Impact of Weather on Urban Freeway Traffic Flow Characteristics and Facility Capacity

This is one of two reports from the "Integration of Road Weather Information with Traffic Data" Aurora project

Sponsored by
the Aurora
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Final Technical Report • August 2005

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About Aurora

The Aurora is administered by the Center for Transportation Research and Education (CTRE) at Iowa State University. Aurora is an international program of collaborative research, development and deployment in the field of road and weather information systems (RWIS), serving the interests and needs of public agencies.

The mission of the University Transportation Centers (UTC) Program is to advance U.S. technology and expertise in the many disciplines comprising transportation through the mechanisms of education, research, and technology transfer at university-based centers of excellence. The Midwest Transportation Consortium (MTC) is the UTC Program regional center for Iowa, Kansas, Missouri, and Nebraska. Iowa State University, through its Center for Transportation Research and Education (CTRE), is the MTC's lead institution. The MTC's theme is "Transportation System Management and Operations," specifically, sustainable transportation asset management principles and techniques.

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16. Abstract

Adverse weather reduces the capacities and operating speeds on roadways, resulting in congestion and productivity loss. A thorough understanding of the mobility impacts of weather on traffic patterns is necessary to estimate speed and capacity reductions. Nearly all traffic engineering guidance and methods used to estimate highway capacity assume clear weather. However, for many northern states, inclement weather conditions occur during a significant portion of the year.

This paper describes how the authors quantified the impact of rain, snow, and pavement surface conditions on freeway traffic flow for the metro freeway region around the Twin Cities. The research database includes four years of traffic data from in-pavement system detectors, weather data over the same period from 3 automated surface observing systems (ASOS), and two years of available weather data from 5 road weather information systems (RWIS) sensors at the freeway's roadside. Our research classifies weather events by their intensities and identifies how changes in weather type and intensities impact the speed, headways, and capacity of roadways.

Results indicate that severe rain, snow, and low visibility cause the most significant reductions in capacities and operating speeds. Rain (more than 0.25 inch/hour), snow (more than 0.5 inch/hour), and low visibility (less than 0.25 mile) showed capacity reductions of 10%–17%,19%–27%, and 12 % and speed reductions of 4%–7%, 11%–15%, and 10%–12%, respectively. Speed reductions due to heavy rain and snow were found to be significantly lower than those specified by the Highway Capacity Manual 2000.

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Final Technical Report
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INTRODUCTION

Adverse weather impacts on freeway traffic operations have become a growing concern for roadway management agencies. Although it is obvious that inclement weather conditions reduce freeway capacities and slow traffic, little research has been conducted to quantify the impacts of rain and snow in the United States. In addition, the results obtained from studies outside the United States or on rural freeway segments within the United States may not be applicable to urban freeway segments due to different roadway and driver characteristics. For example, the decrease in speeds for rural freeway segments of I-35 in Iowa during heavy snowfall may not be same as for the urban freeway segments of I-35 in the Twin Cities.

The effect of inclement weather is important in northern metropolitan areas (e.g., Minneapolis/St. Paul, Denver, Salt Lake City, Detroit, and Buffalo), where appreciable snowfalls (more than 0.1 inch/hour) occur frequently (averaging 38, 35, 34, 39, and 62 days per year, respectively) and heavy snowfalls (more than 2 inches/hour) occur about 8, 7, 10, 7, and 12 times per year, respectively (*1*). A precise estimate of capacity and speed reductions due to adverse weather can be useful in managing freeway systems using control, advisory, and road treatment strategies.

LITERATURE REVIEW

Chapter 22 in the Highway Capacity Manual 2000 provides information regarding speed and capacity reductions due to rain or snow of light and heavy intensities. The manual recommends between 0% and 15% reductions in capacities and 2%–14% and 5%–17% reductions in speeds due to light and heavy rains, respectively. Similarly, it recommends 5%–10% and 25%–30% reductions in capacities and 3%–10% and 20%–35% reductions in speeds because of light and heavy snow conditions. The manual does not describe the precipitation intensities thresholds for these categories, and it is important for freeway operators to know precipitation ranges so that they can optimize capacities and operating speeds due to anticipated precipitation (rain or snow) using intelligent transportation system (ITS) devices (e.g., dynamic message signs, ramp metering).

Knowing the fact that guidelines in Highway Capacity Manual 2000 regarding weather impacts on capacity and speed reductions were based on prior research (*2*, *3*), this study investigated the research in detail. Brilon and Ponzlet (*3*) investigated impacts of pavement conditions, darkness, type of day (weekday or holiday), and others on speed-flow relationships for 15 freeway sites in Germany. They found that wet roadway conditions cause a speed reduction of 9.5 km/h (6 mph) on four-lane highways, and 12 km/h (7.5 mph) on six-lane highways. As a result, authors concluded that freeway capacities were reduced by 350 vehicles per hour (vph) and 500 vph, respectively. However, the study was conducted in Germany, where there are no maximum speed limits on freeways and driver behavior and expectancies may differ from U.S. counterparts.

Ibrahim and Hall (*2*) used dummy variable multiple regression analysis for rain and snow. Their study concluded that light rain and snow resulted in similar reductions in speeds (3%–5%), but heavy rain caused 14%–15% and heavy snow caused 30%–40% reductions in speeds. Although Ibrahim and Hall defined rain and snow in light and heavy categories, they did not specify intensity ranges within these categories. Duration of weather data was also quite limited (they used only six clear, two rainy, and two snowy days). Liang et al. (*4*) explored 75 km (45 miles) of rural section of I-84 and found that mean speed was reduced by 8 km/h (5 mph) and 19.2 km/hr (12 mph) for fog and snow events, respectively. Similarly, a study by Kyte et al. (*5*) found that light rain or snow resulted in 50% higher reductions in speed, but heavy snow caused 20% lower speed reductions than the values stated in the Highway Capacity Manual 2000. They found that wind speeds above 48 km/hr reduced speeds by 5.6 mph, but limited visibility (0.1-23 mile) caused insignificant decrease (< 1 mph) in operating speeds. Interestingly, the Kyte study used the same freeway section of I-84 (with a larger quantity of weather and traffic data). Both studies were limited to rural freeway sections, and did not classify precipitation by intensity.

PROBLEM STATEMENT

Although previous research efforts provide substantial evidence that freeway speed and capacity reductions can be quantified under snowy and rainy conditions, the following issues regarding adverse weather impacts on freeway capacities and speeds remain unaddressed and require further study:

- Much of the research pertaining to weather impact is obtained from studies outside the United States. Also, few studies were conducted on urban freeway segments. Thus, research should be conducted to expand the limited guidance about the impacts of weather on traffic flow for urban freeways, while they operate at or near capacity.
- It is necessary to relate measures of weather's relative intensity (e.g., inches of rain or snow fall per hour) to traffic flow, as there has been limited research on this issue.
- Prior studies used short-term data, primarily focusing on heavy rain or snowfall. Long-term data sets are needed to quantify weather's impacts on traffic flow and highway capacity.

METHODOLOGY

The study area is the freeway road network of the Twin Cities that is managed by the Traffic Management Center. It contains a number of roadside and in-pavement ITS field devices and includes several interstates and trunk highways built to freeway design standards. Unlike prior research, this study used a larger dataset of four years (January 2000 to April 2004) of traffic and weather information and categorized the impacts of weather variables by intensity ranges.

Data Collection

The study area has around 4,000 detector loops installed in freeway lanes that collect traffic data (volume and occupancy) for every 30-second time interval. These data were archived by the University of Minnesota Duluth for the Traffic Management Center. Weather records were obtained from five RWIS sites operated by the Minnesota Department of Transportation

(Mn/DOT) and three ASOS sites at airports near the highway system and managed by the National Climatic Data Center.

The locations of detectors in the vicinity of RWIS environmental sensors were identified using maps obtained from the freeway operations division of Mn/DOT. To obtain the detectors near ASOS sites, a buffer region with a radius of 2.5 miles around ASOS sites was created using ArcView GIS 3.2. The detectors along the freeways and state highways built to freeway design standards in the buffer region were selected for further analysis. The researchers also ensured that the selected detectors were not on highway segments with transitional geometries (e.g., lane drops, weaving sections, significant grades) to avoid biases in results due to road geometries. Table 1 shows the list of detectors and the detectors' field lengths used to estimate flow, speed, and density.

Table 1. List of selected detectors and their field lengths

RWIS site	Detector location	Detector ID	Field length (ft)
330.84	I-35 and Minnetonka Blvd	1874	23.2
		1875	27
330.85	I-35 and Minnesota River	257	24.5
		267	23.5
330.86	I-494 and I-94	2953	33.1
		2864	27.4
330.88	I-35 E and Cayuga St. Bridge	2462	24.2
		2391	23.8
330.89	I-494 and TH-110	2879	18.9
		2940	24
ASOS site	**Detector location**	**Detector ID**	**Field length (ft)**
Minneapolis St. Paul International Airport	Nicollet Ave (I-494)	890	21.18
		891	20.02
		893	18.75
	TH 13	3273	20
		3298	14.3
	TH 77 and Minnesota River	3281	20.5
		3279	23.1
		3292	21
Minneapolis Crystal Airport	TH 169 and 63rd Ave	3005	25
	TH 169 and Bass lake Road	3041	30.8
	I-94 and Brooklyn Blvd.	971	26.66
		972	26.97
		974	23.4
		977	25.2
		979	27.22
		960	29.65
St. Paul Downtown Airport	I-94 and TH-52	3191	31.4
	I-35E and Victoria Street	3240	21
		3431	28.7

Extraction of Traffic Data

As the Mn/DOT does not maintain speed detectors on the freeway system, but instead estimates speeds using flow and occupancy data, the following equations were used to calculate speed, flow, and density for 10-minute time intervals using volume and occupancy data:

$$\text{Flow} = \text{Vehicles/Hour} = (\text{Vehicles} / 10 \text{ minutes}) \times 6 \tag{1}$$
$$\text{Density} = \text{Vehicles/Mile} = (5{,}280 \times \text{Occupancy}) / (\text{Field length} \times 100) \tag{2}$$
$$\text{Speed} = \text{Flow/Density} \tag{3}$$

Even though the detectors' field lengths may also change over time due to variation in construction, design, and age of detectors, this research used a constant field length of detectors to compute flow, speeds, and density (Mn/DOT did not maintain field length history for each detector). While this limitation may introduce a few errors, speed and flow measurements at the same detector were found to be consistent over time. Therefore, as long as comparisons were made for the same detectors with or without the effects of weather, relative capacities and speeds should be consistent for the analysis.

Integration of Weather and Traffic Data

Prior research (*6, 7*) concluded that time intervals between 5 and 15 minutes are appropriate to compute flow rates for an hour. This research assumed a 10-minute time interval per data case for weather and traffic data. Ten-minute interval was considered sufficiently long enough to average out short-lived peaks in flow rates. Thus, weather and traffic data were combined using constraints of similar date, hour, and 10-minute intervals. Different datasets were prepared and analyzed for two years (January 2002–April 2004) of available weather data on different pavement surface conditions, temperatures, and wind speeds with traffic data at 10-minute intervals.

First, an analysis of the database containing pavement conditions and traffic data was conducted to investigate the flow-occupancy relationship for each pavement condition (dry, wet, and icy, as measured by the RWIS pavement sensors). The results obtained for each category were found to be similar to those shown in Figure 1. Figure 1 presents the flow-occupancy relationship during dry conditions. It is clearly evident that what is being observed is the flow-capacity relationship during two different sets of weather conditions. It is likely that the set of points in the cluster to the left was recorded during dry weather. The cluster to the right exhibits lower maximum flow rates and, therefore, there were probably inclement conditions when these data points were collected. In other words, it appears the RWIS road sensors are providing false readings.

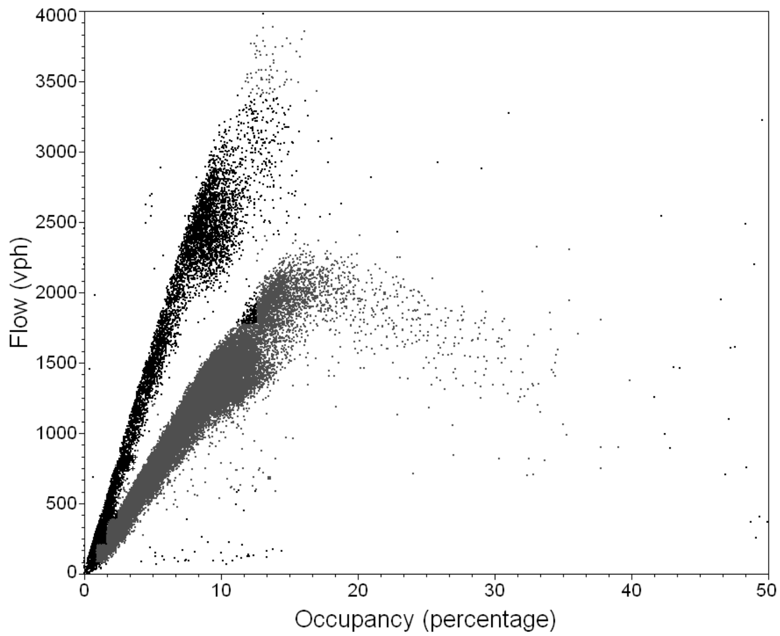


Figure 1. Flow-occupancy for dry pavement surface conditions

Second, the databases on winds and temperature were also prepared, and flow-occupancy relations were examined to verify whether RWIS sensors were giving accurate information on these variables. The database for wind speeds and traffic data showed two linear relationships for flow-occupancy regimes for different ranges of wind speeds, similar to figure shown above. However, the flow-occupancy relationships for the database for temperature and traffic data showed the expected trend (single linear relationship), similar to Figure 2(a). These findings were shared with the Mn/DOT Office of Maintenance and they verified that the RWIS environmental sensors failed to give accurate information on pavement surface conditions, wind speeds, and wind directions. The prevalence of false readings maybe disconcerting, but in all fairness, the data from these sensors were put to use for a purpose they were never intended to fulfill. Road maintenance agencies are generally only interested in data from the sensors during times when inclement weather is known to exist.

Due to the prevalence of false readings, the use of the RWIS weather data on surface conditions and wind speeds was rejected and the analysis proceeded through the uses of pavement surface temperature data only. Data on precipitation, winds speeds, and visibility were obtained from ASOS sites.

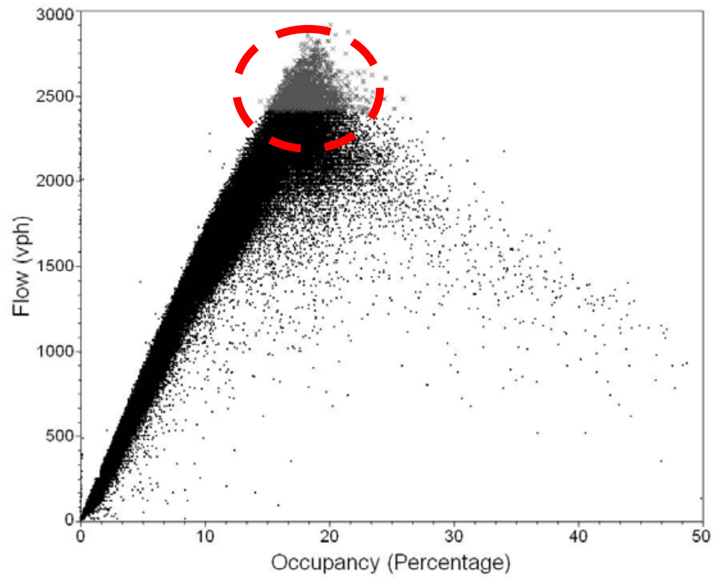
The weather data reported by ASOS sites were not organized by a specific time interval, but provided information on the amount of precipitation (inches/hour) and the start and end timings of precipitation. The weather data were integrated with the traffic data using a few rules. For example, if the weather data indicate that rain started at 7:23 a.m. and ended at 7:53 a.m., the hourly precipitation was 0.2 inches. The time intervals for traffic data from 7:20 a.m. to 8:00 a.m. are assigned a precipitation intensity of 0.4 inches/hour (it actually rained 0.2 inches for 30 minutes, which equals and intensity of 0.4 inches/hour).

Similar rules were applied to prepare the database for extreme winds in the opposite direction of travel and low visibility conditions. Data on wind speed and direction and on visibility were assigned to the corresponding time intervals of traffic data, assuming that wind speeds and visibility remained the same until there was an indication of change in wind speed and visibility for a given hour. The database for winds was further modified by filtering records where the direction of travel was opposite to the wind direction because prior research (*8*) suggested that winds in the same direction of travel did not show significant impacts on traffic flow variables.

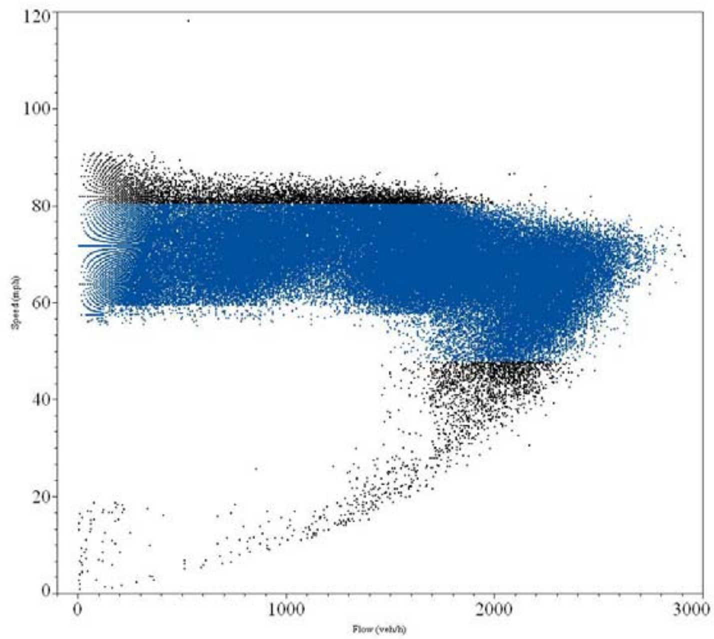
Flow-occupancy relationships were examined for various weather conditions. An example is shown in Figure 2(a) for clear weather. The lightly shaded data points in the dashed circle are the top 5% of flow measured for the weather condition. Similar analyses were conducted for datasets of varying precipitation, wind speeds, surface temperatures, and visibility.

Estimation of Freeway Capacities

This research used the maximum observed throughput approach, as described by Smith et al. (*9*). Prior research (*9*) found that the mean of the highest 5% of the observed flow rates by a detector would represent the effective freeway capacity. This method of estimating capacity is chosen because it ensures that a freeway segment will be able to clear the maximum number of vehicles at least 95% of the time. This method also requires prior examination of the flow-occupancy and the speed-flow relationships to ensure that system demand was sufficiently met to reach congestion, as shown in Figures 2(a) and 2(b). Additionally, this approach fits with the primary objective of this research to determine the percent of changes in freeway capacities and operating speeds due to rain and snow. The collected data were further modified by removing records containing data where very low occupancies (less than 5%) or very high occupancies (greater than 50%) existed. Low occupancies are expected only when the freeway is operating well below capacity, and very high occupancies are only likely to occur after total breakdown of flow caused by a freeway incident. Finally, the freeway capacity for each detector for a selected weather category (e.g., snow intensity between 0.11 and 0.5 inches/hour) was obtained by calculating the average of the top 5% flow rates.



(a)



(b)

Figure 2. Flow-occupancy (a) and speed-flow (b) for clear weather conditions

Estimation of Operating Speeds

The uncongested portion of the speed-flow relationship was examined for the expected relationship (parabolic), as shown in Figure 2(b). Also, past studies (*2, 10, 9*) indicated that speeds are relatively insensitive to the increasing flow rates for the uncongested portion (speed greater than 45 mph) of speed-flow curve until congestion is started. Therefore, to compare the changes in speeds due to each weather type and intensity, a weighted average of speeds (between

45 and 80 mph) by flow rates was calculated to compute the average operating speed. The lower limit of 45 mph was used as a minimum uncongested speed and an upper limit of 80 mph was considered to exclude the errors in the database. This approach is more meaningful for this research because many discrepancies can be avoided using weighted mean values.

Finally, when capacities and operating speeds were calculated for different weather type and weather intensities, the next step was to compare the differences using the Bonferroni method (significance level of α equal to 0.05). The Bonferroni method was selected because it can be used to compare datasets of unequal size without assuming equal variances of selected datasets (*11*).

RESULTS

Once the data were collected and examined for appreciable flow-occupancy and speed-flow relationships, freeway capacities and operating speeds were computed as discussed above. The next step was to calculate an average of freeway capacities and speeds for all detectors near an ASOS site for every weather category. These average values were then compared to evaluate the percent reductions in freeway capacities and speeds due to varying rain and snow intensities, as shown in Table 2.

Rain

The rain data were divided into four categories (0, less than 0.01, 0.01–0.25, and greater than 0.25 inches/hour) for the analysis of the impacts of rain on freeway capacities and speeds. The database contained approximately 50,000, 1,400, 1,250, and 200 records for the above-defined rain categories by intensity values for each selected detector.

The freeway detector sites near the airports (Minneapolis-St. Paul International [MSP], Minneapolis Crystal [MIC], and St. Paul Downtown [STP]) were selected for this research. These sites showed statistically significant average capacity reductions of 1%–3%, 5%–10%, and 10%–17%, for trace, light, and heavy rain conditions, respectively, as shown in Table 2. Statistical test indicated that reductions in capacities were statistically significant when compared with no rain conditions, except trace precipitation conditions. However, this study showed lesser reductions in capacity (10%–17%) than the reductions of 25%–30% obtained by the study (*9*).

Table 2. Percentage reductions due to varying weather type and intensities

Variable	Range	Capacities vphpl (percentage change)			Average Operating Speeds mph (percentage change)		
		MSP	MIC	STP	MSP	MIC	STP
Rain	0	2353(0)	2356(0)	2245(0)	65.63(0)	69.28(0)	63.61(0)
	0-0.01 inch/hour	2319(-1.44)	2329(-1.17)	2168 (-3.43)	64.03(-2.43)	67.84(-1.17)	62.80(-1.27)
	0.01-0.25 inch/hour	2219(-5.67)	2217(-5.94)	2019(-10.10)	62.58(-4.64)	66.35(-4.23)	61.82(-2.81)
	>0.25 inch/hour	2100(-10.72)	2026(-14.01)	1849 (-17.67)	61.13(-6.85)	64.87(-6.37)	60.47(-4.94)
Snow	0	2353(0)	2356(0)	2245(0)	65.63(0)	69.28(0)	63.61(0)
	<= 0.05 inch/hour	2264(-3.93)	2227(-5.51)	2168(-3.44)	63.13(-3.8)	66.8(-3.58)	60.35(-5.14)
	0.06-0.1nch/hour	2145(-8.98)	2085(-11.53)	2122(-5.48)	59.70(-9.03)	63.35(-8.56)	59.15(-7.02)
	0.11-0.5 inch/hour	2181(-7.45)	2066(-12.33)	1946(-13.35)	60.00(-8.56)	61.99(-10.52)	57.82(-9.11)
	>0.5 inch/hour	1896(-19.53)	1887(-19.94)	1621(-27.82)	58.27(-11.20)	58.51(-15.56)	54.95(-13.62)
Temperature	>10° Celsius	2333(0)	2253(0)	-	66.3(0)	69.04(0)	-
	10°-1° Celsius	2308(-1.08)	2229(-1.06)	-	65.63(-1.00)	68.06(-1.42)	-
	0°- (-20)° Celsius	2299(-1.48)	2219(-1.52)	-	65.14(-1.75)	68.39(-0.94)	-
	<-20° Celsius	2094(-10.27)	2104(-6.62)	-	63.91(-3.6)	68.62(-0.61)	-
Wind Speed	<16 km/hr	2354(0)	2313(0)	-	66.17(0)	69.70(0)	-
	16-32km/hr	2337(-0.73)	2280(-1.41)	-	65.98(-0.29)	69.15(-0.79)	-
	>32 km/hr	2337(-0.74)	2262(-2.19)	-	65.67(-0.74)	68.65(-1.5)	-
Visibility	>1 mile	-	2342(0)	-	-	69.77(0)	-
	1-0.51 mile	-	2115(-9.67)	-	-	65.14(-6.62)	-
	0.5-0.25 mile	-	2069(-11.67)	-	-	64.82(-7.10)	-
	< 0.25 mile	-	2096(-10.49)	-	-	61.55(-11.78)	-

Similarly, speed reductions of 1%–2%, 2%–4%, and 4%–7% were found for freeway sites near the airports (MSP, MIC, and STP) for trace, light, and heavy rain, respectively. Statistical analysis showed that differences in speeds for light and heavy rain (0.01–0.25 and more than 0.25 inches/hour) were not statistically significant. Previous research (*9*) also found similar speed reductions (3%–5%) for both light and heavy rain (0.01–0.25 and more than 0.25 inches/hour) were statistically significant compared with clear weather conditions. In contrast, the differences in operating speeds during light and heavy rain (0.01–0.25 and more than 0.25 inches/hour) were not statistically significant. Thus, they concluded that heavy rain effects on operating speeds are similar to those of light rain.

Snow

Datasets on snowfall events were categorized into five categories of none, trace, light, moderate, and heavy (0, less than/equal to 0.05, 0.06–0.1, 0.11–0.5, and greater than 0.5 inches/hour, respectively). The database contained approximately 50,000, 900, 550, 300, and 125 records for these snow categories for each selected detector.

The Highway Capacity Manual 2000 shows that light snow causes 5%–10% reductions in capacity, and this study shows reductions of 3%–5%, 6%–11%, and 7%–13% for trace, light, and moderate snow, as shown in Table 2. Also, capacity reductions of 19%–27% for heavy snow (more than 0.5 inches/hour) compare with the 25%–30% reductions because of heavy snow, as recommended in the Highway Capacity Manual 2000.

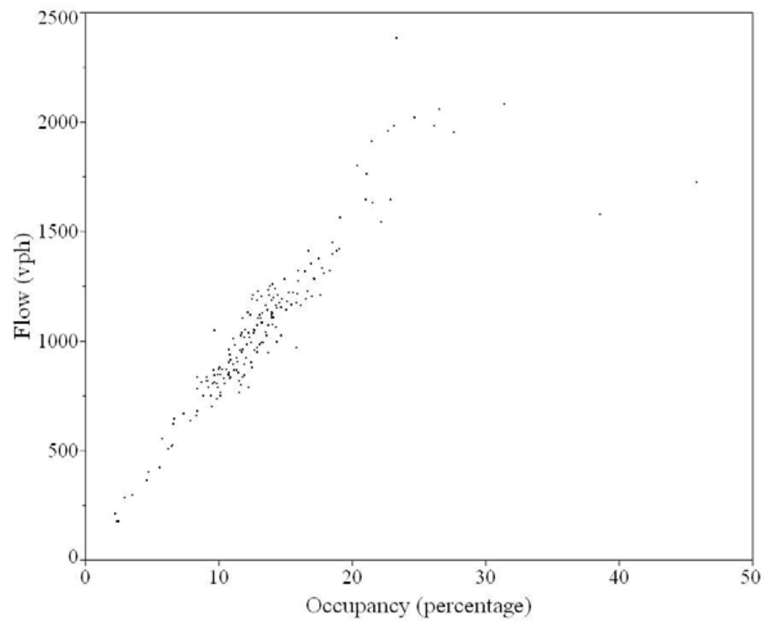
Additionally, speed reductions of 3%–5%, 7%–9%, and 8%–10% for trace, light, and moderate snow, respectively, were obtained, which quantifies reduction in speeds better than recommended speed reductions of 8%–10% in the Highway Capacity Manual 2000 due to light snow only. In contrast, speed reductions of 11%–15% for heavy snow (more than 0.5 inches/hour) significantly differ from the recommended speed reductions (25%–35%) in the Highway Capacity Manual 2000. This larger variation in speed reductions for heavy snow from this study can be attributed to differences in freeway locations, driver familiarity, or better winter maintenance activities in the Twin Cities region. Statistical analysis indicated that capacity and speed reductions were statistically significant for each weather category when compared with no precipitation conditions. However, differences in capacities and speeds for light and moderate snow conditions were not statistically significant for about 17 detectors among 20 selected detectors.

Temperature

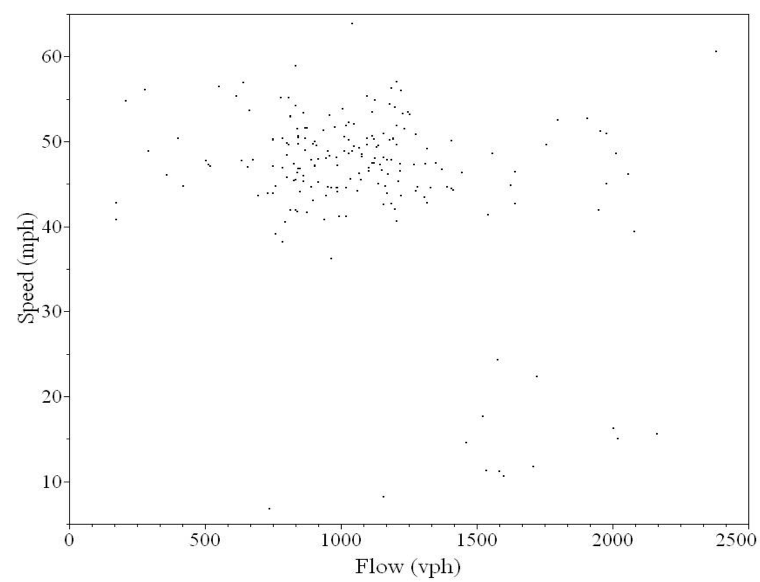
Databases containing temperature for freeway sites near the airports (MSP and MIC) were categorized into four different groups (> 10ºC, 10ºC–1ºC, 0ºC–(-20ºC), and < -20ºC). These databases contained approximately 16,000, 9000, 6000, and 120 records for these categories for each selected detector. However, the analysis showed the surface temperature datasets from an RWIS site (I-35 E at Cayuga St. Bridge) near the St. Paul Downtown Airport were not enough to show the expected trend of flow-occupancy and speed-flow relationships for colder temperatures (< -20ºC), as shown in Figures 3(a) and 3(b).

The surface temperature for detectors near ASOS sites were collected from nearby RWIS sites, because ASOS sites do not collect pavements' surface temperatures. Surface temperature data were obtained from RWIS sites (I-35 at Minnesota River, I-494 at I-94, and I-35 E at Cayuga St. Bridge) and were integrated with traffic data from freeway sites near the airports MSP, MIC, and STP, respectively.

These datasets did not show statistically significant reductions (< 3.6%) on average speeds and capacities except the reduction in capacities (6.5%–10%) for cold temperatures (< -20ºC), as shown in Table 2. Although reductions in capacities and speeds were not statistically significant for temperature categories (10ºC–1ºC and 0ºC–(-20ºC)), severe cold temperatures (< -20ºC) showed significant reductions (10%) in capacities. These results reconfirm the cold temperature effects obtained by Ries (*8*) and provide an additional guidance to traffic managers presently not available in the Highway Capacity Manual 2000.



(a)



(b)

Figure 3. Flow-occupancy (a) and speed-flow (b) for cold temperatures (less than -20ºC)

Wind Speed and Directions

Datasets on gusty winds were categorized into three different groups (< 16, 16–32, and >32 km/hr) in the opposite direction of travel for freeway sites near the two airports (MSP and MIC). Datasets contained approximately 10,000, 8,000, and 400 records for above categories for each selected detector. Additionally, the datasets from sites near the St. Paul Downtown Airport were found inadequate (< 20) to show a linear flow-occupancy and parabolic speed-flow relationships for the wind speeds (>32 km/hr), and trends were found similar to Figures 3(a) and 3(b). Thus, the data from freeway sites near the St. Paul Downtown Airport were not analyzed for wind speeds' impacts on traffic flow variables.

Table 2 shows that the reductions were not statistically significant (< 2%) for operating speeds and capacities at selected wind speed categories. These results for wind speed categories seem to vary from prior studies (*4, 5*). These studies investigated rural freeway sections of I-84, which is primarily affected by extreme winds (greater than 48 km/hr) and snowstorms. This is not the case with the Twin Cities. Thus, a direct comparison of results from this study and the available previous research may not explain the discrepancy of results.

Low Visibility

Data for low visibility conditions, due to fog events, were categorized into four different groups (> 1, 1–0.51, 0.5–0.25, and < 0.25 mile) for freeway sites. The databases contained approximately 50,000, 110, 100, 300, and 60 records for above visibility categories for each selected detector. The datapoints for low visibility condition (< 0.25 mile) for freeway sites near the Minneapolis-St. Paul International Airport and the St. Paul Downtown Airport were not enough to show linear flow-occupancy and parabolic speed-flow relationships. Thus, this research excluded the data from the two airports (MSP, STP) for analysis.

Freeway sites near the Minneapolis Crystal Airport showed statistically significant reductions of 10%-12% in freeway capacities for three groups of visibility ranges (1–0.51, 0.5–0.25, and < 0.25 mile), when compared with capacity for normal weather conditions (visibility > 1 mile), as shown in Table 2. On the other hand, differences in freeway capacities were not statistically significant, when compared pairwise within visibility categories of 1–0.51, 0.5–0.25, and < 0.25 mile, respectively. As a result, low visibility seems to show a potential impact on capacities and speeds, because it reduces capacities by 10%–12% when compared with clear weather conditions. However, no statistically significant differences in capacities among visibility categories (1–0.51, 0.5–0.25, and < 0.25 mile) were found, when compared in pairs.

Speed reductions of 6.63%, 7.10%, and 11.78% were noted for three groups of visibility ranges (1–0.51, 0.5–0.25, and < 0.25 mile) when compared with visibility greater than one mile. These reductions were statistically different when compared with average operating speeds for visibility greater than one mile. However, statistical analysis showed that operating speeds between visibility groups (1–0.51 and 0.5–0.25 mile) were not statistically significant for several detectors.

Table 2 shows that almost similar speed reductions (11.78%) for visibility (< 0.25 mile) were observed as noticed from prior research (*4, 5*). However, the small difference (2%–3%) between this study and prior research can be attributed to speed and volume variability on freeway locations (urban/suburban and rural) and different visibility ranges.

Summary of Findings

Table 3 shows the comparison of results of this research with the current information found in the Highway Capacity Manual 2000. This comparison indicates that the manual underestimates or overestimates the impacts, as listed below:

- This research found that light rain (0.01–0.25 inches/hour) has a significantly greater impact (5%–10%) on capacity, as opposed to no reductions mentioned in the Highway Capacity Manual 2000.
- The results indicate that reductions in operating speeds due to light rain are comparable with recommended reductions in the Highway Capacity Manual 2000. However, the reductions in operating speeds due to heavy rain may be overstated in the manual.
- Light and moderate snow categories show almost similar capacity and speed reductions, which are similar to reductions caused by light snow as stated in the Highway Capacity Manual 2000, except for capacity values for freeway sites near the St. Paul Downtown Airport. Thus, these two categories can be merged into one category.
- Heavy snow shows similar reductions (19%–28%) in capacity as stated in the Highway Capacity Manual 2000. However, speed reductions due to heavy snow obtained from this study were significantly lower (19%–25%) than those recommended by the manual.
- Cold temperatures (< -20^0 Celsius) showed 7%–10% reductions in capacity, while there was no significant reduction in speeds.
- Winds in the opposite direction of travel did not cause a significant decrease in speeds and capacities.
- Lower visibility (fog events) caused capacity reductions of 10%–12% and speed reductions of 6%–12%. However, speed reductions for visibility (< 0.25 mile) were significantly greater than other visibility categories presented in this study.

Table 3. Comparison of percentage reductions in capacity and average operating speeds with the Highway Capacity Manual 2000

Variable	Range	Assumed corresponding categories from the Highway Capacity Manual (2000)	Capacities(percentage reductions)		Average Operating Speeds (percentage reductions)	
			Highway Capacity Manual (2000)	This Study	HCM 2000	This Study
Rain	0-0.01 inch/hour	Light	0	1-3	2-14	1-2.5
	0.01-0.25 inch/hour	Light	0	5-10	2-14	2-5
	>0.25 inch/hour	Heavy	14-15	10-17	5-17	4-7
Snow	<= 0.05 inch/hour	Light	5-10	3-5	8-10	3-5
	0.06-0.1nch/hour	Light	5-10	5-12	8-10	7-9
	0.11-0.5 inch/hour	Light	5-10	7-13	8-10	8-10
	>0.5 inch/hour	Heavy	25-30	19-28	30-40	11-15
Temperature	10^o-1^o Celsius		N/A	1	N/A	1-1.5
	0^o- $(-20)^o$ Celsius		N/A	1.5	N/A	1-2
	<-20^o Celsius		N/A	6-10	N/A	0-3.6
Wind Speed	16-32km/hr		N/A	1-1.5	N/A	1
	>32 km/hr		N/A	1-2	N/A	1-1.5
Visibility	1-0.51 mile		N/A	9	N/A	6
	0.5-0.25 mile		N/A	11	N/A	7
	< 0.25 mile		N/A	10.5	N/A	11

N/A- Not Available

CONCLUSIONS

Overall, the results of this analysis show how weather types and intensities impact traffic flow variables. This research shows that impacts of rain and snow on freeway traffic operations in urban regions are different from recommended values in the Highway Capacity Manual 2000. This research provides additional guidance regarding quantitative estimates of capacity and speed decreases due to varying temperature, wind speeds, and low visibility conditions. Quite clearly, weather matters need to be taken into account when evaluating system operation and capacity in urban areas with significant numbers of days with inclement weather.

This research also concludes that RWIS sensors do not provide the quality and type of weather condition information that is needed to understand the impact of weather on traffic flow. The fact that data derived from RWIS sensors was not useful for the purposes of this research is perhaps understandable. RWIS technology has predominately been designed and installed to support the needs of the winter maintenance community and not the needs of traffic managers. However, as this research has shown, weather does matter for traffic operations and, therefore, RWIS technology can provide useful input to traffic mangers if this system is modified to collect environmental data for weather variables that impact traffic flow and highway capacity.

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