67
140des	06:25	481	65.67
140des	06:30	487	67.13
140des	06:35	443	61.33
140des	06:40	394	48.53
140des	06:45	472	76.00
140des	06:50	476	79.27
140des	06:55	427	55.40
140des	07:00	460	64.40
140des	07:05	492	64.87
140des	07:10	420	44.20
140des	07:15	494	65.53
140des	07:20	407	38.47
140des	07:25	495	66.13
140des	07:30	498	71.73
140des	07:35	483	67.00
140des	07:40	449	41.53
140des	07:45	397	40.73
140des	07:50	431	46.53
140des	07:55	496	61.00
140des	08:00	497	63.67
140des	08:05	373	40.07
140des	08:10	504	63.40
140des	08:15	437	50.67
140des	08:20	501	62.53
140des	08:25	417	46.60
140des	08:30	440	60.73
140des	08:35	436	50.13

Station	Time	Volume	Speed
140des	08:40	480	70.67
140des	08:45	477	65.60
140des	08:50	403	43.33
140des	08:55	488	68.27
140des	09:00	454	70.73
140des	09:05	494	69.67
140des	09:10	511	78.13
140des	09:15	429	57.00
140des	09:20	381	48.29
140des	09:25	464	63.67
140des	09:30	445	81.87
140des	09:35	413	101.47
140des	09:40	480	98.53
140des	09:45	445	100.87
140des	09:50	477	87.60
140des	09:55	454	103.00
140des	10:00	436	106.13
150des	05:35	299	117.00
150des	05:40	362	114.71
150des	05:45	362	116.00
150des	05:50	452	110.20
150des	05:55	504	108.27
150des	06:00	499	106.20
150des	06:05	550	104.33
150des	06:10	558	85.40
150des	06:15	504	60.47
150des	06:20	497	80.13
150des	06:25	489	80.13
150des	06:30	488	79.53
150des	06:35	418	49.93
150des	06:40	424	59.07
150des	06:45	469	87.73
150des	06:50	484	84.27
150des	06:55	404	57.53
150des	07:00	468	60.47
150des	07:05	482	62.00
150des	07:10	440	57.13
150des	07:15	455	67.20
150des	07:20	446	57.47
150des	07:25	492	82.47
150des	07:30	507	82.27
150des	07:35	461	74.27
150des	07:40	402	46.60
150des	07:45	456	50.00
150des	07:50	422	43.67

Station	Time	Volume	Speed
150des	07:55	513	63.93
150des	08:00	446	59.40
150des	08:05	429	60.67
150des	08:10	481	69.67
150des	08:15	456	66.87
150des	08:20	497	78.80
150des	08:25	386	50.20
150des	08:30	479	77.60
150des	08:35	433	55.93
150des	08:40	488	82.87
150des	08:45	463	72.47
150des	08:50	416	56.93
150des	08:55	494	79.07

Station	Time	Volume	Speed
150des	09:00	460	85.53
150des	09:05	488	83.47
150des	09:10	512	84.00
150des	09:15	425	56.20
150des	09:20	409	51.20
150des	09:25	475	78.13
150des	09:30	467	85.20
150des	09:35	417	106.53
150des	09:40	474	104.07
150des	09:45	436	106.07
150des	09:50	471	91.67
150des	09:55	469	104.13
150des	10:00	435	110.07

2. Loop Detectors in the On-Ramps

Station	Time	Volume
030der	05:30:00	102
030der	06:00:00	88
030der	06:30:00	106
030der	07:00:00	185
030der	07:30:00	148
030der	08:00:00	173
030der	08:30:00	181
030der	09:00:00	138
030der	09:30:00	176
030der	10:00:00	143
030der	10:30:00	118
030der	11:00:00	143
030der	11:30:00	153
030der	12:00:00	145
030der	12:30:00	167
030der	13:00:00	137
030der	13:30:00	143
030der	14:00:00	132
030der	14:30:00	137
030der	15:00:00	113
030der	15:30:00	158
030der	16:00:00	192
030der	16:30:00	159
030der	17:00:00	189

Station	Time	Volume
030der	17:30:00	151
030der	18:00:00	159
030der	18:30:00	122
030der	19:00:00	126
030der	19:30:00	104
030der	20:00:00	96
040der	05:30:00	125
040der	06:00:00	126
040der	06:30:00	123
040der	07:00:00	158
040der	07:30:00	183
040der	08:00:00	184
040der	08:30:00	184
040der	09:00:00	161
040der	09:30:00	182
040der	10:00:00	170
040der	10:30:00	184
040der	11:00:00	189
040der	11:30:00	190
040der	12:00:00	204
040der	12:30:00	209
040der	13:00:00	211
040der	13:30:00	206
040der	14:00:00	209

Station	Time	Volume
040der	14:30:00	197
040der	15:00:00	227
040der	15:30:00	212
040der	16:00:00	191
040der	16:30:00	191
040der	17:00:00	179
040der	17:30:00	144
040der	18:00:00	133
040der	18:30:00	177
040der	19:00:00	131
040der	19:30:00	136
040der	20:00:00	4
050der	05:30:00	0
050der	06:00:00	0
050der	06:30:00	0
050der	07:00:00	0
050der	07:30:00	0
050der	08:00:00	0
050der	08:30:00	0
050der	09:00:00	0
050der	09:30:00	0
050der	10:00:00	0
050der	10:30:00	0
050der	11:00:00	0
050der	11:30:00	0
050der	12:00:00	0
050der	12:30:00	0
050der	13:00:00	0
050der	13:30:00	0
050der	14:00:00	0
050der	14:30:00	0
050der	15:00:00	0
050der	15:30:00	0
050der	16:00:00	0
050der	16:30:00	0
050der	17:00:00	0
050der	17:30:00	0
050der	18:00:00	0
050der	18:30:00	0
050der	19:00:00	0
050der	19:30:00	0
050der	20:00:00	0
060der	05:30:00	0
060der	06:00:00	0
060der	06:30:00	0

Station	Time	Volume
060der	07:00:00	0
060der	07:30:00	0
060der	08:00:00	0
060der	08:30:00	0
060der	09:00:00	0
060der	09:30:00	1
060der	10:00:00	0
060der	10:30:00	0
060der	11:00:00	0
060der	11:30:00	0
060der	12:00:00	0
060der	12:30:00	0
060der	13:00:00	0
060der	13:30:00	0
060der	14:00:00	0
060der	14:30:00	0
060der	15:00:00	0
060der	15:30:00	0
060der	16:00:00	0
060der	16:30:00	0
060der	17:00:00	0
060der	17:30:00	0
060der	18:00:00	0
060der	18:30:00	0
060der	19:00:00	0
060der	19:30:00	0
060der	20:00:00	94
070der	05:30:00	118
070der	06:00:00	134
070der	06:30:00	113
070der	07:00:00	146
070der	07:30:00	97
070der	08:00:00	95
070der	08:30:00	135
070der	09:00:00	126
070der	09:30:00	158
070der	10:00:00	130
070der	10:30:00	121
070der	11:00:00	135
070der	11:30:00	139
070der	12:00:00	120
070der	12:30:00	151
070der	13:00:00	117
070der	13:30:00	128
070der	14:00:00	133

Station	Time	Volume
070der	14:30:00	103
070der	15:00:00	119
070der	15:30:00	112
070der	16:00:00	123
070der	16:30:00	139
070der	17:00:00	122
070der	17:30:00	88
070der	18:00:00	91
070der	18:30:00	93
070der	19:00:00	95
070der	19:30:00	61
070der	20:00:00	59
080der	05:30:00	70
080der	06:00:00	67
080der	06:30:00	85
080der	07:00:00	117
080der	07:30:00	111
080der	08:00:00	118
080der	08:30:00	137
080der	09:00:00	136
080der	09:30:00	137
080der	10:00:00	145
080der	10:30:00	144
080der	11:00:00	124
080der	11:30:00	157
080der	12:00:00	174
080der	12:30:00	172
080der	13:00:00	141
080der	13:30:00	164
080der	14:00:00	151
080der	14:30:00	143
080der	15:00:00	158
080der	15:30:00	153
080der	16:00:00	179
080der	16:30:00	186
080der	17:00:00	149
080der	17:30:00	162
080der	18:00:00	124
080der	18:30:00	119
080der	19:00:00	121
080der	19:30:00	98
080der	20:00:00	53
090der	05:30:00	57
090der	06:00:00	54
090der	06:30:00	53

Station	Time	Volume
090der	07:00:00	75
090der	07:30:00	99
090der	08:00:00	80
090der	08:30:00	68
090der	09:00:00	100
090der	09:30:00	127
090der	10:00:00	107
090der	10:30:00	99
090der	11:00:00	99
090der	11:30:00	112
090der	12:00:00	95
090der	12:30:00	108
090der	13:00:00	104
090der	13:30:00	86
090der	14:00:00	100
090der	14:30:00	108
090der	15:00:00	106
090der	15:30:00	130
090der	16:00:00	100
090der	16:30:00	128
090der	17:00:00	157
090der	17:30:00	97
090der	18:00:00	88
090der	18:30:00	75
090der	19:00:00	69
090der	19:30:00	44
090der	20:00:00	105
100der	05:30:00	134
100der	06:00:00	150
100der	06:30:00	156
100der	07:00:00	212
100der	07:30:00	226
100der	08:00:00	178
100der	08:30:00	89
100der	09:00:00	112
100der	09:30:00	157
100der	10:00:00	158
100der	10:30:00	155
100der	11:00:00	154
100der	11:30:00	153
100der	12:00:00	151
100der	12:30:00	172
100der	13:00:00	146
100der	13:30:00	153
100der	14:00:00	158

Station	Time	Volume
100der	14:30:00	147
100der	15:00:00	142
100der	15:30:00	132
100der	16:00:00	153
100der	16:30:00	182
100der	17:00:00	169
100der	17:30:00	142
100der	18:00:00	103
100der	18:30:00	74
100der	19:00:00	85
100der	19:30:00	58
100der	20:00:00	60
110der	05:30:00	67
110der	06:00:00	175
110der	06:30:00	239
110der	07:00:00	320
110der	07:30:00	432
110der	08:00:00	395
110der	08:30:00	275
110der	09:00:00	154
110der	09:30:00	132
110der	10:00:00	108
110der	10:30:00	106
110der	11:00:00	110
110der	11:30:00	114
110der	12:00:00	130
110der	12:30:00	113
110der	13:00:00	111
110der	13:30:00	114
110der	14:00:00	84
110der	14:30:00	98
110der	15:00:00	121
110der	15:30:00	153
110der	16:00:00	160
110der	16:30:00	208
110der	17:00:00	281

Station	Time	Volume
110der	17:30:00	203
110der	18:00:00	125
110der	18:30:00	117
110der	19:00:00	59
110der	19:30:00	66
110der	20:00:00	106
120der	05:30:00	123
120der	06:00:00	201
120der	06:30:00	266
120der	07:00:00	326
120der	07:30:00	429
120der	08:00:00	396
120der	08:30:00	326
120der	09:00:00	277
120der	09:30:00	166
120der	10:00:00	153
120der	10:30:00	153
120der	11:00:00	131
120der	11:30:00	137
120der	12:00:00	144
120der	12:30:00	136
120der	13:00:00	123
120der	13:30:00	111
120der	14:00:00	126
120der	14:30:00	146
120der	15:00:00	158
120der	15:30:00	154
120der	16:00:00	163
120der	16:30:00	218
120der	17:00:00	270
120der	17:30:00	161
120der	18:00:00	120
120der	18:30:00	97
120der	19:00:00	100
120der	19:30:00	64
120der	20:00:00	1

3. Loop Detectors in the Off-Ramps

Station	Time	Volume
300dsr	05:30:00	182
300dsr	06:00:00	285
300dsr	06:30:00	517
300dsr	07:00:00	395
300dsr	07:30:00	649
300dsr	08:00:00	622
300dsr	08:30:00	502
300dsr	09:00:00	361
300dsr	09:30:00	311
300dsr	10:00:00	273
300dsr	10:30:00	221
300dsr	11:00:00	273
300dsr	11:30:00	285
300dsr	12:00:00	269
300dsr	12:30:00	299
300dsr	13:00:00	284
300dsr	13:30:00	284
300dsr	14:00:00	364
300dsr	14:30:00	337
300dsr	15:00:00	329
300dsr	15:30:00	380
300dsr	16:00:00	337
300dsr	16:30:00	384
300dsr	17:00:00	403
300dsr	17:30:00	334
300dsr	18:00:00	276
300dsr	18:30:00	224
300dsr	19:00:00	198
300dsr	19:30:00	208
300dsr	20:00:00	309
310dsr	05:30:00	346
310dsr	06:00:00	368
310dsr	06:30:00	546
310dsr	07:00:00	445
310dsr	07:30:00	494
310dsr	08:00:00	561
310dsr	08:30:00	497
310dsr	09:00:00	414
310dsr	09:30:00	303
310dsr	10:00:00	254
310dsr	10:30:00	241
310dsr	11:00:00	230
310dsr	11:30:00	238
310dsr	12:00:00	246
310dsr	12:30:00	273
310dsr	13:00:00	271

Station	Time	Volume
310dsr	13:30:00	288
310dsr	14:00:00	383
310dsr	14:30:00	339
310dsr	15:00:00	297
310dsr	15:30:00	312
310dsr	16:00:00	311
310dsr	16:30:00	297
310dsr	17:00:00	251
310dsr	17:30:00	278
310dsr	18:00:00	259
310dsr	18:30:00	240
310dsr	19:00:00	209
310dsr	19:30:00	177
310dsr	20:00:00	56
320dsr	05:30:00	61
320dsr	06:00:00	84
320dsr	06:30:00	164
320dsr	07:00:00	158
320dsr	07:30:00	158
320dsr	08:00:00	174
320dsr	08:30:00	229
320dsr	09:00:00	179
320dsr	09:30:00	114
320dsr	10:00:00	83
320dsr	10:30:00	97
320dsr	11:00:00	104
320dsr	11:30:00	93
320dsr	12:00:00	100
320dsr	12:30:00	124
320dsr	13:00:00	104
320dsr	13:30:00	103
320dsr	14:00:00	102
320dsr	14:30:00	119
320dsr	15:00:00	100
320dsr	15:30:00	104
320dsr	16:00:00	123
320dsr	16:30:00	113
320dsr	17:00:00	173
320dsr	17:30:00	214
320dsr	18:00:00	110
320dsr	18:30:00	112
320dsr	19:00:00	78
320dsr	19:30:00	66
320dsr	20:00:00	1036

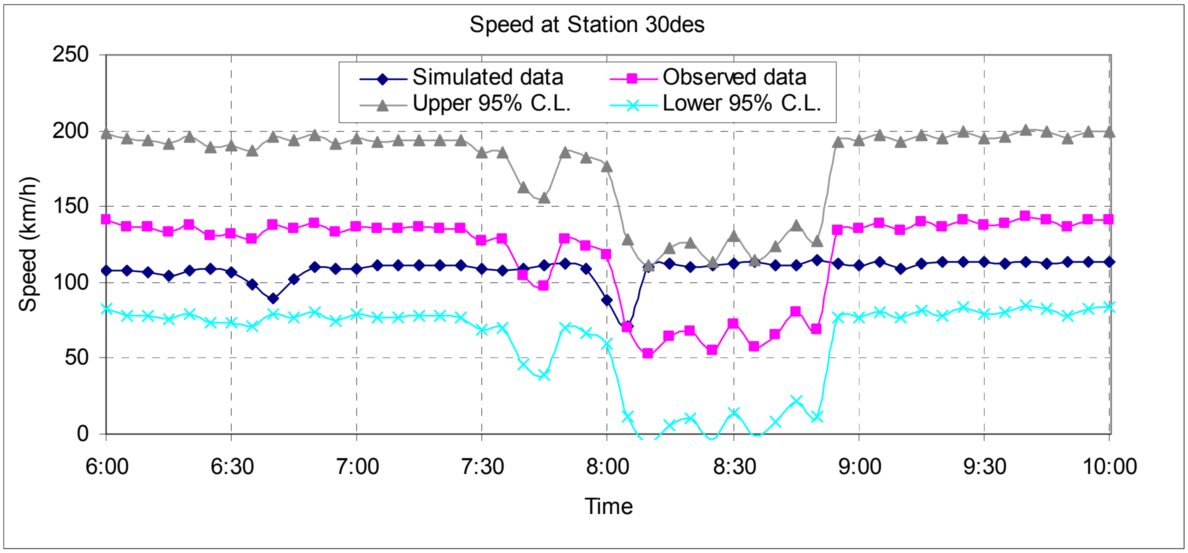
Appendix C
Weather Conditions During April 14, 2005 from Hamilton, ON Weather Station

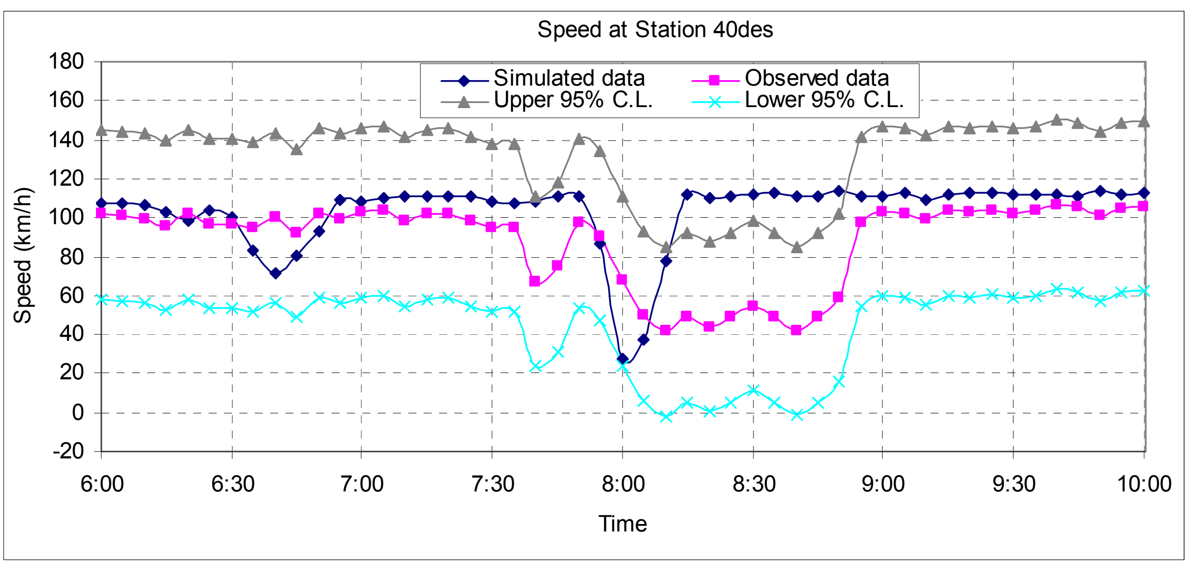
Latitude:	43° 10.200' N	**Longitude:**	79° 55.800' W	**Elevation:**	237.70 m
Climate ID:	6153194	**WMO ID:**	71263	**TC ID:**	YHM

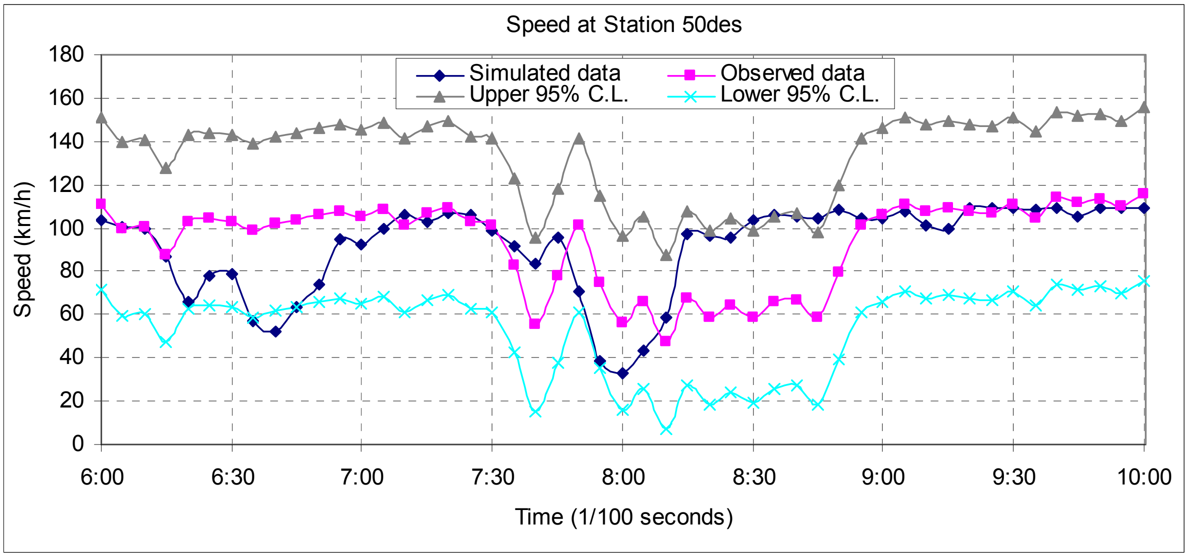
Hourly Data Report for April 14, 2005								
Time	Temperature °C	Dew Point Temperature °C	Relative Humidity %	Wind Direction 10's deg	Wind Speed km/h	Visibility km	Stn Pressure kPa	Weather
0:00	5.2	-5.1	47	33	9	24.1	99.22	Clear
1:00	4.8	-5	49	35	11	24.1	99.21	Clear
2:00	4.4	-5.8	47	1	13	24.1	99.21	Clear
3:00	5.8	-6	42	2	22	24.1	99.21	Clear
4:00	5.3	-6.6	42	1	26	24.1	99.24	Clear
5:00	4.8	-6.5	44	1	20	24.1	99.3	Clear
6:00	4.5	-6.4	45	2	19	24.1	99.39	Clear
7:00	6.5	-6	40	2	19	24.1	99.42	Mainly Clear
8:00	8	-6.3	36	3	26	24.1	99.48	Mainly Clear
9:00	8.2	-5.9	36	5	33	24.1	99.53	Mostly Cloudy
10:00	8.1	-5.8	37	5	28	24.1	99.58	Mostly Cloudy
11:00	9.3	-5	36	7	24	24.1	99.59	Mainly Clear
12:00	10	-4.4	36	5	19	24.1	99.59	Mainly Clear
13:00	10.6	-3.4	37	8	19	24.1	99.58	Mainly Clear
14:00	11	-3.3	37	7	17	24.1	99.58	Clear
15:00	11.7	-2.9	36	4	20	24.1	99.54	Clear
16:00	11.7	-2.9	36	5	19	24.1	99.55	Clear
17:00	12	-3.6	33	7	19	24.1	99.56	Clear
18:00	11.2	-3.3	36	5	19	24.1	99.58	Clear
19:00	8.2	-3.3	44	4	13	24.1	99.62	Clear
20:00	6.6	-3.7	48	2	13	24.1	99.68	Clear
21:00	5.8	-3.5	51	4	15	24.1	99.75	Clear
22:00	4.8	-3.8	54	4	13	24.1	99.78	Mainly Clear
23:00	3.7	-3.3	60	4	15	24.1	99.84	Mainly Clear

Appendix D

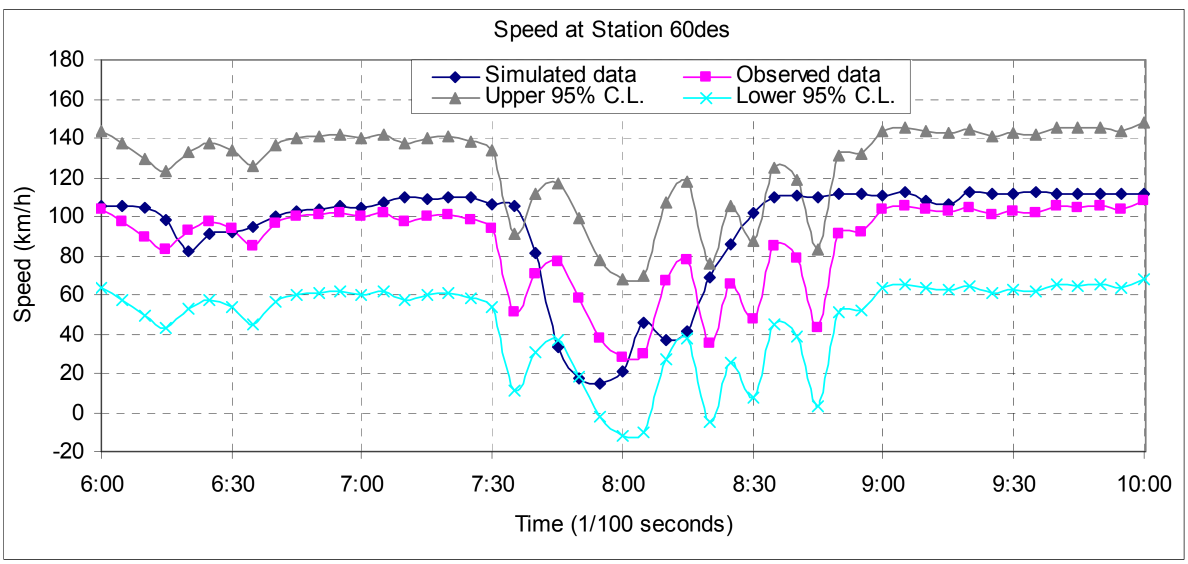
Simulated Speed Versus Observed Speed



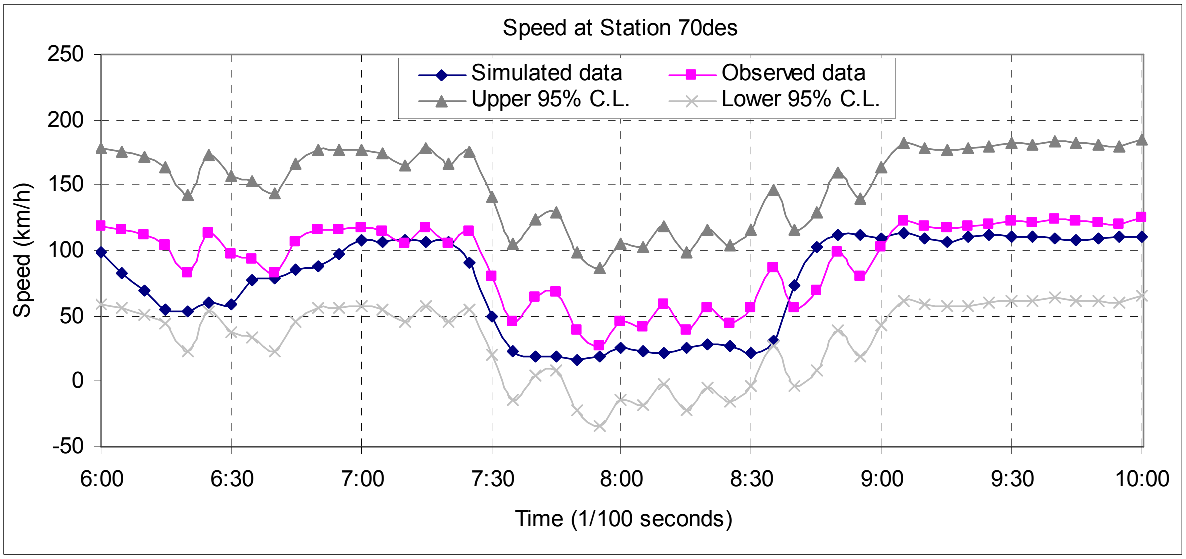




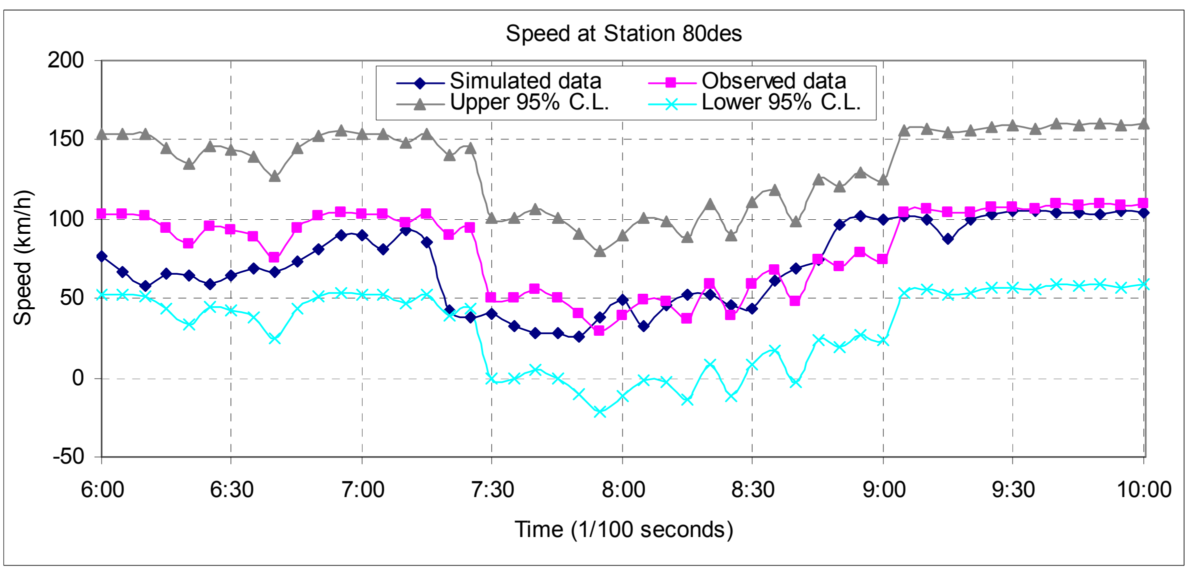
Speed at Station 50des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
180
160
140
120
100
80
60
40
20
0
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)



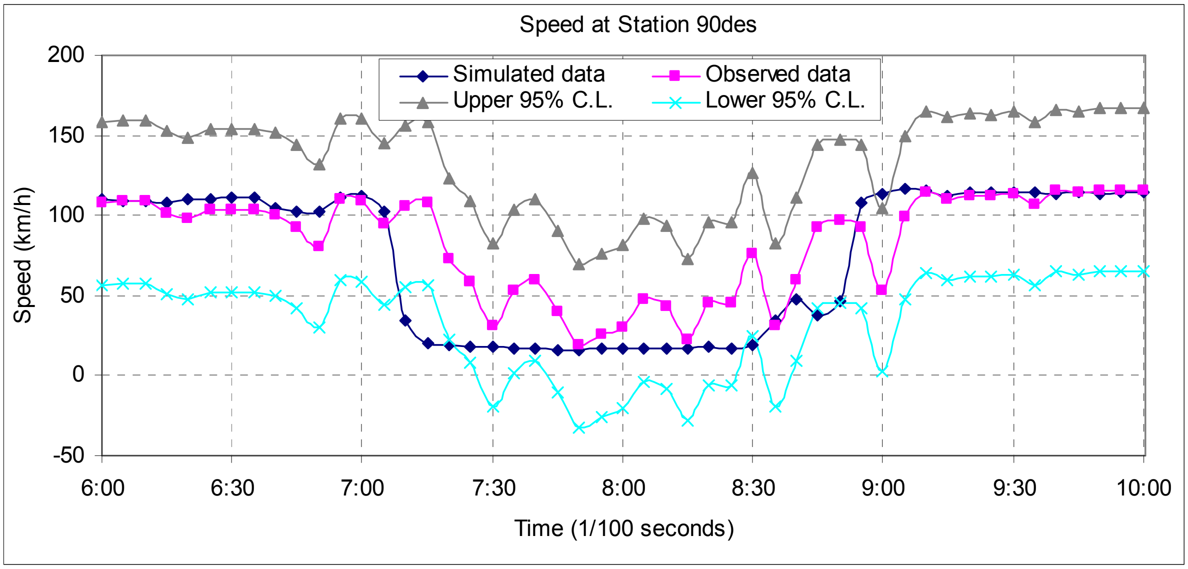
Speed at Station 60des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
180
160
140
120
100
80
60
40
20
0
-20
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

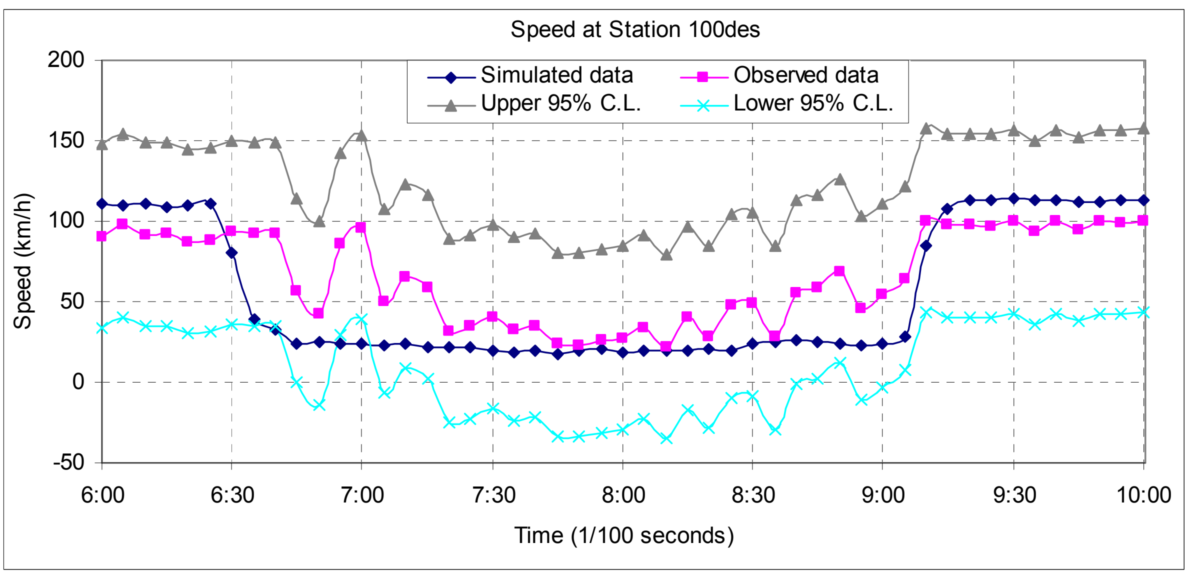


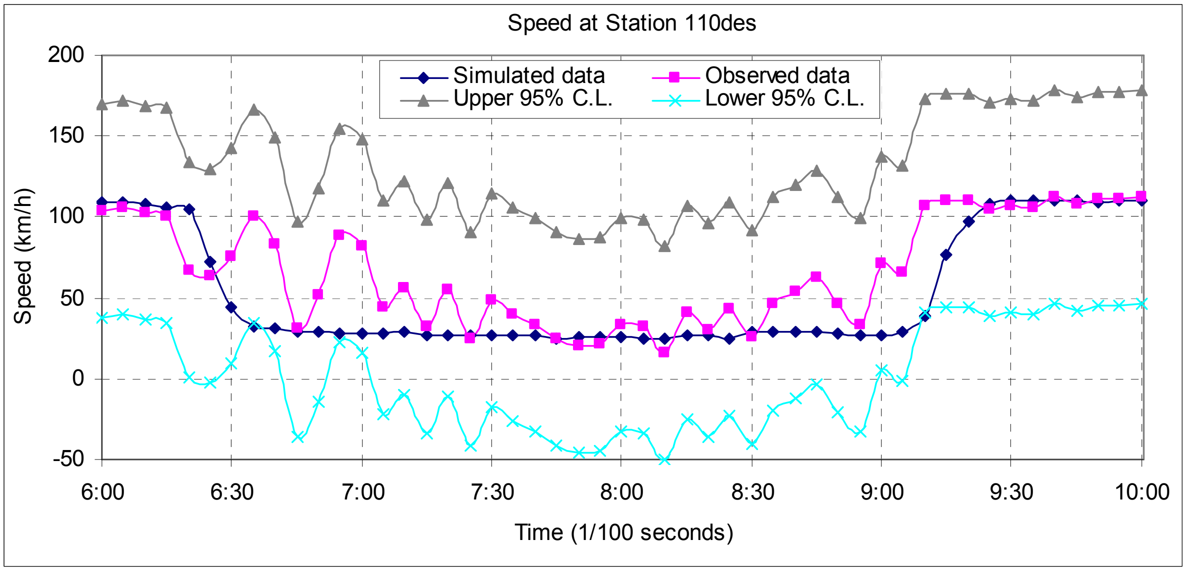
Speed at Station 70des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
250
200
150
100
50
0
-50
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

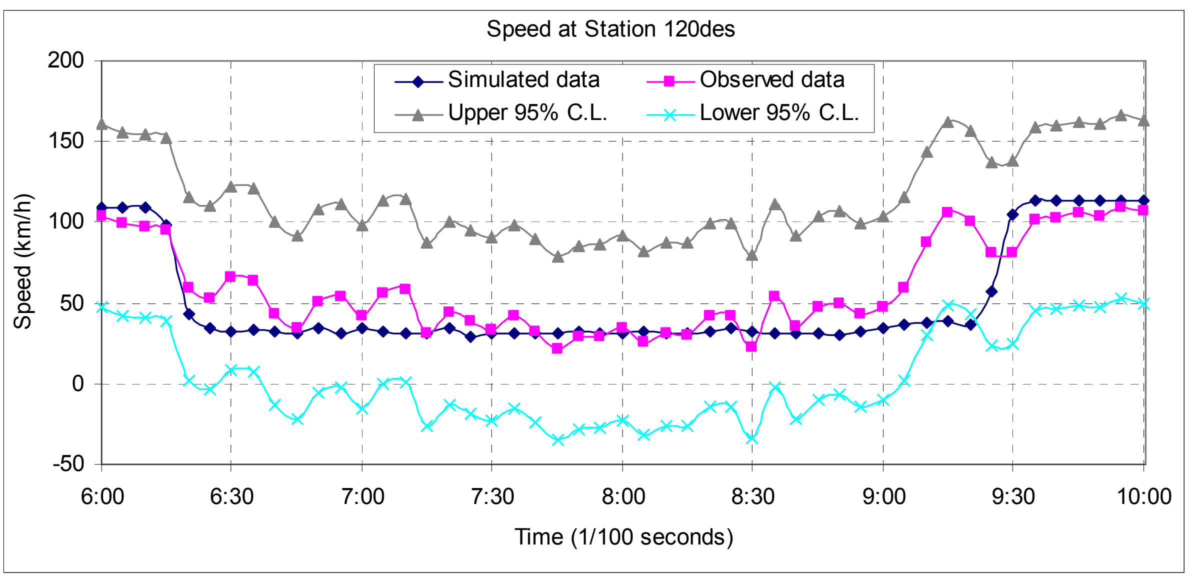


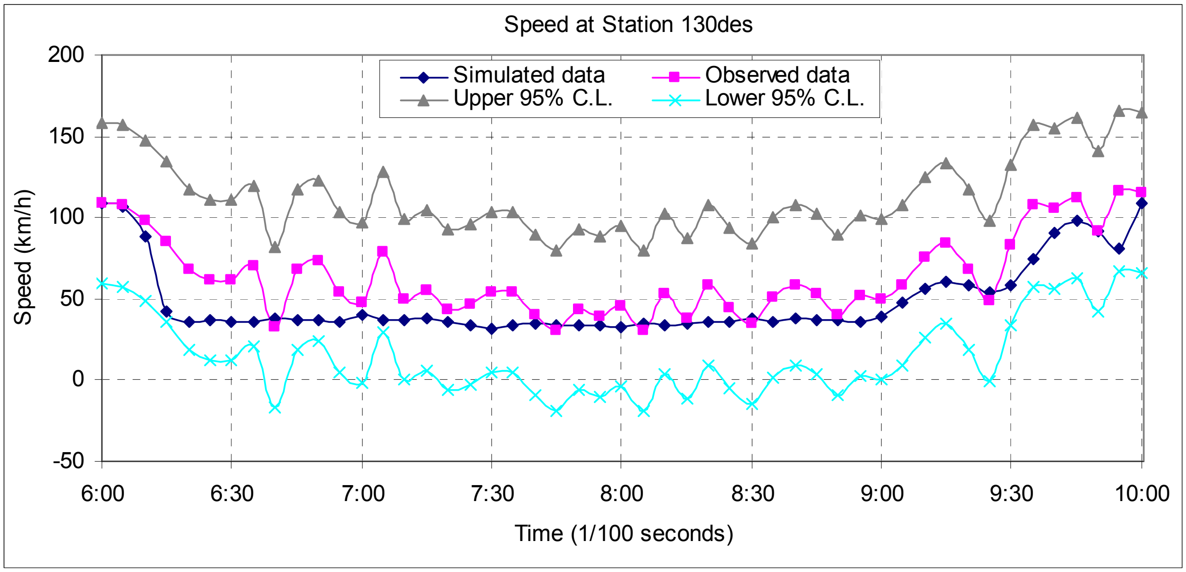
Speed at Station 80des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
200
150
100
50
0
-50
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

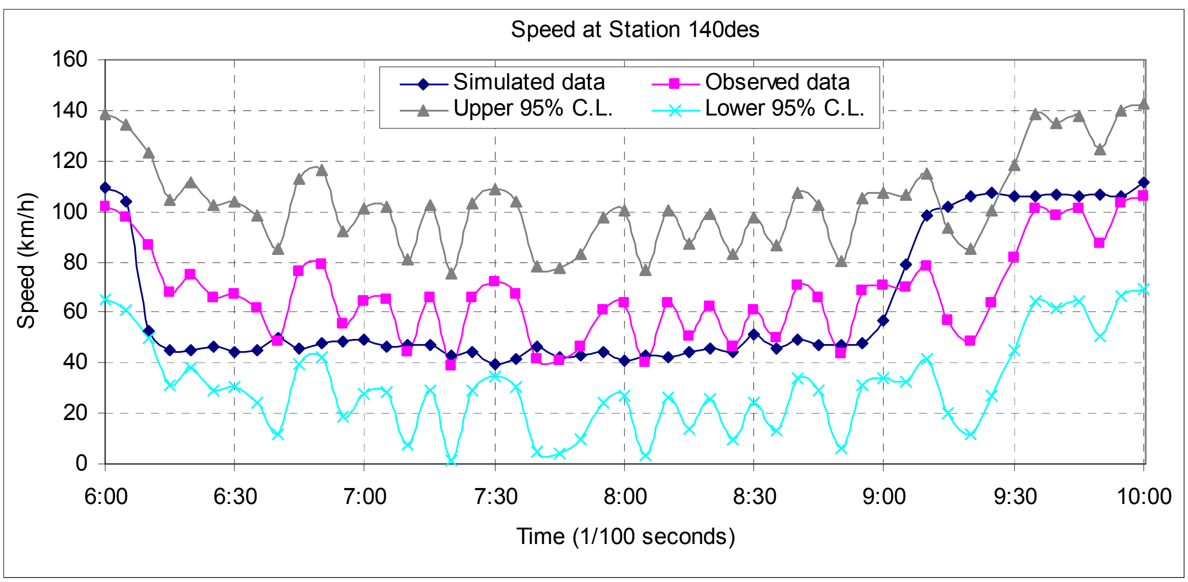

Speed at Station 90des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
200
150
100
50
0
-50
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

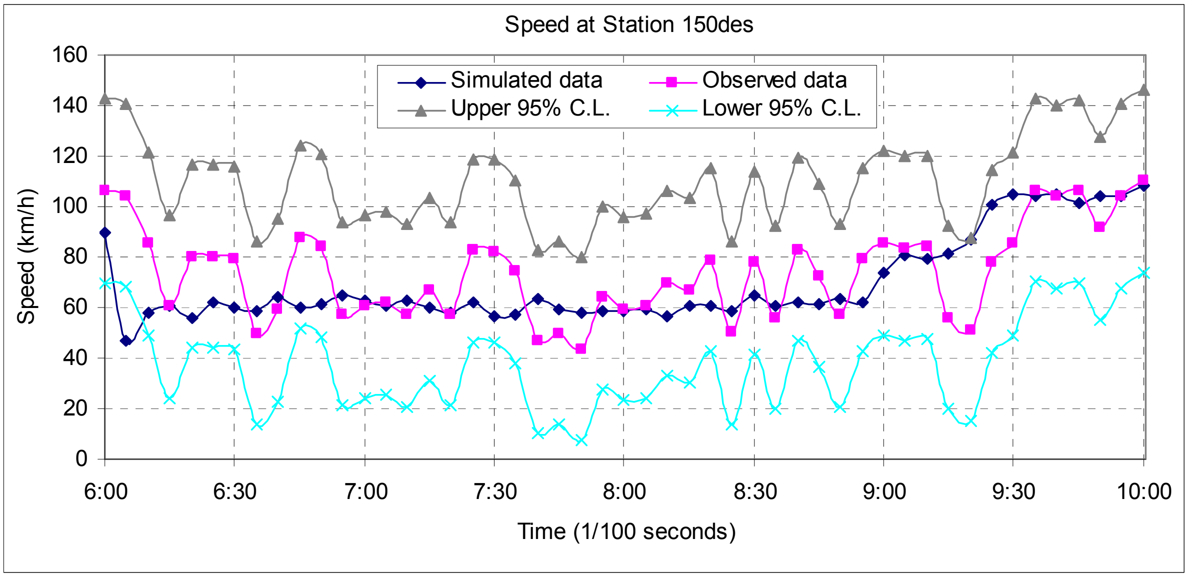

Speed at Station 100des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
200
150
100
50
0
-50
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)


Speed at Station 110des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
200
150
100
50
0
-50
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)


Speed at Station 120des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
200
150
100
50
0
-50
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

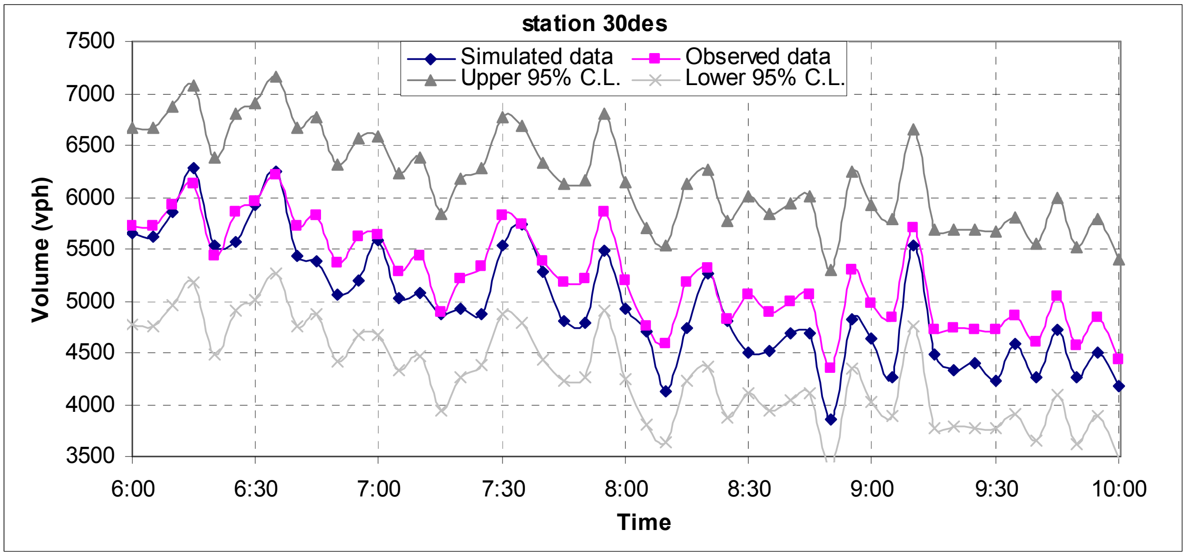

Speed at Station 130des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
200
150
100
50
0
-50
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

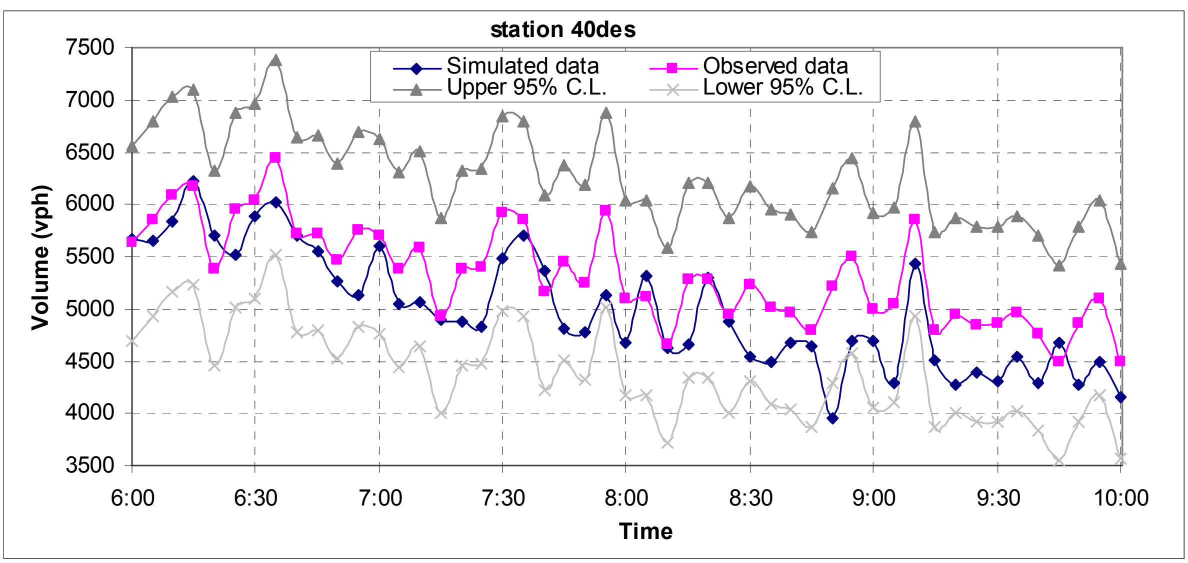

Speed at Station 140des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
160
140
120
100
80
60
40
20
0
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

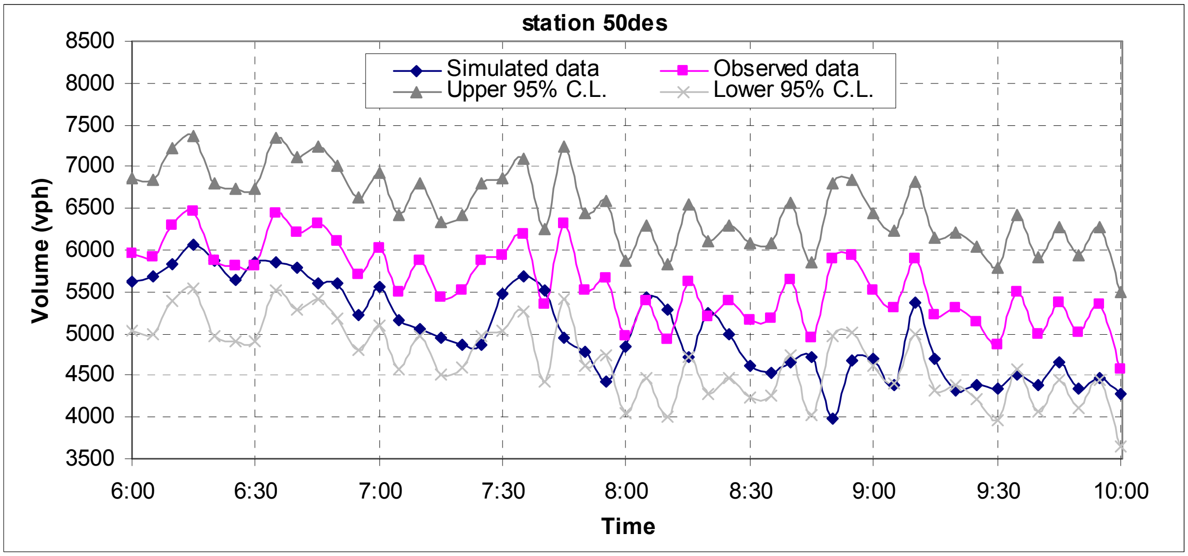

Speed at Station 150des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Speed (km/h)
160
140
120
100
80
60
40
20
0
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time (1/100 seconds)

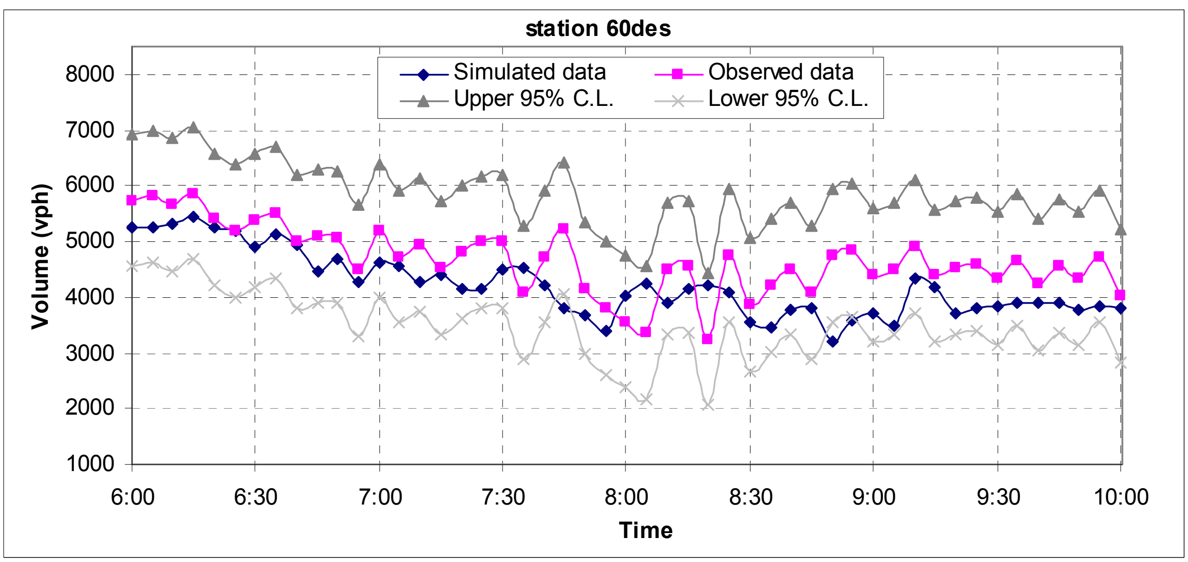
Appendix E

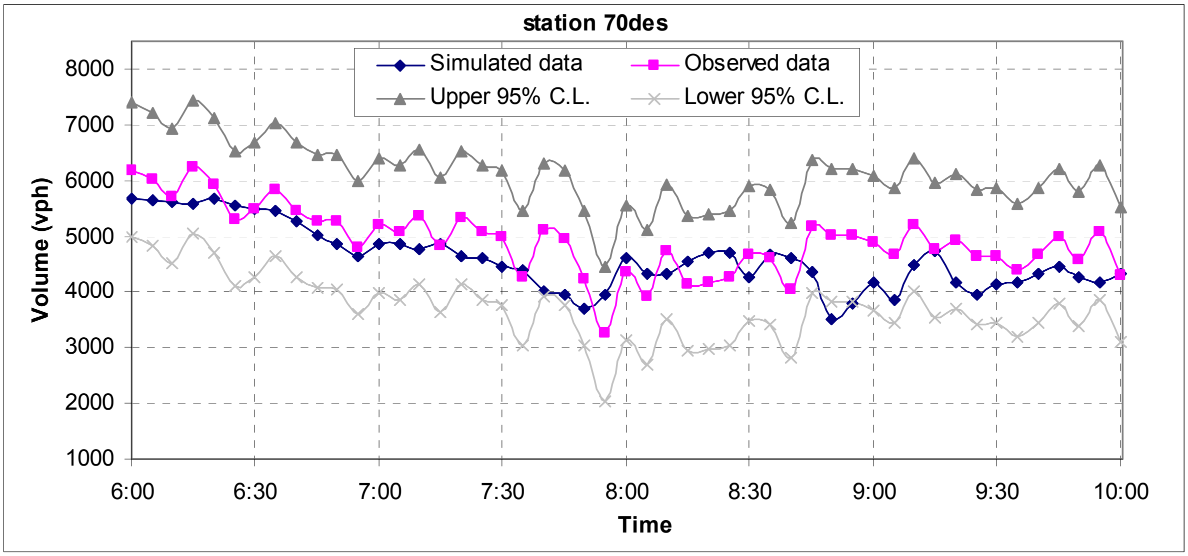
Simulated Traffic Volume Versus Observed Traffic Volume

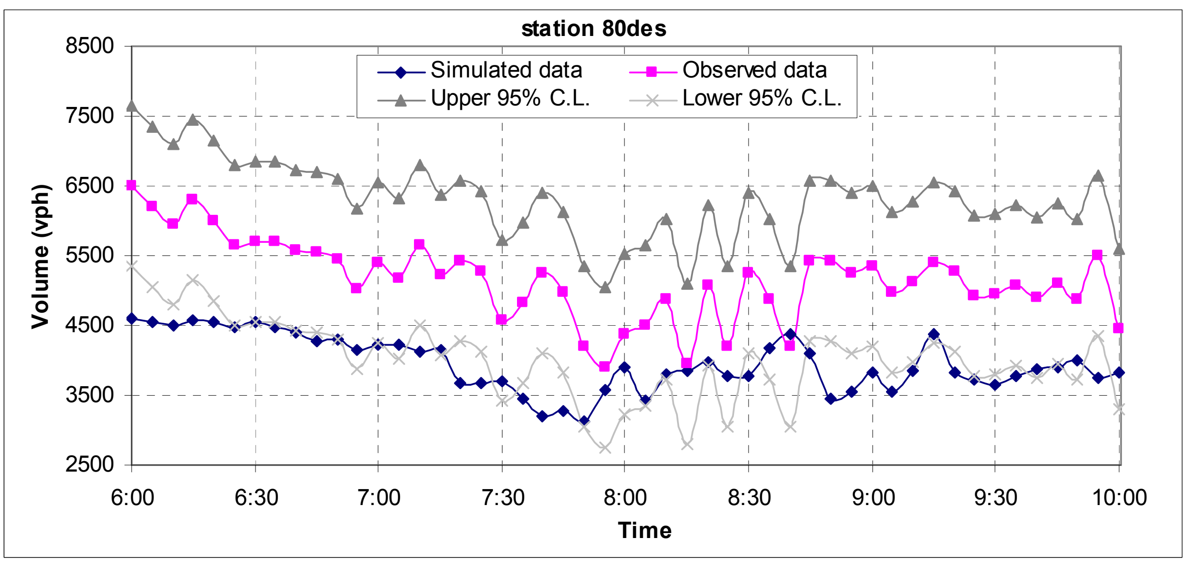


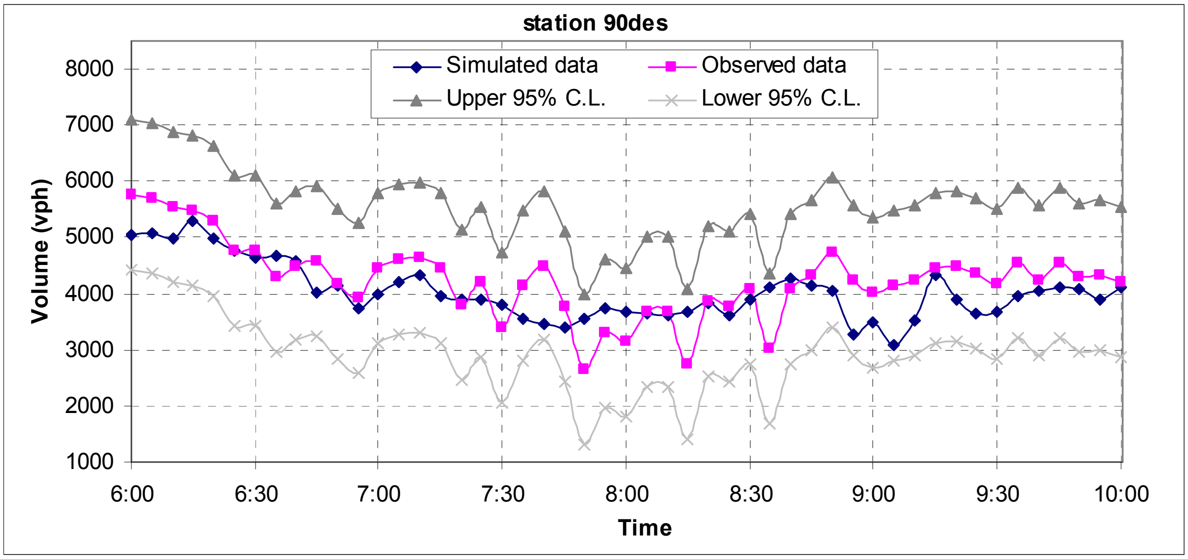


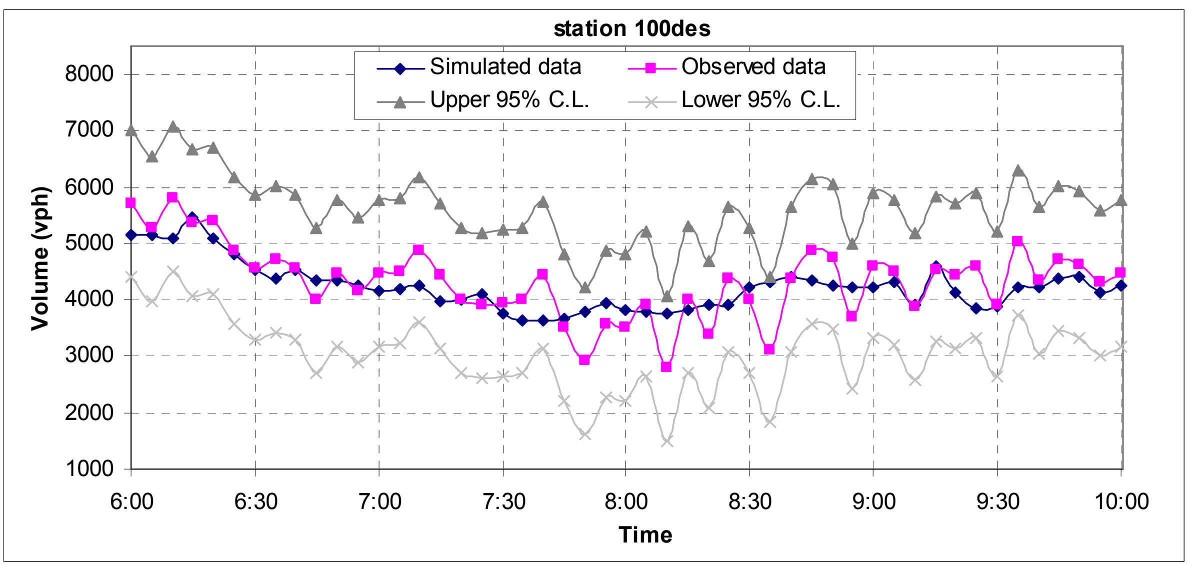

station 50des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time

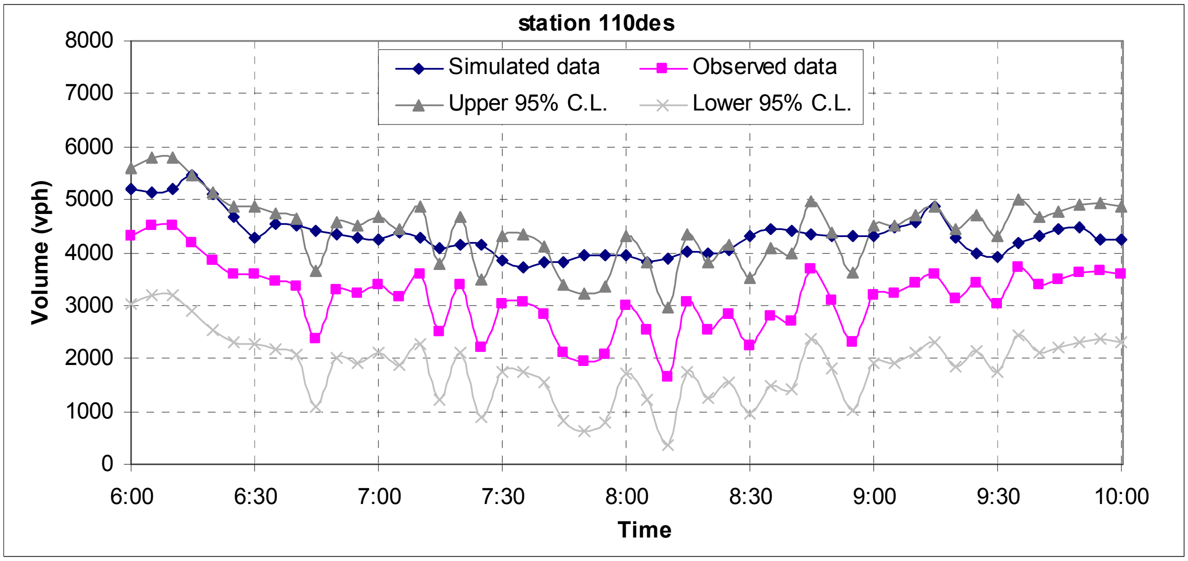

station 60des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8000
7000
6000
5000
4000
3000
2000
1000
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time

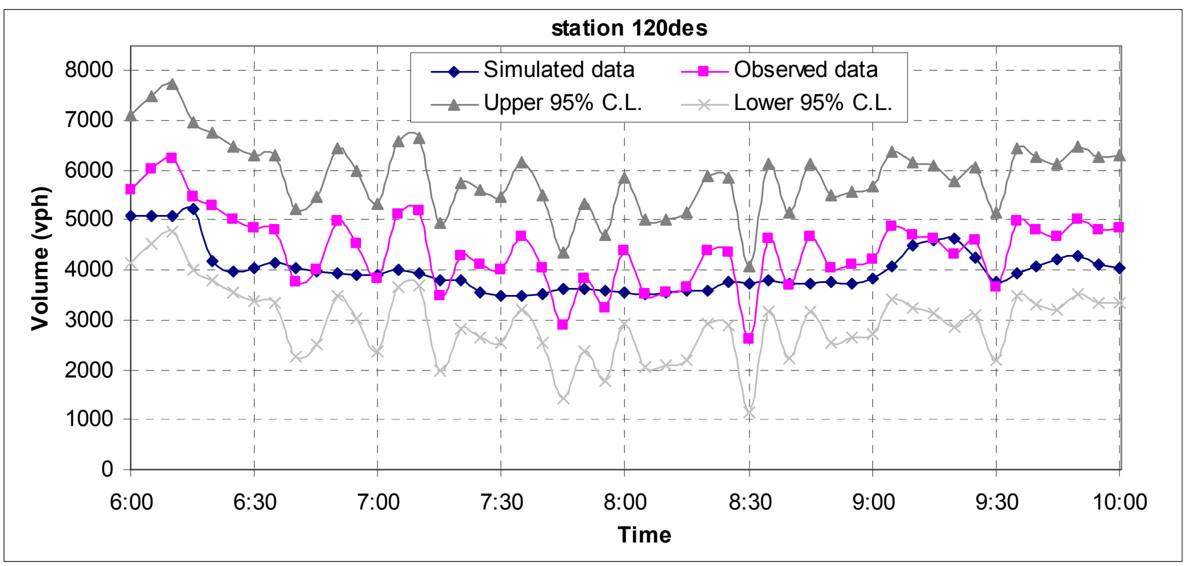

station 70des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8000
7000
6000
5000
4000
3000
2000
1000
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time

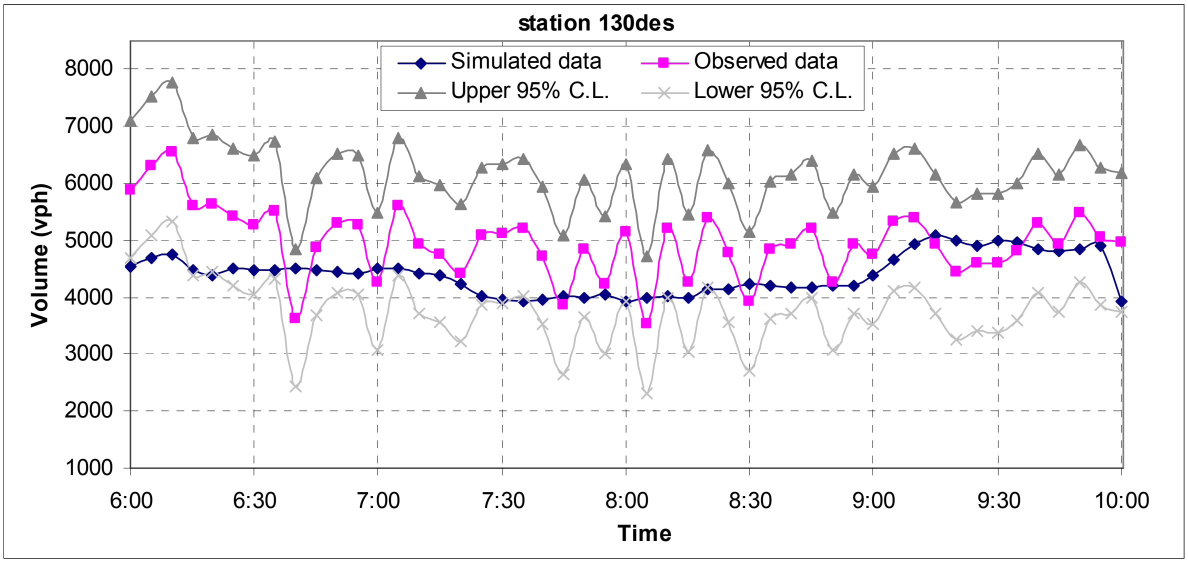

station 80des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8500
7500
6500
5500
4500
3500
2500
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time

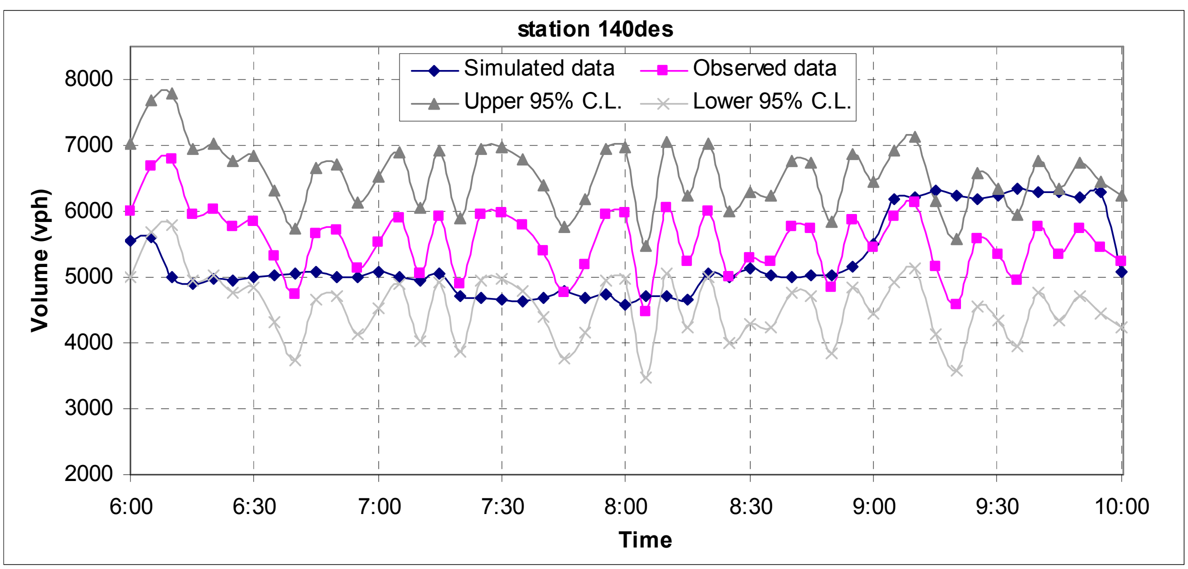

station 90des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8000
7000
6000
5000
4000
3000
2000
1000
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time

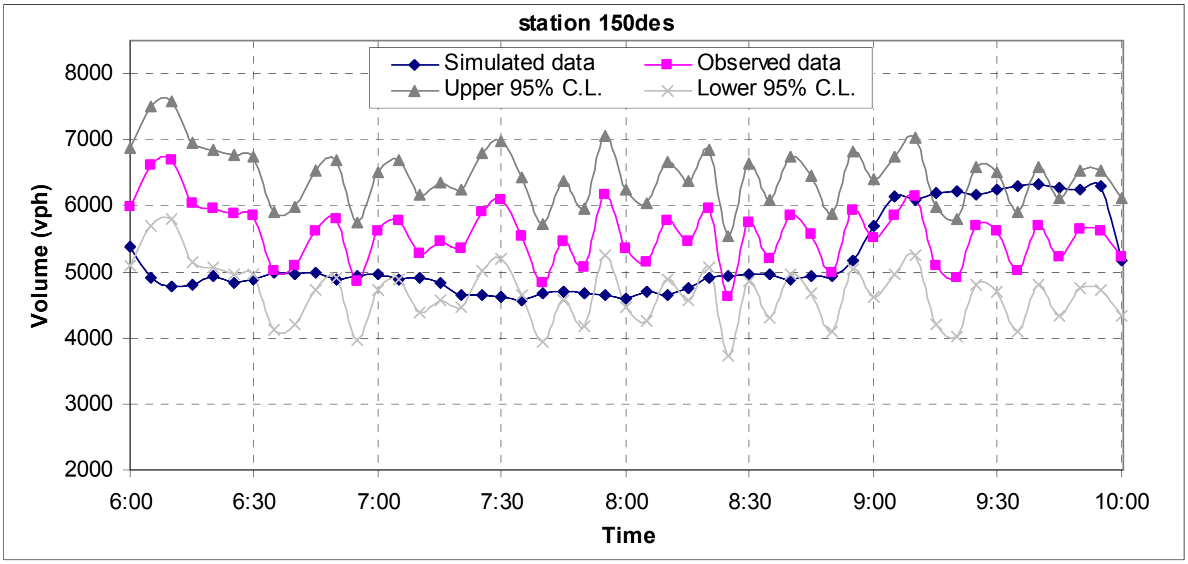

station 100des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8000
7000
6000
5000
4000
3000
2000
1000
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time


station 110des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
Time
8000
7000
6000
5000
4000
3000
2000
1000
0
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00


station 120des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
Time
8000
7000
6000
5000
4000
3000
2000
1000
0
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00


station 130des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8000
7000
6000
5000
4000
3000
2000
1000
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time


station 140des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8000
7000
6000
5000
4000
3000
2000
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time



station 150des
Simulated data
Observed data
Upper 95% C.L.
Lower 95% C.L.
Volume (vph)
8000
7000
6000
5000
4000
3000
2000
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
Time

Appendix F
INTEGRATION Input Files for the Base Case

1. Master File

QEW master file Seed 01

16200.01 1800 0 1 1

QEW\Input\

QEW\Output1\

01QEWnodes.dat

02QEWlinks.dat

03QEWSignals.dat

04QEWOD.dat

05QEWIncidents.dat

none

none

none

none

QEW10.out

none

none

none

none

QEW15.out

QEW16.out

none

none

none

none

21QEWLoopStations.dat

none

2. Node Coordination File

QEW Node Coordinate File

57	1	1				
1	3.00	3.00	3	0	0	zone 1
2	13.04	2.90	2	-1	0	zone 2
3	4.05	3.17	3	0	0	zone 3
4	4.05	2.73	3	0	0	Zone 4
5	6.08	3.17	3	0	0	Zone 5
6	6.08	2.64	2	-2	0	Zone 6
7	6.09	2.51	3	0	0	Zone 7
8	8.24	3.17	3	0	0	Zone 8
9	8.23	2.70	2	-3	0	Zone 9
10	8.23	2.64	3	0	0	zone 10
11	10.26	3.17	3	0	0	zone 11
12	10.26	2.66	2	-4	0	Zone 12
13	10.26	2.61	3	0	0	zone 13
14	12.40	2.61	3	0	0	zone 14
15	3.83	2.90	4	0	0	

16	4.00	2.90	4	0	0
17	4.47	2.90	4	0	0
18	4.61	2.90	4	0	0
19	4.98	2.90	4	0	0
20	5.17	2.90	4	0	0
21	5.60	2.90	4	0	0
22	6.14	2.90	4	0	0
23	6.42	2.90	4	0	0
24	6.73	2.90	4	0	0
25	7.06	2.90	4	0	0
26	7.24	2.90	4	0	0
27	7.63	2.90	4	0	0
28	8.24	2.90	4	0	0
29	8.56	2.90	4	0	0
30	8.87	2.90	4	0	0
31	9.67	2.90	4	0	0
32	10.26	2.90	4	0	0
33	10.56	2.90	4	0	0
34	10.72	2.90	4	0	0
35	11.08	2.90	4	0	0
36	12.86	2.90	4	0	0
37	4.05	2.87	4	0	0
38	3.99	2.78	4	0	0
39	3.93	2.84	4	0	0

40	4.19	2.83	4	0	0
41	5.89	2.85	4	0	0
42	6.02	2.71	4	0	0
43	6.08	2.85	4	0	0
44	6.04	2.78	4	0	0
45	5.97	2.84	4	0	0
46	6.21	2.80	4	0	0
47	8.06	2.84	4	0	0
48	8.24	2.87	4	0	0
49	8.21	2.77	4	0	0
50	8.11	2.86	4	0	0
51	8.35	2.83	4	0	0
52	10.04	2.82	4	0	0
53	10.26	2.85	4	0	0
54	10.15	2.76	4	0	0
55	10.11	2.87	4	0	0
56	10.36	2.85	4	0	0
57	12.51	2.85	4	0	0

3. Links File

QEW Link Characteristics

56 0.001 1 1 1 1

-1 1 15 832.41 125 2300 3 0.1110 140 0 0 0 0 0 0 0 0 0000011111

-2 15 16 172.80 125 2300 3 0.1110 140 0 0 0 0 0 0 0 0 0000011111

3	16	17	472.00	125	2300	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
4	17	18	143.50	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
5	18	19	369.00	125	2300	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
6	19	20	187.50	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
7	20	21	432.00	125	2400	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
8	21	22	538.00	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
9	22	23	282.00	125	2300	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
10	23	24	305.00	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
11	24	25	334.00	125	2300	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
12	25	26	177.00	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
13	26	27	390.00	125	2400	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
14	27	28	613.71	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
15	28	29	313.79	125	2300	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
16	29	30	318.00	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
17	30	31	800.00	125	2400	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
18	31	32	583.00	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
19	32	33	304.00	125	2300	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
20	33	34	162.50	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
21	34	35	360.00	125	2300	4	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
22	35	36	1779.44	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-23	36	2	177.38	125	2300	3	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-24	3	37	298.13	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-25	37	38	112.57	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-26	38	39	91.09	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111

-27	39	16	84.23	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-28	4	40	171.55	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-29	40	18	431.77	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-30	21	41	292.46	125	2300	2	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-31	41	42	186.51	125	2300	2	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-32	42	6	98.88	125	2300	2	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-33	5	43	324.00	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-34	43	44	83.78	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-35	44	45	93.27	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-36	45	22	180.74	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-37	7	46	324.50	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-38	46	24	521.67	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-39	27	47	439.27	125	2300	2	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-40	47	9	219.56	125	2300	2	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-41	8	48	300.23	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-42	48	49	110.78	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-43	49	50	138.93	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-44	50	28	137.42	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-45	10	51	227.98	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-46	51	30	524.12	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-47	31	52	378.24	125	2300	2	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-48	52	12	267.34	125	2300	2	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-49	11	53	325.41	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111
-50	53	54	135.38	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	0000011111

-51	54	55	114.47	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-52	55	32	149.99	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-53	13	56	262.16	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-54	56	34	363.27	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-55	14	57	262.18	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111
-56	57	36	360.15	125	2300	1	0.1110	140	0	0	0	0	0	0	0	0	00000	11111

4. Demand File

QEW O-D Demand file 5 minutes data from 5:30 till 10:00 Am

702	0	0	1										
1	1	6	226	1	0	300	1	0	0	0	0	0	1
2	1	6	226	1	300	600	1	0	0	0	0	0	1
3	1	6	308	1	600	900	1	0	0	0	0	0	1
4	1	6	441	1	900	1200	1	0	0	0	0	0	1
5	1	6	400	1	1200	1500	1	0	0	0	0	0	1
6	1	6	267	1	1500	1800	1	0	0	0	0	0	1
7	1	6	400	1	1800	2100	1	0	0	0	0	0	1
8	1	6	400	1	2100	2400	1	0	0	0	0	0	1
9	1	6	421	1	2400	2700	1	0	0	0	0	0	1
10	1	6	534	1	2700	3000	1	0	0	0	0	0	1
11	1	6	483	1	3000	3300	1	0	0	0	0	0	1
12	1	6	670	1	3300	3600	1	0	0	0	0	0	1
13	1	6	710	1	3600	3900	1	0	0	0	0	0	1
14	1	6	850	1	3900	4200	1	0	0	0	0	0	1

15	1	6	930	1	4200	4500	1	0	0	0	0	0	1
16	1	6	860	1	4500	4800	1	0	0	0	0	0	1
17	1	6	900	1	4800	5100	1	0	0	0	0	0	1
18	1	6	770	1	5100	5400	1	0	0	0	0	0	1
19	1	6	585	1	5400	5700	1	0	0	0	0	0	1
20	1	6	770	1	5700	6000	1	0	0	0	0	0	1
21	1	6	605	1	6000	6300	1	0	0	0	0	0	1
22	1	6	585	1	6300	6600	1	0	0	0	0	0	1
23	1	6	739	1	6600	6900	1	0	0	0	0	0	1
24	1	6	770	1	6900	7200	1	0	0	0	0	0	1
25	1	6	1026	1	7200	7500	1	0	0	0	0	0	1
26	1	6	1077	1	7500	7800	1	0	0	0	0	0	1
27	1	6	821	1	7800	8100	1	0	0	0	0	0	1
28	1	6	1150	1	8100	8400	1	0	0	0	0	0	1
29	1	6	1262	1	8400	8700	1	0	0	0	0	0	1
30	1	6	1323	1	8700	9000	1	0	0	0	0	0	1
31	1	6	1201	1	9000	9300	1	0	0	0	0	0	1
32	1	6	954	1	9300	9600	1	0	0	0	0	0	1
33	1	6	1026	1	9600	9900	1	0	0	0	0	0	1
34	1	6	1129	1	9900	10200	1	0	0	0	0	0	1
35	1	6	913	1	10200	10500	1	0	0	0	0	0	1
36	1	6	1159	1	10500	10800	1	0	0	0	0	0	1
37	1	6	903	1	10800	11100	1	0	0	0	0	0	1
38	1	6	718	1	11100	11400	1	0	0	0	0	0	1

39	1	6	862	1	11400	11700	1	0	0	0	0	0	1
40	1	6	903	1	11700	12000	1	0	0	0	0	0	1
41	1	6	821	1	12000	12300	1	0	0	0	0	0	1
42	1	6	944	1	12300	12600	1	0	0	0	0	0	1
43	1	6	800	1	12600	12900	1	0	0	0	0	0	1
44	1	6	667	1	12900	13200	1	0	0	0	0	0	1
45	1	6	688	1	13200	13500	1	0	0	0	0	0	1
46	1	6	513	1	13500	13800	1	0	0	0	0	0	1
47	1	6	575	1	13800	14100	1	0	0	0	0	0	1
48	1	6	462	1	14100	14400	1	0	0	0	0	0	1
49	1	6	564	1	14400	14700	1	0	0	0	0	0	1
50	1	6	431	1	14700	15000	1	0	0	0	0	0	1
51	1	6	677	1	15000	15300	1	0	0	0	0	0	1
52	1	6	513	1	15300	15600	1	0	0	0	0	0	1
53	1	6	503	1	15600	15900	1	0	0	0	0	0	1
54	1	6	503	1	15900	16200	1	0	0	0	0	0	1
55	1	9	547	1	0	300	1	0	0	0	0	0	1
56	1	9	718	1	300	600	1	0	0	0	0	0	1
57	1	9	741	1	600	900	1	0	0	0	0	0	1
58	1	9	707	1	900	1200	1	0	0	0	0	0	1
59	1	9	559	1	1200	1500	1	0	0	0	0	0	1
60	1	9	673	1	1500	1800	1	0	0	0	0	0	1
61	1	9	559	1	1800	2100	1	0	0	0	0	0	1
62	1	9	479	1	2100	2400	1	0	0	0	0	0	1

63	1	9	718	1	2400	2700	1	0	0	0	0	0	1
64	1	9	673	1	2700	3000	1	0	0	0	0	0	1
65	1	9	855	1	3000	3300	1	0	0	0	0	0	1
66	1	9	912	1	3300	3600	1	0	0	0	0	0	1
67	1	9	878	1	3600	3900	1	0	0	0	0	0	1
68	1	9	1163	1	3900	4200	1	0	0	0	0	0	1
69	1	9	1083	1	4200	4500	1	0	0	0	0	0	1
70	1	9	1151	1	4500	4800	1	0	0	0	0	0	1
71	1	9	1026	1	4800	5100	1	0	0	0	0	0	1
72	1	9	923	1	5100	5400	1	0	0	0	0	0	1
73	1	9	741	1	5400	5700	1	0	0	0	0	0	1
74	1	9	752	1	5700	6000	1	0	0	0	0	0	1
75	1	9	821	1	6000	6300	1	0	0	0	0	0	1
76	1	9	912	1	6300	6600	1	0	0	0	0	0	1
77	1	9	889	1	6600	6900	1	0	0	0	0	0	1
78	1	9	958	1	6900	7200	1	0	0	0	0	0	1
79	1	9	844	1	7200	7500	1	0	0	0	0	0	1
80	1	9	684	1	7500	7800	1	0	0	0	0	0	1
81	1	9	992	1	7800	8100	1	0	0	0	0	0	1
82	1	9	1106	1	8100	8400	1	0	0	0	0	0	1
83	1	9	821	1	8400	8700	1	0	0	0	0	0	1
84	1	9	1186	1	8700	9000	1	0	0	0	0	0	1
85	1	9	958	1	9000	9300	1	0	0	0	0	0	1
86	1	9	1094	1	9300	9600	1	0	0	0	0	0	1

87	1	9	1151	1	9600	9900	1	0	0	0	0	0	1
88	1	9	958	1	9900	10200	1	0	0	0	0	0	1
89	1	9	1117	1	10200	10500	1	0	0	0	0	0	1
90	1	9	1117	1	10500	10800	1	0	0	0	0	0	1
91	1	9	1015	1	10800	11100	1	0	0	0	0	0	1
92	1	9	923	1	11100	11400	1	0	0	0	0	0	1
93	1	9	787	1	11400	11700	1	0	0	0	0	0	1
94	1	9	775	1	11700	12000	1	0	0	0	0	0	1
95	1	9	1003	1	12000	12300	1	0	0	0	0	0	1
96	1	9	1163	1	12300	12600	1	0	0	0	0	0	1
97	1	9	969	1	12600	12900	1	0	0	0	0	0	1
98	1	9	866	1	12900	13200	1	0	0	0	0	0	1
99	1	9	821	1	13200	13500	1	0	0	0	0	0	1
100	1	9	661	1	13500	13800	1	0	0	0	0	0	1
101	1	9	809	1	13800	14100	1	0	0	0	0	0	1
102	1	9	593	1	14100	14400	1	0	0	0	0	0	1
103	1	9	547	1	14400	14700	1	0	0	0	0	0	1
104	1	9	616	1	14700	15000	1	0	0	0	0	0	1
105	1	9	536	1	15000	15300	1	0	0	0	0	0	1
106	1	9	650	1	15300	15600	1	0	0	0	0	0	1
107	1	9	616	1	15600	15900	1	0	0	0	0	0	1
108	1	9	490	1	15900	16200	1	0	0	0	0	0	1
109	5	12	24	1	0	300	1	0	0	0	0	0	1
110	5	12	36	1	300	600	1	0	0	0	0	0	1

111	5	12	36	1	600	900	1	0	0	0	0	0	1
112	5	12	24	1	900	1200	1	0	0	0	0	0	1
113	5	12	36	1	1200	1500	1	0	0	0	0	0	1
114	5	12	48	1	1500	1800	1	0	0	0	0	0	1
115	5	12	48	1	1800	2100	1	0	0	0	0	0	1
116	5	12	36	1	2100	2400	1	0	0	0	0	0	1
117	5	12	60	1	2400	2700	1	0	0	0	0	0	1
118	5	12	48	1	2700	3000	1	0	0	0	0	0	1
119	5	12	24	1	3000	3300	1	0	0	0	0	0	1
120	5	12	36	1	3300	3600	1	0	0	0	0	0	1
121	5	12	60	1	3600	3900	1	0	0	0	0	0	1
122	5	12	36	1	3900	4200	1	0	0	0	0	0	1
123	5	12	36	1	4200	4500	1	0	0	0	0	0	1
124	5	12	24	1	4500	4800	1	0	0	0	0	0	1
125	5	12	36	1	4800	5100	1	0	0	0	0	0	1
126	5	12	24	1	5100	5400	1	0	0	0	0	0	1
127	5	12	36	1	5400	5700	1	0	0	0	0	0	1
128	5	12	60	1	5700	6000	1	0	0	0	0	0	1
129	5	12	48	1	6000	6300	1	0	0	0	0	0	1
130	5	12	60	1	6300	6600	1	0	0	0	0	0	1
131	5	12	36	1	6600	6900	1	0	0	0	0	0	1
132	5	12	24	1	6900	7200	1	0	0	0	0	0	1
133	5	12	36	1	7200	7500	1	0	0	0	0	0	1
134	5	12	24	1	7500	7800	1	0	0	0	0	0	1

135	5	12	24	1	7800	8100	1	0	0	0	0	0	1
136	5	12	36	1	8100	8400	1	0	0	0	0	0	1
137	5	12	24	1	8400	8700	1	0	0	0	0	0	1
138	5	12	36	1	8700	9000	1	0	0	0	0	0	1
139	5	12	24	1	9000	9300	1	0	0	0	0	0	1
140	5	12	36	1	9300	9600	1	0	0	0	0	0	1
141	5	12	24	1	9600	9900	1	0	0	0	0	0	1
142	5	12	24	1	9900	10200	1	0	0	0	0	0	1
143	5	12	36	1	10200	10500	1	0	0	0	0	0	1
144	5	12	36	1	10500	10800	1	0	0	0	0	0	1
145	5	12	24	1	10800	11100	1	0	0	0	0	0	1
146	5	12	60	1	11100	11400	1	0	0	0	0	0	1
147	5	12	48	1	11400	11700	1	0	0	0	0	0	1
148	5	12	36	1	11700	12000	1	0	0	0	0	0	1
149	5	12	36	1	12000	12300	1	0	0	0	0	0	1
150	5	12	48	1	12300	12600	1	0	0	0	0	0	1
151	5	12	36	1	12600	12900	1	0	0	0	0	0	1
152	5	12	48	1	12900	13200	1	0	0	0	0	0	1
153	5	12	48	1	13200	13500	1	0	0	0	0	0	1
154	5	12	36	1	13500	13800	1	0	0	0	0	0	1
155	5	12	24	1	13800	14100	1	0	0	0	0	0	1
156	5	12	36	1	14100	14400	1	0	0	0	0	0	1
157	5	12	36	1	14400	14700	1	0	0	0	0	0	1
158	5	12	48	1	14700	15000	1	0	0	0	0	0	1

159	5	12	60	1	15000	15300	1	0	0	0	0	0	1
160	5	12	48	1	15300	15600	1	0	0	0	0	0	1
161	5	12	36	1	15600	15900	1	0	0	0	0	0	1
162	5	12	48	1	15900	16200	1	0	0	0	0	0	1
163	7	12	24	1	0	300	1	0	0	0	0	0	1
164	7	12	12	1	300	600	1	0	0	0	0	0	1
165	7	12	24	1	600	900	1	0	0	0	0	0	1
166	7	12	12	1	900	1200	1	0	0	0	0	0	1
167	7	12	36	1	1200	1500	1	0	0	0	0	0	1
168	7	12	36	1	1500	1800	1	0	0	0	0	0	1
169	7	12	36	1	1800	2100	1	0	0	0	0	0	1
170	7	12	24	1	2100	2400	1	0	0	0	0	0	1
171	7	12	24	1	2400	2700	1	0	0	0	0	0	1
172	7	12	12	1	2700	3000	1	0	0	0	0	0	1
173	7	12	24	1	3000	3300	1	0	0	0	0	0	1
174	7	12	12	1	3300	3600	1	0	0	0	0	0	1
175	7	12	24	1	3600	3900	1	0	0	0	0	0	1
176	7	12	12	1	3900	4200	1	0	0	0	0	0	1
177	7	12	36	1	4200	4500	1	0	0	0	0	0	1
178	7	12	24	1	4500	4800	1	0	0	0	0	0	1
179	7	12	24	1	4800	5100	1	0	0	0	0	0	1
180	7	12	24	1	5100	5400	1	0	0	0	0	0	1
181	7	12	36	1	5400	5700	1	0	0	0	0	0	1
182	7	12	36	1	5700	6000	1	0	0	0	0	0	1

183	7	12	36	1	6000	6300	1	0	0	0	0	0	1
184	7	12	36	1	6300	6600	1	0	0	0	0	0	1
185	7	12	36	1	6600	6900	1	0	0	0	0	0	1
186	7	12	36	1	6900	7200	1	0	0	0	0	0	1
187	7	12	24	1	7200	7500	1	0	0	0	0	0	1
188	7	12	36	1	7500	7800	1	0	0	0	0	0	1
189	7	12	24	1	7800	8100	1	0	0	0	0	0	1
190	7	12	36	1	8100	8400	1	0	0	0	0	0	1
191	7	12	48	1	8400	8700	1	0	0	0	0	0	1
192	7	12	36	1	8700	9000	1	0	0	0	0	0	1
193	7	12	36	1	9000	9300	1	0	0	0	0	0	1
194	7	12	36	1	9300	9600	1	0	0	0	0	0	1
195	7	12	36	1	9600	9900	1	0	0	0	0	0	1
196	7	12	48	1	9900	10200	1	0	0	0	0	0	1
197	7	12	36	1	10200	10500	1	0	0	0	0	0	1
198	7	12	24	1	10500	10800	1	0	0	0	0	0	1
199	7	12	36	1	10800	11100	1	0	0	0	0	0	1
200	7	12	48	1	11100	11400	1	0	0	0	0	0	1
201	7	12	36	1	11400	11700	1	0	0	0	0	0	1
202	7	12	48	1	11700	12000	1	0	0	0	0	0	1
203	7	12	48	1	12000	12300	1	0	0	0	0	0	1
204	7	12	36	1	12300	12600	1	0	0	0	0	0	1
205	7	12	36	1	12600	12900	1	0	0	0	0	0	1
206	7	12	24	1	12900	13200	1	0	0	0	0	0	1

207	7	12	72	1	13200	13500	1	0	0	0	0	0	1
208	7	12	36	1	13500	13800	1	0	0	0	0	0	1
209	7	12	48	1	13800	14100	1	0	0	0	0	0	1
210	7	12	36	1	14100	14400	1	0	0	0	0	0	1
211	7	12	60	1	14400	14700	1	0	0	0	0	0	1
212	7	12	36	1	14700	15000	1	0	0	0	0	0	1
213	7	12	36	1	15000	15300	1	0	0	0	0	0	1
214	7	12	48	1	15300	15600	1	0	0	0	0	0	1
215	7	12	48	1	15600	15900	1	0	0	0	0	0	1
216	7	12	24	1	15900	16200	1	0	0	0	0	0	1
217	1	12	80	1	0	300	1	0	0	0	0	0	1
218	1	12	91	1	300	600	1	0	0	0	0	0	1
219	1	12	57	1	600	900	1	0	0	0	0	0	1
220	1	12	23	1	900	1200	1	0	0	0	0	0	1
221	1	12	23	1	1200	1500	1	0	0	0	0	0	1
222	1	12	11	1	1500	1800	1	0	0	0	0	0	1
223	1	12	34	1	1800	2100	1	0	0	0	0	0	1
224	1	12	80	1	2100	2400	1	0	0	0	0	0	1
225	1	12	251	1	2400	2700	1	0	0	0	0	0	1
226	1	12	194	1	2700	3000	1	0	0	0	0	0	1
227	1	12	114	1	3000	3300	1	0	0	0	0	0	1
228	1	12	342	1	3300	3600	1	0	0	0	0	0	1
229	1	12	388	1	3600	3900	1	0	0	0	0	0	1
230	1	12	228	1	3900	4200	1	0	0	0	0	0	1

231	1	12	274	1	4200	4500	1	0	0	0	0	0	1
232	1	12	182	1	4500	4800	1	0	0	0	0	0	1
233	1	12	205	1	4800	5100	1	0	0	0	0	0	1
234	1	12	251	1	5100	5400	1	0	0	0	0	0	1
235	1	12	137	1	5400	5700	1	0	0	0	0	0	1
236	1	12	182	1	5700	6000	1	0	0	0	0	0	1
237	1	12	399	1	6000	6300	1	0	0	0	0	0	1
238	1	12	171	1	6300	6600	1	0	0	0	0	0	1
239	1	12	194	1	6600	6900	1	0	0	0	0	0	1
240	1	12	182	1	6900	7200	1	0	0	0	0	0	1
241	1	12	365	1	7200	7500	1	0	0	0	0	0	1
242	1	12	285	1	7500	7800	1	0	0	0	0	0	1
243	1	12	228	1	7800	8100	1	0	0	0	0	0	1
244	1	12	182	1	8100	8400	1	0	0	0	0	0	1
245	1	12	239	1	8400	8700	1	0	0	0	0	0	1
246	1	12	251	1	8700	9000	1	0	0	0	0	0	1
247	1	12	308	1	9000	9300	1	0	0	0	0	0	1
248	1	12	103	1	9300	9600	1	0	0	0	0	0	1
249	1	12	262	1	9600	9900	1	0	0	0	0	0	1
250	1	12	445	1	9900	10200	1	0	0	0	0	0	1
251	1	12	433	1	10200	10500	1	0	0	0	0	0	1
252	1	12	331	1	10500	10800	1	0	0	0	0	0	1
253	1	12	376	1	10800	11100	1	0	0	0	0	0	1
254	1	12	399	1	11100	11400	1	0	0	0	0	0	1

255	1	12	365	1	11400	11700	1	0	0	0	0	0	1
256	1	12	228	1	11700	12000	1	0	0	0	0	0	1
257	1	12	365	1	12000	12300	1	0	0	0	0	0	1
258	1	12	217	1	12300	12600	1	0	0	0	0	0	1
259	1	12	205	1	12600	12900	1	0	0	0	0	0	1
260	1	12	365	1	12900	13200	1	0	0	0	0	0	1
261	1	12	171	1	13200	13500	1	0	0	0	0	0	1
262	1	12	262	1	13500	13800	1	0	0	0	0	0	1
263	1	12	171	1	13800	14100	1	0	0	0	0	0	1
264	1	12	114	1	14100	14400	1	0	0	0	0	0	1
265	1	12	171	1	14400	14700	1	0	0	0	0	0	1
266	1	12	103	1	14700	15000	1	0	0	0	0	0	1
267	1	12	148	1	15000	15300	1	0	0	0	0	0	1
268	1	12	91	1	15300	15600	1	0	0	0	0	0	1
269	1	12	156	1	15600	15900	1	0	0	0	0	0	1
270	1	12	96	1	15900	16200	1	0	0	0	0	0	1
271	5	2	156	1	0	300	1	0	0	0	0	0	1
272	5	2	296	1	300	600	1	0	0	0	0	0	1
273	5	2	234	1	600	900	1	0	0	0	0	0	1
274	5	2	218	1	900	1200	1	0	0	0	0	0	1
275	5	2	296	1	1200	1500	1	0	0	0	0	0	1
276	5	2	374	1	1500	1800	1	0	0	0	0	0	1
277	5	2	359	1	1800	2100	1	0	0	0	0	0	1
278	5	2	312	1	2100	2400	1	0	0	0	0	0	1

279	5	2	284	1	2400	2700	1	0	0	0	0	0	1
280	5	2	230	1	2700	3000	1	0	0	0	0	0	1
281	5	2	88	1	3000	3300	1	0	0	0	0	0	1
282	5	2	164	1	3300	3600	1	0	0	0	0	0	1
283	5	2	284	1	3600	3900	1	0	0	0	0	0	1
284	5	2	164	1	3900	4200	1	0	0	0	0	0	1
285	5	2	281	1	4200	4500	1	0	0	0	0	0	1
286	5	2	156	1	4500	4800	1	0	0	0	0	0	1
287	5	2	218	1	4800	5100	1	0	0	0	0	0	1
288	5	2	187	1	5100	5400	1	0	0	0	0	0	1
289	5	2	281	1	5400	5700	1	0	0	0	0	0	1
290	5	2	390	1	5700	6000	1	0	0	0	0	0	1
291	5	2	328	1	6000	6300	1	0	0	0	0	0	1
292	5	2	406	1	6300	6600	1	0	0	0	0	0	1
293	5	2	312	1	6600	6900	1	0	0	0	0	0	1
294	5	2	218	1	6900	7200	1	0	0	0	0	0	1
295	5	2	234	1	7200	7500	1	0	0	0	0	0	1
296	5	2	156	1	7500	7800	1	0	0	0	0	0	1
297	5	2	172	1	7800	8100	1	0	0	0	0	0	1
298	5	2	281	1	8100	8400	1	0	0	0	0	0	1
299	5	2	140	1	8400	8700	1	0	0	0	0	0	1
300	5	2	296	1	8700	9000	1	0	0	0	0	0	1
301	5	2	140	1	9000	9300	1	0	0	0	0	0	1
302	5	2	234	1	9300	9600	1	0	0	0	0	0	1

303	5	2	218	1	9600	9900	1	0	0	0	0	0	1
304	5	2	156	1	9900	10200	1	0	0	0	0	0	1
305	5	2	265	1	10200	10500	1	0	0	0	0	0	1
306	5	2	234	1	10500	10800	1	0	0	0	0	0	1
307	5	2	218	1	10800	11100	1	0	0	0	0	0	1
308	5	2	406	1	11100	11400	1	0	0	0	0	0	1
309	5	2	312	1	11400	11700	1	0	0	0	0	0	1
310	5	2	218	1	11700	12000	1	0	0	0	0	0	1
311	5	2	265	1	12000	12300	1	0	0	0	0	0	1
312	5	2	359	1	12300	12600	1	0	0	0	0	0	1
313	5	2	234	1	12600	12900	1	0	0	0	0	0	1
314	5	2	312	1	12900	13200	1	0	0	0	0	0	1
315	5	2	374	1	13200	13500	1	0	0	0	0	0	1
316	5	2	281	1	13500	13800	1	0	0	0	0	0	1
317	5	2	203	1	13800	14100	1	0	0	0	0	0	1
318	5	2	265	1	14100	14400	1	0	0	0	0	0	1
319	5	2	250	1	14400	14700	1	0	0	0	0	0	1
320	5	2	374	1	14700	15000	1	0	0	0	0	0	1
321	5	2	437	1	15000	15300	1	0	0	0	0	0	1
322	5	2	390	1	15300	15600	1	0	0	0	0	0	1
323	5	2	281	1	15600	15900	1	0	0	0	0	0	1
324	5	2	374	1	15900	16200	1	0	0	0	0	0	1
325	7	2	125	1	0	300	1	0	0	0	0	0	1
326	7	2	47	1	300	600	1	0	0	0	0	0	1

327	7	2	140	1	600	900	1	0	0	0	0	0	1
328	7	2	125	1	900	1200	1	0	0	0	0	0	1
329	7	2	249	1	1200	1500	1	0	0	0	0	0	1
330	7	2	217	1	1500	1800	1	0	0	0	0	0	1
331	7	2	217	1	1800	2100	1	0	0	0	0	0	1
332	7	2	156	1	2100	2400	1	0	0	0	0	0	1
333	7	2	186	1	2400	2700	1	0	0	0	0	0	1
334	7	2	62	1	2700	3000	1	0	0	0	0	0	1
335	7	2	186	1	3000	3300	1	0	0	0	0	0	1
336	7	2	62	1	3300	3600	1	0	0	0	0	0	1
337	7	2	140	1	3600	3900	1	0	0	0	0	0	1
338	7	2	125	1	3900	4200	1	0	0	0	0	0	1
339	7	2	311	1	4200	4500	1	0	0	0	0	0	1
340	7	2	186	1	4500	4800	1	0	0	0	0	0	1
341	7	2	156	1	4800	5100	1	0	0	0	0	0	1
342	7	2	217	1	5100	5400	1	0	0	0	0	0	1
343	7	2	217	1	5400	5700	1	0	0	0	0	0	1
344	7	2	233	1	5700	6000	1	0	0	0	0	0	1
345	7	2	295	1	6000	6300	1	0	0	0	0	0	1
346	7	2	249	1	6300	6600	1	0	0	0	0	0	1
347	7	2	311	1	6600	6900	1	0	0	0	0	0	1
348	7	2	233	1	6900	7200	1	0	0	0	0	0	1
349	7	2	202	1	7200	7500	1	0	0	0	0	0	1
350	7	2	233	1	7500	7800	1	0	0	0	0	0	1

351	7	2	217	1	7800	8100	1	0	0	0	0	0	1
352	7	2	280	1	8100	8400	1	0	0	0	0	0	1
353	7	2	311	1	8400	8700	1	0	0	0	0	0	1
354	7	2	217	1	8700	9000	1	0	0	0	0	0	1
355	7	2	233	1	9000	9300	1	0	0	0	0	0	1
356	7	2	217	1	9300	9600	1	0	0	0	0	0	1
357	7	2	280	1	9600	9900	1	0	0	0	0	0	1
358	7	2	327	1	9900	10200	1	0	0	0	0	0	1
359	7	2	295	1	10200	10500	1	0	0	0	0	0	1
360	7	2	202	1	10500	10800	1	0	0	0	0	0	1
361	7	2	233	1	10800	11100	1	0	0	0	0	0	1
362	7	2	311	1	11100	11400	1	0	0	0	0	0	1
363	7	2	264	1	11400	11700	1	0	0	0	0	0	1
364	7	2	327	1	11700	12000	1	0	0	0	0	0	1
365	7	2	389	1	12000	12300	1	0	0	0	0	0	1
366	7	2	280	1	12300	12600	1	0	0	0	0	0	1
367	7	2	249	1	12600	12900	1	0	0	0	0	0	1
368	7	2	202	1	12900	13200	1	0	0	0	0	0	1
369	7	2	482	1	13200	13500	1	0	0	0	0	0	1
370	7	2	280	1	13500	13800	1	0	0	0	0	0	1
371	7	2	327	1	13800	14100	1	0	0	0	0	0	1
372	7	2	249	1	14100	14400	1	0	0	0	0	0	1
373	7	2	389	1	14400	14700	1	0	0	0	0	0	1
374	7	2	264	1	14700	15000	1	0	0	0	0	0	1

375	7	2	233	1	15000	15300	1	0	0	0	0	0	1
376	7	2	342	1	15300	15600	1	0	0	0	0	0	1
377	7	2	358	1	15600	15900	1	0	0	0	0	0	1
378	7	2	121	1	15900	16200	1	0	0	0	0	0	1
379	8	2	76	1	0	300	1	0	0	0	0	0	1
380	8	2	43	1	300	600	1	0	0	0	0	0	1
381	8	2	184	1	600	900	1	0	0	0	0	0	1
382	8	2	97	1	900	1200	1	0	0	0	0	0	1
383	8	2	119	1	1200	1500	1	0	0	0	0	0	1
384	8	2	97	1	1500	1800	1	0	0	0	0	0	1
385	8	2	108	1	1800	2100	1	0	0	0	0	0	1
386	8	2	119	1	2100	2400	1	0	0	0	0	0	1
387	8	2	76	1	2400	2700	1	0	0	0	0	0	1
388	8	2	108	1	2700	3000	1	0	0	0	0	0	1
389	8	2	54	1	3000	3300	1	0	0	0	0	0	1
390	8	2	119	1	3300	3600	1	0	0	0	0	0	1
391	8	2	76	1	3600	3900	1	0	0	0	0	0	1
392	8	2	108	1	3900	4200	1	0	0	0	0	0	1
393	8	2	108	1	4200	4500	1	0	0	0	0	0	1
394	8	2	54	1	4500	4800	1	0	0	0	0	0	1
395	8	2	108	1	4800	5100	1	0	0	0	0	0	1
396	8	2	119	1	5100	5400	1	0	0	0	0	0	1
397	8	2	130	1	5400	5700	1	0	0	0	0	0	1
398	8	2	162	1	5700	6000	1	0	0	0	0	0	1

399	8	2	162	1	6000	6300	1	0	0	0	0	0	1
400	8	2	86	1	6300	6600	1	0	0	0	0	0	1
401	8	2	194	1	6600	6900	1	0	0	0	0	0	1
402	8	2	76	1	6900	7200	1	0	0	0	0	0	1
403	8	2	216	1	7200	7500	1	0	0	0	0	0	1
404	8	2	119	1	7500	7800	1	0	0	0	0	0	1
405	8	2	270	1	7800	8100	1	0	0	0	0	0	1
406	8	2	140	1	8100	8400	1	0	0	0	0	0	1
407	8	2	173	1	8400	8700	1	0	0	0	0	0	1
408	8	2	151	1	8700	9000	1	0	0	0	0	0	1
409	8	2	205	1	9000	9300	1	0	0	0	0	0	1
410	8	2	140	1	9300	9600	1	0	0	0	0	0	1
411	8	2	108	1	9600	9900	1	0	0	0	0	0	1
412	8	2	184	1	9900	10200	1	0	0	0	0	0	1
413	8	2	162	1	10200	10500	1	0	0	0	0	0	1
414	8	2	65	1	10500	10800	1	0	0	0	0	0	1
415	8	2	65	1	10800	11100	1	0	0	0	0	0	1
416	8	2	119	1	11100	11400	1	0	0	0	0	0	1
417	8	2	162	1	11400	11700	1	0	0	0	0	0	1
418	8	2	97	1	11700	12000	1	0	0	0	0	0	1
419	8	2	130	1	12000	12300	1	0	0	0	0	0	1
420	8	2	162	1	12300	12600	1	0	0	0	0	0	1
421	8	2	216	1	12600	12900	1	0	0	0	0	0	1
422	8	2	140	1	12900	13200	1	0	0	0	0	0	1

423	8	2	238	1	13200	13500	1	0	0	0	0	0	1
424	8	2	151	1	13500	13800	1	0	0	0	0	0	1
425	8	2	162	1	13800	14100	1	0	0	0	0	0	1
426	8	2	173	1	14100	14400	1	0	0	0	0	0	1
427	8	2	227	1	14400	14700	1	0	0	0	0	0	1
428	8	2	184	1	14700	15000	1	0	0	0	0	0	1
429	8	2	335	1	15000	15300	1	0	0	0	0	0	1
430	8	2	270	1	15300	15600	1	0	0	0	0	0	1
431	8	2	173	1	15600	15900	1	0	0	0	0	0	1
432	8	2	184	1	15900	16200	1	0	0	0	0	0	1
433	10	2	47	1	0	300	1	0	0	0	0	0	1
434	10	2	74	1	300	600	1	0	0	0	0	0	1
435	10	2	81	1	600	900	1	0	0	0	0	0	1
436	10	2	71	1	900	1200	1	0	0	0	0	0	1
437	10	2	74	1	1200	1500	1	0	0	0	0	0	1
438	10	2	104	1	1500	1800	1	0	0	0	0	0	1
439	10	2	81	1	1800	2100	1	0	0	0	0	0	1
440	10	2	104	1	2100	2400	1	0	0	0	0	0	1
441	10	2	104	1	2400	2700	1	0	0	0	0	0	1
442	10	2	67	1	2700	3000	1	0	0	0	0	0	1
443	10	2	64	1	3000	3300	1	0	0	0	0	0	1
444	10	2	84	1	3300	3600	1	0	0	0	0	0	1
445	10	2	43	1	3600	3900	1	0	0	0	0	0	1
446	10	2	127	1	3900	4200	1	0	0	0	0	0	1

447	10	2	91	1	4200	4500	1	0	0	0	0	0	1
448	10	2	71	1	4500	4800	1	0	0	0	0	0	1
449	10	2	60	1	4800	5100	1	0	0	0	0	0	1
450	10	2	131	1	5100	5400	1	0	0	0	0	0	1
451	10	2	127	1	5400	5700	1	0	0	0	0	0	1
452	10	2	148	1	5700	6000	1	0	0	0	0	0	1
453	10	2	94	1	6000	6300	1	0	0	0	0	0	1
454	10	2	114	1	6300	6600	1	0	0	0	0	0	1
455	10	2	121	1	6600	6900	1	0	0	0	0	0	1
456	10	2	108	1	6900	7200	1	0	0	0	0	0	1
457	10	2	138	1	7200	7500	1	0	0	0	0	0	1
458	10	2	118	1	7500	7800	1	0	0	0	0	0	1
459	10	2	141	1	7800	8100	1	0	0	0	0	0	1
460	10	2	127	1	8100	8400	1	0	0	0	0	0	1
461	10	2	127	1	8400	8700	1	0	0	0	0	0	1
462	10	2	108	1	8700	9000	1	0	0	0	0	0	1
463	10	2	84	1	9000	9300	1	0	0	0	0	0	1
464	10	2	114	1	9300	9600	1	0	0	0	0	0	1
465	10	2	121	1	9600	9900	1	0	0	0	0	0	1
466	10	2	108	1	9900	10200	1	0	0	0	0	0	1
467	10	2	77	1	10200	10500	1	0	0	0	0	0	1
468	10	2	94	1	10500	10800	1	0	0	0	0	0	1
469	10	2	60	1	10800	11100	1	0	0	0	0	0	1
470	10	2	34	1	11100	11400	1	0	0	0	0	0	1

471	10	2	43	1	11400	11700	1	0	0	0	0	0	1
472	10	2	60	1	11700	12000	1	0	0	0	0	0	1
473	10	2	50	1	12000	12300	1	0	0	0	0	0	1
474	10	2	50	1	12300	12600	1	0	0	0	0	0	1
475	10	2	30	1	12600	12900	1	0	0	0	0	0	1
476	10	2	43	1	12900	13200	1	0	0	0	0	0	1
477	10	2	57	1	13200	13500	1	0	0	0	0	0	1
478	10	2	64	1	13500	13800	1	0	0	0	0	0	1
479	10	2	131	1	13800	14100	1	0	0	0	0	0	1
480	10	2	50	1	14100	14400	1	0	0	0	0	0	1
481	10	2	77	1	14400	14700	1	0	0	0	0	0	1
482	10	2	77	1	14700	15000	1	0	0	0	0	0	1
483	10	2	108	1	15000	15300	1	0	0	0	0	0	1
484	10	2	94	1	15300	15600	1	0	0	0	0	0	1
485	10	2	108	1	15600	15900	1	0	0	0	0	0	1
486	10	2	64	1	15900	16200	1	0	0	0	0	0	1
487	11	2	140	1	0	300	1	0	0	0	0	0	1
488	11	2	140	1	300	600	1	0	0	0	0	0	1
489	11	2	187	1	600	900	1	0	0	0	0	0	1
490	11	2	250	1	900	1200	1	0	0	0	0	0	1
491	11	2	172	1	1200	1500	1	0	0	0	0	0	1
492	11	2	156	1	1500	1800	1	0	0	0	0	0	1
493	11	2	312	1	1800	2100	1	0	0	0	0	0	1
494	11	2	421	1	2100	2400	1	0	0	0	0	0	1

495	11	2	515	1	2400	2700	1	0	0	0	0	0	1
496	11	2	437	1	2700	3000	1	0	0	0	0	0	1
497	11	2	686	1	3000	3300	1	0	0	0	0	0	1
498	11	2	359	1	3300	3600	1	0	0	0	0	0	1
499	11	2	546	1	3600	3900	1	0	0	0	0	0	1
500	11	2	655	1	3900	4200	1	0	0	0	0	0	1
501	11	2	655	1	4200	4500	1	0	0	0	0	0	1
502	11	2	530	1	4500	4800	1	0	0	0	0	0	1
503	11	2	702	1	4800	5100	1	0	0	0	0	0	1
504	11	2	640	1	5100	5400	1	0	0	0	0	0	1
505	11	2	608	1	5400	5700	1	0	0	0	0	0	1
506	11	2	593	1	5700	6000	1	0	0	0	0	0	1
507	11	2	718	1	6000	6300	1	0	0	0	0	0	1
508	11	2	796	1	6300	6600	1	0	0	0	0	0	1
509	11	2	1076	1	6600	6900	1	0	0	0	0	0	1
510	11	2	1201	1	6900	7200	1	0	0	0	0	0	1
511	11	2	1186	1	7200	7500	1	0	0	0	0	0	1
512	11	2	1139	1	7500	7800	1	0	0	0	0	0	1
513	11	2	1248	1	7800	8100	1	0	0	0	0	0	1
514	11	2	1108	1	8100	8400	1	0	0	0	0	0	1
515	11	2	905	1	8400	8700	1	0	0	0	0	0	1
516	11	2	1154	1	8700	9000	1	0	0	0	0	0	1
517	11	2	1139	1	9000	9300	1	0	0	0	0	0	1
518	11	2	1092	1	9300	9600	1	0	0	0	0	0	1

519	11	2	889	1	9600	9900	1	0	0	0	0	0	1
520	11	2	1030	1	9900	10200	1	0	0	0	0	0	1
521	11	2	1014	1	10200	10500	1	0	0	0	0	0	1
522	11	2	998	1	10500	10800	1	0	0	0	0	0	1
523	11	2	718	1	10800	11100	1	0	0	0	0	0	1
524	11	2	889	1	11100	11400	1	0	0	0	0	0	1
525	11	2	858	1	11400	11700	1	0	0	0	0	0	1
526	11	2	686	1	11700	12000	1	0	0	0	0	0	1
527	11	2	406	1	12000	12300	1	0	0	0	0	0	1
528	11	2	733	1	12300	12600	1	0	0	0	0	0	1
529	11	2	499	1	12600	12900	1	0	0	0	0	0	1
530	11	2	593	1	12900	13200	1	0	0	0	0	0	1
531	11	2	437	1	13200	13500	1	0	0	0	0	0	1
532	11	2	359	1	13500	13800	1	0	0	0	0	0	1
533	11	2	281	1	13800	14100	1	0	0	0	0	0	1
534	11	2	234	1	14100	14400	1	0	0	0	0	0	1
535	11	2	390	1	14400	14700	1	0	0	0	0	0	1
536	11	2	312	1	14700	15000	1	0	0	0	0	0	1
537	11	2	281	1	15000	15300	1	0	0	0	0	0	1
538	11	2	562	1	15300	15600	1	0	0	0	0	0	1
539	11	2	187	1	15600	15900	1	0	0	0	0	0	1
540	11	2	328	1	15900	16200	1	0	0	0	0	0	1
541	13	2	180	1	0	300	1	0	0	0	0	0	1
542	13	2	264	1	300	600	1	0	0	0	0	0	1

543	13	2	240	1	600	900	1	0	0	0	0	0	1
544	13	2	156	1	900	1200	1	0	0	0	0	0	1
545	13	2	360	1	1200	1500	1	0	0	0	0	0	1
546	13	2	276	1	1500	1800	1	0	0	0	0	0	1
547	13	2	384	1	1800	2100	1	0	0	0	0	0	1
548	13	2	372	1	2100	2400	1	0	0	0	0	0	1
549	13	2	348	1	2400	2700	1	0	0	0	0	0	1
550	13	2	540	1	2700	3000	1	0	0	0	0	0	1
551	13	2	360	1	3000	3300	1	0	0	0	0	0	1
552	13	2	408	1	3300	3600	1	0	0	0	0	0	1
553	13	2	456	1	3600	3900	1	0	0	0	0	0	1
554	13	2	564	1	3900	4200	1	0	0	0	0	0	1
555	13	2	612	1	4200	4500	1	0	0	0	0	0	1
556	13	2	576	1	4500	4800	1	0	0	0	0	0	1
557	13	2	480	1	4800	5100	1	0	0	0	0	0	1
558	13	2	504	1	5100	5400	1	0	0	0	0	0	1
559	13	2	528	1	5400	5700	1	0	0	0	0	0	1
560	13	2	612	1	5700	6000	1	0	0	0	0	0	1
561	13	2	648	1	6000	6300	1	0	0	0	0	0	1
562	13	2	600	1	6300	6600	1	0	0	0	0	0	1
563	13	2	852	1	6600	6900	1	0	0	0	0	0	1
564	13	2	672	1	6900	7200	1	0	0	0	0	0	1
565	13	2	696	1	7200	7500	1	0	0	0	0	0	1
566	13	2	876	1	7500	7800	1	0	0	0	0	0	1

567	13	2	768	1	7800	8100	1	0	0	0	0	0	1
568	13	2	1128	1	8100	8400	1	0	0	0	0	0	1
569	13	2	756	1	8400	8700	1	0	0	0	0	0	1
570	13	2	924	1	8700	9000	1	0	0	0	0	0	1
571	13	2	900	1	9000	9300	1	0	0	0	0	0	1
572	13	2	840	1	9300	9600	1	0	0	0	0	0	1
573	13	2	756	1	9600	9900	1	0	0	0	0	0	1
574	13	2	588	1	9900	10200	1	0	0	0	0	0	1
575	13	2	924	1	10200	10500	1	0	0	0	0	0	1
576	13	2	744	1	10500	10800	1	0	0	0	0	0	1
577	13	2	588	1	10800	11100	1	0	0	0	0	0	1
578	13	2	600	1	11100	11400	1	0	0	0	0	0	1
579	13	2	708	1	11400	11700	1	0	0	0	0	0	1
580	13	2	648	1	11700	12000	1	0	0	0	0	0	1
581	13	2	648	1	12000	12300	1	0	0	0	0	0	1
582	13	2	720	1	12300	12600	1	0	0	0	0	0	1
583	13	2	600	1	12600	12900	1	0	0	0	0	0	1
584	13	2	588	1	12900	13200	1	0	0	0	0	0	1
585	13	2	432	1	13200	13500	1	0	0	0	0	0	1
586	13	2	672	1	13500	13800	1	0	0	0	0	0	1
587	13	2	624	1	13800	14100	1	0	0	0	0	0	1
588	13	2	408	1	14100	14400	1	0	0	0	0	0	1
589	13	2	324	1	14400	14700	1	0	0	0	0	0	1
590	13	2	324	1	14700	15000	1	0	0	0	0	0	1

591	13	2	264	1	15000	15300	1	0	0	0	0	0	1
592	13	2	480	1	15300	15600	1	0	0	0	0	0	1
593	13	2	288	1	15600	15900	1	0	0	0	0	0	1
594	13	2	312	1	15900	16200	1	0	0	0	0	0	1
595	1	2	3450	1	0	300	1	0	0	0	0	0	1
596	1	2	3689	1	300	600	1	0	0	0	0	0	1
597	1	2	3775	1	600	900	1	0	0	0	0	0	1
598	1	2	4497	1	900	1200	1	0	0	0	0	0	1
599	1	2	4730	1	1200	1500	1	0	0	0	0	0	1
600	1	2	4852	1	1500	1800	1	0	0	0	0	0	1
601	1	2	4818	1	1800	2100	1	0	0	0	0	0	1
602	1	2	5158	1	2100	2400	1	0	0	0	0	0	1
603	1	2	5034	1	2400	2700	1	0	0	0	0	0	1
604	1	2	4218	1	2700	3000	1	0	0	0	0	0	1
605	1	2	4337	1	3000	3300	1	0	0	0	0	0	1
606	1	2	4210	1	3300	3600	1	0	0	0	0	0	1
607	1	2	4485	1	3600	3900	1	0	0	0	0	0	1
608	1	2	3247	1	3900	4200	1	0	0	0	0	0	1
609	1	2	3248	1	4200	4500	1	0	0	0	0	0	1
610	1	2	3089	1	4500	4800	1	0	0	0	0	0	1
611	1	2	3384	1	4800	5100	1	0	0	0	0	0	1
612	1	2	3781	1	5100	5400	1	0	0	0	0	0	1
613	1	2	3771	1	5400	5700	1	0	0	0	0	0	1
614	1	2	3630	1	5700	6000	1	0	0	0	0	0	1

615	1	2	3321	1	6000	6300	1	0	0	0	0	0	1
616	1	2	3519	1	6300	6600	1	0	0	0	0	0	1
617	1	2	3274	1	6600	6900	1	0	0	0	0	0	1
618	1	2	3945	1	6900	7200	1	0	0	0	0	0	1
619	1	2	3674	1	7200	7500	1	0	0	0	0	0	1
620	1	2	3429	1	7500	7800	1	0	0	0	0	0	1
621	1	2	2982	1	7800	8100	1	0	0	0	0	0	1
622	1	2	2582	1	8100	8400	1	0	0	0	0	0	1
623	1	2	3515	1	8400	8700	1	0	0	0	0	0	1
624	1	2	2402	1	8700	9000	1	0	0	0	0	0	1
625	1	2	2273	1	9000	9300	1	0	0	0	0	0	1
626	1	2	2194	1	9300	9600	1	0	0	0	0	0	1
627	1	2	2629	1	9600	9900	1	0	0	0	0	0	1
628	1	2	3083	1	9900	10200	1	0	0	0	0	0	1
629	1	2	2452	1	10200	10500	1	0	0	0	0	0	1
630	1	2	2244	1	10500	10800	1	0	0	0	0	0	1
631	1	2	2465	1	10800	11100	1	0	0	0	0	0	1
632	1	2	2944	1	11100	11400	1	0	0	0	0	0	1
633	1	2	2987	1	11400	11700	1	0	0	0	0	0	1
634	1	2	2174	1	11700	12000	1	0	0	0	0	0	1
635	1	2	3045	1	12000	12300	1	0	0	0	0	0	1
636	1	2	2544	1	12300	12600	1	0	0	0	0	0	1
637	1	2	2641	1	12600	12900	1	0	0	0	0	0	1
638	1	2	3970	1	12900	13200	1	0	0	0	0	0	1

639	1	2	2940	1	13200	13500	1	0	0	0	0	0	1
640	1	2	3196	1	13500	13800	1	0	0	0	0	0	1
641	1	2	3166	1	13800	14100	1	0	0	0	0	0	1
642	1	2	3416	1	14100	14400	1	0	0	0	0	0	1
643	1	2	3579	1	14400	14700	1	0	0	0	0	0	1
644	1	2	3450	1	14700	15000	1	0	0	0	0	0	1
645	1	2	3657	1	15000	15300	1	0	0	0	0	0	1
646	1	2	3296	1	15300	15600	1	0	0	0	0	0	1
647	1	2	3585	1	15600	15900	1	0	0	0	0	0	1
648	1	2	3384	1	15900	16200	1	0	0	0	0	0	1
649	14	2	614	1	0	300	1	0	0	0	0	0	1
650	14	2	743	1	300	600	1	0	0	0	0	0	1
651	14	2	743	1	600	900	1	0	0	0	0	0	1
652	14	2	928	1	900	1200	1	0	0	0	0	0	1
653	14	2	1035	1	1200	1500	1	0	0	0	0	0	1
654	14	2	1024	1	1500	1800	1	0	0	0	0	0	1
655	14	2	1254	1	1800	2100	1	0	0	0	0	0	1
656	14	2	1272	1	2100	2400	1	0	0	0	0	0	1
657	14	2	1150	1	2400	2700	1	0	0	0	0	0	1
658	14	2	1133	1	2700	3000	1	0	0	0	0	0	1
659	14	2	1115	1	3000	3300	1	0	0	0	0	0	1
660	14	2	1112	1	3300	3600	1	0	0	0	0	0	1
661	14	2	953	1	3600	3900	1	0	0	0	0	0	1
662	14	2	967	1	3900	4200	1	0	0	0	0	0	1

663	14	2	1070	1	4200	4500	1	0	0	0	0	0	1
664	14	2	1104	1	4500	4800	1	0	0	0	0	0	1
665	14	2	922	1	4800	5100	1	0	0	0	0	0	1
666	14	2	1067	1	5100	5400	1	0	0	0	0	0	1
667	14	2	1099	1	5400	5700	1	0	0	0	0	0	1
668	14	2	1003	1	5700	6000	1	0	0	0	0	0	1
669	14	2	1556	1	6000	6300	1	0	0	0	0	0	1
670	14	2	1526	1	6300	6600	1	0	0	0	0	0	1
671	14	2	1682	1	6600	6900	1	0	0	0	0	0	1
672	14	2	1734	1	6900	7200	1	0	0	0	0	0	1
673	14	2	1577	1	7200	7500	1	0	0	0	0	0	1
674	14	2	1375	1	7500	7800	1	0	0	0	0	0	1
675	14	2	1560	1	7800	8100	1	0	0	0	0	0	1
676	14	2	1443	1	8100	8400	1	0	0	0	0	0	1
677	14	2	1755	1	8400	8700	1	0	0	0	0	0	1
678	14	2	1526	1	8700	9000	1	0	0	0	0	0	1
679	14	2	1467	1	9000	9300	1	0	0	0	0	0	1
680	14	2	1645	1	9300	9600	1	0	0	0	0	0	1
681	14	2	1039	1	9600	9900	1	0	0	0	0	0	1
682	14	2	1133	1	9900	10200	1	0	0	0	0	0	1
683	14	2	880	1	10200	10500	1	0	0	0	0	0	1
684	14	2	1093	1	10500	10800	1	0	0	0	0	0	1
685	14	2	987	1	10800	11100	1	0	0	0	0	0	1
686	14	2	1112	1	11100	11400	1	0	0	0	0	0	1

687	14	2	1055	1	11400	11700	1	0	0	0	0	0	1
688	14	2	948	1	11700	12000	1	0	0	0	0	0	1
689	14	2	563	1	12000	12300	1	0	0	0	0	0	1
690	14	2	131	1	12300	12600	1	0	0	0	0	0	1
691	14	2	139	1	12600	12900	1	0	0	0	0	0	1
692	14	2	146	1	12900	13200	1	0	0	0	0	0	1
693	14	2	122	1	13200	13500	1	0	0	0	0	0	1
694	14	2	117	1	13500	13800	1	0	0	0	0	0	1
695	14	2	136	1	13800	14100	1	0	0	0	0	0	1
696	14	2	133	1	14100	14400	1	0	0	0	0	0	1
697	14	2	119	1	14400	14700	1	0	0	0	0	0	1
698	14	2	135	1	14700	15000	1	0	0	0	0	0	1
699	14	2	124	1	15000	15300	1	0	0	0	0	0	1
700	14	2	134	1	15300	15600	1	0	0	0	0	0	1
701	14	2	134	1	15600	15900	1	0	0	0	0	0	1
702	14	2	124	1	15900	16200	1	0	0	0	0	0	1

5. Loop Detectors File

QEW loop detector stations

25 0

1	1	2	0.0448	0.005	300	QEWDE0030DES
2	1	4	0.0667	0.005	300	QEWDE0040DES
3	1	6	0.0733	0.005	300	QEWDE0050DES
4	1	8	0.1072	0.005	300	QEWDE0060DES
5	1	10	0.1100	0.005	300	QEWDE0070DES

6	1	12	0.1700	0.005	300	QEWDE0080DES
7	1	14	0.2028	0.005	300	QEWDE0090DES
8	1	16	0.1993	0.005	300	QEWDE0100DES
9	1	17	0.2875	0.005	300	QEWDE0110DES
10	1	18	0.2526	0.005	300	QEWDE0120DES
11	1	20	0.1480	0.005	300	QEWDE0130DES
12	1	22	0.3700	0.005	300	QEWDE0140DES
13	1	22	1.0547	0.005	300	QEWDE0150DES
14	1	25	0.0600	0.005	300	QEWDE0050DER
15	1	29	0.2000	0.005	300	QEWDE0060DER
16	1	33	0.1500	0.005	300	QEWDE0070DER
17	1	37	0.1500	0.005	300	QEWDE0080DER
18	1	41	0.1500	0.005	300	QEWDE0090DER
19	1	46	0.2500	0.005	300	QEWDE0100DER
20	1	49	0.1500	0.005	300	QEWDE0100DER
21	1	53	0.1300	0.005	300	QEWDE0120DER
22	1	30	0.1500	0.005	300	QEWDE0300DSR
23	1	39	0.2000	0.005	300	QEWDE0310DSR
24	1	47	0.1700	0.005	300	QEWDE0320DSR
25	1	56	0.0500	0.005	300	

Appendix G

Snowstorms Data for the Winter Season 2003/2004

1. Snowfall Data

Date	Event Duration (hr)	Precipitation (cm/hr)
11/25/2003	10	2.00
11/28/2003	3	2.40
11/29/2003	2	2.00
11/29/2003	11	2.11
12/1/2003	2	1.40
12/1/2003	6	1.40
12/2/2003	9	2.33
12/2/2003	2	2.60
12/2/2003	3	2.60
12/2/2003	2	2.60
12/12/2003	4	1.60
12/12/2003	2	1.60
12/14/2003	17	8.80
12/17/2003	2	3.00
12/17/2003	2	3.00
12/18/2003	2	1.50
12/19/2003	2	1.00
12/20/2003	6	0.80
12/20/2003	2	0.80
1/2/2004	3	0.20
1/5/2004	16	3.28
1/8/2004	11	1.87
1/11/2004	13	4.40
1/12/2004	13	2.00
1/12/2004	10	4.16
1/13/2004	10	0.20
1/13/2004	2	0.20
1/13/2004	8	1.10
1/15/2004	3	0.60
1/15/2004	22	4.38
1/17/2004	6	2.00
1/18/2004	6	1.00
1/20/2004	5	0.40
1/20/2004	3	0.40
1/21/2004	6	1.80
1/22/2004	11	2.40
1/23/2004	3	1.60
1/23/2004	4	1.60

Date	Event Duration (hr)	Precipitation (cm/hr)
1/24/2004	12	0.27
1/26/2004	5	3.84
1/27/2004	8	14.00
1/27/2004	31	16.32
1/28/2004	6	0.20
1/29/2004	14	0.09
1/30/2004	3	0.80
1/31/2004	4	0.40
2/3/2004	11	6.20
2/6/2004	11	3.20
2/10/2004	9	0.40
2/20/2004	6	0.60
2/21/2004	13	1.40
2/24/2004	13	4.62
3/7/2004	11	3.40
3/8/2004	15	1.00
3/12/2004	2	0.20
3/12/2004	2	0.40
3/12/2004	4	0.40
3/12/2004	2	0.40
3/13/2004	8	0.65
3/13/2004	4	0.80
3/17/2004	8	1.20
3/17/2004	20	3.84

2. Estimate of Statistical Distribution for Event Duration

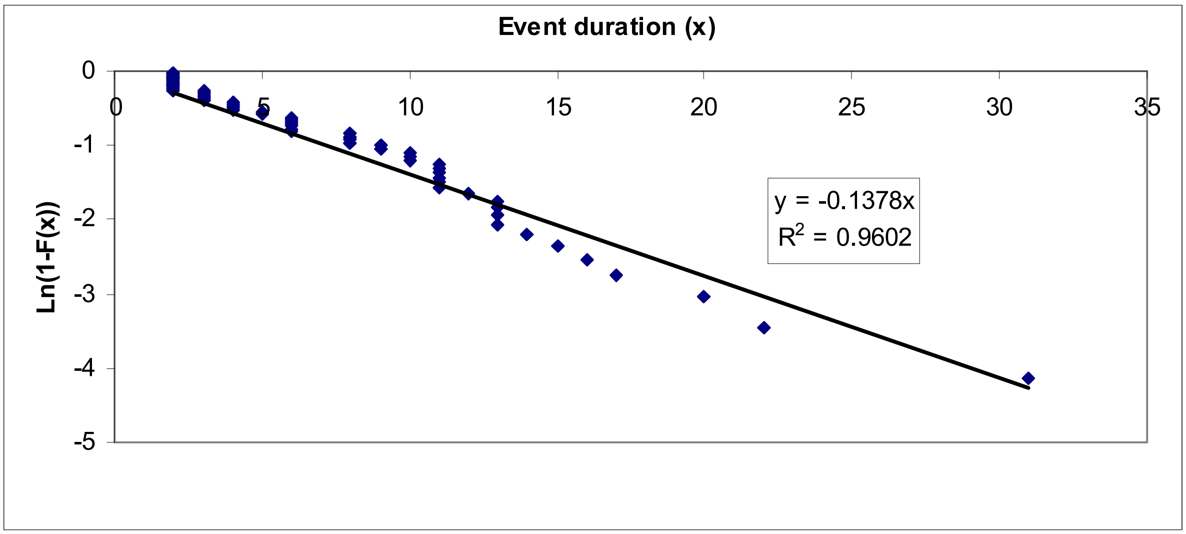
The Exponential Probability Paper Plot (PPP) calculation for event duration

Rank	Event Duration (X)	Cumulative Probability	Y = Ln(1 - F(x))
1	2	0.016	-0.016
2	2	0.032	-0.032
3	2	0.048	-0.049
4	2	0.063	-0.066
5	2	0.079	-0.083
6	2	0.095	-0.100
7	2	0.111	-0.118
8	2	0.127	-0.136
9	2	0.143	-0.154
10	2	0.159	-0.173
11	2	0.175	-0.192
12	2	0.190	-0.211
13	2	0.206	-0.231

Rank	Event Duration (X)	Cumulative Probability	Y = Ln(1 - F(x))
14	2	0.222	-0.251
15	3	0.238	-0.272
16	3	0.254	-0.293
17	3	0.270	-0.314
18	3	0.286	-0.336
19	3	0.302	-0.359
20	3	0.317	-0.382
21	3	0.333	-0.405
22	4	0.349	-0.430
23	4	0.365	-0.454
24	4	0.381	-0.480
25	4	0.397	-0.506
26	4	0.413	-0.532
27	5	0.429	-0.560
28	5	0.444	-0.588
29	6	0.460	-0.617
30	6	0.476	-0.647
31	6	0.492	-0.677
32	6	0.508	-0.709
33	6	0.524	-0.742
34	6	0.540	-0.776
35	6	0.556	-0.811
36	8	0.571	-0.847
37	8	0.587	-0.885
38	8	0.603	-0.924
39	8	0.619	-0.965
40	9	0.635	-1.008
41	9	0.651	-1.052
42	10	0.667	-1.099
43	10	0.683	-1.147
44	10	0.698	-1.199
45	11	0.714	-1.253
46	11	0.730	-1.310
47	11	0.746	-1.371
48	11	0.762	-1.435
49	11	0.778	-1.504
50	11	0.794	-1.578
51	12	0.810	-1.658
52	13	0.825	-1.745
53	13	0.841	-1.841
54	13	0.857	-1.946
55	13	0.873	-2.064
56	14	0.889	-2.197
57	15	0.905	-2.351

Rank	Event Duration (X)	Cumulative Probability	Y = Ln(1 - F(x))
58	16	0.921	-2.534
59	17	0.937	-2.757
60	20	0.952	-3.045
61	22	0.968	-3.450
62	31	0.984	-4.143

3. Exponential Probability Paper Plot for Event Duration



4. Boundaries for Snowfall Intensities

The snowfall intensity is based on the NNOA's National Weather Service Forecast office in Binghamton, NY (http://www.erh.noaa.gov/bgm/hwo/sio.php) as following:

Snowfall intensity	Snowfall (cm per hour)
Low	< 1.27
Medium	1.27 to 3.81
High	> 3.81

5. Macro to Generate Snowstorms

```
Private Sub CommandButton1_Click()
Randomize
Dim StartT(100) As Integer
Dim EndT(100) As Integer
Dim D(100) As Integer
Dim Duration(100) As Integer
Dim Benefit(10000) As Integer
Dim RTime(100) As Integer
Niteration = Sheet1.Cells(7, 9)
For k = 1 To Niteration
Randomize
BenefitL = 0
BenefitM = 0
BenefitH = 0
RBenefitL = 0
RBenefitM = 0
RBenefitH = 0
'Calculate Mobility Benefit Associated with Snow-Storm with Low Intensity
N1 = Sheet1.Cells(3, 8)
For i = 1 To N1
StartT(i) = Int(Rnd * 24) + 1
D(i) = Round((Application.WorksheetFunction.Ln(Rnd) / (-1 / (Sheet1.Cells(5, 5)))), 0)
    If D(i) >= 1 Then
```

```
    Duration(i) = D(i)
    Else
    Duration(i) = 1
    End If
EndT(i) = StartT(i) + Duration(i)
   For j = StartT(i) To EndT(i)
     Benefit(j) = Sheet1.Cells(9 + j, 3)
     BenefitL = BenefitL + Benefit(j)
   Next j
'Bare Pavement Recovery Time
R = Sheet1.Cells(24, 9)
RTime(i) = EndT(i) + R
For L = (EndT(i) + 1) To RTime(i)
     Benefit(L) = Sheet1.Cells(9 + j, 6)
     RBenefitL = RBenefitL + Benefit(L)
   Next L
Next i
'Calculate Mobility Benefit Associated with Snow-Storm with Medium Intensity
N2 = Sheet1.Cells(3, 9)
For i = 1 To N2
StartT(i) = Int(Rnd * 24) + 1
D(i) = Round((Application.WorksheetFunction.Ln(Rnd) / (-1 / (Sheet1.Cells(5, 5)))), 0)
    If D(i) >= 1 Then
    Duration(i) = D(i)
```

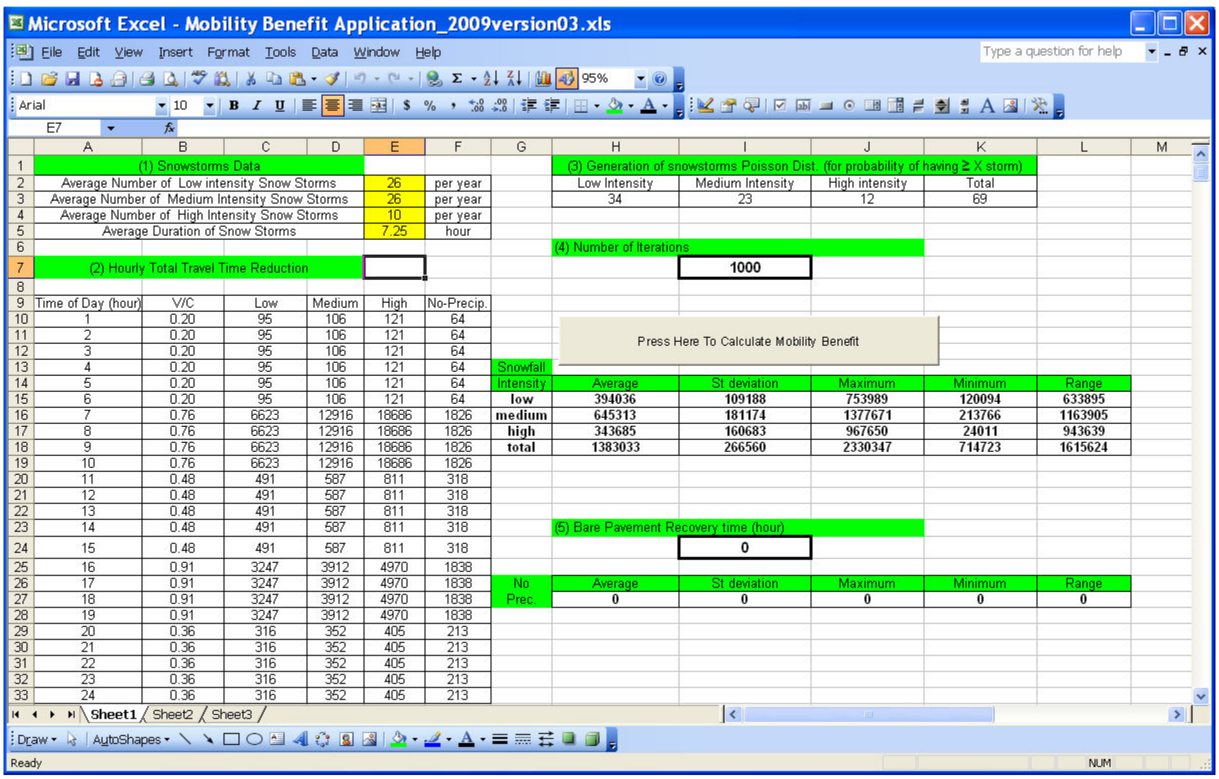
```
    Else
    Duration(i) = 1
    End If
EndT(i) = StartT(i) + Duration(i)
   For j = StartT(i) To EndT(i)
     Benefit(j) = Sheet1.Cells(9 + j, 4)
     BenefitM = BenefitM + Benefit(j)
   Next j
'Bare Pavement Recovery Time
R = Sheet1.Cells(24, 9)
RTime(i) = EndT(i) + R
For L = (EndT(i) + 1) To RTime(i)
     Benefit(L) = Sheet1.Cells(9 + j, 6)
     RBenefitM = RBenefitM + Benefit(L)
   Next L
Next i
'Calculate Mobility Benefit Associated with Snow-Storm with High Intensity
N3 = Sheet1.Cells(3, 10)
For i = 1 To N3
StartT(i) = Int(Rnd * 24) + 1
D(i) = Round((Application.WorksheetFunction.Ln(Rnd) / (-1 / (Sheet1.Cells(5, 5)))), 0)
    If D(i) >= 1 Then
    Duration(i) = D(i)
    Else
```

```
 Duration(i) = 1
 End If
EndT(i) = StartT(i) + Duration(i)
   For j = StartT(i) To EndT(i)
     Benefit(j) = Sheet1.Cells(9 + j, 5)
     BenefitH = BenefitH + Benefit(j)
   Next j
'Bare Pavement Recovery Time
R = Sheet1.Cells(24, 9)
RTime(i) = EndT(i) + R
For L = (EndT(i) + 1) To RTime(i)
     Benefit(L) = Sheet1.Cells(9 + j, 6)
     RBenefitH = RBenefitH + Benefit(L)
   Next L
   Next i
Sheet1.Cells(2 + k, 14) = k
Sheet1.Cells(2 + k, 15) = N1
Sheet1.Cells(2 + k, 16) = N2
Sheet1.Cells(2 + k, 17) = N3
Sheet1.Cells(2 + k, 18) = BenefitL
Sheet1.Cells(2 + k, 19) = BenefitM
Sheet1.Cells(2 + k, 20) = BenefitH
Sheet1.Cells(2 + k, 21) = BenefitL + BenefitM + BenefitH
Sheet1.Cells(2 + k, 22) = RBenefitL + RBenefitM + RBenefitH
```

Next k

End Sub

6. Mobility Benefit Calculation Sheet



Microsoft Excel - Mobility Benefit Application_2009version03.xls

(1) Snowstorms Data		
Average Number of Low intensity Snow Storms	26	per year
Average Number of Medium Intensity Snow Storms	26	per year
Average Number of High Intensity Snow Storms	10	per year
Average Duration of Snow Storms	7.25	hour

(2) Hourly Total Travel Time Reduction

Time of Day (hour)	V/C	Low	Medium	High	No-Precip.
1	0.20	95	106	121	64
2	0.20	95	106	121	64
3	0.20	95	106	121	64
4	0.20	95	106	121	64
5	0.20	95	106	121	64
6	0.20	95	106	121	64
7	0.76	6623	12916	18686	1826
8	0.76	6623	12916	18686	1826
9	0.76	6623	12916	18686	1826
10	0.76	6623	12916	18686	1826
11	0.48	491	587	811	318
12	0.48	491	587	811	318
13	0.48	491	587	811	318
14	0.48	491	587	811	318
15	0.48	491	587	811	318
16	0.91	3247	3912	4970	1838
17	0.91	3247	3912	4970	1838
18	0.91	3247	3912	4970	1838
19	0.91	3247	3912	4970	1838
20	0.36	316	352	405	213
21	0.36	316	352	405	213
22	0.36	316	352	405	213
23	0.36	316	352	405	213
24	0.36	316	352	405	213

(3) Generation of snowstorms Poisson Dist. (for probability of having ≥ X storm)

Low Intensity	Medium Intensity	High intensity	Total
34	23	12	69

(4) Number of Iterations

1000

Press Here To Calculate Mobility Benefit

Snowfall Intensity	Average	St deviation	Maximum	Minimum	Range
low	394036	109188	753989	120094	633895
medium	645313	181174	1377671	213766	1163905
high	343685	160683	967650	24011	943639
total	1383033	266560	2330347	714723	1615624

(5) Bare Pavement Recovery time (hour)

0

No Prec.	Average	St deviation	Maximum	Minimum	Range
	0	0	0	0	0