

Impacts of Weather on Rural Highway Operations

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APPROVAL

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This writing project has been read by the writing project director and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the Statistics Faculty.

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INTRODUCTION

Problem Statement

In rural environments, intelligent transportation systems (ITS) are deployed for problems of non-recurrent congestion. Sources of non-recurrent congestion include weather events, traffic incidents, and work zones. In order to more efficiently use and evaluate ITS, it is important to determine baseline highway capacity and speeds in these environments. Several studies on the impact of severe weather events on highway capacity and speed in rural environments have been conducted; however, the results have not proven very conclusive.

Research Objectives

The goal of this project is to find a better method to estimate road capacities due to weather events with greater accuracy while adding another element: roadway geometry (horizontal and vertical). Previous studies have not considered roadway geometry in their models. This element is especially critical in the study area for the Rural California/Oregon Advanced Transportation System (COATS) project, where the terrain is often mountainous representing safety challenges.

Scope

Former studies involving the impact of weather events on traffic volume and speed will be reviewed. These studies will be used as references throughout this project as the geometry elements are added.

Different models will be developed for volume and speed based on the previous studies. Only one of the studies reviewed had both volume and speed in the same model (1).

The literature review is broken into several sections:

- volume models;
- speed models;
- summary of volume models and speed models;
- number of sites used for each study;
- variables to consider, parts of the studies to use in this project; and
- data resources.

Possible models involving volume and speed will also be explored in this study.

LITERATURE REVIEW

VOLUME

Two studies involving the effect of winter storm events on traffic volume are described below.

Volume Study #1: Mobility and Safety Impacts of Winter Storm Events in a Freeway Environment Final Report (1)

Data Collection

In the first volume study, Knapp investigated the impact of winter storm events on the volume, safety, and speed characteristics of interstate traffic flow in Iowa. Knapp's volume model will be reviewed in this section. The relationships between winter storm events and crash impacts and speed will be examined in the speed section.

Archived data of roadway and weather conditions and hourly traffic volumes from seven locations where road weather information system (RWIS) stations and automated traffic recorders (ATR) were collocated, and daily snowfall data from the National Weather Service (NWS) and Iowa Department of Agriculture and Land Stewardship (IDALS) for the winters of 1995-1998 were used to develop a model for volume reduction.

Only severe winter storm events (determined from IDALS/NWS data) were considered. Knapp required the following conditions to define a severe winter storm event, which led to more reliable data (less variability with respect to traffic volume and speed):

- air temperature below freezing,
- wet pavement surface,
- pavement temperature below freezing,
- more than 0.2 inches of snowfall per hour,
- minimum of four hours of duration,
- event not occurring near a holiday, and
- event not occurring on a day when hourly volumes were estimated (exact traffic counts unavailable).

Analysis

Twenty-six percent of the 336 winter storm events collected qualified as acceptable for data analysis. These events encompassed 618 hours of data. When creating the database, the following variables were included:

- traffic volume during winter storm event,
- comparable average monthly non-storm volumes for that time period and day of the week, and
- winter storm event percent volume reduction (calculated from volume difference and percent change between winter storm event volume and average non-storm volume).

Stepwise regression analysis was then used to describe the relationships between the following variables:

- winter storm event percent volume reduction (dependent variable),
- storm event duration,
- snowfall intensity,
- total snowfall,
- minimum and maximum average wind speed, and
- maximum wind gust speed.

The variables excluded from the model (e.g. storm event duration, snowfall intensity, minimum wind speed, maximum wind speed) were either not statistically significantly related to winter storm event percent volume reduction or were correlated with other variables and, therefore, should not be included.

Results

The following model was developed. Table 1 provides the variables, variable ranges, and coefficient estimates. The response is winter storm event percent volume reduction. All variables are significant at the 0.05 level. The reported regression model is:

$$SV = -1.583 + 0.0296WGS^2 + 2.289TS$$

The variables in the model are the following:

- winter storm event percent volume reduction (SV): response calculated from the volume difference and percent change between winter storm event volume and average non-storm volume (dependent variable),

- maximum wind gust speed (WGS): variable for the maximum wind gust speed in (km/h) squared, and
- total snowfall (TS): variable for the inches of snow fallen during the winter storm event.

Table 1: Variables for Volume Study #1

Variable	Variable Range	Coefficient
Intercept		-1.583
(Maximum wind gust speed) ²	36.0 to 2,916.0	0.0296
Total snowfall (inches)	1.05 to 10.83	2.289
R ²		0.544

Although snowfall intensity (0.2 inches per hour) was used as criteria for the winter storms, no relationship was found between percent traffic volume reductions and snowfall intensity (inches of snow per hour). The model indicates that as the square of maximum wind gust speed and total snowfall increase, the average volume reductions increase. The coefficient of determination, R², of 0.544 indicates that the model does explain at least half of the variability in the data.

Statistical Critique

No evidence was provided that the normality or independence assumptions were checked. It was stated only that normality was assumed for the analysis. (See last section of paper for further explanation.)

Volume Study #2: Traffic Volume Reductions Due to Winter Storm Conditions (2)

Data Collection

In the second volume study, Hanbali and Kuemmel studied the traffic volume reductions caused by snow and icy conditions on eleven highways outside of urban areas in Minnesota (Olmstead County), Illinois (Ogle and Lee counties), New York (Wayne, Monroe, Steuben, and Onondaga counties), and Wisconsin (Walworth, Kenosha, and Waukesha counties). They also examined the impact of the interaction between the trip makers' willingness to travel, the importance of the destination, and winter storms on traffic volume.

Eleven ATRs were used for data collection. The annual average daily traffic and 24-hour counts were measured continuously and collected at all sites in Minnesota, Illinois, New York, and Wisconsin from January to March of 1991. Additional data was acquired in Wisconsin (December 1990) and New York (December 1989 to March 1990 and December 1990).

The weather data was acquired from the participating highway agencies and the National Climatic Data Center in Asheville, North Carolina. The type of data collected included temperature range (high and low), storm period (start and end time, day, date), and depth and type of snow (dry, wet, sleet, etc.).

Analysis

Traffic counts were categorized by day of the week (weekday or weekend), snow precipitation, temperature range, and normal average daily traffic volume (ADT). Each ATR was categorized based on its normal ADT:

- rural and suburban freeways: 11,000 to 20,000, and 21,000 to 30,000; and
- rural and suburban highways: 3,000 to 6,000, and 7,000 to 10,000.

The hourly traffic volumes during the winter storm events were compared to the normal hourly traffic volumes for the same location during a similar hour at the same day, month, and year. Hourly reduction factors were then derived for each snowstorm:

$$SRF = SV / NV$$

The variables in the equation are the following:

- snowstorm reduction factor (SRF): (snow volume) / (normal volume) in relative time (hour),
- snow volume (SV): hourly traffic volume during snowstorm, and
- normal volume (NV): normal traffic volume.

Results

One of Hanbali and Kuemmel's conclusions was that the average reduction in traffic volume due to winter storm event conditions increases with the severity of the weather.

The following summary was provided of the range of percent average traffic volume reductions for rural and suburban freeways and highways for weekdays and weekends. Volume counts occurring on holidays were not included. No justification was provided for the determination of the precipitation endpoints provided in Table 2.

Table 2: Variables for Volume Study #2

Amount of snow precipitation	Weekday average traffic volume reduction	Weekend average traffic volume reduction
< 25 mm (< 0.98 in)	7 – 17%	19 – 31%
25 – 75 mm (0.98 – 2.95 in)	11 – 25%	30 – 41%
75 – 150 mm (2.95 – 5.91 in)	18 – 43%	39 – 47%

150 – 225 mm (5.91 – 8.86 in)	35 – 49%	41 – 51%
225 – 375 mm (8.86 – 14.76 in)	41 – 53%	44 – 56%

Based on Table 2, they claimed the average traffic volume decreases as the amount of precipitation increases, and the average reduction in traffic volume due to precipitation was less during weekday hours than weekend hours.

The authors divided similar snowstorm events into hourly periods: peak-hour periods and off-peak-hour periods. Dividing the sum of the hourly reductions by the sum of the respective hourly normal volumes resulted in an average reduction for each group. It was concluded from these comparisons that weekday and weekend peak-hour periods (necessary trips) experienced a lower average reduction in traffic volume than weekday and weekend off-peak-hour periods (discretionary trips).

Statistical Critique

The authors did not provide justification for the breakdown of the snowfall amounts into the five categorical levels: < 25 mm, 25 – 75 mm, 75 – 150 mm, 150 – 225 mm, 225 – 375 mm. Was this done out of convenience or does evidence exist that these levels have statistically significantly different effects on driving patterns? If actual snowfall amounts were available, then why not use the actual amounts instead of a less precise categorical variable?

SPEED

Past studies on the impact of severe weather on vehicle speed had varying results. Visibility, wind speed, and roadway snow cover were included in each of the following three models while precipitation intensity (inches of precipitation per hour) was included in only one of them.

Speed Study #1: Mobility and Safety Impacts of Winter Storm Events in a Freeway Environment Final Report

Data Collection

Knapp's investigation of speed characteristics during winter storms used different data than the volume study (1). Over twenty-seven hours of data for seven winter storms from December 1998 to March 1999 were collected using the Autoscope, a mobile video traffic data collection system. This data and manually collected data included recorded approximate roadway snow cover (snow on the roadway lanes or not) and visibility (estimation of how far one can see through snow fall and blowing snow) near seven bridges over Interstate 35 between Des Moines, Iowa and the Iowa/Minnesota border. Eventually, only one site provided sufficient traffic data collection--Northeast 142nd Avenue, which is two miles north of the I-35 Elkhart Interchange in Polk County.

The data were summarized into 109 15-minute increments and identified as occurring either during peak-period or during off-peak period times. Knapp used ninety 15-minute off-peak-period increments for the modeling because only nineteen peak-period increments were available, and because off-peak-period and peak-period increments have different traffic patterns.

Analysis

The database included the following variables:

- average vehicle speed,
- traffic volume,
- estimated visibility,
- average gap between vehicles,
- headway (distance between front bumper of a vehicle to the front bumper of the following vehicle) between vehicles, and
- roadway condition (cross section percent snow cover).

These data were then compared graphically to data collected during similar time periods in the month of May under normal conditions.

Results

These comparisons and multiple regression analysis led to the following model. Table 3 provides the variables, variable ranges, and coefficient estimates. The response is average vehicle speed in miles per hour (mph). All variables are statistically significant at the 0.05 level. The reported regression model is:

$$SP = 55.7 - 7.23RCI - 3.88VI + 0.00002TV^2$$

The variables in the model are the following:

- speed (SP): average vehicle speed in mph (dependent variable),
- roadway cover index (RCI): variable indicating the absence (0) or presence (1) of snow on the roadway,
- visibility index (VI): variable indicating visibility less than (0) or greater than (1) 0.25 miles, and
- traffic volume (TV): variable for the square of traffic volume measured in vehicles per hour squared.

Table 3: Variables for Speed Study #1

Variable	Variable Range	Coefficient
Intercept		55.7
Roadway Cover Index	0 = snow is on shoulders or is nonexistent on roadway surface 1 = snow is impacting roadway lanes	-7.23
Visibility Index	0 = > 0.25 miles (0.40 km) 1 = < 0.25 miles (0.40 km)	-3.88
Traffic Volume ² (vph) ²		0.00002
R ²		0.618

The model indicates that as the traffic volume increases during winter storm events, the average vehicle speed increases. This suggests that drivers are more comfortable driving in poor conditions when more drivers are on the road.

The model also shows that average vehicle speed decreases as the visibility decreases and more roadway snow cover is present. When snow is impacting the roadway lanes, the average vehicle speed will decrease by 7 mph (11.3 km/h). If visibility is less than 0.25 miles (0.40 km), the average vehicle speed will decrease by 4 mph (6.4 km/h). When both events occur simultaneously, average vehicle speed is reduced by 11 mph (17.7 km/h).

The R^2 value indicates that the model explains 61.8% of the variability in the data. However, Knapp stated that as weather conditions decreased, the variability in the driving speeds increased.

Statistical Critique

No evidence was provided that the normality or independence assumptions were checked. It was stated only that normality was assumed for the analysis.

No justification for the critical value of visibility 0.25 miles was given.

Speed Study #2: Effect of Weather on Free-Flow Speed (3)

Data Collection

Kyte, Khatib, Shannon, and Kitchener analyzed capacity and level-of-service during less than ideal weather conditions. The baseline of normal/ideal weather conditions are no precipitation, dry roadway, visibility greater than 0.37 km (0.23 miles), wind speed less than 16 km/h (9.9 mph) for the Idaho Storm Warning Project.

The data were collected between 1996 and 2000 on a four-lane section of Interstate 84 in southeastern Idaho. Data were collected from sensors measuring volume, visibility, roadway, and weather. ATRs recorded lane number, time, speed, and length of each vehicle passing the sensor site. Two types of visibility sensor systems (Surface Systems, Inc. and Handar Corporation) were used and provided the following data: wind speed and direction, air temperature, relative humidity, road surface condition, and the type and amount of precipitation. The weather and visibility sensors were located adjacent to the ATRs. Of the data collected, the authors focused on the effects of reduced visibility, high winds, and pavement condition on free-flow speed.

Analysis

The authors calculated a critical wind speed by plotting passenger car speed against wind speed in order to find the points at which wind speed affects passenger-car speeds. In the graph, there was a significant drop in passenger-car speed when the wind speed reached 24 km/h (14.9 mph), and therefore this was considered the critical wind speed. The plot indicated that wind speed below 16 km/h had little effect on passenger-car speed. Neither wind direction, nor its impact on speed was specified.

A similar process, plotting passenger car speed against visibility, was used to calculate a critical visibility, the level of visibility at which driver speeds are affected. The authors noted that when visibility dropped below 0.3 km (0.19 miles), there was a significant drop in speed. Therefore, the decided critical visibility was 0.28 km (0.17 miles), indicating that vehicle speeds drop significantly when visibility falls below this level.

Results

A model was developed using multiple regression analysis. Table 4 provides the variables, variable ranges, and coefficient estimates. The response is average vehicle speed in km/h. All variables are significant at the 0.05 level. The reported regression model is:

$$SP = 100.2 - 16.4S - 9.5W + 77.3V - 11.7WS$$

The variables in the model are the following:

- speed (SP): average passenger car speed in km/h (dependent variable),
- snow-covered surface (S): variable indicating the absence (0) or presence (1) of snow on roadway,
- wet surface (W): variable indicating that the pavement is dry (0) or wet (1),
- visibility (V): variable in km that takes on value of 0.28 when visibility exceeds 0.28 km (0.17 miles) and value of actual visibility when visibility is below 0.28 km (0.17 miles), and
- wind speed (WS): variable indicating that wind speed is less than (0) or greater than (1) 24 km/h (15 mph).

Table 4: Variables for Speed Study #2

Variable	Variable Range	Coefficient
Intercept		100.2
Snow-covered surface	0 = snow is absent on roadway 1 = snow is present on roadway	-16.4
Wet surface	0 = roadway is dry 1 = roadway is wet	-9.5
Visibility (km)	0.28 => 0.28 km (0.17 miles) visibility = < 0.28 km (0.17 miles)	77.3
Wind speed	0 = < 24 km/h (15 mph) 1 = > 24 km/h (15 mph)	-11.7
R ²		0.34

This model indicates a greater average speed reduction when there is snow (16.4 km/h (10.2 mph)) than for a wet surface (9.5 km/h (5.9 mph)). When wind speed exceeds 24 km/h (14.0 mph), average speed drops by 11.7 km/h (7.3 mph). When visibility is less than 0.28 km (0.17 miles), average passenger car speeds decline 0.773 km/h (0.48 mph) for every 0.01 km (0.06 miles) below the critical visibility.

The R² value (0.34) indicates the ability of the model to explain the variability in the data. Note the use of all indicator variables resulted in a model with a lower R². It was stated

and shown graphically that more variability in the average car speed occurred on days of bad weather.

Statistical Critique

No evidence was provided that the normality or independence assumptions were checked. It was stated only that normality was assumed for the analysis.

A linear relationship between the variables is assumed. Given the poor fit of the model to the data, if the data is indeed normal, a transformation may provide a better fitting model.

It is not stated if the variables for wet surface or snow-covered surface are mutually exclusive (cannot both occur at the same time).

Speed Study #3: Effect of Environmental Factors on Free-Flow Speed (4)

Data Collection

In another study, Kyle, Khatib, Shannon, and Kitchener also studied the effect of weather-related environmental factors on speed flow rates and speed during poor driving conditions in Shoshone, Idaho.

The data were collected during the winters of 1997-1998 and 1998-1999. Data were collected in the same manner as the study conducted by Kyle, Khatib, Shannon, and Kitchener (3). Eighty-six 5-minute observations were used to determine normal driver speeds based on the baseline of normal/ideal weather conditions of no precipitation, dry roadway, visibility greater than 0.37 km (0.23 miles), and wind speed less than 16 km/h (9.9 mph).

Analysis

Four weather-related factors were considered: visibility, roadway surface condition, precipitation intensity, and wind speed.

The wind speed was categorized into four groups:

- 0 – 16 km/h (0 – 9.9 mph),
- 16 – 32 km/h (9.9 – 19.9 mph),
- 32 – 48 km/h (19.9 mph – 29.8 mph), and
- greater than 48 km/h (greater than 29.8 mph).

The precipitation is classified into four levels:

- none,

- light,
- moderate, and
- heavy.

The sensors record this data based on National Weather Service criteria. The snowfall rate is converted into its liquid equivalent and its rate represents the rate of its liquid equivalent.

Visibility was categorized in three groups:

- 0 – 0.16 km (0 – 0.10 miles),
- 0.16 – 0.37 km (0.10 – 0.23 miles), and
- greater than 0.37 km (greater than 0.23 miles).

Results

Multiple regression analysis led to the development of several models. Table 5 provides the variables, variable ranges, and coefficient estimates of the first model. The first model developed is the following. The response is average vehicle speed in km/h. The first reported regression model is:

$$SP = 115.82 - 0.34WS - 4.77PI + 0.62V - 4.54RC$$

The variables in the model are the following:

- speed (SP): average vehicle speed in km/h (dependent variable);
- wind speed (WS): variable indicating speeds less than 16 km/h (9.9 mph) (1), between 16 and 32 km/h (9.9 and 19.9 mph) (2), between 32 and 48 km/h (19.9 and 29.8 mph) (3), and greater than 48 km/h (29.8 mph) (4);
- precipitation intensity (PI): variable indicating increasing levels of precipitation: none (1), light (2), medium (3), heavy (4);
- visibility (V): variable indicating speeds less than 0.16 km (0.10 miles) (1), between 0.16 and 0.37 km (0.10 and 0.23 miles) (2), greater than 0.37 km (0.23 miles) (3); and
- roadway condition: variable indicating dry (1), wet (2), or snowy/icy (3) roadways.

Table 5: Variables for Speed Study #3 Draft Model

<u>Variable</u>	<u>Variable Range</u>	<u>Coefficient</u>
Intercept		115.82
Wind speed (km/h)	1 = 0 – 16 km/h (0 – 9.9 mph) 2 = 16 – 32 km/h (9.9 – 19.9 mph) 3 = 32 – 48 km/h (19.9 – 29.8 mph) 4 = > 48 km/h (> 29.8 mph)	-0.34
Precipitation intensity	1 = none 2 = light 3 = medium 4 = heavy	-4.77
Visibility (km)	1 = < 0.16 km (< 0.10 miles) 2 = 0.16 – 0.37 km (0.10 – 0.23 miles) 3 = > 0.37 km (> 0.23 miles)	0.62
Pavement condition	1 = dry 2 = wet 3 = snow/ice	-4.54
R ²		0.40

The coefficients for wind speed and visibility are small relative to the other variables, 0.34 and 0.62 respectively, which indicates that they are not influential in the prediction. Consequently, a second model was estimated with wind speed having only two levels: less than 48 km/h (29.8 mph) and greater than 48 km/h (29.8 mph). In this model, however, visibility was not statistically significant. Visibility was excluded from the third and final model because of its lack of significance.

The final model best represents the factors affecting speed. Table 6 provides the variables, variable ranges, and coefficient estimates. The response is average vehicle speed in km/h. All variables are significant at the 0.05 level. The final reported regression model is:

$$SP = 126.53 - 9.03WS - 8.74PI - 5.43RC$$

The variables in the model are the following:

- speed (SP): average vehicle speed in km/h (dependent variable);
- wind speed (WS): variable indicating speeds less than (1) or greater than (2) 48 km/h (29.8 mph);
- precipitation intensity (PI): variable indicating increasing levels of precipitation: none (1), light (2), medium (3), heavy (4); and
- roadway condition (RC): variable indicating dry (1), wet (2), or snowy/icy (3) roadways.

Table 6 : Variables for Speed Study #3 Final Model

Variable	Variable Range	Coefficient
Intercept		126.53
Wind speed (km/h)	1 = < 48 km/h (29.8 mph) 2 = > 48 km/h (29.8 mph)	-9.03
Precipitation intensity	1 = none 2 = light 3 = medium 4 = heavy	-8.74
Roadway condition	1 = dry 2 = wet 3 = snow/ice	-5.43

The variables are additive. If normal conditions exist (wind speed is less than 48 km/h (29.8 mph), no precipitation exists, and the roadway is dry), the average vehicle speed is 103.3 km/h (64.2 mph). If the wind speed is greater than 48 km/h (29.8 mph), heavy snow is falling, and there is snow or ice on the roadway, average vehicle speed is reduced by 69.3 km/h (43.1 mph) to 57 km/h (35.5 mph). Heavy snow has the largest effect on free-flow speed. As a result of the high wind speed of 48 km/h (29.8 mph) as a critical value, high wind speed becomes a critical factor in determining average vehicle speed.

No R^2 value was provided once visibility was removed and wind speed was collapsed into two categorical levels.

Statistical Critique

No evidence was provided that the normality or independence assumptions were checked. It was stated only that normality was assumed for the analysis.

No R^2 value is provided. Therefore, it is not possible to know how well the model fits the data and if the linear model is indeed the best fit. The data may not be normal, or a transformation may be needed.

This regression treats an ordered categorical variable as continuous. This should not be done. A linear relationship is assumed between the categorical variables and the response.

A definition of the four precipitation levels is not provided.

Speed Study #4: Effect of Adverse Weather Conditions on Speed-Flow-Occupancy Relationships (5)

Data Collection

Ibrahim and Hall conducted a study of the effect of rainy and snowy weather on flow-occupancy and speed-flow relationships on the Queen Elizabeth Way (QEW) in Mississauga, Ontario.

Traffic data were recorded at two locations (Stations 14 and 21) 24 hours a day at 30-second intervals and obtained from the freeway traffic management system (FTMS) for the QEW. The data were collected on the median lane and as an average across three lanes. The variables measured were volume, occupancy, and speed. Weather data was obtained from the Atmospheric Environment Service and compared with FTMS weather data.

In order to ensure the collection of adverse weather data, the months of October 1990 through February 1991 were considered. Six days of data were collected for each of the weather conditions clear, snowy, and rainy. Definitions of light precipitation and heavy precipitation were not provided. However, it was stated that visibility was used to determine the snowfall intensity and rate of fall was used to determine the rainfall intensity. Data collection was limited to the same time of day (10:00 a.m. to 4:00 p.m.) on weekdays because of the reliable traffic patterns.

Analysis

Two steps were used in the analysis of the data. First, in order to examine each weather condition for consistency, regression analysis was conducted for each day separately for each weather condition. Then the six underlying functions for each weather condition were plotted on the same graph resulting in three different graphs. The lowest and highest functions were selected. Second, multiple regression analyses were then conducted to test for statistically significant differences between the highest functions (light precipitation) and lowest functions (heavy precipitation) for each weather condition.

It was concluded that there was not a statistically significant difference between the low and high functions for clear weather. However, statistically significant differences did exist between the lowest and highest functions for both rainy weather and snowy weather. Therefore, the three weather categories were divided into five weather conditions: clear, light rain, heavy rain, light snow, and heavy snow.

Comparisons were then made within and between the following weather conditions: clear and rainy weather, clear and snowy weather, and rainy and snowy weather. It was concluded that light rain and light snow had nearly the same effect on free-flow speed. A statistically significant difference exists between the effects of heavy snow and heavy rain on free-flow speed with heavy snow having a greater effect than heavy rain. These tests between functions also indicated that there was a greater difference within rainy weather (light rain versus heavy rain) and within snowy weather (light snow versus heavy snow) than between rainy weather and snowy weather or between clear weather and light precipitation (light rain or light snow).

Results

Table 7 provides the conclusions made regarding the change in free-flow speed:

Table 7: Type of Precipitation for Speed Study #4

Type of precipitation	Amount of decrease
Light rain	Maximum of 2 km/h (1.2 mph)
Light snow	Maximum of 3 km/h (1.9 mph)
Heavy rain	5 to 10 km/h (3.1 to 6.2 mph)
Heavy snow	38 to 50 km/h (23.6 to 31.0 mph)

It is evident from the table that more severe weather conditions are associated with a greater decrease in traffic speed. Also, it is evident that light snow and light rain have nearly the same effect on free-flow speed.

Statistical Critique

No evidence was provided that the normality or independence assumptions were checked before the regression analysis was performed or the dummy variable models were developed. It was stated only that normality was assumed for the analysis.

How were the levels of rain and snow categorized? No cut-off points were provided.

Summary of Study Components

Table 8 provides a summary of number of sites used for the speed studies reviewed. Table 9 provides a summary of the variables used in Knapp's volume model. Table 10 provides a summary of the variables used in the four speed models.

Table 8 : Number of Sites Used for Each Study

Study Type	Author	Number of sites	Additional information
Volume	Hanbali and Kuemmel	11	
Volume	Knapp	7	64 storm events with 618 hours of data
Speed	Ibrahim and Hall	2	68 data files
Speed	Knapp	1	90 15-minute off-peak-period increments
Speed	Kyte, Khatib, Shannon, and Kitchener (2000)	Not given	86 5-minute increments
Speed	Kyte, Khatib, Shannon, and Kitchener (2001)	Not given	5-minute increments

Table 9: Variables Included in Volume Models

Study	(Maximum wind gust speed) ²	Total snowfall
Mobility and Safety Impacts of Winter Storm Events in a Freeway Environment	X	X

Note: Other variables were considered but not included in the final model.

Table 10: Variables Included in Speed Models

Study	Roadway Cover Index	Wet Surface Index	Snow-covered Surface Index	Visibility Index
Mobility and Safety Impacts of Winter Storm Events in a Freeway Environment Final Report	X			X
Effect of Weather on Free-Flow Speed		X	X	X
Effect of Environmental Factors on Free-Flow Speed	X			

Table 10: Variables Included in Speed (cont)

Study	Precipitation Index	Wind Speed Index	(Traffic Volume) ²
Mobility and Safety Impacts of Winter Storm Events in a Freeway Environment Final Report			X
Effect of Weather on Free-Flow Speed		X	
Effect of Environmental Factors on Free-Flow Speed	X	X	

Parts of Studies to Use

The parts of the studies above to consider for use in this project are the multiple regression analyses in building the series of models and the variables both used and considered in the models.

Based on the studies above, the following weather variables will be considered:

- maximum wind gust speed,
- average wind speed,

- precipitation intensity,
- total precipitation,
- precipitation type,
- precipitation rate,
- roadway surface status, and
- visibility.

Otherwise, the variables considered in this study will depend on the data provided from the RWIS systems. The possible variables are not limited to those listed above, but these variables do adequately cover the range of variables RWIS systems provide that are relevant to this study. Since volume and speed models are sought in this project, volume and speed variables will naturally be included.

Roadway Geometry

In order to evaluate the effect of weather on traffic speed and volume in mountainous regions, roadway geometry will also be included in this study. In *Principles of Highway Engineering and Traffic Management* (6), Mannering and Kilareski state that roadway geometry involves measures of both horizontal and vertical alignments. Horizontal alignment refers to the directional transition between two straight (tangent) sections of roadway. Measures include the radius of the curve (how close or wide the curve measured in degrees) and the superelevation of the curve (the number of vertical meters rise per 100 meters of horizontal distance measured in percent). Vertical alignment involves the transition curves between two grades. Grade is measured in percent--negative values for downward grade and positive values for upward grade. Vertical curves can be classified as crest vertical curves or sag vertical curves. A maximum height (crest) and minimum height (sag) are expressed in meters.

Parts of Studies to Avoid

None of these studies considered interactions in the models developed, and only Knapp considered higher-order terms in the models he developed. Therefore, variables that were excluded from the models in the studies may still be important to consider in a future study. Better fitting models may be possible with further analysis.

Kyle, Khatib, Shannon, and Kitchener converted continuous variables to categorical variables in their speed models. This does not make sense statistically and should be avoided. This may partially explain why these models had such small R^2 values of 0.34 and 0.40 while Knapp's volume and speed models had larger R^2 values of 0.618 and 0.544, respectively.

Not only did Kyle, Khatib, Shannon, and Kitchener convert continuous variables to multilevel categorical variables, they then treated them as continuous variables in the multiple regression model.

It was stated in several studies that as the severity of the weather conditions increased, the variability in the responses of both volume and speed increased. This is indication that a problem with the homogeneity of variance assumption exists in the models. The authors never stated that the models' residuals were analyzed to see if a problem did indeed exist. No residual plots were provided or discussed. If a homogeneity of variance problem did exist, a transformation may have rendered a better fitting model.

The large variability of the response during winter storm conditions leads to questioning whether or not average vehicle speed is a good response for the models. The model may be appropriate for prediction during ideal weather conditions, but it may be highly inaccurate during severe weather conditions as the variability of the response increases. Considering the high variability in the response and the lack of resistance of a calculated average, perhaps the median vehicle speed would be a more appropriate and resistant measure.

It is often necessary that the data be normal when using regression analysis for statistical inference. Not a single author provided evidence that the data was checked to see if it met the normality assumptions. Knapp stated that the data was assumed to be normal while the other authors did not even mention normality of the data. No normality tests or normal probability plots were provided. Therefore, one may question the validity of all of the models developed.

The independence assumption of the data was also violated by using a time series of intervals. The error terms in the model are most likely correlated. Therefore, examination of this correlation must also be included in the data analysis before regression analysis is completed.

Data Resources

The California Department of Transportation, Oregon Department of Transportation, and Montana Department of Transportation will provide the RWIS and ATR data for this study. Additional weather data can also be found on the National Climatic Data Center website (www.lwf.ncdc.noaa.gov) or the National Weather Service website (www.nws.noaa.gov).

GLOSSARY OF ABBREVIATIONS

ADT	average daily traffic
ATR	automated traffic recorder
COATS	California/Oregon Advanced Transportation System
FTMS	freeway traffic management system
IDALS	Idaho Department of Agriculture Land Stewardship
ITS	intelligent transportation systems
NWS	National Weather Service
QEW	Queen Elizabeth Highway
RWIS	remote weather information system

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