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A Comprehensive Analysis of the Association of Highway Traffic with Winter Weather Conditions

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Abstract

This paper is based on the past several years of research carried out by transportation research group at the University of Regina, Canada to understand the impact of cold and snow on traffic volume during winter months in Canada. A detailed investigation of highway traffic variations i.e. total traffic, passenger car and truck traffic with severity of cold, the amount of snow, and various combinations of cold and snow intensities is presented here. These investigations were conducted using hourly traffic data from 350 permanent traffic counter sites, 6 Weigh in Motion sites and weather data from 598 weather stations located in the province of Alberta, Canada, from 1995 to 2010. Multiple regression analysis is used in the modeling process. The model parameters include three sets of variables: the amount of snowfall as a quantitative variable, categorized cold as a dummy variable, and an interaction variable formed by the product of these two variables. The study results indicate that the association of highway traffic flow with cold and snow varies with day of week, hour of day, and severity of weather conditions. A reduction of 1% to 2% in total traffic volume for each centimeter of snowfall is observed when the mean temperature is above 0°C. For the days with zero precipitation, reductions in total traffic volume due to mild and severe cold are 1% and 31%, respectively. An additional reduction of 0.5% to 3% per centimeter of snowfall results when snowfall occurs during severe cold conditions. Traffic volumes decreased with increase in the severity of cold temperatures. During extremely cold weather (below -25°C), the average winter daily traffic volume was reduced by about 30%. Weekend traffic volumes were more susceptible to cold than weekday numbers for all types of highways. Commuter and regional commuter roads experienced the lowest variations with cold. The impact of cold was very high for recreational roads and moderate for rural, long distance roads. This study also shows a clear indication in the reduction in daily traffic volumes due to snow (reductions between 7% and 17% for each centimeter of snowfall were observed). When individual vehicle classes were analyzed, it is found that passenger cars are more vulnerable to adverse weather conditions than trucks. Trucks are not as greatly affected as passenger cars by adverse weather conditions. Interestingly, the modeling results for one of the study sites reveal that higher truck traffic volumes can result during heavy snowfall (or other adverse weather conditions) in winter months due to shifting of trucks from secondary highways with poor winter maintenance to primary highways. This is contradictory to observations from other similar studies in the literature. The traffic-weather models developed from the past studies have two major

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applications in transportation engineering. These models have been tested for: (1) imputation of missing traffic data during winter months and (2) estimation of annual average daily traffic (AADT) from short-term traffic counts undertaken during winter months. The imputation efficiency of the traffic-weather models was compared with the most efficient imputation methods used by highway agencies. A new factor approach, incorporating weather conditions, was proposed in this paper to estimate AADT from short duration counts taken during winter months. Therefore, the developed traffic-weather models can be recommended to highway agencies to impute missing traffic data and to estimate AADT from short duration counts taken during winter months.

Keywords: Weather; Snowfall; Temperature; Traffic variation; Road type; Regression

1. Introduction

Traffic volumes on highways vary with both time and space. Temporal variation occurs with respect to hour, day and month of the year. The highway type and location cause spatial variation. Even at the same time and location, the variations of traffic volumes could differ substantially when each vehicle class travelling in the traffic stream is analyzed separately. The winter weather in Canada and many parts of the United States is very severe, with high wind chills, heavy snowfall, and extremely cold temperatures (In Alberta and other provinces of Canada, −35°C is a frequent occurrence.). Such conditions may cause huge variation in highway traffic volumes adding another dimension to variations of traffic stream. Understanding of such temporal and spatial variations of truck and passenger car traffic under different weather conditions is very useful for both macroscopic and microscopic modeling of highway traffic. Andrey et al. (2003) reported that snow is an influential weather parameter for Canadian roads. Hence, cold and snow are the weather conditions of concern in this research.

The existing literature indicates that a reduction in traffic movement occurs because of travelers' reduced desire to travel during wet or snowy weather (Palutikof, 1981). Past studies on the impact of weather on highway traffic flow conditions can be broadly categorized into two groups: (1) studies focusing on the impact of weather on traffic parameters such as volume, speed, and headway and (2) studies focusing on the impact of weather events such as snow, rain, fog, smoke, high winds, and extreme temperatures on the quality of traffic flow (i.e., operating level of service, crash rates, traffic delays, start-up delays at intersections, and traffic congestion). Existing literature (Hanbali and Kuemmel, 1993; Knapp and Smithson, 2000; Changnon, 1996; Palutikof, 1981; Goodwin, 2002; Hall and Barrow, 1988; Hassan and Barker, 1999; Ibrahim and Hall, 1994; Keay and Simmonds, 2005; Maze et al., 2006; Shah et al., 2003; Smith et al., 2004; Andrey et al., 2003) also reveals that winter weather is associated with greater changes in traffic volumes than summer weather.

Hanbali and Kuemmel (1993) studied the average traffic volume reductions due to snowstorms on highways away from the major urban centers in the United States. They analyzed the effect of snow storms with respect to average daily traffic, time of day, and day of week (weekday or weekend). The reported traffic volume reductions ranged from 7% to 56%, depending on adversity of the snowstorm. Knapp and Smithson (2000) analyzed the average traffic reductions on interstate highways in Iowa State during winter storms. They considered only the storm events having air temperature below freezing, wet pavement surface, pavement temperature below freezing, and a snowfall of at least 4-h duration with intensity higher than 0.51 cm/h. The results indicated that the impact of winter storms on traffic volume variation is highly varied. The reported average reductions ranged from 16% to 47% for different storm events. Hassan and Barker (1999) studied the impact of unseasonable or extreme weather on urban traffic activity within the Lothian region of Scotland. The meteorological parameters, such as minimum and maximum temperatures, snow and rainfall, snow on the ground, and sunshine hours, were considered in their study. The 10% of days with either the highest or lowest values for each meteorological variable were treated as

extreme weather. It was concluded that the average traffic reductions were less than 5% under extreme weather conditions, but there was a reduction of 10% to 15% in traffic activity when snow was lying on the ground. Keay and Simmonds (2005) reported the association of rainfall and other weather variables with traffic volume on urban arterials in Melbourne, Australia. They designed regression models incorporating the trend of historical traffic, day of the week, holidays, and weather. Separate analyses were conducted for daytime and nighttime during winter and spring. The reported reductions during wet days were 1.35% in winter and 2.11% in spring. A maximum reduction of 3.43% was reported for a rainfall ranging from 2 mm to 5 mm in spring. On Interstate Highway 35 in northern rural Iowa, Maze et al. (2006) reported a strong correlation between the percentage reduction in traffic volume and wind speed and visibility during snowy days. They reported 20% reduction in traffic during snowy days with good visibility and low wind speed. The reductions are approximately 80% when the visibility is less than 1⁄4 mi and wind speed is high (as high as 40 mph). Several other studies also reported variant traffic patterns during adverse weather conditions (Hall and Barrow, 1988, Ibrahim and Hall, 1994, Smith et.al, 2004, Goodwin, 2002). However, limited research has been done in the past to quantify the association of highway traffic volumes with weather conditions. All of these studies have reported average traffic volume reductions due to adverse weather conditions, but the relationships between weather conditions and traffic volumes have not been well established. The changes in traffic-weather relationships with respect to the road type and vehicle class have also not been explored.

None of the above investigations have considered the effect of severe cold on car and truck traffic volume variation separately. Furthermore, none of the past studies have evaluated the usefulness of traffic weather relations in transportation engineering applications. The main objective of this paper is to review all the weather related traffic studies carried out by the transportation research group at the University of Regina. The paper also includes some of the findings from some of the research in progress to address the above-mentioned shortfalls in the literature. The research was conducted based on a large traffic and weather data from the province of Alberta, Canada. The highlight of this paper is the analysis of truck traffic association with the interaction of snow and temperature, and highway type.

2. Study Data

2.1 Traffic data (PTC and WIM data)

The main sources of traffic data for these studies are the system of PTC and WIM sites located on the provincial highways in Alberta, Canada. In 1995, Alberta Infrastructure and Transportation stated to use nearly 350 PTC sites to monitor its highway network. The most recent data available at the start of this study were hourly traffic volume data for 16 years from year 1995 to 2010. Preliminary investigation has been carried out to check the abnormalities in the study data because of special events such as school or government closings, highway construction, road accidents, and the like. The days with abnormal traffic patterns were identified and treated as outliers and not used in the study investigations. The classified traffic data were collected from the six WIM sites located on two primary highways i.e. Highway 2 and Highway 2A. These WIM sites were installed in July 2004 and have continuously been collecting vehicle classification and load data for programs such as Alberta's Strategic Highway Research and Long Term Pavement Performance Programs. The available WIM data spanning over a period of 5 years from 2005 to 2009 were used for this study. More than 154 million vehicle records were analyses and Federal Highway Administration (FHWA) 13-category classification scheme called “scheme F” applied to classify the vehicles from WIM data. However, due to lower number of total trucks (80% passenger cars and 20% trucks in the traffic composition) in general and too many truck classes; sample data could not generate sufficient samples to carry out detailed statistical analysis by each vehicle class. Therefore, the

13 vehicle classes were aggregated into four major categories i.e. passenger car and 3 truck type classes namely single unit trucks, single trailer and multi trailer units.

2.2 Climate data

The climate data were obtained from Environment Canada (2013). There were 598 weather stations operated by Environment Canada in the province of Alberta between the years 1995 and 2010. The weather parameters such as maximum, minimum, and mean temperatures; rain; snowfall; precipitation; and snow on ground were recorded at most of the stations on a daily basis. The unit for temperature is centigrade and snow is in centimetres. Complete details of the weather parameters along with the measuring procedures are available from Environment Canada (2013). The amount of rainfall is very insignificant in winters, hence, it is not considered in the analysis. The spatial correlation analysis that was performed to measure the aerial distance up to which the weather conditions could be considered similar to the conditions at the weather station site led to the following conclusions:

a. In the case of temperature, the inter-station correlation coefficients are very high, consistent, and do not vary extensively with distance. In other words spatial variation of temperature is not too extensive. Therefore the weather stations located at even quite far distances from the PTC sites (up to 32 km) can provide accurate information about the temperature conditions at the PTC sites.

b. In the case of snowfall, the inter-station correlation coefficients decrease considerably with increases in distance. The coefficients are relatively consistent at lower distances, and a wider spread in the values result at higher distances. The highest correlation coefficients result for the 0 to 4 km distance category, indicating that the weather conditions are very similar for shorter distances. A great majority of coefficient values are between 0.65 and 0.85 for distances up to 16 km, 0.55 and 0.85 for distances from 16 to 24 km, and 0.4 and 0.85 for distances greater than 24 km. These values indicate that the weather stations located within a 16 km distance from the PTC sites provide reasonably accurate snowfall conditions at the PTC sites. The snowfall data from weather stations located at 16 km to 24 km distance from the PTC sites may be considered acceptable. This conclusion is consistent with another study in Alberta (Andrey and Olley, 1990), which concluded that weather data within a 25 km radius would generally be similar. In view of these observations, it is reasonable to assume that the weather conditions are generally homogeneous within a 16 km area around the weather stations; however, in some cases, PTC-to-weather station distances up to 24 km may be acceptable.

3. Methodology

Traffic patterns on highways vary with location and characteristics of the traffic stream. The association of traffic volumes with weather conditions may also differ from highway to highway based on these factors. To study such differences in traffic weather relationships, it is necessary to classify the highway segments. Among the several highway classification methods available in the literature, the grouping method proposed by Sharma et al. (1986) is used in this study. Following the Sharma et al. (1986) grouping procedure, All the PTC sites in the province of Alberta were classified into different groups using average monthly factors (the ratio of monthly average daily traffic to annual average daily traffic). Then, the daily and hourly traffic variation patterns of highway segments belonging to each group were analyzed to identify the road types. Based on these observations and previous research by Sharma et al. (1986), four major road groups are identified for study purposes. They are: commuter (COM), regional commuter (RCOM), rural long distance (RLD), and recreational (REC) road

groups. According to Sharma et al. (1986), the roads classified as commuter roads are predominantly used for work and business trips. Regional commuter roads serve work, business, and regional trips. Inter-regional and long distance business trips make use of rural long distance roads. Recreational roads carry large portions of social, recreational, and other discretionary trips.

The typical daily volume variations of different road types indicated that the traffic volumes on Mondays to Thursdays were generally similar, but Friday volumes were significantly higher. Sunday and Saturday volumes also seemed to be different. Therefore, separate models were developed for four different day groups (DG), namely, Mondays-Thursdays combined, Fridays, Saturdays, and Sundays. The structure of the proposed model for daily traffic volume is:

$$\mathbf{V}F_{WDYCG} = B_a * EVF_{WDCG} + B_s * S_{WDYCG} + \sum_{R=1}^{R=6} B_R * C_{RWDYCG} \text{.....} (3.1)$$

Where: *W* represents the week number of the 13 winter weeks identified for the analysis, *D* indicates the day group (*M* for Monday to Thursday, *F* for Friday, *Sa* for Saturday, and *Su* for Sunday). *Y* represents the year (1995 to 2010), *C* is the PTC number, and *G* represents the road type to which the PTC site *C* belongs. VF_{WDYCG} is the daily Volume Factor (daily volume to AADT ratio) of a particular day group, *D,* in the week, *W,* of a year, *Y,* for the PTC site, *C,* belonging to the road type, *G*. For example: $VF_{3F96CRec}$ is the volume factor of the 3rd Friday in 1996 on the highway segment represented by a PTC site, *C,* that belongs to a recreational road type. EVF_{WDCG} (Expected Volume Factor) is the average VF_{WDYCG} calculated using all available years of data for a particular *WDCG*. For example: EVF_{3FCRec} is the average volume factor calculated from 16 years of data from 1995 to 2010 (i.e., $VF_{3F95CRec}$ to $VF_{3F05Crec}$) for the 3rd Friday on site *C*, which belongs to a recreational road type. S_{WDYCG} is the total snow on a *WDYCG* in centimetres. Both EVF_{WDCG} and S_{WDYCG} are taken as quantitative, independent variables in the model. The cold variable C_{RWDYCG} is treated as a dummy variable (Hardy, 1993) and an additional suffix, *R,* is added to this variable to represent the cold category. For the reasons mentioned earlier, temperature is categorized into 7 classes: above 0°C, 0°C to -5°C, -5°C to -10°C, -10°C to -15°C, -15°C to -20°C, -20°C to -25°C, and below -25°C. The value of C_{RWDYCG} is 1 if the mean temperature of a *WDYCG* falls in class *R*, and it is *'0'* otherwise. For example, if the mean temperature of the day under study is -23°C, it falls in class five, and the value of variable C_{5WDYCG} becomes *'1',* while *'0'* will be assigned to the remaining classes of *R*. Any temperature above 0°C is not included in the cold categorization because this category is taken as the reference class. B_a, B_s, and B_R are coefficients to be estimated using regression analysis. When an independent variable is continuous (such as EVF_{WDCG} and S_{WDYCG}), the distribution of the dependent variable, $VF_{WDYCG,}$ is also continuous and the regression coefficients, B_a and B_s, indicate slope. In contrast, when an independent variable is a dummy variable (such as C_{RWDYCG}), the predicted value of VF_{WDYCG} changes by B_R units each time membership in the specified category, *R*, is switched on or off because a "unit" change in a dummy variable (from *'0'* to *'1'* or from *'1'* to *'0'*) indicates membership or non-membership in the designated category, *R*. Therefore, the coefficient $B_{a,}$ in Equation 3.1 represents the deviation of VF_{WDYCG} from $EVF_{WDCG,}$ when there is zero snow and the daily temperature falls in the reference class. Coefficient B_s gives the change in VF_{WDYCG} for each centimetre of change in the amount of total snowfall. B_R indicates the change in VF_{WDYCG} from the reference category (above 0°C) to category *R*.

To analyze the impact of different combinations of cold and snowfall, a separate model structure has been proposed. The structure of the proposed cold and snow interactions model for daily traffic volume is:

$$VF_{WDYCG} = B_a * EVF_{WDCG} + B_s * S_{WDYCG} + \sum_{R=1}^{R=6} B_R * C_{RWDYCG} + \sum_{R=1}^{R=6} B_{RS} * S_{WDYCG} * C_{RWDYCG} \text{.....} (3.2)$$

The notations of the model parameters are the same as described for the daily traffic weather model given in Equation 3.1. To analyze the effect of snowfall on traffic volume under different cold conditions, the interaction variable is included in the model. The coefficient B_{RS}, which is formed by combining the snowfall (continuous) and cold (dummy variables), represents the net effect of each centimetre of snowfall on traffic volumes in addition to B_S (B_S indicates the effect of each centimetre of snowfall when the temperature is above 0°C) for cold category R.

4. Summary of Results and Discussions

A summary of the study findings are presented in this section:

1. Careful examination of the daily and hourly volume factors when plotted against corresponding weather conditions led to the following conclusions:

    a. The yearly traffic volume variations appear to be related to yearly temperature variation. For example, the cold temperatures during winter months result in lower traffic volumes on highways. User (traveler) friendly temperatures during the summer months cause peaking of traffic in those months. The moderate traffic volumes during spring and fall could be attributed to moderate temperatures during these seasons.
    b. Significant drops or rises in traffic volume can result when temperatures become either extremely cold or very mild. Such changes in traffic volumes due to temperature are consistently observed over the study period.
    c. Severe weather conditions can cause more trip adjustments for home-leaving traffic than returning traffic.
    d. Significant changes in shapes of hourly volume patterns can result with extremely cold temperatures.
    e. A reduction in traffic volume occurs with snowfall, as well, and the amount of reduction varies with the number of centimetres of snowfall.
    f. Intensity and time of occurrence of snowfall can affect the hourly traffic variations, but the effect of snowfall on traffic volumes is consistently higher for evening hours as compared to morning and afternoon hours. The higher evening peak hour reductions may be caused by travelers' perception of snowfall conditions for the whole day rather than the actual time of occurrence of snowfall conditions.
    g. The traffic volume reductions become exaggerated if snowfall occurs during severe cold conditions.
    h. The commuter highways experience the lowest traffic variation due to cold and snow. The impact of cold and snow is very high on recreational roads. The traffic variations are moderate for rural long distance roads and low for regional commuter roads.

2. A reduction in traffic volume patterns during severe cold conditions result due to trip adjustments. Such trip adjustments can be fewer during low to medium cold and much higher during extreme cold conditions. In order to consider such occurrences in the modeling process, the cold temperatures were categorized into 7 ranges with 5°C intervals. A total of 16 daily traffic volume models (four highway types and four day groups) were developed (using the model form shown in Equation 3.1) to relate the traffic volume with categorized cold as a dummy variable and total snowfall as a continuous variable. All of the 16 models were statistically significant at 0.001 or higher levels when tested against a null hypothesis using F-tests. From the results of the statistical tests, it can be assumed that the selected

regression model with both continuous and dummy variables is appropriate to relate traffic volume with snow and cold.

3. The impact of cold on traffic volume varies with the day of the week, type of highway, and severity of the cold. The impact of cold on traffic volume for commuter roads is relatively low (0% to -14%). The difference in impact between regular weekdays (-1% to -9%) and weekends (0% to -14%) is also less for these roads. The impact of cold on regional commuter roads is similar to the commuter roads (0% to -16%). The rural long distance roads seem to be affected more (0% to -20%) by the extreme cold in comparison with the commuter and regional commuter roads. The differences between regular weekdays (-2% to -15%) and weekends (0% to -20%) are also greater for rural long distance roads than the commuter and the regional commuter roads. The highest impact of cold on traffic volume (0% to -31%) is observed on the recreational roads. The difference in impact of cold between regular weekdays (-2% to -19%) and weekends (0% to -31%) is also high for these roads.

   3.1 From these results, it can be concluded that the amount of reduction in traffic volume due to severe cold is related to the proportion of discretionary trips. The existence of more discretionary trips results in higher trip adjustments and, hence, higher traffic reductions. The commuter and regional commuter roads carry mostly work and business trips (necessary trips); thus, they encounter low trip adjustments and low traffic reductions due to cold. The impact of cold on such roads is almost the same for both weekdays and weekends, indicating the existence of other necessary trips in addition to weekend work and business trips. The impact of cold is much higher for recreational roads because they carry a high proportion of social-recreational trips, which are discretionary in nature. The social-recreational trip makers have more choices as to whether or not they will make a trip with respect to cold conditions during weekends as compared to weekdays; hence, the weekend traffic is more influenced by severe cold. The impact of cold on traffic volume variations for rural long distance roads is generally similar to the recreational roads. However, numeric values are slightly lower than recreational roads and higher than the commuter and the regional commuter roads. It may also be noted that the differences in impact of weather for shorter (commuter roads) and longer (recreational roads) trips could be because of respective risks associated with them. For example, recreational trips are associated with higher risk for being away from the population centres during travel, and, hence, they experience higher reductions in traffic volumes.

4. A clear reduction in daily traffic volume due to snowfall was also identified in this study. The amount of reduction varies from -7% to -17% for snowfall of '10 cm' unit. The reductions can be as high as -21% to -51% during snowstorms (a snowfall of '30 cm' or above). However, no definite patterns are observed with respect to the day of week and highway type. The possible reasons for lack of any definite patterns, as found in the case of cold, could be low sample size, as compared to the cold data, and varying snow clearing policies used in different jurisdictions in which the study sites are located. Another reason could be that the duration and time of occurrence of snowfall may influence the impact of snow on traffic volume rather than total snowfall. These observations are similar to the study findings previously reported by other researchers (Hanbali and Kuemmel, 1993; and Knapp and Smithson, 2000).

5. 94% of the hourly traffic volume models developed using a model form similar to the one shown in Equation 3.1 are statistically significant at a 95% confidence level (using F-test) with the R^2 values ranging from 0.847 to 0.998. A thorough examination of these models led to following inferences.

5.1 The impact of extreme cold on peak hours (-6% to -10%) is less than the daytime off-peak hours (-10% to -15%) for regular weekdays on commuter roads. A high proportion of work and business trips (necessary trips) during the peak hours may be one reason for lower reductions. The impact of extreme cold on weekend hourly volumes (-13% to -17%) is similar to weekdays. The traffic reduction patterns of Fridays are similar to regular weekdays but with slightly higher reductions, which could result from the high proportion of discretionary trips, such as shopping and evening weekend trips, during Fridays. For recreational roads, the impact of extreme cold on peak hours (-20% to -26%) is higher than all other hours (-17% to -22% for day time off-peak hours and -2% to -15% for late evening and early morning hours) for regular weekdays. This pattern is opposite to the commuter road pattern wherein peak hour reductions are less than off-peak hour reductions. The high proportion of social and recreational trips (which are discretionary in nature) during peak hours of recreational roads may be the main reason for such patterns. Due to the high amount of recreational travel that usually takes place during weekends, the impact of cold on morning and evening peak hours of weekends is very high (-30% to -58%). The traffic during morning peak hours (home leaving traffic) is more discretionary than evening peak hours (returning traffic); hence, the reductions during morning peak hours (-42% to -58%) are higher than evening peak hours (-30% to -40%).

6. Careful examination of plots of traffic volumes versus cold and snow interactions (model developed using Equation 3.2) clearly indicated that the impact of cold and snow interactions on traffic volumes is very low for commuter roads. In other words, the effect of snowfall on commuter roads is generally the same at all temperature ranges. This finding is confirmed by the low increase in model R^2 values associated with the inclusion of an interaction variable in the model. Therefore, the traffic weather models without interaction variables are adequate for commuter roads. On the other hand, for recreational roads, the reductions in traffic volumes due to snowfall increase with the severity of cold temperatures. The reductions due to each centimetre of snowfall range from -0.5% to -3.1% for low to high intensities of cold. The increases in model R^2 values with the inclusion of an interaction variable are also high for these roads. Therefore, for recreational roads, the traffic weather models with interaction variables can provide better results than the models that do not consider interaction effects of cold and snowfall.

7. The traffic weather relationships that were analyzed to examine the adaptability of drivers to worsening winter weather conditions led to another important conclusion. The impacts of cold temperature on highway traffic volumes vary within the winter season. In general, the starting months of the winter season experience much higher reductions in traffic volume as compared to the same temperature range during other winter months. This can be attributed to more trip adjustments during the start of the winter season. As winter progresses, the behaviour of travelers may change due to psychological adaptation to winter weather conditions.

8. A number of conclusions were drawn from the impact of weather on truck traffic study. Firstly, both car and truck traffic volumes on highways vary with severity of cold and amount of snowfall. The impact of cold temperature on both car and truck volumes is marginal during no snowfall days. The reduction in traffic volume due to cold temperature would intensify with a rise in amount of snowfall indicating the existence of cold and snowfall interactions. With higher amounts of snowfall, passenger cars experience higher reductions due to cold and snowfall as compared to trucks. A snowfall of 15cm or higher during severe cold conditions (-20°C or lower) would result in very few Cars travelling on the road. Moreover

passenger cars experience higher traffic reductions in weekends as compared to weekdays. In the case of trucks the impact of cold and snow on truck traffic is similar for weekdays and weekends.

It is evident from this study that passenger cars are more vulnerable to adverse weather conditions than trucks. This vulnerability to severe weather conditions could be attributed to such behavior of drivers as choosing flexible departure times, changing routes, or canceling travel entirely and being able to make trip adjustments by avoiding discretionary trips. Trucks are not as greatly affected as passenger cars by adverse weather conditions. Trucks (or commercial vehicles) are usually required to follow rigid schedules to complete their mandatory travel irrespective of severe weather conditions. These kinds of business-oriented mandatory movements are most likely to generate unique truck travel patterns even when weather is unfavorable for making a trip. Interestingly, the modeling results for one of the study sites reveal that higher truck traffic volumes can result during heavy snowfall (or other adverse weather conditions) in winter months. This is contradictory to observations from other similar studies in the literature. None of the studies in literature have reported such an increase in traffic volumes during severe weather conditions. A further investigation carried out for this study to understand the reasons for such behavior indicated shifting of trucks from secondary highways to primary highways due to poor winter maintenance programs. Therefore it can be concluded that there is a possibility of traffic volume increases on high standard highways during adverse weather conditions; which could happen due to shift of traffic from parallel low standard highways.

5. Study Applications

The traffic-weather relationships developed in this study have several applications in the field of transportation engineering. Two major applications among them were selected for detailed analyses: (1) imputation of missing traffic data during winter months and (2) estimation of AADT from short-term traffic counts undertaken during winter months. The traditional imputation methods, when used to impute missing data during winter months, result in very large imputation errors. However, traffic weather models that consider the traffic variations during winter weather conditions reduce the imputation errors considerably if they are used to impute missing traffic data during winter months. For example, in the case of recreational roads, the average errors resulting from traffic weather models are in the range of 6% to 9% and 7% to 13% for weekdays and weekends, respectively. In the case of commuter roads, the average imputation errors are in the range of 3% to 7% for weekdays and 5% to 11% for weekends. These error statistics are about 30% to 60% less than the errors resulting from the South Dakota method, which showed better imputation accuracy among the traditional imputation methods.

Therefore, it can be concluded that inclusion of weather conditions in the imputation analysis results in better estimates of missing values for winter months. Hence, the traffic weather relationships developed in this study can be used by highway agencies for imputation of missing traffic volumes during winter months. The application of the traffic-weather relationships to develop and use weather adjustment factors for accurate estimation of AADT from short duration counts taken during winter months is also thoroughly investigated in this study. The following equation shows the AADT estimation method with the weather adjustment factor:

$$EAADT_W = SDC_{dm} * AF_{dm} * WF_{dR} \quad (5.1)$$

Where $EAADT_W$ is estimated AADT by the proposed method, which considers weather conditions; AF_{dm} is the adjustment factor for a 48-hour count starting at noon on day ‘d’ in the month ‘m’; WF_{dR} is the weather factor for the counting period starting on day ‘*d*’ during which the average temperature lies in cold category ‘*R*’. The AADT estimation errors that result from the proposed study approach, when applied to winter short duration counts, are in the range of 9% to 14% for commuter roads and 12% to 23% for recreational roads. These error

statistics are comparable to the AADT estimation errors of 9% to 13% (for commuter roads) and 11% to 18% (for recreational roads) that result from the traditional factor approach when applied to summer short duration counts. Based on these results, it can be concluded that short duration counts taken during winter months using such methods as radar and video cameras can also provide equally reliable estimates of AADT. Therefore, for efficient traffic monitoring programs, it is recommended that highway agencies carry out short duration counts during winter months as well.

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