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# Analysis of the relationship between adverse road-weather conditions and free-flow speed on highways

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## Abstract

This study attempts to investigate the driver behavior under adverse road-weather conditions and the impacts of the application of different data treatment methods. The study site is located in Highway 16 in Edmonton, Alberta. The road-weather and traffic data collection devices are located alongside, permitting vehicles with accurate tagging of the exact pertaining weather conditions. The study has two main objectives: To investigate the impacts of weather events on the free-flow speed of vehicles and to explore the variability caused by adopting different data analysis methods. Separate linear and nonlinear regression models were developed under three statistical approaches with separate statistical models developed for light and heavy vehicles travelling under shoulder and median lanes, resulting 24 models in total. The study results reveal that slight, moderate and heavy snow will respectively reduce the free-flow speed of light vehicles travelling in shoulder lane by 0.2%, 3.4% and 0.8% and by 0.3%, 0.4% and 1.5% when travelling in the median lane. Moreover, heavy vehicles travelling in slight, moderate and heavy snow are estimated to reduce their free-flow speeds by 1.7%, 0.1% and 1.3% in shoulder lane and by 1.1% and 1% in median lane. The free-flow speed reduction for heavy vehicles under heavy snow in median lane is excluded due to absence of data. Further, it was unveiled that the driver reactions for pavement surface conditions of “Ice warning” is maximum. The linear functional form with an aggregated dependent variable over time indicated the best performance measures among all the models developed.

*Keywords:* Free-flow speed;Adverse road-weather conditions;Pavement condition;Data treatment methods

## 1. Introduction

Every year a significant proportion of road accidents are attributed to inclement road-weather conditions, particularly in countries and regions with extreme weather conditions. For example, in Canada, 29% of traffic

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collisions in 2014 were occurred under adverse road-weather conditions. Moreover, 37% of road accidents on Canadian highways in 2014 occurred in the presence of unsafe pavement conditions resulted mainly from adverse weather conditions (Transport Canada, 2014). In a provincial context, the SGI (Saskatchewan Government Insurance) reported that 3% of the collisions occurred in the province of Saskatchewan in 2016 were due to snowy conditions, while another 2% took place under rainy conditions. Surprisingly, 22% of the province's traffic collisions occurred in the presence of snow and icy pavement conditions (Saskatchewan Government Insurance, 2016). According to road accident statistics issued by the Canadian government, 532 people were killed by traffic accidents occurred under rain, frozen precipitation, snow, visibility limitations or strong winds in 2014 (Transport Canada, 2014). Over and above, speed has always been a primary concern in traffic safety. For instance, over speeding is a renowned primary cause of traffic accidents, and is directly related to road safety. However, astounding technological advancements coupled with improved standards of living have remarkably reversed collision statistics in the recent years. Yet, the numbers stand considerable and need further rectifications. As a prospective attempt of reformation, the researchers have adopted the pertaining road-weather conditions at the time of traveling, as the missing dimension in improving road safety. According to the past literature, prevailing road-weather conditions are capable of varying the travel patterns (Ibrahim & Hall, 1994; Zang et al., 2004). However, acute impacts are apprehended under road-weather events. Weather events are defined as degraded climatic conditions compared to the "ideal" weather conditions. The ideal weather is represented by a weather condition with no precipitation, dry roadways, visibilities greater than 0.4 km and winds less than 16 km/h (Zang et al., 2004). Over the past few decades, transportation researchers manifested an expansion of the rudimentary area of interest of road safety related studies, by incorporating the impacts of adverse road-weather conditions as a salient concern in highway transportation. In this study, the authors intend to provide a deeper insight into the trade-offs between inclement road-weather conditions and the drivers' desired speed, which is manifested as free-flow speed of the vehicles.

Free- flow speed is an extensively used attribute in highway engineering (Kyte et al., 2000). Accordingly, free-flow speed is studied in many perspectives. Free-flow speed is influenced by the posted speed limit of the freeway, road-weather conditions, and driver's mood and characteristics. Even though all these factors govern the free- flow speed of a particular vehicle, the linkage between the road-weather conditions and the free-flow speed is the most analytical cause, which can be studied in a numerical approach.

Road-weather related speed studies established a novel strategy in transportation research. So far, there are many credible studies conducted on the impacts of road-weather events on the free-flow speed of vehicles (Kyte et al., 2000; Ibrahim & Hall, 1994; Oh et al., 2002; Billot et al., 2009; Edwards, 1999). However, it is still an emerging concept, which needs continuous evolving through quality research, appraising different aspects of the concept. In addition, as describes in the Literature Review section, some of the past literature on the topic reveal contradictory results recommending further research on the matter. Moreover, despite the considerable amount of past studies, most of the past studies left some areas untouched. For example, the impact of precipitation situation is highly studied (Ibrahim & Hall, 1994; Billot et al., 2009; Edwards, 1999), yet the impact of pavement condition is loosely investigated (Kyte et al; 2000). Majority of the past studies employed traffic and road-weather data collected considerably distant from each other, leaving a credibility gap in the results. Moreover, each study exercised different data analysis methods resulting in variability in the results caused solely by the way of treating the data. This study aims to fill the aforementioned research gaps by setting forth the following main objectives;

i. To investigate the impacts of road-weather events on free-flow speed of vehicles
ii. To explore the variability caused through adopting different data analysis methods

The study presents several empirical models developed to estimate the free-flow speeds under different road-weather conditions. The models provide a better understanding regarding the desired speed a typical diver would adopt, under the prevailing road-weather conditions. This, in turn can be used by transportation authorities to impose new speed rules on roads under adverse road-weather conditions. Although the design manuals such as Highway Capacity Manual, HCM (2016) provides some guidance on the impact of inclement road-weather conditions on traffic operations, applications of such models in different geographic regions with divergent demographics is subject to further research and investigations. This study aims to strengthen the literature by contributing the particulars about extremely cold regions. Withal, the study presents the differences captured while utilizing different statistical methods for treating the data, which will be of utmost importance to the researchers in the similar fields. Furthermore, while the majority of the existing literature focus on rainy or moderately cold road-weather conditions, this study encompasses the extremely cold road-weather conditions.

## 2. Literature Review

Existing literature on the impacts of adverse road-weather conditions on traffic operations can be divided into two main categories, namely: volume studies and speed studies. Volume studies probe the effects of weather events on the traffic volume of the roads while the speed studies investigate the adjustments in driving patterns, in terms of the traffic speeds. This study falls under the second category and this review presents an extensive appraisal on the speed studies.

Ibrahim & Hall (1994) developed regression models to simulate the traffic operations under adverse road-weather conditions for a freeway in Mississauga, Ontario. They claimed that adverse road-weather conditions cause a downward shift of the speed flow fundamental diagram. A new approach was introduced in their study through the adaptation of several tactics for cleaning the data. The purpose was to remove the intervention of the impertinent data samples. The authors employed a specific data collection time period and selected specific dates to represent the road-weather conditions best. Moreover, only median lane data during 10 a.m. to 4 p.m. in each selected representative day were used in the study. The representative dates are the specific dates with adverse road-weather conditions all over the considered six continuous hours. This strategy helped reducing the noise in the data population which was used to develop the linear regression models in the study. The results acknowledged the reductions of speed under adverse road-weather conditions. However, it was noted that the driver and highway characteristics, such as the familiarity of the driver under driving in different road-weather conditions and drainage conditions of the highway, might also contribute towards the diminution of speed.

Conversely, Edwards (1999) questions the authenticity of the theoretical conception proposing the speed reductions under adverse road-weather. The analysis declared contradictory, yet interesting results. The spot speeds of the vehicles travelling in an uncongested situation were collected and were then subjected to a thorough statistical analysis, mainly focusing on the descriptive statistics. The resultant speed reductions under rainy and misty conditions in British motorways, were small compared to other similar researches conducted. Thus, the author emphasized the antithetical behavior of the drivers where they accept the notion of reducing the speeds in road-weather events, but perform contradictory. In a further explanation, Edwards states that although the drivers understand the requirement of reducing the speed under inclement road-weather, they tend to ignore the gravity of the consequences of speeding under the road-weather events.

Kyte et al. (2000) examined the fluctuations of free-flow speeds under different road-weather conditions for vehicles running in a roadway segment in Idaho. The collected data belonged to two winter seasons in consecutive years. The authors investigated the effects of wind speed, precipitation intensity, visibility and the pavement condition. However, visibility was excluded as an independent variable due to the statistical insignificance. The authors developed linear regression models incorporating dummy variables for categorical variables. Moreover, it should be noted that the data used in the study were in the form of five-minute aggregate observations. The empirical models developed by the authors suggest that higher precipitation intensities, higher wind speeds and the snowy or icy pavement conditions reduce the free-flow speeds of the vehicles. Peculiarly, the authors highlighted the importance of using wind speed to explain the variability in speed reductions under adverse road-weather conditions. Withal, the results deferred significantly from the estimations of HCM 2000 being 50% higher in terms of the effects under light rain or snow and heavy rain and 20% lower in terms of the effects under heavy snow.

In a similar attempt, Oh et al. (2002) confirmed the general hypothesis proclaiming the reduction of free-flow speed under adverse road-weather conditions. Unlike the other studies, Oh et al. (2002) incorporated a different aspect to explain the phenomenon. The authors separated day and night and developed separate regression models for selected data collection locations in Incheon, South Korea. As a result, they captured that a rainy condition in daytime can reduce the free-flow speeds by 7%, while the snowy days are capable of reducing only 5% of the free-flow speed. Correspondingly, the rainy and snowy nights reported speed reductions of 5% and 6% respectively. The aforesaid are based on one of the two sites they have studied. In contrast, the other site they've considered did not exhibit any astonishing difference of speed drops in day and night times.

A study by Hong & Oguchi (2007) proposed a new aspect to be considered. In their study on Japanese expressways, the heavy vehicles ratio was considered as a substantial influence on the speed regulation of the vehicles. The solitary-vehicle speeds (SVS) reduced in a large extent in the presence of higher heavy vehicles ratios, regardless the environmental condition. The same dataset exposed SVS reductions for each millimeter of rainfall. However, the data were subjected to data elimination methods to extract an analyzable data sample from the colossal data population. For instance, the vehicles recorded under unsuitable traffic conditions such as vehicles travelling under the minimum uncongested speed were removed by employing a stochastic method suggested by previous literature. Moreover, the effects of any malfunctioning of the data collection devices were filtered by careful inspection of any significant deviations of the travelling speeds compared to the six month average speeds in the respective road-weather and traffic conditions. Additionally, the authors defined and employed 5-minute aggregate vehicular speed, which is not affected by any other vehicles. The specific speed was introduced to reduce the number of data points and it was referred as Solitary-Vehicle Speed (SVS). Yet, the authors underline the existence of unfitting data, leading to probable imprecisions in the results.

The macroscopic analysis conducted by Billot et al. (2009) reports a decrease in the free-flow speed of vehicles in a range spanning from 8% to 12.6%. Even though the study encompassed considerably intense rainy conditions, the authors recommended further research including heavy rain conditions, as well as other precipitation types.

On the account of the guidance from design manuals, the Highway Capacity Manual (2016) specifies basic designs for the roadway conditions under good environmental and incident free conditions. In Chapter 10, HCM (2016) encourages free-flow speed reductions of 6 mi/h (10 km/h) and 12 mi/h (19 km/h) under light rain or snow and heavy rain, respectively. Further, a reduction of 31 mi/h (50 km/h) is suggested under heavy snow. However, the speed reductions are compared to an assumed base free-flow speed of 75 mi/h (120 km/h) and under clear and dry road-weather conditions. On top of that, HCM (2016) values are based on the research papers by Ibrahim & Hall (1994), and Brilon & Ponzlet (1996). Thus, the values can be significantly different, if used in a completely different context.

In conclusion, a number of researchers have recognized that adverse road-weather conditions are capable of retarding the vehicular speeds (Ibrahim & Hall, 1994; Kyle et al., 2000; Oh et al., 2002; Hong & Oguchi, 2007; Billot et al., 2009). Yet, there are contradictory results implying the existence of covert dimensions to be ascertained through further research. Besides, most of the studies have relied on less representative road-weather data for the vehicles due to considerable distance between traffic and road-weather data collection points. Thus, the results might have been misleading, causing variations in numerical terms. On the other hand, many authors concluded their results in terms of a range of speed reduction. This results from the dearth of explanatory variables used to describe the variations. However, continual research have diachronically appended different facets to the dilemma. For instance, recent studies underlined the importance of employing time of the day, heavy vehicles ratio (Oh et al., 2002) and wind speed (Kyte et al., 2000) in predictive models. Further, some researchers (Ibrahim & Hall, 1994; Hong & Oguchi, 2007) have demonstrated the possible effects of data cleansing methods.

The previous studies lay a profound foundation to the research question. Despite the numerical estimates, most of the researches consent upon the collective agreement: the vehicular speeds decrease in the presence of adverse road-weather. The subsequent quandaries following this agreement are, “How much is the reduction for different geographic regions” and “What variables cause the difference”. Moreover, as many of the past studies noted, more research is required to resolve the research query. To fill this research gap, the authors present a new analysis and approach to estimate the free-flow speed reductions under adverse road-weather conditions. In addition, an analysis of the results on adopting different data treatment methods is presented.

## 3. Study Data

### *3.1. Data collection*

The data used in this study can be divided into two categories: road-weather data and traffic data. Road-weather and traffic records collected on a highway 16 location west of the city of Edmonton, Alberta are studied in this research. Highway 16 is a four lane segment of the “Yellowhead Highway” and connects Jasper and Lloydminster through Edmonton. The data collection sites were selected after a rigorous study, focusing on the distance between the Road-Weather-Information-System (RWIS) station and the Weigh-in-Motion (WIM) station. Unlike in the studies conducted so far, the road-weather station and the WIM station are located alongside. According to Datla & Sharma (2008), the road-weather data obtained by a RWIS can be approximated as correct within a radius up to 25km. Thus, the road-weather conditions recorded, precisely represent the existing road-weather at the time when each vehicle is recorded by WIM station. The study data include road-weather and traffic records for 15 months spanning from October, 2014 to December, 2015.

### *3.1.1. Road-weather data*

Road-weather data were obtained from the Road-Weather Information System (RWIS) station installed on highway 16 running through Alberta. Highway 16 constitutes a principal portion of the "Yellowhead highway" which is a major inter provincial highway in Canada. The RWIS station used in this study is neighboring Edson and is located in decimal lat-long coordinates of 53.57821, -116.04753. With the aid of the sensors and the cameras, the RWIS stations automatically record the field meteorological conditions which in turn is used primarily for winter road maintenance operations. Most importantly, the RWIS station lies next to the WIM station and hence records the real-time road weather information related to each vehicle recorded by the WIM station. The RWIS station recorded the pertaining road-weather conditions each 20 minutes throughout the 15 month study period. A description for each road-weather attribute used in the study is presented in Table 1. In addition to the traits presented, the RWIS stations recorded the atmospheric pressure, wind maximum speed, subsurface deep temperature and subsurface shallow temperature.

Table 1. Road-weather attribute details

| Road-weather Attribute | Description | |
|---|---|---|
| Air Temperature | Wet bulb temperature falling between minus and plus 40 | |
| Pavement Surface-Status | Dry | No moisture or unusual condition detected |
| | Trace Moisture | Detection of isolated moisture on pavement surface |
| | Wet | Wet roadway with significant moisture detection |
| | Ice Warning | The sensor detects ice or black ice |
| | Ice Watch | The risk of the formation of ice or black ice on the roadway is elevated, but its occurrence, location, and/or timing is still uncertain |
| | Frost | The sensor detects the formation of frost |
| Pavement Temperature | The pavement temperature value at the depth of the sensor | |
| Wind Average-Direction | A two minute average of the direction from which the wind is blowing measured clockwise in degrees from true North | |
| Wind Average-Speed | A two minute average of the wind speed in tenths of meters per second as measured by the primary wind sensor | |
| Precipitation Situation | No precipitation (NP) | 0 mm/h of any kind of precipitation |
| | Slight rain (SR) | <2 mm/h |
| | Moderate rain (MR) | ≥2 and <8 mm/h |
| | Heavy rain (HR) | ≥8 mm/h |
| | Slight frozen precipitation (SFP) | <2 mm/h water equivalent |
| | Moderate frozen precipitation (MFP) | ≥2 and <8 mm/h water equivalent |
| | Heavy frozen precipitation (HFP) | ≥8 mm/h water equivalent |
| | Slight snow (SS) | <2 mm/h water equivalent |
| | Moderate snow (MS) | ≥2 and <8 mm/h water equivalent |
| | Heavy snow (HS) | ≥8 mm/h water equivalent |

### *3.1.2. Traffic data*

Traffic data used in the study were obtained from the Weigh-In-Motion (WIM) permanent traffic counter located in highway 16. The WIM device is located in 53.57854, -116.04534 in a decimal lat-long system and is located alongside with the RWIS station. Thus, the road-weather information assigned to each vehicle were highly representative of the actual conditions. The embedded loop and a piezo sensor of the WIM station count the vehicles and capture vehicles' characteristics as they pass the loop. Collected data includes site details, date and time, travel speed, weight of each axle and distance between the axels for each vehicle recorded.

## *3.2. Preliminary data analysis*

Road-weather and traffic data were subjected to a data elimination process prior to conducting any analysis. As the first step, all the outliers for each road-weather attribute collected through the RWIS station were removed. Further, the vehicle records bearing travelling speeds below 60 km/h or above 180 km/h were rejected to avoid any estimations far beyond the posted speed limit of 110 km/h. Thus, the models were facilitated to replicate the driving behavior of a reasonable driver travelling on the highway.

The present study develops separate models for the two main vehicle categories pondered in transportation engineering, i.e. light and heavy vehicles. Each vehicle record is clearly examined and assigned the appropriate vehicle classification. This study adopts the aggregated vehicle classification system by Roh (2015). The group of light vehicles include the vehicle groups of passenger cars (FHWA classification- Bin 1, 2, 3) and the single unit trucks (FHWA classification- Bin 4, 5, 6, 7). The single (FHWA classification- Bin 8, 9, 10) and multi-trailer trucks (FHWA classification- Bin 11, 12, 13) were compounded to one group namely heavy vehicles. Afterwards, a data analysis was conducted for the combined road-weather and traffic data. The variation of free-flow speed was first analyzed by producing box and whisker plots for various road-weather conditions. The box plots depicting the variation of free-flow speed with the atmospheric precipitation situation and with the pavement surface condition are presented in Fig. 1. The outliers were removed and the median free-flow speed pertaining to no precipitation condition is marked by a horizontal line to allow an easy comparison.

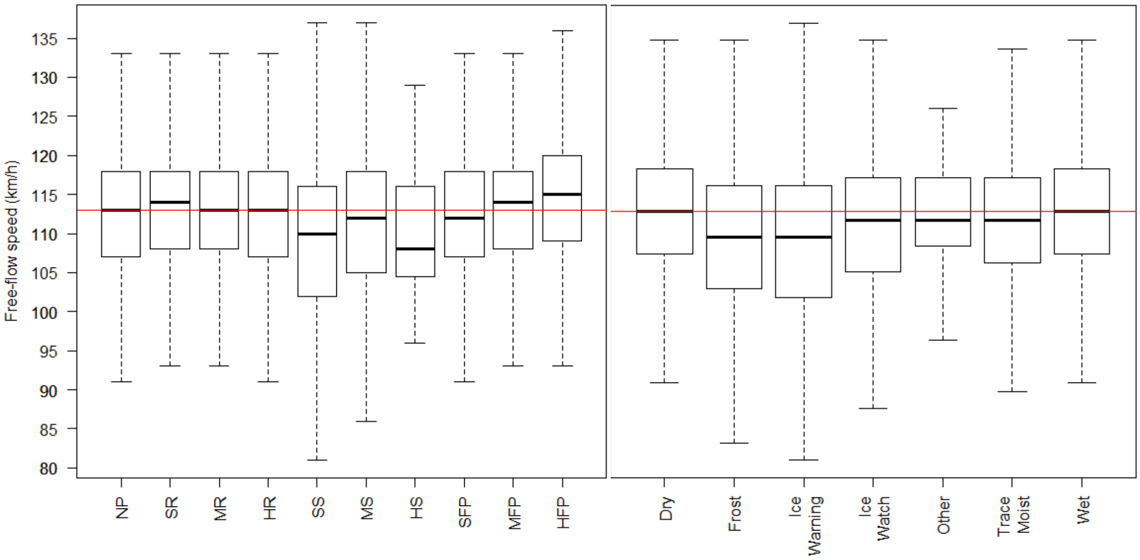

Fig. 1. (a) free-flow speed variation with precipitation situation (left); (b) free-flow speed variation with pavement surface condition (right).

According to Fig. 1 (a), the distribution of free-flow speed in the presence of rain and frozen precipitation as a whole, exhibit higher upper and lower quartiles as well as higher median values compared to the event of no precipitation. Notably, the lowest free-flow speeds recorded in rain are equal or greater than that when there's no precipitation. This implies a free-flow speed increase, instead of a decrease in the presence of a rain. Moderate and heavy frozen precipitation follows the same behavior as rain with almost equal lower values of free-flow speed.

In contrast, the median free-flow speeds recorded under snowy conditions suggest that the drivers slow down their vehicles when the precipitation turns to snow. Moreover, Fig. 1 (b) indicates similar driver behaviors under different pavement surface conditions. As the graphical interpretation implies, the drivers tend to reduce their desired speed under adverse pavement surface conditions. The drivers respond most, when the pavement surface signals ice warning while the wet surface condition receives the lowest reaction from the drivers, with the reaction indicated by reduction in free-flow speed.

The preliminary investigations proposed an opposing, yet intriguing appraisal for the driver behavior under raining and frozen precipitation conditions. Unlike in the past researches, the analysis revealed higher free-flow speeds under raining and frozen precipitation, compared to no precipitation. However, the literature suggests that the number of heavy vehicles might regulate the vehicle speeds under any condition (Brilon and Ponzlet, 1996; Roh, 2015). Therefore, the rolling average hourly free-flow speeds were calculated for each vehicle travelling and were plotted against the respective hourly heavy vehicle percentages (Fig. 2).

According to Fig.2, the average free-flow speed of all vehicle types decrease as the percentage of heavy vehicles increase on the road. Moreover, it was revealed that the presence of heavy vehicles reduce the travelling speed of the vehicles, regardless of the road-weather condition.

On the other hand, the percentage of heavy vehicles recorded under different road-weather conditions (Fig. 3), help resolving the conflicting revelation regarding the vehicle speeds in the presence of any intensity of rain or frozen precipitation. As Fig.3 depicts, compared to no precipitation conditions, lower percentages of heavy vehicles were recorded under rainy and frozen precipitation situations while the percentage of heavy vehicles recorded in snowy conditions is higher. As revealed before, the drivers are inclined to drive slower when the proportion of heavy vehicles

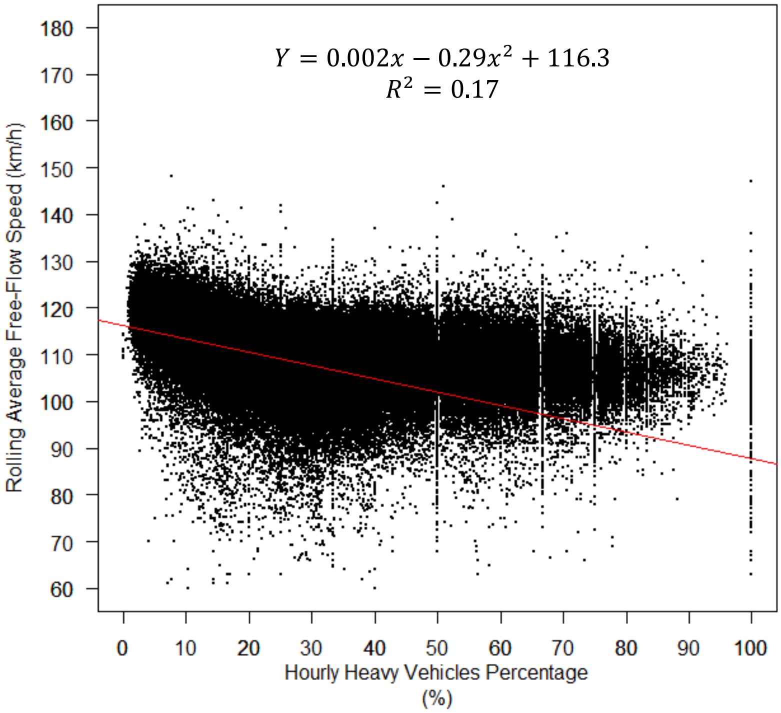

Fig. 2. Rolling average speed Vs. Hourly heavy vehicles percentage.

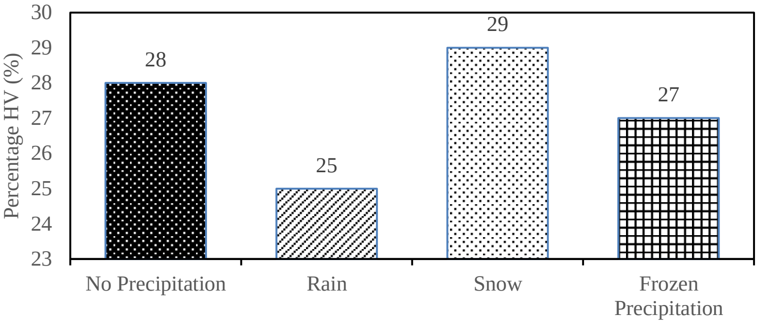

Fig. 3. Presence of Heavy Vehicles as a Percentage of Flow in Edson, Highway 16

is increasing in traffic stream. On the contrary, vehicle speeds tend to increase when the percentage of heavy vehicles is lower regardless of road-weather condition existing in the surrounding environment. Thus, rain and frozen precipitation data were excluded from the study.

### 3.2.1. Correlation analysis

According to literature, widely used independent variables in similar studies are precipitation intensity, temperature, wind speed, time of day (day or night) and visibility. However, the RWIS station used in this study is not programmed to record visibility as a road-weather parameter, limiting the analysis to a certain extent. In addition, the heavy vehicles percentage, the lane type (shoulder or median) and the headed direction (Eastbound or Westbound) were also included as independent variables and were tested for correlation. The correlation matrix for the continuous independent variables and the prospective dependent variable (free-flow speed) of the initial statistical model, is shown in Table 2. The correlation coefficients were determined based on the Pearson's method for the 20 minute aggregate values of continuous independent variables and dependent variable i.e. free-flow speed.

Table 2. Correlation Coefficients between Continuous Variables.

| | Humidity | Atmospheric Temperature | Atmospheric Precipitation Rate | Pavement Temperature | Wind Average Speed | HV Percentage | Free-flow speed |
|---|---|---|---|---|---|---|---|
| Humidity | 1.00 | -0.51 | 0.00 | -0.41 | -0.49 | -0.09 | -0.07 |
| Atmospheric Temperature | -0.51 | 1.00 | 0.11 | 0.74 | 0.24 | -0.02 | 0.13 |
| Atmospheric Precipitation Rate | 0.00 | 0.11 | 1.00 | 0.10 | 0.03 | 0.01 | 0.03 |
| Pavement Temperature | -0.41 | 0.74 | 0.10 | 1.00 | 0.18 | -0.02 | 0.10 |
| Wind Average Speed | -0.49 | 0.24 | 0.03 | 0.18 | 1.00 | 0.05 | 0.01 |
| HV Percentage | -0.09 | -0.02 | 0.01 | -0.02 | 0.05 | 1.00 | 0.12 |
| Free-flow speed | -0.07 | 0.13 | 0.03 | 0.10 | 0.01 | 0.12 | 1.00 |

Note: p-value<$2.2\times10^{-6}$ for all the correlation coefficients

According to the resultant correlation coefficients, the strongest relation appears between the pavement temperature and the atmospheric temperature. The high correlation between the two continuous variables restricts using the two parameters simultaneously in the statistical models. Considering the correlation with the other variables, the pavement temperature accounts for less co-linearity than that with atmospheric temperature. Therefore, pavement temperature was selected to be used as a predictor variable in the models instead of the atmospheric temperature. Further, the only negative co-linearity with the dependent parameter (free-flow speed) is exhibited by humidity. All the other continuous independent variables account for positive, but smaller correlation coefficients with the free-flow speed. Apart from rejecting the atmospheric temperature as an independent variable, all the other tested continuous variables were further tested statistically as prospective predictor variables of the trial statistical models.

The chi-squared statistic was employed to test the extent of correlation between categorical variables; pavement surface status, atmospheric precipitation situation, headed direction and the lane type. The chi squared probability between all the possible interactions of the categorical variables resulted in values less than $2.2\times10^{-6}$, which ultimately is less than 0.05, provides justification for rejecting the null hypothesis of chi-squared test. Therefore, all the categorical variables tested were concluded as statistically independent. "Wilcoxon Rank Sum Test" was used to examine the statistical independency of the interaction of categorical and continuous variables. The non-parametric test was applied to each of the interactions between all categorical variables and all continuous variables except the atmospheric temperature. The resultant probability for all the tests were less than 0.05. Hence, the null hypothesis was rejected and it was concluded that the two interacting variables imply different means. Therefore, it was concluded that all the categorical and continuous variables tested are suitable for statistical model development.

The independent variables to be used after the correlation analysis are humidity, wind average speed, pavement temperature, atmospheric precipitation rate, heavy vehicles percentage, pavement surface status, headed direction and time of day. Moreover, the pavement temperature and pavement surface condition will be used in two different models to capture the difference in the coefficients. Similarly, the atmospheric precipitation rate and the atmospheric precipitation situation will be separately employed as different modelling approaches.

### *3.2.2. Statistical significance tests*

Chi-squared test and Kolmogorov–Smirnov test (K–S test) were conducted to test the significance of the difference in the free-flow speed distributions under different road-weather conditions, with respect to the event of no precipitation. As rain and frozen precipitation were removed from further analysis, only the results for snowing are included.

Both Chi Squared and K-S test provide a null hypothesis (H0) and an alternative hypothesis (H1) as follows. The results are tabulated in Table 3.

H0: The two samples are drawn from the same distribution

H1: The two samples are not drawn from the same distribution

Table 3. Tests of significance results.

| Precipitation Situation | | Precipitation Intensity (mm/h water equivalent) | Chi Squared Test | | K–S Test | |
|---|---|---|---|---|---|---|
| | | | Chi Squared Statistic ($\chi$) | P - value | Kolmogorov–Smirnov statistic (D) | P - value |
| No precipitation | Snow | Any | 11069 | $< 2.2\times10^{-6}$ | 0.13556 | $< 2.2\times10^{-6}$ |
| | Slight Snow | < 2 | 11057 | $< 2.2\times10^{-6}$ | 0.0021624 | $7.472\times10^{-6}$ |
| | Moderate Snow | >= 2 and < 8 | 497.96 | $< 2.2\times10^{-6}$ | $9.6936\times10^{-5}$ | 1 |
| | Heavy Snow | >8 | 125.53 | 0.01389 | $2.4417\times10^{-6}$ | 1 |

The calculated probability values of the chi squared test are less than 0.05 which designates that we can be 95% confident in concluding that the samples are not drawn from the same distribution. On the other hand, the resultant Kolmogorov–Smirnov statistics (D) which is the maximum difference between the two probability mass functions tested, are less than 1 km/h. Thus, the K-S test also confirms that the distributions are not drawn from the same distribution. Moreover, the calculated probability of having snow statistically proves that the free-flow speed distribution under snow is significantly different than the free-flow speed distribution under no precipitation. Although the p-values resulted in the k-s test for moderate and heavy snow categories produced contrasting test results to having slight snow, the results of the first category, which resembles having snow at any extent validated the significance of the two distinct free-flow speed distributions. Accordingly, the concluding remarks of the statistical tests of significance appraise the statistical significance of the study.

## 4. Regression models

### 4.1. Data preparation

Apart from the comprehensive statistical analyses conducted in advance, some actions were still required before the development of the models. This study aims to estimate the free-flow speed of the vehicles during different road-weather conditions. Accordingly, vehicles with regulated speeds due to reasons other than road-weather were removed from the database. Unlike the other studies (Argwal et.al, 2006; Hong & Oguchi, 2007), a threshold based on the time headway between vehicles were used in this study instead of using merely a speed threshold calculated based on the maximum flow. The decision to use the time headway to remove the follower vehicles were based on the comparatively low traffic volumes recorded. The time headways between freely moving vehicles were calculated based on the maximum traffic density corresponding to free-flow condition as defined by HCM (2016). HCM defines the vehicular density for the level of service “A” as 11 veh/km, where the vehicles are considered to be in a free-flow condition. As the next step, the lower threshold of time headway was determined considering a common free-flow speed of 110 km/hr, which is the posted speed limit for the data collection point on highway 16. Therefore, all the vehicles with a time headway below 3 seconds were labelled as follower vehicles and were eliminated from the dataset.

In terms of the functional form of the statistical models, the lion’s share of the past studies used a linear relationship. For instance, many studies (Kyte et.al, 2000; Ibrahim & Hall, 1994; Billot et.al, 2009) used multiple linear regression to develop their statistical models. However, in this study, the free-flow speed distribution of the data population was extensively analyzed instead of adapting the same functional form proposed by the past studies. Thus, each road-weather parameter was graphed against free-flow speed variations and analyzed to capture the best fitting functional form. But, the functional forms were difficult to be determined by trend analysis, since the points were scattered all over the plots. Therefore, both linear and nonlinear statistical models were developed in this study.

Multiple linear regression models were developed based on three different treatments of free-flow speed as the dependent variable of the models. The models developed take three main approaches:

- With dependent variable as individual vehicle speeds (Group I models)
- With dependent variable as 20 minute aggregate vehicle speeds (Group II models)
- With sampled data (Group III models)

The initial model uses individual vehicle speeds as the dependent parameter. The other approaches were employed to fine-tune the initial model. As an improvement to Group I models, the dependent variable was replaced with the 20 minute aggregate vehicle speeds in Group II models. The 20 minute aggregate vehicle speeds were determined by averaging the vehicle speeds recorded in each 20 minute RWIS interval. The averaging cancels out any outliers recorded during the interval. Group III models used extracted data samples through distinct data elimination methods. This approach allows the comparison between the results of using different data treatment methods. Both linear and nonlinear statistical models are developed separately for all three data treatment approaches discussed above.

As this study only focused on the free-flow speed variations caused by different road-weather conditions, rain and frozen precipitation were not included in the study in order to maintain the consistency. The independent variables used in the study are as follows. The most frequent condition under each independent parameter is appointed as the reference condition.

- Relative Humidity (%)
- Pavement Surface Temperature (°C)
- Atmospheric Precipitation Rate (mm/h) or Atmospheric Precipitation Situation
- Average Wind Speed (km/h)
- Pavement Surface Condition

- Heavy Vehicles Percentage (%)
- Headed Direction (Eastbound or Westbound)
- Time of Day (Daytime or Night-time)

The heavy vehicles percentage was calculated on an hourly basis and expressed as a percentage of the hourly flow in the respective hour. The consecutive hour starts when a vehicle passes the WIM station. Moreover, the time of day was determined by the recorded sunrise and sunset times for the study area.

### *4.2. Linear regression models*

Three main categories of linear regression models were developed in this study. The categorization is based on the dependent parameters used or the data elimination method used. However, all linear regression models follow the same general format as presented in Eq.1.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_n x_n + \varepsilon \tag{1}$$

Where,
Y: Individual vehicle speed or the 20 minute aggregate free-flow speed of the vehicles
$\beta_0$: Intercept for the reference conditions
$\beta_i$, i= 1 to n: Model coefficient for independent variable, $x_i$
$x_i$: Independent variable
ε: Error term

The resultant variables of each model estimate the individual or 20 minute aggregate free-flow speeds, respectively. To obtain the free-flow speed estimated by the models at a particular time, the prevailing road-weather attributes and the other relevant parameters should be substituted as the corresponding independent variables.

- Group I models

The raw data obtained through the WIM station record the individual vehicle speeds for each vehicle passing the WIM station. As an initial step, it was attempted to scrutinize the relations between the absolute speeds and the respective road-weather conditions. Separate models were developed for light and heavy vehicles for each lane type (shoulder and median) resulting in four statistical models in total. The model coefficients are presented in Table 4. The t-statistic and calculated probabilities for each independent variable confirmed that all independent variables used in the models are significant.

The linear models developed indicated higher free-flow speeds for the vehicles travelling in the median lanes. However, the free-flow speed reductions under different road-weather conditions exhibit slight differences in all cases. As a whole, the drivers reduce their speeds when the pavement surface is warned with a possibility of ice, regardless of the lane or the type of vehicle. Although the model coefficients indicate reductions under adverse road-weather conditions, the model performance measures alarm that the model accuracy could be low. This could be due to the inclusion of unfitting data points in the data population. For instance, the variations in the vehicular speeds can be a resultant of adverse road-weather conditions or some other reason. As described by other researchers (Edwards, 1999; Ibrahim & Hall, 1994), the speed reductions may result due to the variability in highway as well as driver characteristics. In order to elude the resultant free-flow speed reductions from causes other than adverse road-weather, the models' dependent parameter was changed from individual vehicle speeds to the 20 minute aggregate free-flow speed. Therefore, Group II model will include the average free-flow speeds during each road-weather data recording interval, introducing a better estimation basis for the models.

- Group II models

The models in this category are developed with the 20 minute aggregate free-flow speeds as the dependent parameter of the models. The dependent parameter is calculated as the time mean free-flow speed of the vehicles during the 20 minute data collection interval, which is also the interval adopted by the RWIS station to collect road-weather conditions data. The correlation between the new dependent parameter and the independent parameters used indicated similar correlations as before. The model coefficients are presented in Table 4.The attempt resulted in comparatively higher adjusted R squared values than Group I models. On the other hand, the model coefficients resulted provoke some contradictory scenarios. Notably, the relationship between the free-flow speed and the atmospheric precipitation situation provides some conflicting implications. This implies the possibility of the existence of inappropriate data samples in the population. Therefore, a thorough data elimination was carried out in Group III models.

- Group III models

The next renovation to the models was attempted with a data elimination technique. This technique was first used by Hall and Barrow (1988) in their study. The method emphasizes on using the absolutely representative dates for specific road-weather conditions. Prior to selecting the representative days, the observations were screened to select the data recorded for seven hours from 9 a.m. to 4 p.m. The representative days for each road-weather condition were selected based on the criteria that each representative day should sustain a particular road-weather attribute for more than 3 hours out of the filtered sample enclosing 7 hours per day. Accordingly, 20 days were selected and used to build the statistical models. The selection of the representative days allow the sample to include a similar number of observations from each independent variable. Hence, the data elimination method prevents bias in the models. The dependent variable is further used as the 20 minute aggregate free-flow speed established from the previous refinement. According to the results (Table 4), the model performance was not improved as estimated. The lower R-squared values coupled with unrealistic model coefficients outline the need for further improvements required for the models. The performance measures of all the linear regression models developed so far imply poor performance of the models. Although the linear functional form was suggested by the researchers, the method seems to be unfitting to this specific data population. Therefore, another set of models were developed with a nonlinear functional form.

### *4.3. Nonlinear regression models*

The nonlinear models were developed in the same way as described for three linear regression models. The functional form for each nonlinear model is obtained by trend analysis of the variation of each continuous independent parameter with individual vehicle speeds. To improve the performance of the models, the categorical variables atmospheric precipitation situation and the pavement surface situation were replaced by the continuous variables atmospheric precipitation rate and the pavement surface temperature respectively. The functional form to be used in nonlinear models (Eq.2) is based on the linear behavior of humidity and average wind speed, the quadratic behavior of the pavement surface temperature and the heavy vehicles percentage and the cubic behavior of the precipitation rate.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_2 x_3^2 + \beta_4 x_4^2 + \beta_5 x_5^3 + \varepsilon \qquad (2)$$

Where,
Y: Individual vehicle speed or the 20 minute aggregate free-flow speed of the vehicles
β0: Model coefficient for the reference conditions
β1: Model coefficient for the relative humidity (linear)
β2: Model coefficient for the average wind speed (linear)
β3: Model coefficient for the pavement surface temperature (quadratic)
β4: Model coefficient for the heavy vehicles percentage (quadratic)
β5: Model coefficient for the precipitation rate (cubic)
ε: Error term

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- Table 4: Model Coefficients for Linear Regression Models

| Variable | | Group I models | | | | Group II models | | | | Group III models | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle Type | | LV | | HV | | LV | | HV | | LV | | HV | |
| Lane | | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median |
| Intercept | | 115.334 | 123.845 | 115.840 | 117.218 | 117.202 | 115.428 | 116.028 | 114.386 | 115.840 | 117.218 | 117.203 | 115.428 |
| Relative Humidity | | -0.010 | -0.003 | -0.009 | 0.002 | -0.011 | -0.006 | -0.002 | S/I | -0.009 | 0.002 | -0.011 | -0.006 |
| Pavement Surface Condition | Frost | -1.556 | -0.972 | -1.788 | -0.900 | -1.402 | -1.500 | -1.513 | -1.328 | -0.972 | -1.788 | -0.900 | -1.402 |
| | Ice Warning | -2.300 | -1.959 | -2.301 | -1.789 | -2.111 | -2.423 | -2.547 | -2.541 | -1.959 | -2.301 | -1.789 | -2.111 |
| | Ice Watch | -0.533 | -0.242 | -0.752 | -0.157 | -0.418 | -0.528 | -0.474 | -0.300 | -0.242 | -0.752 | -0.157 | -0.418 |
| | Trace Moisture | -0.286 | -0.458 | -1.214 | -0.712 | -0.100 | -0.883 | -0.383 | -0.732 | -0.458 | -1.214 | -0.712 | -0. 100 |
| | Wet | -0.257 | -0.130 | -0.454 | -0.052 | -0.298 | -0.349 | 0.213 | -0.291 | -0.130 | -0.454 | -0.052 | -0.298 |
| Atmospheric Temperature | | 0.039 | 0.051 | 0.079 | 0.078 | 0.093 | 0.074 | 0.081 | 0.073 | 0.079 | 0.078 | 0.093 | 0.074 |
| Atmospheric Precipitation Situation | Slight Snow | -1.708 | -0.556 | 0.071 | -0.663 | -0.211 | -0.332 | -1.980 | -1.290 | -0.556 | 0.071 | -0.663 | -0.211 |
| | Moderate Snow | -1.701 | -5.746 | -3.042 | -5.433 | -3.938 | 0.442 | 0.104 | -1.184 | -5.746 | -3.042 | -5.433 | -3.938 |
| | Heavy Snow | -1.634 | -8.419 | -0.060 | N/A | -0.877 | -1.773 | -1.518 | N/A | N/A | N/A | N/A | N/A |
| Average Wind Speed | | -0.044 | -0.025 | -0.037 | -0.031 | -1.264 | -0.017 | -0.036 | -0.032 | -0.041 | -0.029 | -0.060 | -0.037 |

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| Variable | Group I models | | | | Group II models | | | | Group III models | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle Type | LV | | HV | | LV | | HV | | LV | | HV | |
| Lane | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median |
| Heavy Vehicles Percentage | -0.012 | -0.033 | -0.010 | -0.075 | -0.033 | -0.007 | -0.063 | -0.059 | -0.026 | -0.033 | -0.081 | -0.112 |
| Time of Day (Night) | -0.358 | -0.042 | -0.308 | -0.896 | -1.832 | -1.369 | -1.405 | -0.991 | - | - | - | - |
| Headed Direction (West Bound) | -0.983 | -4.493 | -1.939 | -3.292 | -0.678 | -0.597 | -1.030 | S/I | -0.350 | -2.662 | -0.399 | 0.325 |
| Adjusted R Squared | 0.0308 | 0.0287 | 0.035 | 0.0893 | 0.288 | 0.205 | 0.323 | 0.313 | 0.216 | 0.184 | 0.268 | 0.276 |
| Number of Observations | 1,250,041 | 434,791 | 471,686 | 35,361 | 1,248,762 | 429,534 | 471,215 | 35,014 | 432,113 | 204,212 | 137,765 | 16,722 |

Note: N/A and S/I refers to entries with no observations and statistically insignificant observations respectively

Table 5: Model Coefficients for nonlinear models

| Variable | | Group IV models | | | | Group V models | | | | Group VI models | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle Type | | LV | | HV | | LV | | HV | | LV | | HV | |
| Lane | | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median | Shoulder | Median |
| Intercept | | 117.698 | 120.690 | 106.677 | 115.05 | 117.509 | 113.988 | 117.351 | 115.568 | 119.336 | 115.768 | 119.553 | Insignificant |
| Relative Humidity | | -0.027 | -0.014 | -0.013 | -0.032 | -0.008 | 0.002 | -0.011 | -0.016 | -0.021 | -0.007 | -0.025 | Insignificant |
| Average Wind Speed | | -0.082 | -0.050 | -0.055 | -0.036 | -0.051 | -0.026 | -0.055 | -0.053 | -0.072 | -0.037 | -0.083 | Insignificant |
| Pavement Surface Temperature | Linear | 0.094 | 0.091 | 0.062 | 0.061 | 0.107 | 0.098 | 0.119 | 0.101 | 0.090 | 0.086 | 0.103 | Insignificant |
| | Quadratic | -0.003 | -0.003 | -0.002 | -0.002 | -0.002 | -0.001 | -0.003 | -0.001 | -0.002 | -0.001 | -0.001 | Insignificant |
| Heavy Vehicles Percentage | Linear | -0.125 | -0.150 | -0.022 | -0.205 | -0.214 | -0.147 | -0.173 | -0.145 | -0.208 | -0.198 | -0.207 | Insignificant |
| | Quadratic | 0.001 | 0.002 | 0.000 | 0.001 | 0.002 | 0.001 | 0.001 | 0.001 | 0.002 | 0.002 | 0.002 | Insignificant |
| Atmospheric Precipitation Rate | Linear | -1.811 | -2.041 | -0.929 | -1.662 | -1.910 | -1.023 | -2.598 | -2.768 | -0.102 | S/I | 0.261 | Insignificant |
| | Quadratic | 0.472 | 0.649 | 0.316 | 0.529 | 0.622 | 0.433 | 0.933 | 1.041 | -1.407 | S/I | -2.513 | Insignificant |
| | Cubic | -0.020 | -0.030 | -0.014 | -0.074 | -0.028 | -0.021 | -0.043 | -0.088 | 0.202 | -0.363 | 0.497 | Insignificant |
| Adjusted R Squared | | 0.021 | 0.030 | 0.001 | 0.054 | 0.201 | 0.173 | 0.221 | 0.253 | 0.214 | 0.206 | 0.216 | - |
| Number of Observations | | 1,250,041 | 434,791 | 471,686 | 35,361 | 1,248,762 | 429,519 | 471,215 | 35,014 | 432,113 | 204,199 | 137,765 | - |

- Group IV models

  The models in this category are developed with the individual vehicle speeds as the dependent parameter. The model coefficients resulted (Table 5) are higher compared to the linear regression models coefficients in Group I models. However, the model performance is declined.

- Group V models
  This category of models were developed with the 20 minute aggregate vehicle speeds as the dependent parameter. The models with 20 minute aggregate vehicle speeds exhibit similar coefficients to the nonlinear model coefficients of the linear models; Group I models. But the model performance declined similar to the nonlinear models with the individual vehicle speeds.
- Group VI models with sampled data
  This group of models were developed using the sampled data while the dependent variable is remained as 20-minute aggregate free-flow speed. Similar data elimination technique used in developing the linear regression models was adopted in developing the nonlinear models as well. Group VI models resulted in higher free-flow speeds in normal conditions compared to Group IV and V models. However, the model coefficients remain almost same with slight variations. Notably, many coefficients were statistically insignificant and hence, are not presented.

## 5. Discussion

The study probes the suitability of the application of several distinct statistical methods to investigate the effects of adverse road-weather conditions on the free-flow speed of the vehicles. Among the models developed, the best performing statistical model for both light and heavy vehicles in any lane can be concluded as the linear regression models developed with the 20 minute aggregate free-flow speeds as the dependent variable (Group II models). Thus, usage of a linear function with an aggregated dependent parameter is recommended by this study.

### *5.1. Effect of road-weather conditions on vehicle free-flow speeds*

The study confirms that the drivers tend to reduce their traveling speeds under adverse environmental conditions. Unlike the other studies conducted so far, this study examines the effects under different parameters, which allows the users to have an idea about the impacts of adverse road-weather conditions from different aspects. As a result, the free-flow speed reductions concluded by the study can be comparatively smaller compared to the studies conducted so far. However, it can be assumed that model coefficients resulted by this study is a disaggregation of the model coefficients of the previous studies. The major findings are listed below.

- Both light and heavy vehicles tend to drive faster in shoulder lanes under the reference conditions (clear road-weather). Yet, the difference is much smaller and is probably resulted due to the low traffic volume in the study area.

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- Drivers of all vehicle types are estimated to reduce their travelling speeds under high relative humidity values, higher heavy vehicle percentages and higher wind speeds.
- Lower free-flow speeds are estimated at night, compared to the day time, regardless of the vehicle type they are handling. The reduction in the visibility during night time is probably causing a reduction of the free-flow speed of the vehicles in the night time.
- Drivers reduced the free-flow speeds when they are headed to the west compared to the vehicles headed to the east, regardless the vehicle type. This could be due to the direct sunlight faced by the drivers travelling west bound. However, although this provides an interesting phenomena, further studies in different study areas should be conducted to confirm the trend.
- An increase of the temperature is estimated to cause an increase in free-flow speeds of the vehicles in similar highways.
- Ice warning pavement surface condition has the highest negative impact on free-flow speeds of the vehicles, while wet pavement surfaces exhibit the minimum negative impact.
- Vehicles travelling under heavy snow presented smaller free-flow speed reductions than the vehicles travelling under slight snow conditions. Therefore, other road-weather variables associated with atmospheric precipitation situation were carefully analyzed in order to find out the underlying reason for the difference. Surprisingly, the major difference among slight, moderate and heavy snow was the pavement surface condition recorded under each event. Table 6 presents the prevalence of pavement surface condition affected under slight snow, moderate snow and heavy snow. As presented in Table 6, the pavement surface condition recorded under different levels of snow are quite different. For example, under slight snow, most of the vehicles recorded drove under ice warning pavement condition (57%), whereas all the vehicles travelling under heavy snow were travelling in dry pavement conditions. In contrast, the majority of the vehicles driven under moderate snow faced wet pavement surface conditions (74%). By analyzing the numerical values, it can be clearly interpreted that winter road maintenance operations are more frequent and the pavements are cleaned frequently under heavy snow conditions compared to slight snow conditions. A particular road winter maintenance operation scheme such as cleaning the pavement surface only when there is a heavy snow fall and apply salt and sand when the pavement is under moderate snow falls will lead the commuters to drive faster in moderate and heavy snow compared to slight snow conditions. With this justification, the drivers focus on the prevailing pavement conditions instead of deciding their behavior upon the precipitation situation at the time of driving. This observation highlights the significance of an efficient winter road maintenance program to improve traffic operations and safety in cold regions.

Table 6. Pavement Surface Condition Variation under Different Precipitation Situations.

| Atmospheric Precipitation Situation | Frequency | | Pavement Surface Condition | | | | |
|---|---|---|---|---|---|---|---|
| | Number of Observations | Percentage | Dry | Ice Warning | Ice Watch | Trace Moisture | Wet |
| Slight Snow | 27022 | 93.5% | 16.69 % | 56.82 % | 0.20 % | 0.03 % | 26.26 % |
| Moderate Snow | 1859 | 6.4% | 6.94 % | 19.53 % | 0.00 % | 0.00 % | 73.53 % |
| Heavy Snow | 35 | 0.1% | 100.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % |

### *5.2. Effect of the functional form and the data treatment methods used in the models*

The study used both linear and nonlinear functional forms as the base functional form of the models. As per the results, the linear regression models with aggregated speed can be concluded as the best fit for the data used in this study. The linear, quadratic and cubic functional forms were determined by the trend analysis of the behavior of each independent variable with the dependent. Although the trend judgment provided some clues for the functional form, the data do not fit exactly to the specific functional forms suggested. It was attempted to resolve this dilemma through eliminating part of the data and retaining only the truly representative data. Yet, the data sample extracted from the population did not enhance the model performance as expected. However, it is clear that the different functional forms used and the data elimination methods used are capable of changing the model parameters. For instance, the model coefficients change significantly when different functional forms and data elimination methods are applied for the same data sample. Therefore, it is recommended to examine the individual relationships between independent and dependent parameters, and apply additional data elimination techniques in future studies.

### *5.3. Comparison with existing research*

The study developed several regression models to estimate the driver behavior under adverse road-weather conditions. Table 7 presents a comparison outlining the differences between the models developed in this study and some similar studies conducted in the past. The reductions in free-flow speed under each condition with respect to the clear weather conditions are presented in the table. The comparison includes the best performing models selected from the study which is Group II models. Moreover, the model coefficients related to the shoulder lane are selected for the comparison due to the frequent usage by the motorists, given that the compared studies have not considered the lane-wise reductions.

Kyle et al., 2000 was selected to be compared with the present study due to the similarity of the independent variable types used in both studies. In addition, HCM (2016) was selected as a reference to be compared with the present study's results. However, it should be noted that different independent variables and aspects are considered in each study or reference. Thus, the compared literature suggestions vary significantly from that of the present study.

Table 7. Comparison with existing research (reduction factors for different road-weather conditions).

| | Present Study | | Kyte et al.,2000 | HCM (2016) |
|---|---|---|---|---|
| | Light Vehicles | Heavy Vehicles | | |
| Slight Snow | 0.2% | 1.7% | 3.2% | 8% |
| Moderate Snow | 3.4% | 0.1% | 11.6% | - |
| Heavy Snow | 0.8% | 1.3% | 20.1% | 41.6% |
| Wet Pavement | 0.3% | 0.3% | 5.3% | - |
| Snow/Icy Pavement | 2.2% | 2.6% | 10.5% | - |

According to Table 7, the resultant free-flow reductions obtained from the present study are significantly lower compared to the past literature. However, unlike in the compared studies, the present study considers additional aspects which spreads the speed reduction among many aspects. For example, the present study estimates a speed reduction of 0.8% for the light vehicles travelling under a heavy snow condition. In contrast, Kyte et al., 2000 and HCM (2016) suggests a speed reduction of 20.1% and 41.6% for the same atmospheric precipitation condition. However, Kyte et al., 2000 and HCM (2016) estimations are irrespective of the lane or vehicle type. Another explanation for observing smaller reduction factors for estimating the impact of adverse road-weather conditions on free-flow speed is drivers' familiarity with driving under extreme weather conditions as winter driving is very common in Canadian highways. This in turn implies the significance of driver population, demographics, and geographical conditions when investigating the impact of inclement road-weather conditions on traffic operations.

## 6. Conclusions and future research

This study investigated the impact of adverse road-weather conditions on free-flow speed on highways while highlighting the effects of different data treatment and analysis methods. Based on the speed reduction factors estimated by the regression models, it's apparent that the drivers tend to drive slower in the presence of ice watch and ice warning pavement surface conditions. For instance, according to Group II models, the free-flowing light vehicles travelling in an ice warning pavement condition are estimated to reduce their traveling speed by 2km/h and 2.4km/h respectively for vehicles travelling in shoulder and median lanes, respectively. Similarly, a 2.5km/h free-flow speed reduction is estimated for heavy vehicles travelling in either shoulder or median lane. In contrast, the wet pavement conditions will result in a free-flow speed reduction of 0.3km/h and 0.2km/h for light and heavy vehicles, respectively. These figures reveal the importance of winter road maintenance in extremely cold regions. The frequent snow and ice removal in highways will have a considerable impact on the speeds of the vehicles, which will prevent the drivers from reducing the travelling speeds and eventually result in less weather related delays. Thus, the findings highlight the importance of winter road maintenance operations run by highway agencies to improve the traffic operations and road safety in winter. The significance of driver population, demographics, and geographical conditions were also highlighted when investigating the impact of inclement road-weather conditions on traffic operations

The study developed separate statistical models for each lane and vehicle types. As mentioned before, the model coefficients for each independent variable stand different for different lane and vehicle types. Thus, imposing a fixed speed limit for different lane and vehicle types in a multi-lane highway with mixed traffic may pose safety risks to drivers in adverse road-weather conditions due to the variability observed in setting their desired speed. To maintain a safe distance from leading and following vehicles some drivers may have to adopt travel speeds which are significantly higher or lower than what they prefer, which is highly insecure especially under adverse road-weather and free-flowing driving conditions. Therefore, the study stresses the importance of imposing independent speed limits for each lane and vehicle type in adverse road-weather conditions. The findings will serve the transportation authorities with similar environmental conditions to regulate the speed limits under extreme road-weather conditions.

The road-weather and traffic data for the study were collected from a RWIS and WIM station located alongside in highway 16 respectively. The two data collection devices are located side by side allowing a highly accurate designation of the existing road-weather condition for each vehicle recorded. However, the location of the RWIS and WIM stations in highway 16 does not engage with high traffic volumes resulting a lower amount of data points to be used in the study. Therefore, the study performance was limited to a certain extent due to the restricted samples. Nevertheless, this restriction can be eliminated by employing multiple locations with similar environmental conditions. In addition, the research can be expanded by investigating the driver behaviors in other highway types. Moreover, the study can be improved by conducting a cost-benefit analysis of investing more in winter road maintenance operations and variable speed limit operations which will yield more benefits in terms of improved safety and traffic operations in winter. Further, several studies will be conducted to investigate the driver behavior in terms of lane utilization and car following behavior under adverse road-weather conditions on highways.

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## References

Billot, R., El Faouzi, N.E. and De Vuyst, F., 2009. Multilevel Assessment of the Impact of Rain on Drivers' Behavior: Standardized Methodology and Empirical Analysis. Transportation Research Record: Journal of the Transportation Research Board, (2107), pp.134-142.

Brilon, W. and Ponzlet, M., 1996. Variability of speed-flow relationships on German autobahns. Transportation Research Record: Journal of the Transportation Research Board, (1555), pp.91-98.

Datla, S. and Sharma, S., 2008. Impact of cold and snow on temporal and spatial variations of highway traffic volumes. Journal of Transport Geography, 16(5), pp.358-372.

Edwards, J.B., 1999. Speed adjustment of motorway commuter traffic to inclement weather. Transportation research part F: traffic psychology and behaviour, 2(1), pp.1-14.

Hall, F.L. and Barrow, D., 1988. Effect of weather on the relationship between flow and occupancy on freeways (No. 1194).

Hong, S. and Oguchi, T., 2007. Effects of rainfall and heavy vehicles on speed-flow relationship for multilane expressways in Japan (No. 07-1933).

Ibrahim, A.T. and Hall, F.L., 1994. Effect of adverse weather conditions on speed-flow-occupancy relationships (No. 1457).

Kyte, M., Khatib, Z., Shannon, P. and Kitchener, F., 2000. Effect of environmental factors on free-flow speed. Transportation Research Circular, Transportation Research Board, Washington, DC.

Manual, H.C., 2000. HCM2000. Transportation Research Board, National Research Council, Washington, DC.

Manual, H.C., 2016. HCM2016. Transportation Research Board, National Research Council, Washington, DC.

National Collision Database Online Retrieved from http://wwwapps2.tc.gc.ca/Saf-Sec-Sur/7/NCDB-BNDC/p.aspx?c=100-0-0&l=en on 30/05/2018 at 1738h CST

Oh, J.S., Shim, Y.U. and Cho, Y.H., 2002. Effect of weather conditions to traffic flow on freeway. KSCE Journal of Civil Engineering, 6(4), pp.413-420.

Roh, H.J., 2015. Impacts of Snowfall, Low Temperatures, and their Interactions on Passenger Car and Truck Traffic (Doctoral dissertation, Faculty of Graduate Studies and Research, University of Regina).

Saskatchewan Government Insurance (2017), 2016 Saskatchewan Traffic Accident Facts Retrieved from https://www.sgi.sk.ca/documents/625510/627017/TAIS_2016_Annual_Report.pdf/8787ed62-adfc-4a4c-a38a-fa3887817090 on 30/05/2018 at 1728h CST

Zhang, L., Holm, P. and Colyar, J., 2004. Identifying and Assessing Key Weather-Related Parameters and Their Impacts on Traffic Operations Using Simulation. Publication No. FHWA-HRT-04-131, US Department of Transportation, USA.

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