Highway Traffic Volume Variations with Cold and Snow Interactions

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Abstract:

Present study investigates the traffic volume variations due to the interaction of sever weather conditions. The study is based on hourly traffic data from 350 permanent traffic counter sites located on provincial highway system of Alberta, Canada, and weather data obtained from Environment Canada weather stations located within 15 miles from the selected permanent traffic counter sites, during the period 1995-2005. Multiple regression analysis is used for the study analysis. The model parameters include three sets of variables: amount of snowfall as a quantitative variable, categorized cold as a dummy variable and an interaction variable formed by the product of above variables. The developed models closely fit to the real data with R-square values of above 0.99. The study results indicate that the impact of cold and snow on traffic volume varies with day of week, hour of day and adversity of weather conditions. Traffic volume on a day decreases with the increase in severity of cold and snow. A reduction of 1% to 2% in traffic volume for each centimeter snowfall is observed when the mean temperatures are above 0^{o}. For the days with zero precipitation, reductions in traffic volume due to mild and severe cold are 1% and 31% respectively. An additional reduction of 0% to 3% per one centimeter of snowfall results when snowfall occurs during severe cold conditions.

1. Introduction

It has long been recognized that adverse weather is associated with risky driving conditions. The risk levels depend on intensity of bad weather and exposure of a vehicle to other traffic during such conditions. Furthermore, there is some evidence in literature that severe weather conditions can cause reduction in highway traffic volumes. Hence, the risk of an accident during severe weather conditions is dependent on the traffic volume, which itself is dependent on the same conditions. Therefore, a relationship between weather and traffic volume can be helpful in analyzing the effect of weather on highway safety.

Highway agencies in North America and many other parts of the world maintain Permanent Traffic Counters (PTC) and sample traffic counts to monitor the traffic volumes on their highway system. However, presence of missing values in the collected data due to malfunctioning of PTCs is inevitable. Several imputation methods to estimate the missing traffic data are available in literature. But, none of the known methods used by highway agencies consider the distorted traffic conditions caused by weather. Estimation of missing traffic volumes without considering the association of traffic with adverse weather may result in large estimation errors. Moreover, quantifying the influence of weather on traffic volume variation is helpful to establish traveler information systems and traffic management systems through accurate short term traffic predictions. By considering the above mentioned practical applications the present study attempts to quantify the traffic volume variations due to the interaction of different weather conditions.

Owing to the geographical locations, the winter weather in Canada and many parts of the United States is very severe with high wind chills, heavy snowfall, blizzards, freezing rain and extremely cold temperatures (below -35^{o}C). These extreme weather conditions may cause a significant variation in traffic movement. Existing literature indicates that a reduction in traffic movement occurs due to travelers' less desire to travel during wet or snowy weather (Palutikof, 1981). The reduction is a function several factors such as the type of highway, hour, day, normal traffic volume, level of service, road-user behavior & satisfaction, weather conditions, and other factors (Hanbali and Kuemmel, 1993). Attempts have been made in literature to quantify the impact of various weather parameters on traffic volume (Such as, Hanbali and Kuemmel, 1993; Knapp and Smithson, 2000; Changnon 1996; 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). But none of the research efforts include the impact of cold on traffic volume in Canada or elsewhere. Andrey *et al.,* (2003) reported that snow is an influential weather parameter for Canadian roads. Hence, cold and snow are chosen to represent the weather conditions.

The main objective of this investigation is to study the effect of cold and snow interactions on daily and hourly traffic volume variations with detailed considerations given to the highway type and location. The study is based on hourly traffic data from 350 PTC sites and weather data from 598 weather stations in the province of Alberta, Canada, using 11 years of data from 1995 to 2005.

2. Review of Literature

Among the past studies on the impact of weather on traffic volume, the studies which are most relevant to the present investigation are discussed in this section.

Hanbali and Kuemmel (1993) studied the average traffic volume reductions due to snow storms on highways away from the major urban centres in the United States. The study was based on data collected from 11 locations during first 3 months of 1991. They analyzed the effect of snow storms with respect to Average Daily Traffic (ADT), time of day and day of week (weekday or weekend). The reported traffic volume reductions ranged from 7% to 56% depending on the adversity of snow storm. Hassan and Barker (1999) studied the impact of unseasonable or extreme weather on urban traffic activity within Lothian region, Scotland. Data from one site over a period of 5 years from 1987 to 1991 were used in the analysis. The meteorological parameters such as minimum and maximum temperatures, snow and rain fall, snow on ground and sunshine hours were considered in their study. The 10% of days with either 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. Knapp and Smithson (2000) analyzed the average traffic reductions on interstate highways in Iowa State during winter storms. The study data was obtained from 7 sites during 3 winter seasons over the period 1995-1998. 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/hr. 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. Keay and Simmonds (2005) reported the association of rainfall and other weather variables with traffic volume on urban arterials in Melbourne, Australia. The study data consists of 802 days (171 days in summer, 208 days in autumn, 264 days in winter and 159 days in spring) spread over a period of 1989 to 1996. They designed regression models incorporating the trend of historical traffic, day of the week, holidays and weather. Separate analyses were conducted for day time and night time 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.,* reported a strong correlation between the percentage reduction in traffic volume and wind speed and visibility during snowy days. They have reported 20% reduction in traffic during snowy days with good visibility and low wind speed. The reductions are about 80 percent when the visibility less than one-quarter mile and high wind speed (as high as 40 miles per hour).

None of the above investigations considered the interaction effect of severe cold and snow on traffic volume variation. The traffic volume variation with respect to the highway type has also not been explored in the past studies. Moreover, there is no evidence of thorough statistical analysis in the literature, due to the data limitations. Based on large traffic and weather data from the province of Alberta, a detailed investigation is carried out in this study to analyze the traffic variation due to cold and snow with respect to the hour of day, day of week and type of the highway.

3. Study Data

3.1 Traffic Data

The main source of Traffic data for this study is the system of Permanent Traffic Counter (PTC) sites located on the provincial highways in Alberta, Canada. In 1995, Alberta Infrastructure and Transportation (the agency responsible for provincial transportation in Alberta) employed nearly 350 PTC sites to monitor its highway network. Each PTC represents a particular highway segment. The most recent data available at the start of this study were hourly traffic volume data for 11 years from year 1995 to 2005.

The PTC sites were classified into different groups namely, commuter, regional commuter, rural long distance and recreational roads using the classification method proposed by Sharma et al., (1986). The typical monthly and daily variations of these road groups are shown in Figure 1. The monthly factor (the ratio of monthly average daily traffic to annual average daily traffic) plots in Figure 1a show high monthly variation for the recreational roads and little variation for the commuter roads. The average winter (November to March) daily traffic volume to annual average daily traffic (AADT) ratio versus day of week plots are shown in Figure 1b. There is an upward trend in weekday (Monday to Friday) traffic for all the counters irrespective of the group. There is only a slight increase from Monday to Thursday, however, traffic on Friday increases substantially in both cases. The weekend traffic volumes are higher than weekday traffic for recreational roads and an opposite pattern is observed for commuter roads. It may also be noted that, the commuter roads carry predominantly work and business trips, and Recreational roads carry large portion of both recreational and other discretionary trips. Among these four groups, two major road types, commuter roads and recreational roads, are chosen for illustration.

3.2 Weather Data

The climate data were obtained from Environment Canada (Environment Canada, 2006). There were 598 weather stations operated by Environment Canada in the province of Alberta between the years 1995 to 2005. The weather parameters such as maximum, minimum, and mean temperatures, rain, snow fall, 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 in Environment Canada (2006).The amount of rain fall is very insignificant for winters, hence, it is not considered in the analysis.

3.3 Selection of Study Sites

Geographical Information Systems (GIS) database for 350 PTC sites and 598 weather stations was developed using the GIS software TransCAD 4.5 (TransCAD, 2005). Preliminary investigations indicated that at least 6 years of traffic data without any missing values would be required to get enough data points for the study analysis. The PTC sites having minimum 6 years of traffic data (within the study period 1995-2005) without missing values were identified using GIS. A set of sites with at least two weather stations within 15 miles from the PTC location were identified using overlay analysis of GIS. Based on the distance decay effect of weather reported by Andrey and Olley (1990), it was assumed that the weather is homogeneous within the 15 mile area around the PTC site. The PTC sites satisfying both the above conditions were short listed. Five short listed PTC sites belonging to each group (total 10 PTCs) were selected for study investigations. Wide range of AADTs and spread of counters were also taken into consideration while selecting the PTC sites.

The weather data for stations belonging to each PTC site were obtained and the missing values in closest weather station data were augmented with the data from other nearby stations. A map showing provincial highway network, weather stations and selected PTC sites along with their road group and AADT is presented in Figure 2.

On the basis of Environment Canada (2006) climate database, the province of Alberta experiences significant snow and severe cold conditions during the period of mid-November to end of March. For this reason the present analysis was limited to the months November to March. There are 3 holidays observed in the study months namely, Christmas day (25^{th} December), New Year Day (1^{st} January) and Alberta Family Day (3^{rd} Monday of February). Because of the unique travel characteristics during the holiday and neighboring days (Liu and Sharma, 2006)**,** they were not included in this study. Thus, 13 weeks (5 weeks from Mid-November to December and 8 weeks from January to March) from each year were considered for detailed analysis.

4. Methodology

Literature indicates standard regression analysis is appropriate to quantify the association of weather with road traffic. For example, Keay et al. (2005) successfully used regression analysis to quantify the effect of rainfall on road traffic volume. Furthermore, Knapp et al. (2000) showed the relationship between traffic volume and total snowfall using regression analysis. Based on these previous successful experiences, a regression model is designed to relate the traffic volume with categorized cold, total snowfall, cold and snow interactions and expected traffic volume (assumed to be based on range of weather conditions) which is calculated from 6 to 11 years of historical data. In order to analyze the effect of cold according to its severity, it is categorized into 5^{o}C intervals. The reason for selecting such an interval is to match with general practice of presenting Canadian weather norms by Environment Canada. The interaction variable is formed by the product of categorized cold and snow variables. The normal traffic volume and the trend in weekly traffic volumes at a PTC site are considered by including expected traffic volume (determined using historical data of the same month, week, and day) as an independent variable in the model. The traffic volume factors (volume to AADT ratios) rather than traffic volumes (number of vehicles) are used in the analysis to take care of yearly variations in traffic volumes. Thus, proposed models include four sets of variables: amount of snowfall and expected traffic volume as quantitative variables, categorized cold as a dummy variable and the interaction variable formed by the product of cold and snow variables

4.1 Structure of the Proposed Model

The structure of the proposed model for daily traffic volume is:

$$VF_{WDYCG} = B_a * EVF_{WDCG} + B_s * S_{WDYCG} + \sum_{R=1}^{6} B_R * C_{RWDYCG} + \sum_{R=1}^{6} B_{RS} * S_{WDYCG} * C_{RWDYCG} \quad \textbf{[1]}$$

Where: W represents the week number it can be any value from 1 to 13; D indicates the day group: M for Monday to Thursday, F for Friday, Sa for Saturday and Su for Sunday; Y represents the year, from 1995 to 2005 based on the availability of traffic data for the corresponding PTC site; C is the PTC number; G represents the group number to which the PTC site C belongs to;

VF_{WDYCG} is the daily Volume Factor (daily volume to AADT ratio) of a particular day D of the week W of a year Y for the PTC site C belongs to group G. For example: $VF_{3F96CRec}$ is volume factor of 3rd Friday of 1996 on the highway segment represented by a PTC site C which belongs to Recreational group.

EVF_{WDCG} (Expected Volume Factor), is the average VF_{WDYCG} calculated using all available years of data for a particular $WDCG$ (example: EVF_{3FCRec} is average VF_{WDYCG} calculated from $VF_{3F95CRec}$ to $VF_{3F05CRec}$).

S_{WDYCG} is the total snow on a $WDYCG$ in centimeters. Both EVF_{WDCG} and S_{WDYCG} are treated as quantitative independent variables in the model.

The cold variable C_{RWDYCG} is treated as a dummy variable, an additional suffix R is added to this variable to represent the cold category. For the reasons mentioned earlier the cold is categorized into 6 classes: 0^oC to -5^oC, -5^oC to -10^oC, -10^oC to -15^oC, -15^oC to -20^oC, -20^oC to -25^oC, and below -25^oC. The value of C_{RWDYCG} equals 1 if the mean temperature of a $WDYCG$ falls in the class R or *'0'* otherwise. Example: if the mean temperature of the day under study is -23^o,it falls in class five, the value of variable C_{5WDYCG} becomes *'1'* and *'0'* for remaining classes of R. The temperature above 0^oC is not included in the cold categorization because this category is taken as the reference class. More details on incorporating dummy variables in regression analysis are available in Hardy (1993).

To analyze the effect of snowfall on traffic volume at different cold conditions, the interaction variable is added in the model. Interaction variables are computed by multiplying total snowfall with each of the six categories of cold.

B_a, B_s, B_R and B_{RS} are coefficients to be estimated by regression analysis. When an independent variable is continuous (such as EVF_{WDCG} and S_{WDYCG}) the distribution of dependent variable VF_{WDYCG} is also continuous and the regression coefficients B_a and B_s indicate slope. In contrast, when independent variable is a dummy variable (such as C_{RWDYCG}), the predicted value 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. The coefficients B_{RS} of interaction variable. which is a product of continuous and dummy variables, indicate the variation in B_s with each category of cold.

Therefore, the coefficient B_a, in Equation 1 represents the deviation of VF_{WDYCG} from EVF_{WDCG}, when there is zero snow and the daily temperature falls in reference class.

The coefficient B_s gives the change in VF_{WDYCG} for each ‘cm’ of additional snowfall when the temperature is above 0^oC. B_R indicates the change in VF_{WDYCG} from reference category (above 0^oC) to category R. The coefficients B_{RS} estimates the net effect of each centimeter snowfall on VF_{WDYCG} in addition to B_S (i.e effect of snowfall when temperature is above 0^oC) for the cold category R.

To make the Equation 1 easy to understand, a vector form shown below is developed for the input data corresponding to a Friday on PTC site *C* of recreational group (represented with *‘1’*), which has data from 1995 to 2005. The total data points for this example are: 13 winter Fridays in a year and 11 years from 1995 to 2005, making 143 data points. A total of 16 similar vector forms (4 highway groups and 4 days of week) were used for the modeling process.

$$\begin{bmatrix} \begin{bmatrix} VF_{1F95C1} \\ . \\ VF_{1F05C1} \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \\ \begin{bmatrix} VF_{2F95C1} \\ . \\ VF_{2F05C1} \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \\ . \\ . \\ . \\ \begin{bmatrix} VF_{13F95C1} \\ . \\ VF_{13F05C1} \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \end{bmatrix}_{143*1} = B_a \begin{bmatrix} \begin{bmatrix} EVF_{1FC1} \\ . \\ EVF_{1FC1} \end{bmatrix} \\ \begin{bmatrix} EVF_{2FC1} \\ . \\ EVF_{2FC1} \end{bmatrix} \\ . \\ . \\ . \\ \begin{bmatrix} EVF_{13FC1} \\ . \\ EVF_{13FC1} \end{bmatrix} \end{bmatrix}_{143*1} + B_s \begin{bmatrix} \begin{bmatrix} S_{1F95C1} \\ . \\ S_{1F05C1} \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \\ \begin{bmatrix} S_{2F95C1} \\ . \\ S_{2F05C1} \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \\ . \\ . \\ . \\ \begin{bmatrix} S_{13F95C1} \\ . \\ S_{13F05C1} \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \end{bmatrix}_{143*1} + \begin{bmatrix} \begin{bmatrix} C_{11F95C1} & . & . \\ . \; .. \; .. & . & . \\ . \; .. \; .. & . & . \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \\ \begin{bmatrix} 1 & 0 & . & . & 0 \\ 0 & 1 & . & . & 0 \\ . & .. & .. & . & . \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \\ . \\ . \\ . \\ \begin{bmatrix} 0 & 0 & . & . & 1 \\ 0 & 0 & . & . & 0 \\ . & .. & .. & . & . \end{bmatrix} \begin{matrix} 95 \\ . \\ 05 \end{matrix} \end{bmatrix}_{143*1} \begin{bmatrix} B_{R=1} \\ B_{R=2} \\ B_{R=3} \\ B_{R=4} \\ B_{R=5} \\ B_{R=6} \end{bmatrix}^T + \sum_{R=1}^{6} B_{RS} * S_{WDYCG} * C_{RWDYCG}$$

[V1]

4.2 Statistical Tests

The overall fitness of the regression model to the sample data was evaluated using R^2, which is the square of multiple correlation coefficient. Because the effect of cold on traffic volume is captured by a set of dummy variables rather than by a single dummy variable, F-test is an appropriate significance test for the model (Hardy, 1993).

$$F = \frac{R^2 / K}{1 - R^2 / N - K - 1} \qquad \textbf{[2]}$$

Where k is the number of independent variables in the model and N is the total number of data points used.

The t-tests are used to assess the significance of individual coefficients of dummy variables. As the population variance is not known, the t-distribution is preferable than Z distribution. The coefficient B_R in the model measures the average effect of being in a particular cold category rather than in the reference category. Therefore, the standard error of coefficient B_R provides the standard error of the differences in effect when cold category falls in reference class and when it falls in category *R*. In order to test a coefficient against a null hypothesis of a zero effect (*i.e.,* no additional impact of being in that category rather than in reference category), its t value is calculated (ratio between the coefficient B_R and its standard error) and compared with critical t value.

4.3 Interpretation of Model Coefficients

Once a model was developed using regression analysis, the coefficient B_a gives the deviation of volume factor from the average when there is zero snow and the daily temperature falls in reference class. The coefficient B_S provides the effect of unit ('1 cm') snow on traffic volume when daily temperature falls in reference class. The six (cold categories) values of coefficient B_R gives the reduction in volume factor of being in each cold category relative to reference category. The coefficients B_{RS} estimates the net effect of unit snowfall on traffic volume in addition to B_S for cold category *R*. The percentage reduction in traffic volume factor due to each category of cold relative to reference category is the ratio between coefficient B_R and the average of VF_{DWYCG} for the sample data with above 0^oC temperature (reference class). The mathematical form to compute percentage reductions is shown in Equation 3.

$$PR_R = \frac{B_R}{\frac{1}{N}\sum_{1}^{N} VF_{DWYCG}\left[1 - \sum_{1}^{6} C_{RWDYCG}\right]} \qquad \textbf{[3]}$$

Where PR_R is percentage reduction in volume factor for cold category *R* relative to reference category, *N* is the sample size *i.e.,* 13 (winter weeks) multiplied by the number of years of data available for the *DCG* (day *D*, counter *C* which belongs to group *G*) under observation (varies from 6 to 11); *n* is the number of days in the sample data falling in reference category for the *DCG* under observation*.* The other terms are same as defined for Equation 1.

5. Analysis and Results

The effects of cold and snow on temporal and spatial variation of traffic volume are analyzed using the model coefficients calculated using Equation 1.

5.1 Effect of Cold on Daily Volumes

The typical daily volume variations of each highway group in Figure 1b show that, the traffic volumes on Mondays to Fridays are generally similar. Friday volumes are significantly higher than other weekday volumes. The Sunday and Saturday volumes also seem to be different. Therefore, analysis is performed separately for four day groups (DG), namely, Mondays-Thursdays combined, Fridays, Saturdays and Sundays. Table 1 shows the 8 daily models (two highway types and four day groups) developed using Equation 1. The models shown in Table 1 are developed with combined data from five PTC sites belonging to each highway group. For example, the vector form *V1* shows the data for a single PTC site with 143 days of data. Five such vector forms belonging to different PTC sites of each group making a total of 715 days of data (for this particular case) are collectively used for the model development. The sample size is varied from 414 to 2123 days, depending on the available years of data and day group. In Table 1 the values of coefficient B_a are positive and above *'1'* for all cases indicating that, traffic volume factors are higher than expected traffic volume factors when there is no snowfall and the temperature falls in reference class (above 0^o). The coefficient B_s clearly shows a reduction in volume factor due to each 'cm' of snowfall. The values of coefficient B_R are increasing from B_1 to B_6 showing increase in effect of cold with its severity. Apparent variation in interaction coefficients B_{RS} (from B_{1S} to B_{6S}) in the developed models indicate the existence of interaction effect of cold and snow. The R^2 values of all models are greater than 0.99. The sample size and calculated F-values using Equation 2 are shown in the bottom rows of the table. All the F-values are statistically significant at 0.001 or a higher level. Based on these statistical test results it could be acknowledged that selected regression model with both continuous and dummy variables is appropriate to relate traffic volume with snow and cold.

Figure 3 shows percentage reduction (PR) in traffic volumes calculated using Equation 3 for different days of week and cold categories for each highway group. It is evident from these histograms that the traffic volume on a day varies with severity of cold. The patterns clearly indicate decreasing trends of traffic with increase in severity of cold. As mentioned earlier, the PR values shown in this figure are the average percentage reductions in volume factors due to each category of cold relative to the reference category (above 0^o). The amount of decrease in traffic volume due to a cold category depends on its difference from the reference category. The daily traffic volume can be expected to decrease up to about 30% if the cold is very severe (below -25^{o}C).

In general, weekend traffic is more susceptible to cold than weekdays. The reason may be due to the large proportion discretionary trips during weekends. Even though Friday is a weekday its percentage reduction patterns differ from other weekdays for all groups of highways. The proportion of discretionary trips in Mondays-Thursdays (mentioned as regular weekdays hereafter) are generally low but the Friday is a special case where certain number of discretionary trips exists in addition to the nondiscretionary trips. This might be the reason for altered patterns for Fridays. Moreover, the plots shown in Figure 1b indicated significant differences between Saturdays and Sundays, but the percentage reduction patterns are generally similar for Saturdays and Sundays.

Figure 3 clearly shows that different groups have different patterns of PR values. The impact of cold (based on the range of PR values from category 1 to 6) on traffic volume for commuter roads (Figure 3a) appear to be very low (0% to -14%). The difference in impact between regular weekdays (-1% to -9%) and weekends (0% to -14%) is also less. The impact of cold on traffic volume (0% to -31%) is very high for recreational roads (Figure 3d). The difference in impact of cold between regular weekdays (-2% to -19%) and weekends (0% to -31%) are also high for this group. With respect to the Friday variations, commuter roads show little deference between regular weekdays and Fridays, but noticeable differences are observed for recreational roads.

In summary, the commuter roads carry mostly work and business trips (necessary trips), hence they encounter lowest variation 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 high proportion of social-recreational trips which are discretionary in nature. The social-recreational trip makers may be more decisive in making or not making a trip with respect to cold condition during weekends as compared to weekdays, hence, the weekend traffic is more influenced by cold.

5.3 Effect of Cold and Snow Interactions on Daily Volumes

The percentage reduction in traffic volume with the occurrence of unit snowfall ('1 cm') during the days with above 0^{o}C temperature, for different days of week corresponding to each highway group is presented in Figure 4. A clear indication of reduction in traffic volume due to snow can be observed in this figure. The amount of reduction varies from -0.5% to -1.7% for each 'cm' snowfall. 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 shown in the case of cold, could be the rare occurrence of snowfall when the average temperature of a day is above 0^{o}C.

To study the variation in traffic volume reductions due to the occurrence of snowfall during sever cold conditions, the values of coefficients B_{RS} of different models are thoroughly examined. As mentioned earlier, the interaction coefficients B_{RS} indicate the reduction in traffic volume for each centimeter snowfall when temperature falls in cold category '*R*', in addition to the reduction occur due to the same amount of snowfall when temperature is above 0^{o}C. Therefore, the total effect of snow is calculated by adding each interaction coefficient to the coefficient B_S. Figure 5a & 5b shows the variation in effect (total) of 1 cm snowfall with severity of cold and for different days of week corresponding to considered highway types. Similar to cold the effect of snow on traffic volume is very low for commuter roads (Figure 5a). Little to no reduction (-0.7% to +1.7%) in traffic volume due to snow and cold interactions is observed i.e, the effect of snowfall on commuter roads is generally consistent at different cold intensities. The day of week effect is also very low. The reasons for such patterns may be large proportion of necessary trips on commuter roads and generally consistent traffic during both weekdays and weekends.

For recreational roads (Figure 5b), the reduction in traffic volume due to '1 cm' snowfall would increase with severity of cold. The reductions may vary from +2% to -3.1% for low to high intensities of cold. The positive values indicate that the traffic volume may be higher than expected when the cold is in the range of 0^{o}C to -5^{o}C. The reason may be due to increased winter recreational trips when the average temperature in a day is between 0^{o}C to -5^{o}C. Significantly high reductions would occur when snowfall happens during sever cold conditions. The effect of day of week is also high for recreational roads. The reductions are low for regular weekdays, medium for Fridays and Saturdays and High for Sundays. These patterns can be attributed to the amount of social and recreational trips on recreational roads during different days of week.

5.4 Effect of Cold on Hourly Volumes

To relate the hourly volume variations with cold, the average daily volume factors in Equation 1 were replaced with historical average hourly volume factors (ratio between hourly volume and AADT) calculated from the same hour, day and week data. Considering that the hourly traffic volume of a given day depends on the perceived daily temperature rather than hourly temperatures, the daily mean temperature of the corresponding day was used in the model instead of the hourly temperature. The effect of snow on hourly volume variation is not performed because the snow data with duration and time of occurrence details are not available. Therefore, the days with zero snowfall are only used in this analysis. This altered procedure produced 24 hourly models for each DG and highway type (total 192 models *i.e.,* 8*24). About 96% of these models were statistically significant at 95% confidence level (using F-test given in Equation 2). The R^2 values ranged from 0.897 to 0.998. Detailed observations on the models indicated that the low R^2 values and failure in the F-test were associated with the models of late night and early morning hours. When only the models of day time hours (7AM to 7 PM) were considered, the R^2 values were between 0.952 and 0.998.

To investigate the effect of cold on hourly volume variations, the hourly percentage reductions due to adverse cold (below -25^{o}C *i.e.,* cold category 6) were calculated from hourly models by using Equation 3. The daily volume factors in Equation 3 were replaced with each of the 24 hourly volume factors to get hourly percentage reductions. Figure 6 and 7 show the hourly PR values for regular weekdays (Mondays-Thursdays) and Weekends for commuter and recreational groups. The typical winter hourly factor (hourly volume to AADT ratios) variations of respective days are also given in these figures using secondary y-axis. The hourly factor variation of regular weekdays on commuter roads (Figure 5a) show morning peak from 7AM to 9AM and evening peak from 4PM to 7PM. A single peak from 2PM to 6PM is observed for weekends (Figure 6b). The weekday pattern of recreational roads (Figure 7a) shows morning peak from 8AM to 11AM and evening peak from 4PM to 7PM. The weekend peaks on these roads (Figure 7b) are observed from 8AM to 10AM and from 4PM to 7PM. It is worthwhile to note here that commuter roads carry high proportion of work and business trips (necessary trips) during peak hours. On the other hand**,** the proportion of social and recreational trips (discretionary trips) is high during peak hours for recreational roads. In order to facilitate the discussion, the hours of a day are divided into early hours (hour 1 to hour 5), day-time hours (6 to 19), and evening hours (20 to 24).

It is evident from the plots shown in Figure 6 and 7 that the impact of cold on traffic volume varies with hour of the day, day of the week and highway type. The PR values of regular weekdays for commuter roads (Figure 6a) indicate the impact of adverse cold on peak hours (-6% to -10%) is less than the day-time off-peak hours (-10% to -15%). The reason for lower reductions may be high proportion of work and business trips (necessary trips) during the peak hours. Even though, the traffic volume variation during weekends is not same as weekdays the impact of adverse cold on weekend hourly volumes (-13% to -17%) is similar to weekdays (Figure 6b).

The PR values of regular weekdays for recreational roads (Figure 7a) show that the impact of adverse 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). This pattern is opposite to the commuter road pattern wherein peak hour reductions are less than off peak hour reductions. High proportion of social and recreational trips (which are discretionary in nature) during peak hours of recreational roads may be the reason for such patterns. Due to high amount of recreational travel that usually take place during weekends, the impact of cold on morning and evening peak hours of weekends is highly intensive (-42% to -58% during morning peak and -30% to -40% during evening peak) as shown in Figure 7b. Moreover, the traffic during morning peaks (home leaving traffic) is more discretionary than evening peaks (returning traffic), hence, the reductions during morning peak hours are higher than evening peak hours.

6. Summary and Conclusions

Limited attempts have been made in past studies to quantify the impact of various weather factors on traffic volume. None of them considered the effect of severe cold on traffic volume variation. The traffic volume variation with respect to the highway type has also not been explored in the previous studies. Based on large traffic and weather statistics from the Province of Alberta, a detailed investigation is carried out in this study to analyze the highway traffic volume variations due to cold and snow with respect to the hour of day, the day of week and the type of highway.

Daily and hourly regression models are developed in this study to relate the traffic volume with cold, total snowfall and the expected traffic volume. In order to analyze the effect of cold according to its severity, it is categorized into 5^{o}C intervals. The R^2 values of the daily traffic volume models are greater than 0.99 and all of them are statistically significant at 0.001 or a higher level when they are tested against null hypothesis using F-test. A great majority of hourly traffic volume models are also statistically significant at 95% confidence level (using F-test). The R^2 values of hourly models of day-time hours range from 0.952 to 0.998. Based on these statistical test results it can be concluded that selected regression model with both continuous and dummy variables is appropriate to relate traffic volume with snow and cold.

The model results indicate that the impact of cold and snow on traffic volume varies with day of the week, hour of the day, type of the highway and the adversity of cold. Traffic volume on a day decreases with the increase in severity of cold. In case of extreme cold (below -25^{0}C) the average winter daily volume can be expected to reduce by about 30%. Even though driving conditions may not be affected due to severe cold, the reduction in traffic volumes may be due to less desire of travelers to travel during severe cold temperatures because of risk in travel and increased necessity for precautionary measures for safe journeys.

For reasons explained earlier in this paper in terms of discretionary and non-discretionary trips, the weekend traffic is more susceptible to cold than weekdays for all types of highways. Even though Friday is a weekday, its response to cold differs from other weekdays. Commuter roads, which carry large proportion of necessary trips, experience lowest variation with cold. Due to high proportion of discretionary trips the impact of cold is significant for recreational roads. The impact of cold on peak hours is more than off-peak hours for recreational roads which is opposite to the commuter road pattern wherein peak hour reductions are less than off peak hour reductions. A clear indication of reduction in daily traffic volume due to snow is also concluded in this study.

Little to no reduction in traffic volume due to snow and cold interactions was observed for commuter roads. For recreational roads, the reduction in traffic volume due to snowfall would increase with severity of cold. The reductions are low for regular weekdays, medium for Fridays and Saturdays and High for Sundays.

Finally the results of this study clearly imply that the association of cold and snow with highway traffic volume should be given due consideration for transportation analyses.

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Table 1 Daily volume factor models

Road Type		Commuter				Recreational			
Day of week		Sun	M-Th	FRI	SAT	Sun	M-Th	FRI	SAT
B_a		1.0284	1.0239	1.0229	1.0364	1.0543	1.0212	1.0375	1.0523
B_s		-0.0102	-0.0126	-0.0170	-0.0127	-0.0131	-0.0090	-0.0053	-0.0110
Coefficients B_R	B_1	-0.0140	-0.0097	-0.0152	-0.0090	-0.0194	-0.0134	-0.0029	-0.0083
	B_2	-0.0222	-0.0226	-0.0254	-0.0178	-0.0369	-0.0229	-0.0212	-0.0261
	B_3	-0.0401	-0.0339	-0.0489	-0.0293	-0.1065	-0.0376	-0.0712	-0.0975
	B_4	-0.0630	-0.0404	-0.0617	-0.0530	-0.1797	-0.0543	-0.1086	-0.1475
	B_5	-0.0770	-0.0737	-0.0767	-0.0865	-0.2612	-0.0735	-0.1281	-0.2175
	B_6	-0.1076	-0.1000	-0.1362	-0.1053	-0.3234	-0.1196	-0.1991	-0.2378
Coefficients B_{RS}	B_{1S}	-0.0019	-0.0048	-	-	-	0.0111	0.0068	-
	B_{2S}	-0.0040	0.0009	0.0069	-0.0026	0.0009	0.0011	-0.0065	0.0072
	B_{3S}	-0.0017	-0.0029	0.0036	-0.0012	-0.0127	-0.0014	-0.0081	-0.0060
	B_{4S}	-0.0023	0.0050	0.0094	0.0018	-0.0155	-0.0053	-0.0170	-0.0112
	B_{5S}	-0.0023	-0.0031	0.0067	-0.0004	-0.0161	-0.0093	-0.0190	-0.0121
	B_{6S}	-	-0.0022	-	-	-	-0.0120	-0.0260	-
R^2		0.997	0.998	0.998	0.997	0.992	0.996	0.996	0.993
Data size		492	1971	492	492	413	1653	414	414
F-statistic		11574	67830	15071	11268	2642	19960	5012	2932

Empty cells implies coefficients not significant at 95% confidence level when tested using t-test

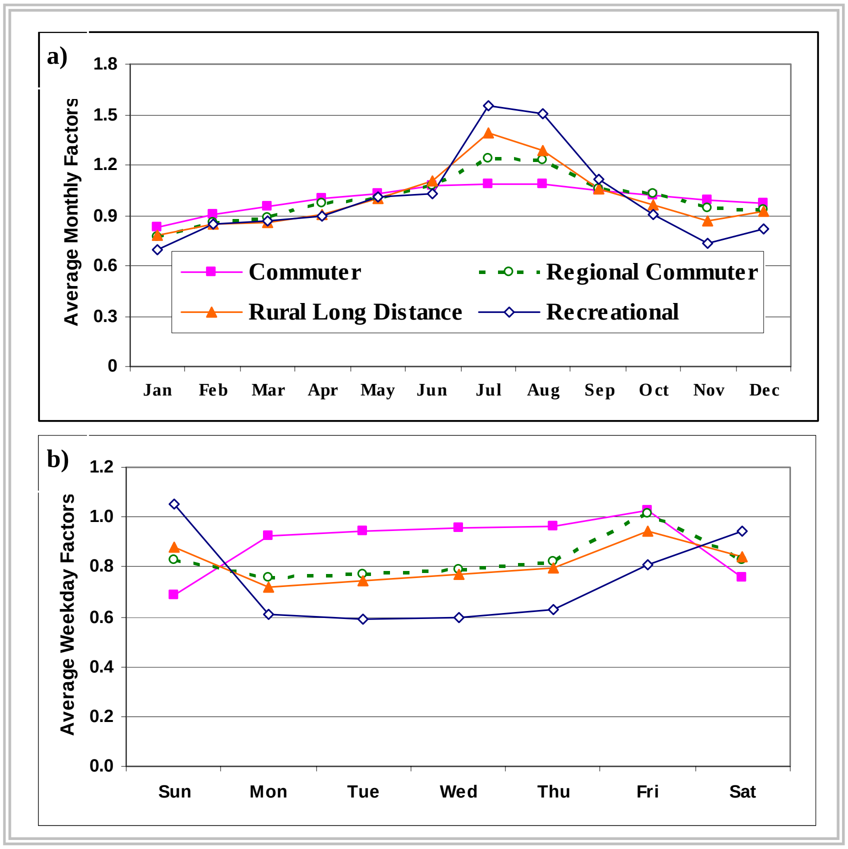


Figure 1 Traffic Volume Variations (a) Monthly (b) Day of the Week

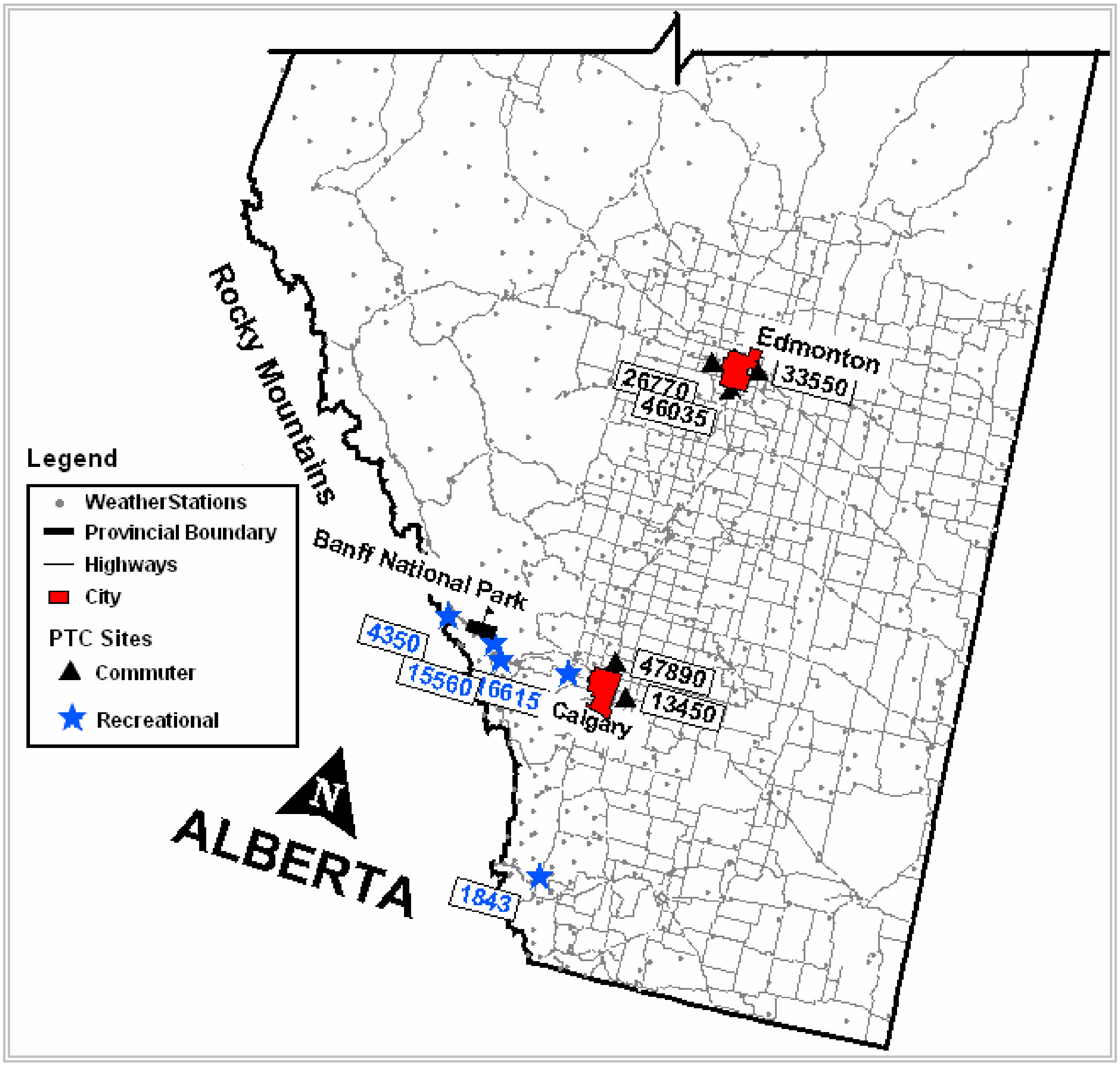
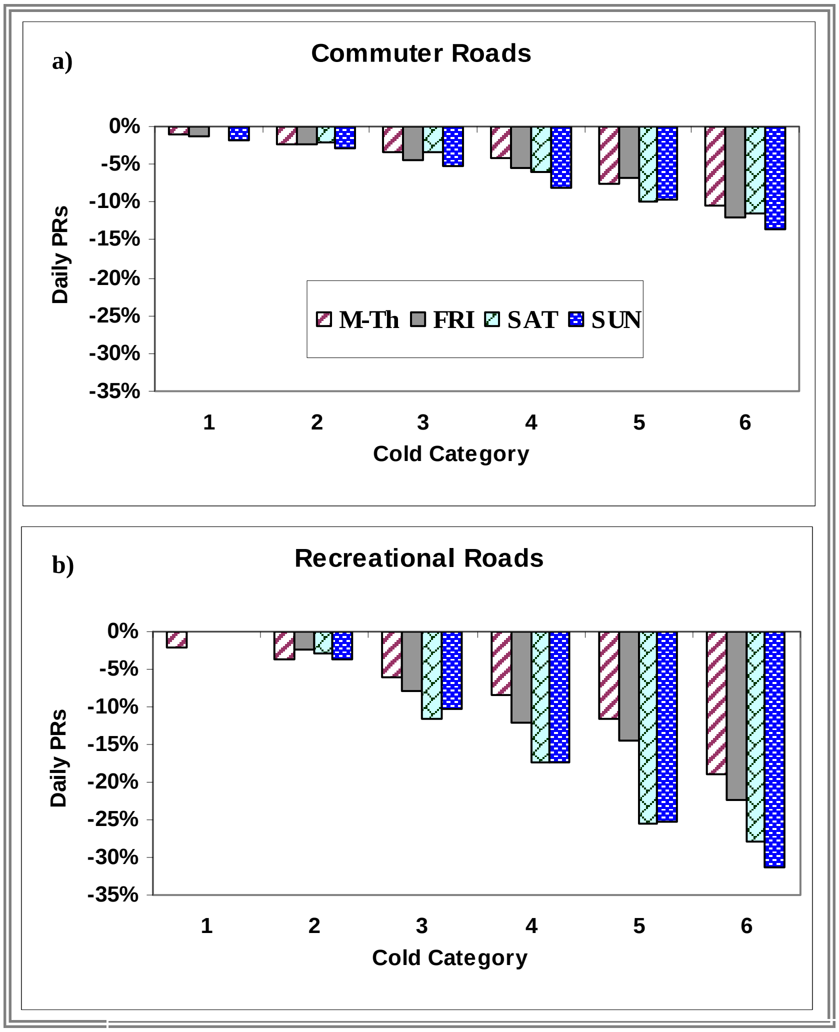


Figure 2 Thematic Map showing Highway Network, Major Cities, Famous Recreational Sites, Selected PTC's and Weather Stations



M-Th Monday to Thursday; FRI Friday; SAT Saturday; SUN Sunday

Figure 3 Effect of Cold on Daily Traffic Volumes of Different Highway Groups

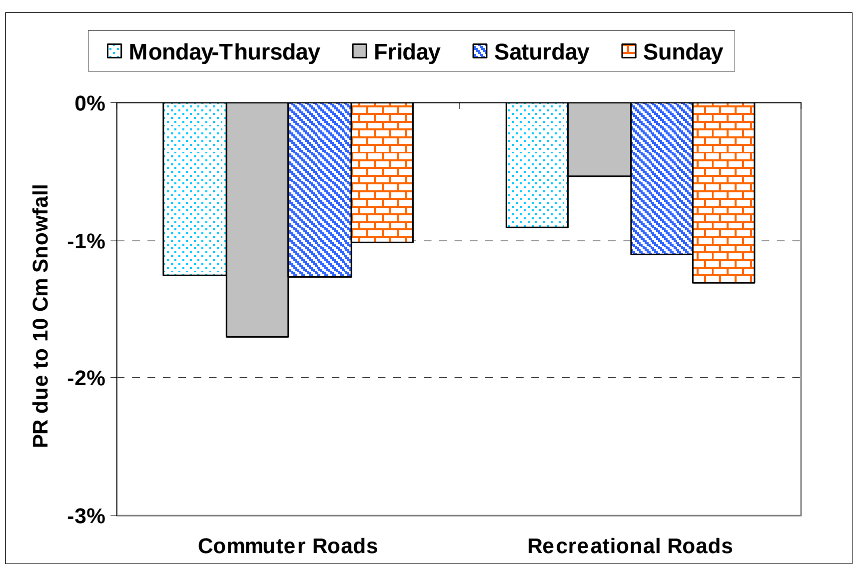


Figure 4 Effect of Snow on Daily Traffic Volumes of Different Highway Groups

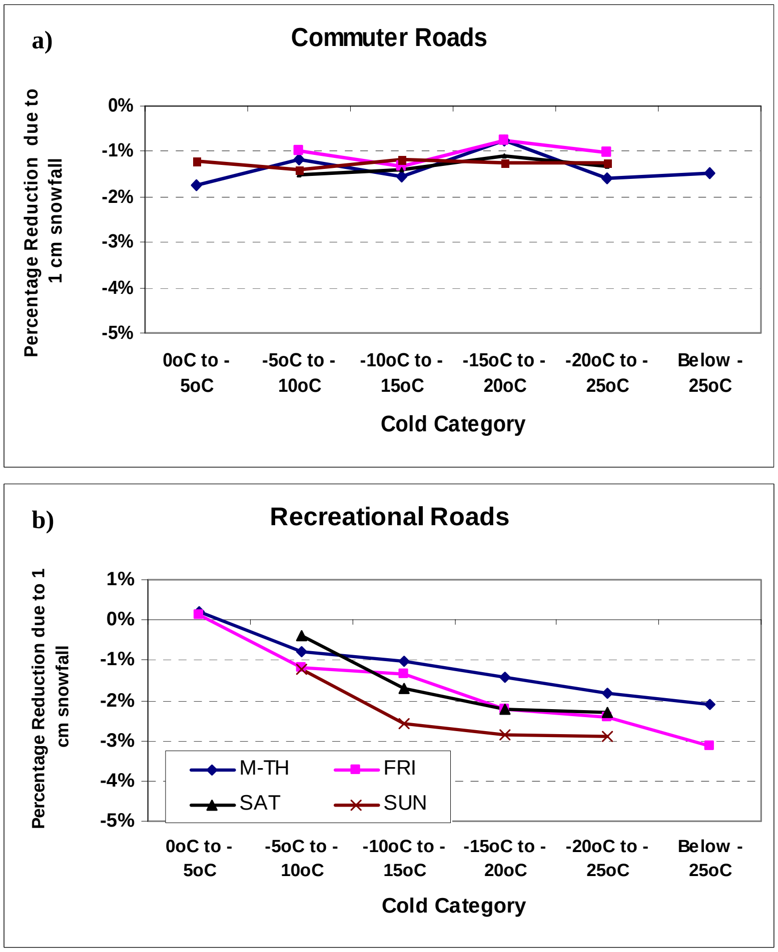
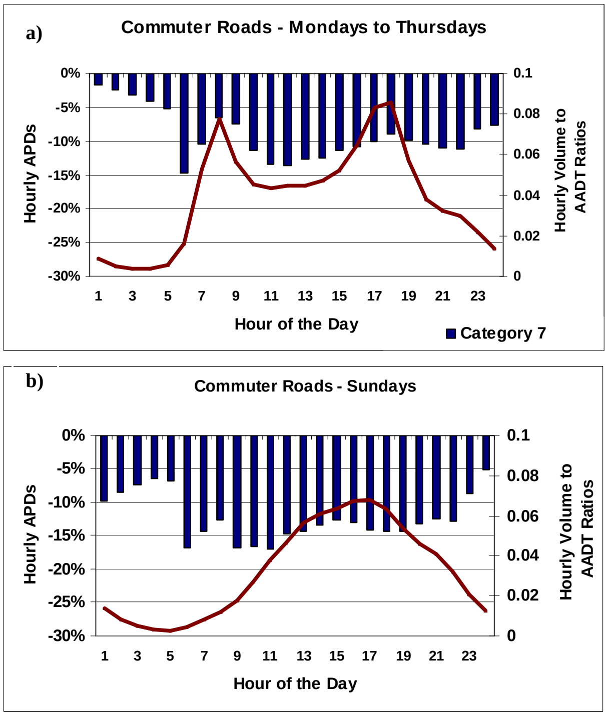


Figure 5 Effect of Cold and Snow Interactions on Traffic Volume



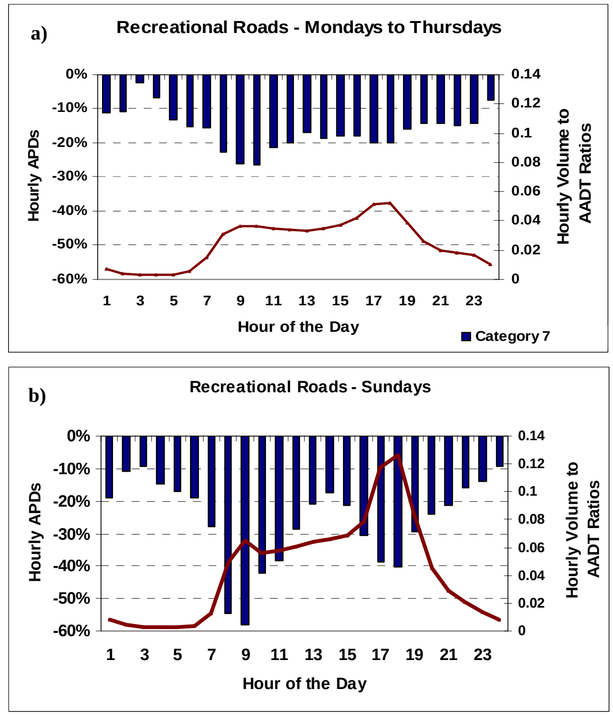


Figure 6 Effect of Cold on Hourly Volumes of Commuter Roads

Figure 7 Effect of Cold on Hourly Volumes of Recreational Roads