Effect of Environmental Factors on Free-Flow Speed

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ABSTRACT

The estimation of free-flow speed is an important part of the process of determining the capacity and level of service for a freeway. The *Highway Capacity Manual* notes that the free-flow speed depends on both the traffic and roadway conditions found on a given freeway facility. Particularly important are lane width, lateral clearance, number of lanes, interchange density, and vehicle stream composition. The draft chapter on freeway facilities, to be included as chapter 22 of the HCM 2000, notes that “adverse weather can affect not only capacity, but also reduces operating speeds significantly.” The chapter cites several studies that investigated the effects of rain, snow, and fog on both capacity and speed.

The authors have studied the effects of a variety of weather-related environmental factors on driver speeds as part of an Intelligent Transportation Systems project that has been on-going in Idaho since 1993. Visibility and roadway sensors were installed on a segment of I-84 in southeastern Idaho in 1995. This project has generated substantial data on traffic flow rates and driver speeds during periods of reduced visibility and other hazardous driving conditions.

While capacity is not an issue along this section of rural interstate freeway, the sensor infrastructure now in place provides an opportunity to determine the effects of various factors on free-flow speed. This study reports on data collected during two winter periods, 1997–1998 and 1998–1999.

1. INTRODUCTION

Free-flow speed is a critical parameter in the capacity analysis procedures for basic freeway segments and multilane highways described in the *Highway Capacity Manual* (Transportation Research Board 1997). Procedures for both facility types are based on standard or ideal conditions, which assume good weather, good visibility, and bare and dry pavement. More recently, consideration has been given to the effect of weather conditions on free-flow speed.

This paper reports on a study that has been conducted as part of an Intelligent Transportation System field operational test of a storm warning system located on an isolated rural section of Interstate 84 in southeastern Idaho. The system is designed to give drivers advanced information on weather and roadway conditions. The data collected as part of this study provide new insights on how environmental conditions affect free-flow speed on freeway facilities.

Section 2 summarizes recent relevant studies on weather effects on speed and capacity. Section 3 describes the manner in which data are collected for this current study. Section 4 summarizes the data analysis conducted to identify the effects of environmental factors on free-flow speed. Section 5 presents the findings and conclusions.

2. PREVIOUS STUDIES

Several recent studies have examined driver behavior and vehicle speed under a variety of environmental conditions.

Lamm, Choueiri, and Mailaender (1990) examined 24 curved road sections of rural two-lane highways during both dry and wet conditions. They found no statistical difference in the operating speeds between those two conditions. Their data were collected when visibility was not affected by heavy rain, which may explain the lack of difference in the measured speeds.

Ibrahim and Hall (1994) studied the effect of adverse weather on freeway operations in Canada. They conducted tests on the effects of rain and snow on speed-flow-occupancy relationships, summarizing their findings into three categories: clear and rainy weather, clear and snowy weather, and rainy and snowy weather. They found the following reductions in the free-flow speed:

- Light rain caused a 2 km/h drop.
- Light snow caused a 3 km/h drop.
- Heavy rain caused a 5 to 10 km/h drop.
- Heavy snow caused a 38 to 50 km/h drop.

They also note that their measurements are site-specific and that other factors may cause different speed changes at other locations based on varying driver experience with poor weather and the design of the highway itself.

Brilon and Ponzlet (1996) investigated 15 sites in Germany to assess the effects of weather conditions, daylight or darkness, and other factors on speed-flow relationships. They concluded that darkness reduces driver speeds by 5 km/h. They also found a drop of 9.5 km/h and 12 km/h on two-lane and three-lane wet roadway segments, respectively.

May (1998) considered the effects of capacity reducing occurrences on freeway operations. He considered reductions due to adverse weather including rain, snow, fog, and other factors. Using two of the studies cited above [Ibrahaim and Hall 1994; Brilon and Ponzlet (1996)], he proposed the free-flow speed reductions in Table 1. These factors will be included in the year 2000 version of the *Highway Capacity Manual.*

TABLE 1 Free-Flow Speed for Different Weather Conditions

Conditions	Recommended value (km/h)
Clear and dry	120
Light rain and light snow	110
Heavy rain	100
Heavy snow	70

3. SPEED AND ENVIRONMENTAL FACTOR MEASUREMENTS

The Idaho Storm Warning Project was initiated in the fall of 1993. The purpose of this ITS field test is to evaluate the feasibility of using advanced weather and visibility sensing equipment to provide early warning to Idaho Transportation Department personnel and information to motorists regarding dangerous driving conditions due to low visibility caused by rain, blowing snow, or blowing dust. The project was instituted as a result of 18 major traffic accidents involving 91 vehicles resulting in 9 fatalities and 46 injuries between 1988 and 1993.

Sensors measuring traffic, visibility, roadway, and weather data are located near Shoshone, Idaho, in southeastern Idaho adjacent to I-84. Automatic traffic counters record the lane number, time, speed, and length of each vehicle passing by the sensor site. Two visibility sensor systems, manufactured by Surface Systems, Inc., and Handar Corporation, measure visibility using point detection systems based on a forward scatter detection technology. In addition, Surface Systems, Inc., provides a weather system to measure wind speed and direction, air temperature, relative humidity, roadway surface condition, and the type and amount of precipitation. All weather and visibility sensors are located adjacent to the automatic traffic counters on I-84. Data generated by these systems are transmitted to a master computer, which records readings every five minutes. Table 2 lists the sensor data that are collected in this study.

Liang and others (1998) reported on the effects of snow and fog on driver speed during winter 1995–1996, the first year that the storm warning system was in place. They found a 8.0 km/h reduction of driver speed during fog events and a 19.2 km/h reduction during snow events. This study considered the effects of visibility reductions, precipitation levels, and wind speeds. Pavement condition sensors were not yet operational thus somewhat limiting the results of this study. Using multiple regression analysis so that all environmental factors are considered simultaneously, the study identified several speed-related effects:

- Wind speed reduces driver speed by 1.1 km/h for every km/h of wind speed exceeding 40 km/h.
- Drivers reduced their speed by 1.6 km/h during nighttime periods.
- The presence of a snow floor reduced average speeds by 5.6 km/h.

This current paper includes data collected during the winters of 1997–1998 and 1998–1999. In addition to an expanded database, data on pavement conditions are included.

TABLE 2 Sensor Data

Data	Description
Date	Current date
Weather classification	General classification of weather: clear, snow, fog
Time	Beginning of five minute time period
Wind speed	Wind speed, km/h
Wind speed category	Classification of wind speed: 0–16 km/h, 16–32 km/h, 32–48 km/h, and greater than 48 km/h
Precipitation intensity	Intensity of precipitation: none, light, moderate, and heavy
Speed, all vehicles	Mean speed of al vehicles for 5-minute interval, km/h
Speed, passenger cars	Mean speed of passenger cars, km/h
Speed, trucks	Mean speed of truck, km/h
Flow rate, all vehicles	Flow rate, veh/h, all vehicles
Flow rate, passenger cars	Flow rate, veh/h, passenger cars
Flow rate, trucks	Flow rate, veh/h, trucks
Surface chemicals	Presence of de-icing surface chemicals, either none or some
Visibility	Point visibility, km
Visibility category	Point visibility categories: < 0.16 km, 0.16–0.23 km, > 0.23 km
Road status	Road is either opened or closed
Variable message sign	Variable message sign is either on or off
Road condition	Road condition is dry, wet, or snow/ice

4. DATA ANALYSIS

4.1 Normal Conditions

The authors established a baseline of normal conditions, in which drivers base their speeds on roadway geometry and traffic volumes:

- No precipitation
- Dry roadway
- Visibility greater than 0.37 km
- Wind speed less than 16 km/h

The authors used 86 five-minute observations meeting these four criteria to determine normal driver speeds. The mean speed for all vehicles was 109.0 km/h. Passenger car speed averaged 117.1 km/h while truck speed averaged 98.8 km/h. The mean 5-minute flow rate was 269 veh/h, with flow rates ranging from 12 veh/h to 636 veh/h. Trucks made up an average of 52 percent of the vehicle flow rate. Table 3 shows the speeds and flow rates during normal conditions.

Figure 1 shows the plot of mean speed versus flow rate for the 5-minute data for all vehicles. It is evident from this figure that because of the low volumes, these measurements provide an indication of the free-flow speed during normal conditions. While there is some variation, the data are clustered about the mean of 109.0 km/h.

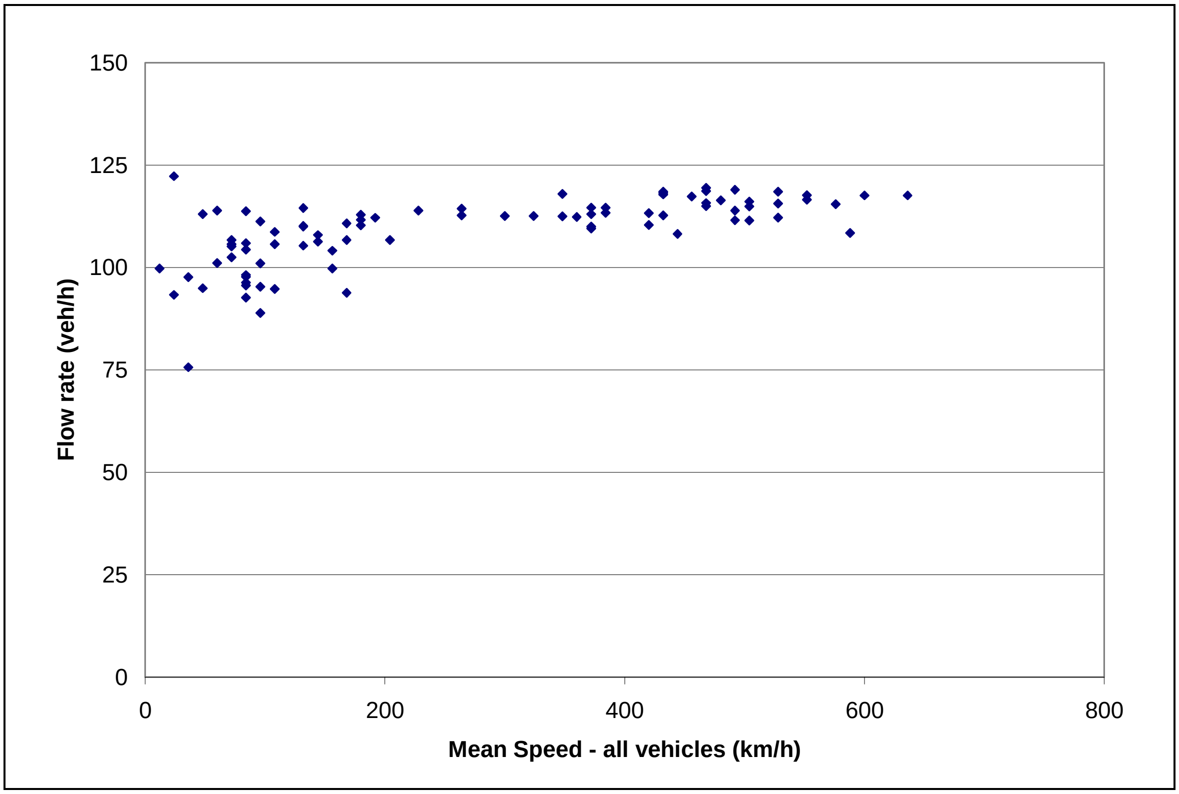

FIGURE 1 Speed vs. flow rate, normal day.

4.2 Aggregate Effects of Environmental Factors

Table 4 shows the effects of each of the four key factors (visibility, road surface condition, precipitation intensity, and wind speed) on vehicle speed. These data show the aggregate effects of each variable alone, without accounting for the interactive effects with the other variables.

When visibility drops to less than 0.16 km, driver speeds drop by more than 14 km/h below the level when visibility is not a factor. Snow or ice on the roadway reduces vehicle speeds by nearly 10 km/h below dry pavement conditions. Precipitation has a varying effect, depending on the intensity. Wind speeds above 48 km/h have a statistically significant effect on driver speed. Snow, with its more lingering effects on pavement condition, has a more significant effect than does fog. Note that fog days include both heavy rain and transitions to fog clouds. But clearly these effects are interactive. A more disaggregate analysis is needed to sort out the effect of each of the four factors.

TABLE 3 Speed and Flow Rates During Normal Conditions

Variable	All vehicles	Passenger cars	Trucks
Number of 5-minute observations	86	82	85
Mean speed, km/h	109.0	117.1	98.8
Standard deviation of mean speed	8.42	8.49	10.71
Maximum speed, km/h	122.3	133.6	113.7
Minimum speed, km/h	75.6	85.3	54.7
Mean 5-minute flow rate, veh/h	269	167	94
Maximum 5-minute flow rate, veh/h	636	504	216
Minimum 5-minute flow rate, veh/h	12	0	0

TABLE 4 Mean Speed for Each Variable

Variable	Range	Mean speed, fog days, km/h (obs*)	Mean speed, snow days, km/h (obs)	Mean speed, all days, km/h (obs)
Visibility	0.0 – 0.16 km	92.4 (53)	39.6 (21)	77.4 (74)
	0.16 – 0.37 km	101.0 (110)	50.7 (90)	79.7 (200)
	> 0.37 km	106.8 (306)	85.9 (1140)	90.8 (1446)
Road surface condition	Dry	107.2 (126)	85.1 (128)	96.1 (254)
	Wet	-	85.7 (256)	85.7 (256)
	Snow/Ice	98.7 (81)	73.3 (194)	81.9 (275)
Precipitation intensity	None	103.8 (469)	100.7 (20)	103.7 (489)
	Light	-	83.1 (335)	83.1 (335)
	Medium	-	80.1 (169)	80.1 (169)
	Heavy	-	77.1 (54)	77.1 (54)
Wind speed	0 – 16 km/h	103.7 (458)	91.7 (93)	101.7 (551)
	16 – 32 km/h	107.2 (11)	103.7 (233)	103.8 (244)
	32 – 48 km/h	-	83.2 (557)	83.2 (557)
	> 48 km/h	-	55.3 (368)	55.3 (368)

**obs* is the number of observations.

4.3 Disaggregate Effects of Environmental Factors

Data with common characteristics were identified to sort out the individual or disaggregate effects on vehicle speed. The results shown in Table 5, Table 6 and Table 7 should be compared with the normal day mean of 109 km/h.

4.3.1 Effects of wind and precipitation

Three groups of data were identified that shed some light on the effects of wind speed and precipitation on driver speed. Table 5 shows three cases in which there was either light or medium precipitation and high wind speeds. Visibility was good and the pavement was dry for each case. Mean speeds ranged from 82.0 km/h to 85.9 km/h, or 24 to 27 km/h below the “normal day” conditions of 109 km/h. The seemingly contradictory sensor readings of dry pavement and light to medium precipitation cannot be explained.

TABLE 5 Reduction in Vehicle Speed Due to Winds and Precipitation

General Conditions	Wind and Precipitation	Mean Speed (km/h)	Observations
Good visibility Dry pavement Some precipitation	Light precipitation; wind speed between 32 and 48 km/h	85.9	67
	Light precipitation; wind speed exceeds 48 km/h	82.0	23
	Medium precipitation; wind speed between 32 and 48 km/h	84.9	22

TABLE 6 Reduction in Vehicle Speed Due to Snow- and Ice-Covered Pavement

General Conditions	Wind	Mean Speed (km/h)	Observations
Good visibility Snow/ice on pavement No precipitation	Wind speed less than 16 km/h	88.1	30
	Wind speed between 32 and 48 km/h	86.3	74

TABLE 7 Reduction in Vehicle Speed Due to Low Visibility

General Conditions	Mean Speed (km/h)	Observations
Limited visibility Dry pavement No precipitation Low wind speeds	107.3	28

4.3.2 Effects of pavement conditions

Two cases were identified in which the effects of snow- or ice-covered pavement could be identified. See Table 6. In each case, visibility was good, there was no precipitation, and wind speed was less than 16 km/h. Both cases had mean speeds ranging from 21 to 23 km/h less than normal day speed of 109 km/h. These results show that the presence of ice or snow on the pavement cause drivers to dramatically reduce their speeds.

4.3.3 Effects of visibility

One set of data, shown in Table 7, had limited visibility (between 0.16 and 0.37 km), dry pavement, no precipitation, and wind speeds less than 16 km/h. Mean driver speed was about 2 km/h less than the speed measured for normal conditions. This shows that visibility by itself may not significantly affect driver speeds. However, it may be that visibility below 0.16 km is required before its effect on speed become evident.

4.4 Isolating Environmental Effects—Regression Analysis

While the previous discussion helps to identify some of the individual effects, multiple regression analysis was used to separate the effects of the environmental variables on driver speed. Three linear regression models were developed to identify these effects.

Model 1 is shown in Table 8. Wind speed was modeled in four groups, visibility was modeled in three groups, and pavement condition was noted as dry, wet, or covered with snow or ice. Precipitation intensity was classified as either none, light, medium, or heavy. Indicator variables were used for each variable to account for each category since the variable ranges were not continuous. Thus the variables become step functions, with discrete changes in the speed forecast when moving from one range to the next. Wind speed and visibility data classification ranges were made after review of the data. Other data classifications are dependent directly on the sensor outputs.

For model 1, all variables were statistically significant at the 0.05 level. The r^2 value was 0.40; 733 observations were used in this analysis.

For base conditions (good visibility, dry pavement, no precipitation, and no wind), this model estimated the mean driver speed to be 104.38 km/h. By inserting various conditions into this model, the resulting driver speed can be estimated. The results of this analysis are shown in Fig. 2. As before, visibility had only a minor effect on speed. However, high wind speeds and heavy precipitation resulted in reductions of more than 10 km/h. The other variables also showed some effects on driver speed.

Note that to assess the effect of more than one variable, the speed reductions are additive. For example, the effect of light precipitation and a wet roadway surface, indicative of light rain, the cumulative effect is 4.8 + 4.5, or a 9.3 km/h speed reduction.

TABLE 8 Speed Model 1

Variable	**Variable Range**	**Coefficient**	**t Statistic**
Intercept		115.82	62.23
Wind speed (km/h)	1 = 0–16 km/h 2 = 16–32 km/h 3 = 32–48 km/h 4 = >48 km/h	–0.34	–9.64
Precipitation intensity	1 = none 2 = light 3 = medium 4 = heavy	–4.77	–6.65
Visibility (km)	1 = < 0.16 km 2 = 0.16 – 0.37 km 3 = > 0.37 km	0.62	4.57
Pavement condition	1 = dry 2 = wet 3 = snow/ice	–4.54	–6.84

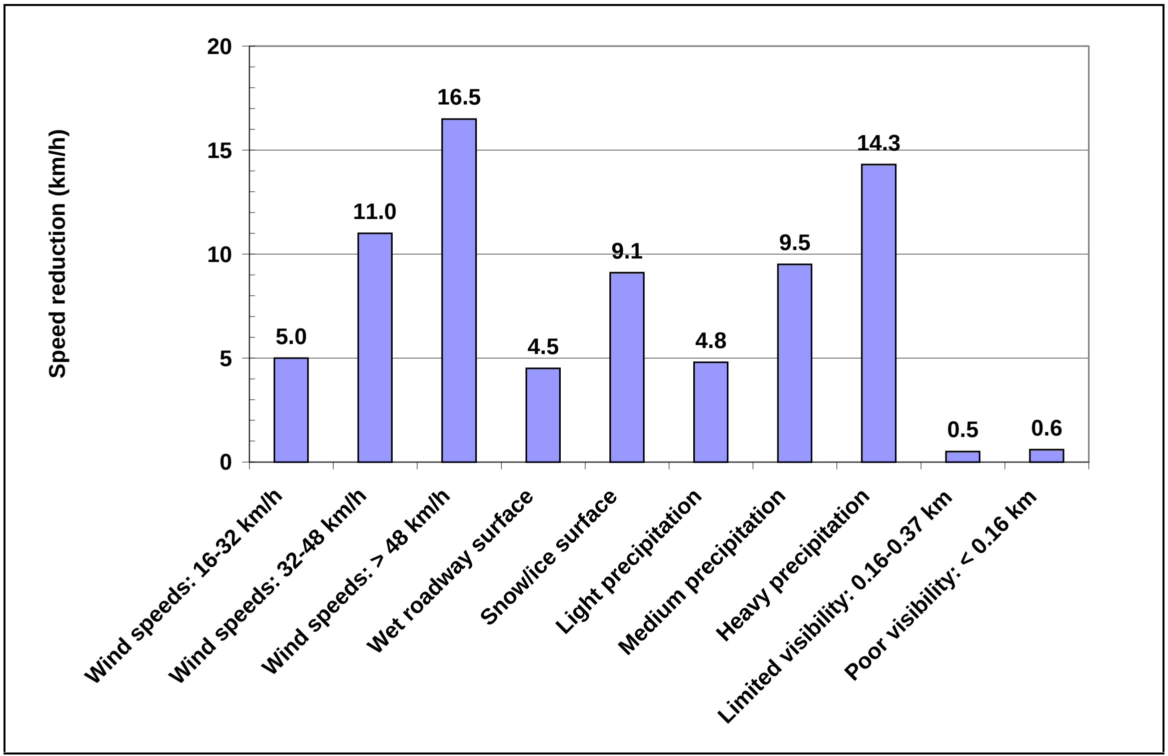

FIGURE 2 Forecasted speed reductions, model 1.

A second model was also estimated, this time with wind speed effects captured in an indicator variable with two values: less than 48 km/h and greater than 48 km/h. The model variables estimated using linear regression methods are shown in Table 9. The visibility variable, however, was not statistically significant. This is not too surprising since the visibility parameter values in the first model were very small.

A third model was developed that included only wind speed, precipitation intensity, and roadway conditions. All variables were statistically significant. Moderate to heavy precipitation showed a significant effect on speed, while light precipitation and wind speed showed some effect (see Table 10). The third model best represents the causal factors affecting driver speed.

5. FINDINGS AND CONCLUSIONS

This study presents new data that can be used to estimate the effect that various environmental factors have on free-flow speed. The results from this study (as represented by model 3) and from May and Ibrahim and Hall are presented in for comparison purposes.

The effect of light precipitation from model 3 (14.1 to 19.5 km/h speed reduction) is about 50 percent higher than the 10 km/h reduction recommended in the May study. The effect of heavy rain is also about 50 percent higher in model 3 than the value recommended by May (31.6 and 20 km/h, respectively).

TABLE 9 Speed Model 2

Variable	Variable Range	Coefficients	t Statistic
Intercept		125.00	31.92
Wind Speed (km/h)	1 = < 48 km/h 2 = > 48 km/h	–9.13	–4.61
Precipitation intensity	1 = none 2 = light 3 = medium 4 = heavy	–8.96	–14.22
Visibility (km)	1 = < 0.16 km 2 = 0.16 – 0.37 km 3 = > 0.37 km	0.87	0.82
Pavement condition	1 = dry 2 = wet 3 = snow/ice	–5.53	–8.03

TABLE 10 Speed Model 3

Variable	Variable Range	Coefficients	t Statistic
Intercept		126.53	45.05
Wind speed (km/h)	1 = < 48 km/h 2 = > 48 km/h	–9.03	–4.43
Precipitation intensity	1 = none 2 = light 3 = medium 4 = heavy	–8.74	–13.73
Roadway condition	1 = dry 2 = wet 3 = snow/ice	–5.43	–7.70

Of all effects, heavy snow has the most significant effect on driver speed. This finding is consistent for all three sources.

High wind is a new variable identified in this study that can be used in estimating free-flow speed. The estimated effect is a 9.0 km/h reduction in free-flow speeds for wind speeds above 48 km/h.

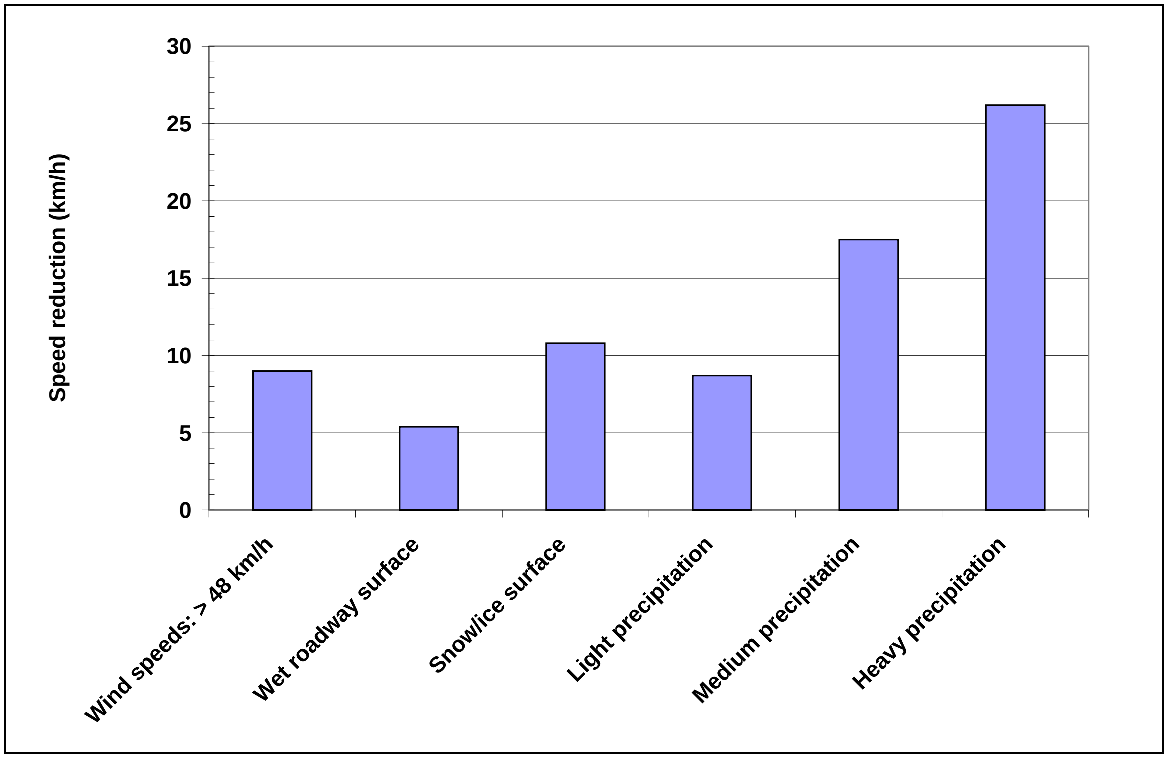

FIGURE 3 Forecasted speed reductions, model 3.

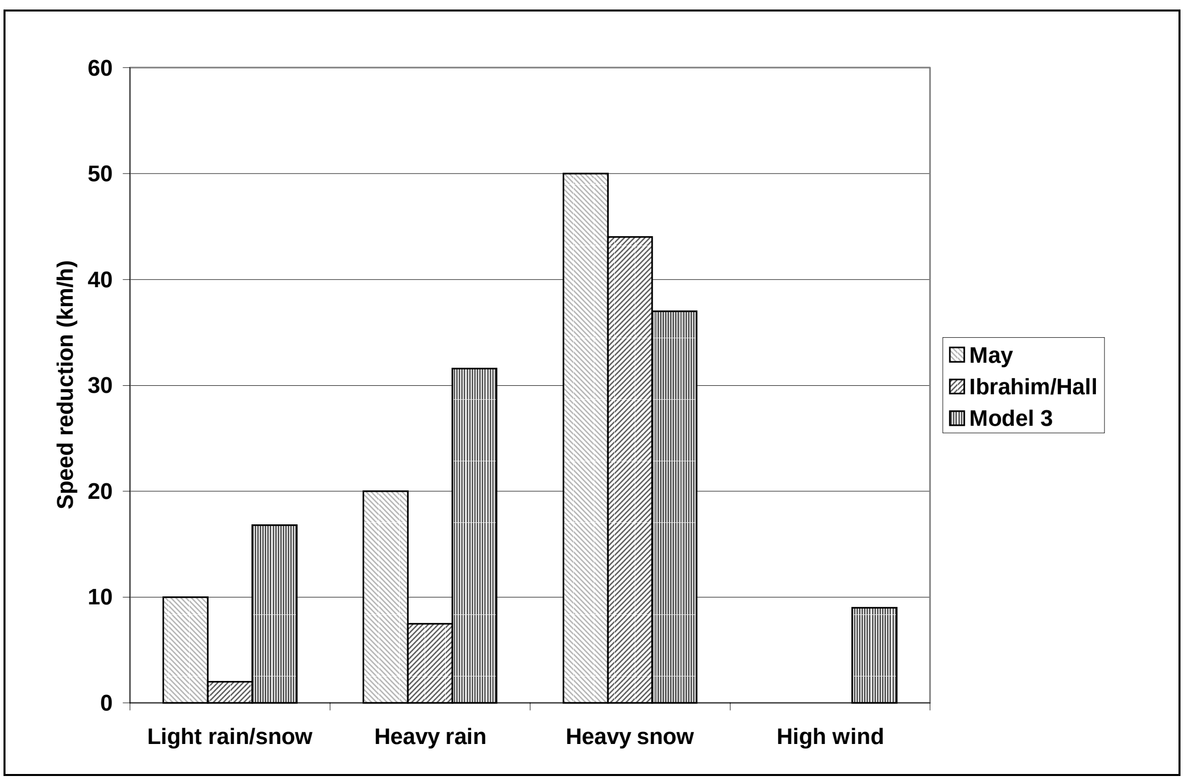

FIGURE 4 Comparison of speed reduction forecasts.

How should these results be used by analysts in determining the effects of environmental factors on free-flow speed? Clearly, additional research is needed to more adequately quantify these factors. But while the data presented in this study are only from one site located along a rural section of an interstate freeway, consideration should be given to the following changes should be considered to the factors included in the HCM 2000:

- The effects of light rain or snow and heavy rain may be 50 percent higher than stated in the HCM 2000.
- The effect of heavy snow may be about 20 percent lower than stated in the HCM 2000.

The effect of high wind should also be included in the assessment of free-flow speed.

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