Whether Weather Matters to Traffic Demand, Traffic Safety, and Traffic Flow

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

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and
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Iowa State University

Final General 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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Experienced travelers know that during inclement weather, they need to adjust their schedule to take delays and unreliable travel times into account. Some travelers will even defer trips to another time or cancel the trip. While the ordinary traveler evaluates travel options based on experience, it might be expected that transportation professional managing highway and transit systems would have something more analytical than experience to make decisions regarding traveler information, traffic management, and transportation system control. Unfortunately, traffic analysis and operational tools (simulations models) and standards for traffic performance (e.g., the Highway Capacity Manual 2000) assume clear conditions, and transportation managers are left with only their own experience to manage and control the transportation system when faced with inclement weather of varying intensities.

This report describes the impacts of inclement weather identified through the literature and through prior research conducted by the Center for Transportation Research and Education (CTRE). The finds of recently completed research conducted to quantify the impact of weather on traffic flow are specifically highlighted.

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WHETHER WEATHER MATTERS TO TRAFFIC DEMAND, TRAFFIC SAFETY, AND TRAFFIC FLOW

This is one of two reports from the
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Final General Report
August 2005

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INTRODUCTION

Any experienced snowbelt driver understands that weather matters to traffic operation and safety. During snowy morning in big metropolitan areas, the radio and television provide commuters with copious reports regarding the amount and intensity of snowfall and wind speeds. Television news often shows live videos of congested freeways in the area as commuters slip and slide their way to work through the snow. Further, through experience, commuters understand that forecasts of snow accumulations of a quarter inch, one inch, and six inches are likely to imply very different impacts for their travel. Through experience, drivers learn that inclement weather results in a more hazardous trip and travel times are longer and less reliable. Experienced travelers know that during inclement weather, they need to adjust their schedule to take delays and unreliable travel times into account. Some travelers will even defer trips to another time or cancel the trip.

While the ordinary traveler evaluates travel options based on experience, it might be expected that transportation professional managing highway and transit systems would have something more analytical than experience to make decisions regarding traveler information, traffic management, and transportation system control. Unfortunately, traffic analysis and operational tools (simulations models) and standards for traffic performance (e.g., the Highway Capacity Manual 2000) assume clear conditions, and transportation managers are left with only their own experience to manage and control the transportation system when faced with inclement weather of varying intensities.

Inclement weather (fog, rain, snow, high winds, and extreme cold) impacts traffic operations during a significant proportion of the year. Inclement weather significantly impacts annual safety performance and the annual vehicle carrying capacity of urban highways. For example, the proportion of the US that receives more than five inches of snow (on the average) includes 69 percent of the country’s population and 74 percent of its roads (*1*). Clearly, the effect of inclement weather is even more important in snowy metropolitan areas like Minneapolis/St. Paul, Denver, Salt Lake City, Detroit, and Buffalo, where appreciable snowfalls (more than 0.1 inch) occur frequently (averaging 38, 35, 34, 39, and 62 days per year, respectively) and heavy snowfalls (more than 2 inches) occur often (8, 7, 10, 7, and 12 times per year, respectively) (*2*).

In Minneapolis/St. Paul and Buffalo, for example, it snows on 10 percent and 17 percent of the days of the year, respectively. To the snowy days, add days with heavy rain, blowing snow, and fog, and as many as 25 percent of the days during the year are impacted by weather events that degrade the safety performance and capacity of urban highways. However, no traffic operation analysis tools or standards are available which take into account the impact of weather. This paper describes the impacts of weather identified through the literature and through prior research conducted by the Center for Transportation Research and Education (CTRE). We specifically highlight the finds of recently completed research conducted to quantify the impact of weather on traffic flow.

WEATHER'S IMPACTS ON TRAFFIC OPERATIONS AND SAFETY

There are three predominate traffic variables that weather impacts: (1) traffic demand—in the face of inclement weather some trips will be postponed, deferred, or eliminated; (2) traffic safety—crash rates (crashes per mile) increase dramatically during inclement weather; and (3) traffic flow relationships change—changes in the relationship between volume, speed, and density result in reduced capacities. Most of the literature describes the impacts of snowy conditions on highway transportation, while only a few references were found to estimate the impacts of rain, reduced visibility, and extreme cold.

Impact on Traffic Demand

Several studies have found that traffic volumes decline during winter storms (*3, 4, 5, 6*). This may be due to several reasons, including motorists diverting trips to other modes or other paths, motorists canceling trips, and motorist taking trips at other times, before or after the storm. For example, Hanbali and Kuemmel investigated volume reductions due to winter storms across varied intensity of snow fall, time of the day, day of the week, and roadway type (*7*). Overall, they found that reductions ranged from 7% to 56% depending on the category of winter event. Hanbali and Kuemmel conclude that volume reductions increase with the total volume of snow, and volume decreases are smaller during the peak travel periods and on weekdays than during off-peak hours and on weekends.

On Interstate highway 35 (I-35) in northern rural Iowa, we extracted traffic counts from automatic traffic recorders (ATRs) during a number of snowy days (days when more than 1 inch of snow fell in 24 hours) and found a strong correlation between the percentage of traffic volume reduced (when compared to the volume on a clear day, during the same year, the same month, and the same day of the week) and wind speed and visibility (*8*). On snowy days with good visibility and low wind speed, I-35 experienced a 20% reductions in traffic, and, with poor visibility (less than one quarter mile) and high wind speed (as high as 40 miles per hour), we found that traffic levels were reduced by 80%, a much higher reduction than even that found by Hanbali and Kuemmel in an urban area. We also found that during snowstorms, commercial vehicles became a higher percentage of the traffic stream (by as much as 38% to 70%) than their typical proportion during clear weather. This indicated that although motorists where diverting trips, commercial vehicle operators were much less likely to divert trips due to inclement conditions.

From the literature and from our results on I-35, we can see that travel demand reductions are partially dependent on the type of trip (e.g., work trip, recreational trip): travelers are more likely to postpone long-distance trips and commercial trips are least likely to be deferred.

Impact on Traffic Safety

The findings of research on safety impacts of weather events are varied. All the literature we reviewed indicated that crash rates increased as roadways became wet or snow or ice covered (*5, 9, 10, 11, 12, 13, 14, 15, 16*). Swedish studies found that severe injury rates on roads with snow and ice can be several times greater than on roadways under normal conditions (*10, 11*). Perry and Symons found that in the UK total injuries and fatalities increased by 25% on snowy days, and the rate of injuries and fatalities increased by 100% (*12*). On the other hand, some studies found that crashes during winter storms are less severe (relatively fewer fatal crashes) than their counterparts during clear conditions (*4, 9*). The reduction in relative rate of fatal crashes is probably due to vehicles reducing their speed during winter storms, thereby reducing the severity of crashes. A study by Golob and Recker suggests that certain maneuvers prior to a crash may have significant impact on whether weather is a contributing factor (*17*). They found that multiple vehicle crashes associated with lane changing and merging movements are more likely when pavements are wet.

Probably the most dramatic findings of increased crash rates were those found by CTRE researchers Khattak, Knapp, Giese, and Smithson (*14*). Khattak et al. compared crash rates on interstate highways for periods when more than 0.2 inches of snow fell per hour to crash rates during the same time period on the same day of the week during the same month when conditions were clear. By comparing crash rates during non-snow and snow periods in this way, they hoped to reduce the impact on their findings of seasonal and weekly variations. They gathered data across 54 snowstorms and found a storm crash rate of 5.86 crashes per million vehicle kilometers on rural interstate highways. During non-storm periods, the crash rate was 0.41 crashes per million vehicle kilometers—the crash rate increased by 13 times during snowy weather. The authors go on to estimate a Poisson model where the dependent variable is the probability of the observed number of crashes and the independent variables are the characteristics of the storm (snowfall intensity, wind speed, etc.). They found that snowfall duration and intensity have a positive and statistically significant relationship to the number of crashes.

During our study of rural I-35, we found that during snow days (days when more than one inch of snow fell), crashes increased and were highly correlated with visibility and wind speed. During low visibility conditions (visibility of one quarter mile or less) and high wind speeds (winds as high as 40 miles per hour), crash rate increased to 25 times the normal crash rate. What is occurring during winter storms is that there are fewer vehicles on the road and those that remained are much more likely to be in crash and, as a result, the crash rate skyrockets.

We also investigated the severity of crashes during winter storms in Iowa. Table 1 presents five years of Iowa crash data. The first three columns are all the crashes that occurred in Iowa during the entire five-year period, the average crash severity, and average loss based on the Iowa DOT crash loss estimates per crash type (e.g., economic loss per fatal crash, per major injury crash). Note the severity of crashes involving commercial vehicles (trucks) is slightly higher than the severity of all crashes. This is what we would expect since crashes involving heavy trucks tend to be more severe. On the right side of the table is the same information for winter weather storm conditions. These are crashes where the reporting officer noted that there was snow or sleet falling, or the officer noted the roadway was snowy or icy. Note that 21% of crashes occurred during winter weather.

To help put the 21% of crashes during winter storm condition into perspective, the weather in Ames, Iowa, can be used as an average for the entire state. Ames is very near the geographic state center. On the average, Ames has 18.2 snow events per year (*2*). An average duration of the impact of each storm is considered to be 24 hours—some will take longer to clean-up, but many will take less than 24 hours. Assuming that, on the average, winter storms impacted the roadway system for 24 hours, about five percent of the year the roadways in Iowa are impacted by snowy weather. Thus, even though many drivers divert trips during snowstorms, 21% of the crashes take place during roughly five percent of the time.

Reflecting the fact that commercial vehicles are less likely to divert trips due to wintry weather, a higher percentage of commercial vehicle crashes occur during wintry weather. The crash severity during wintry weather is slightly lower, but it is only 14% lower as measured by the Iowa DOT's crash severity index.

Clearly, through the literature and through our analysis of Iowa crash data, it is apparent that snowy weather greatly increases crash frequency and crash rate. Crash severity tends to be slightly lower, but the increase in crash rate greatly exceeded the reduction in crash severity.

Impact on the Relationship Between Traffic Flow Variables and Capacity

Traffic flow is a function of traffic density (vehicles per mile per lane) and traffic speed (miles per hour). Freeway capacity is defined in the Highway Capacity Manual 2000 as the "maximum flow rate that can be expected to be achieved repetitively at a single freeway location and at all locations with similar roadway, traffic and control conditions without breakdown" (*18*). The capacity of a freeway segment (its maximum flow) is dependent on the speed of the traffic stream and the density (or density's inverse—headway). Under inclement conditions, drivers moderate their speed and increase the headway between vehicles; hence, weather impacts the capacity of a freeway segment.

Several researchers have measured the extent to which traffic flow and capacity are impacted by weather. Studies have focused on different parameters (highway capacity, speed, and detector occupancy) related to traffic flow. For typically urban facilities that operate near, at, and above capacity, some studies have focused at measuring strictly capacity during wet and/or snowy conditions (*19, 20, 21*). Others have investigated capacity reductions during wet and/or snowy conditions as a result of changes in flow characters (slower speeds and lower densities) when urban facilities are operating near, at, or above capacity (*22, 23*). Other studies have concentrated on speed reductions alone, principally because measurements were being taking in uncongested and/or rural segments of highway (*24, 25, 26, 27, 28, 29*).

Fairly indicative of the capacity studies is one by Ries of I-35W in Minneapolis and its suburbs, in which a trace of rain was found to result in 8% reduction in capacity, and each additional 0.01 inch beyond a trace decreased capacity by 0.6% (*20*). The studies by Hall and Barrow and by

Brilon and Ponzlet are example of studies in which the authors estimate the impact on capacity and on other traffic flow parameters as a result of weather conditions (*22, 24*). Hall and Barrow on the Queen Elizabeth Way in Hamilton, Ontario, Canada, and Brilon and Ponzlet on the Autobahn in Germany both used weather information from remote meteorological stations and traffic data from inductive loop detectors (Hall and Barrow state that they used weather information from the Hamilton Airport, and although Brilon and Ponzlet do not state the nature of the meteorological stations, they are presumably airports located remotely from the highway.). Hall and Barrow found that during rainstorms, traffic flow changes from uncongested to congested at lower occupancy rates, thus implying that capacity is reduced. Brilon and Ponzlet found that speed reductions due to wet roadway conditions amount to about 9.5 km/hr on two-lane sections and 12 km/hr on three-lane sections. Consequently, reductions in capacity to 350 vph for autobahns with two lanes in each direction and more than 500 vph on autobahns with three lanes in each direction are expected.

Examples of speed reduction studies include work done by Ibrahim and Hall and by Kyte et al. (*24, 29*). Ibrahim and Hall used traffic data from inductive loops on the Queen Elizabeth Way near Toronto and weather data from the Toronto metropolitan airport.

Data analyzed were restricted to uncongested flow. Using dummy variables for different weather conditions (light and heavy rain and light and heavy snowfall), they found that traffic operation was statistically different for each type of weather. They estimated the following drops in speed for each weather condition:

- 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.

Kyte et al. derived data from a rural section of I-84 that can be treacherous due to weather conditions (fog, blowing snow, high winds, etc.). This section of I-84 is heavily instrumented with traffic and environmental sensors. The researchers sought to determine the impact of traffic operations for four environmental variables—precipitation intensity, wind speed, visibility, and road surface condition (dry, wet, or icy/snowy)—when compared to normal conditions. They found that wet roadway conditions reduce speeds by 4.5 km/h, snow and ice reduce speeds by 9.1 km/h, and wind speeds from 16 to 32 km/h reduce speeds by an average of 5 km/h. Therefore, if there are wet pavements and wind speeds from 16 to 32 km/h, the reduction in speed is expected to be 9.5 km/h (4.5 + 5 = 9.5).

In developing the guidelines in the Highway Capacity Manual 2000 regarding weather impacts on freeway capacity, May considered the effects of capacity reducing occurrences on freeway operations (*30*). He considered reductions due to adverse weather, including rain, snow, fog, and other factors. Using the studies conducted by Ibrahaim and Hall and by Brilon and Poszlet, May proposed the flow relationships, shown in the Table 1. These factors are reported in the Highway Capacity Manual 2000 (*18*).

Table 1. Free-flow speed for different weather conditions

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

When addressing freeway capacity reduction due to weather in Chapter 22 of the Highway Capacity Manual 2000, the following is stated (*31*):

- No significant reductions in capacities due to light rains until visibility is effected
- Light snow causes 5% to 10% reductions in capacities
- Heavy rain causes 14% to 15% reductions in capacities
- Heavy snow causes 25% to 30% reductions in capacities

Although the works by Brilon and Poszlet and by Ibrahaim and Hall are very insightful, both studies were not conducted on U.S. roadways. Particularly, the Ibrahaim and Hall study used an extremely small set of data (they used only six clear, two rainy, and two snowy days). To enrich the knowledge of weather's impact on traffic flow and capacity, we estimated relationship between highway capacity and traffic speed on congested freeways in the Minneapolis/St. Paul (the Twin Cities) metropolitan area (For a more detailed description of this research, see the thesis written by the Iowa State University student Manish Agrawal, "The Effects of Inclement Weather Conditions on Freeway Traffic Operations"). Our data set included four years of data from traffic detectors on the Twin Cities freeway system, four years of environmental data taken from five Road Weather Information System (RWIS) stations located adjacent to the freeway network, and four years of environmental data from three Automated Surface Observing Systems (ASOS) stations at airports nearby the freeway network.

The Twin Cities freeway traffic management system has employed inductive loop detectors to monitor traffic. A single loop detects only presences of a vehicle (occupancy) and volume. Assumption about the average vehicle length and detector field length can be used to estimate the speed of vehicle passing over the detector. Figure 1 shows a plot of data taken from a detector on Twin Cities freeway system. Each dot represents the average data taken over a ten-minute period during clear weather. It is important to note that the data points fit into an upside down V shape. At the top of V is the maximum flow, or capacity, for the lane given clear weather conditions. To the left of the maximum flow are data points taken under uncongested flow, and data points to the right (greater than about 18% occupancy) are data taken during congested flow. The data in the uncongested area form a typical straight line along the left most edge of the cloud of data points. The red circle encompasses the data points that fall in the top five percent (top measurement of flow). To arrive at a capacity estimate for this segment of highway, we take the average volume of the top five percent.

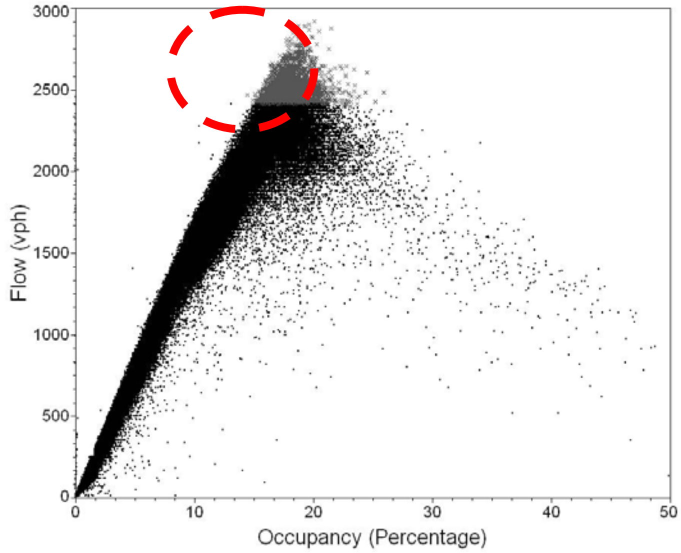

Figure 1. Occupancy and flow detector data during clear weather

Figure 2 presents a graphic of what we would expect to observe when the leading edge of the uncongested portion of occupancy and flow data plots taken during clear weather and then data taken during increasingly more severe weather. As the weather becomes more severe, drivers reduce their speed and increase their headway (or reduce density), thus reducing flow and resulting in reduced highway capacity. This is in fact what we saw as we examined individual plot.

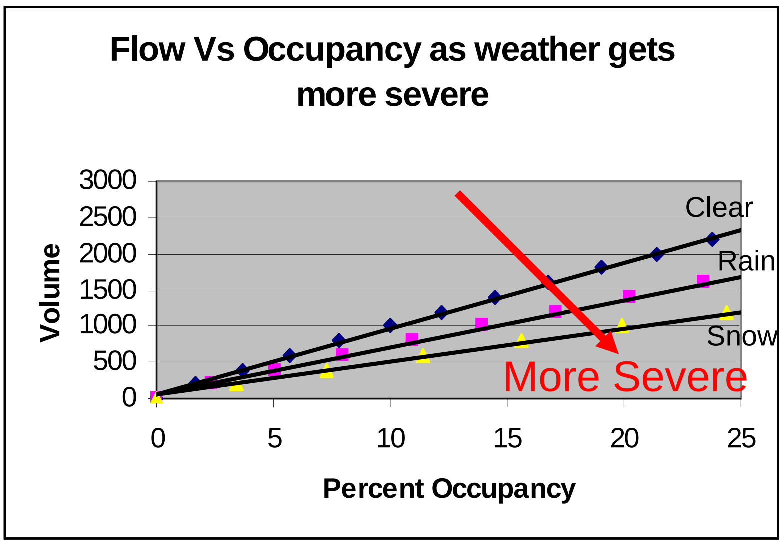

Figure 2. Occupancy and flow relationship as weather becomes more severe

Figure 3, however, shows what we saw when we plotted occupancy and flow data while the RWIS station in-pavement sensor reported dry pavement. By looking at the plot, it is apparent that we are observing two weather conditions. The left most data points were, in all likelihood, taken when the pavement was dry. The other points seemed to be faulty readings (reporting dry when the pavement was really wet or icy). After attempting to use the data from the RWIS stations, we concluded that the data were too unreliable for our purposes. Further, we hypothesized that precipitation intensity and visibility would impact our traffic flow relationships and the RWIS stations located adjacent to the Twin Cities freeway system lack the technology necessary to measure visibility or precipitation intensity. Therefore, we dismissed the use of data from the RWIS stations in our research and proceeded with use of weather observations from ASOS stations and traffic data from detectors less than two and one-half miles from the ASOS site.

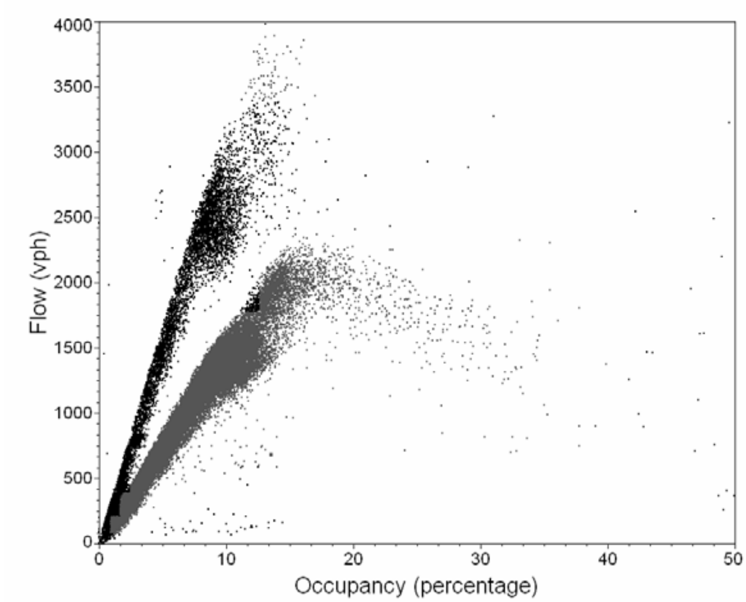

Figure 3. Occupancy and flow relationship when in-pavement sensors reported dry pavement

Table 2 presents the results of the capacity and speed reduction during rain and snow of increasing intensity and during cold temperatures, high head winds, and reduced visibility. Measurements of capacity and speed at each type of increment weather at each intensity level are statistically different than the measurement during clear weather at the 95% confidence level; although, the measurements at each interval above zero intensity may not be statistically different than one another. That is, the average speeds for trace amounts of rain (0–0.01 inches/hour) and light rain (0.01–0.25 inch/hour) were not statically different.

Table 2. Iowa crash history (1996–2000)

Vehicle Type	All Crashes			Winter Weather Crashes			
	Crashes	Average Severity	Average Loss	Crashes	Percent of Total	Average Severity	Average Loss
Commercial Vehicle	22,048	13.6	$38,103	5,487	25%	11.8	$34,223
All Vehicles	342,732	9.4	$19,374	71,879	21%	8.1	$16,770

In Table 3, the reported capacity reductions for snowfall are lower than those reported by the Highway Capacity Manual 2000. There are two explanations that might lead to better performance than that identified in the manual. The first explanation is that we simply used a richer source of data than what was used to develop the estimates in the manual and, therefore, the estimates reported in Table 2 are more likely to be true values. The second explanation is related to the characteristics of the Twin Cities highway system. The drivers in the Twin Cities may drive with lower headways and higher speeds than other drivers given comparable inclement conditions in other urban areas, and drivers in the Twin Cities may benefit from above average winter maintenance (roadway snow and ice removal).

In examining the data in Table 3 we were also surprised by the impact of very cold temperatures (less than -20°C) on capacity and by the insensitivity of traffic to low visibility. However, since Twin Cities area does not experience many foggy days, the dataset used to estimate the impact of visibility was limited.

Table 3. The average impact of weather on freeway capacity and speed

Weather Variable	Intensity	Capacity (Veh per hour)	Percent Reduction Compared to Clear	Speed (MPH)	Percent Reduction Compared to Clear
Rain	0	2318		66.2	
	0-0.01 inch/hour	2272	2%	64.9	2%
	0.01-0.25 inch/hour	2152	7%	63.6	4%
	>0.25 inch/hour	1992	14%	62.2	6%
Snow	0	2318		66.2	
	<= 0.05 inch/hour	2220	4%	63.4	4%
	0.06-0.1nch/hour	2117	9%	60.7	8%
	0.11-0.5 inch/hour	2064	11%	59.9	9%
	>0.5 inch/hour	1801	22%	57.2	13%
Temperature	>10° Celsius	2293		67.7	
	10° -1° Celsius	2269	1%	66.8	1%
	0° - (-20)° Celsius	2259	1%	66.8	1%
	<-20° Celsius	2099	8%	66.3	2%
Wind Speed	<16 km/hr	2334		67.9	
	16-32km/hr	2309	1%	67.6	1%
	>32 km/hr	2300	1%	67.2	1%
Visibility (fog)	>1 mile	2342		69.8	
	1-0.51 mile	2115	10%	65.1	7%
	0.5-0.25 mile	2069	12%	64.8	7%
	< 0.25 mile	2096	11%	61.6	12%

CONCLUSIONS

The most important conclusion from our work and the findings of other transportation weather researchers is that weather matters. Weather conditions have an important impact on traffic safety, traffic demand, and traffic flow. With the exception of the recent addition of weather into the Highway Capacity Manual 2000 in Chapter 22, highway design, traffic safety, and traffic operations guidance is generally silent on issues related to weather. Much more research is needed to measure, understand, and develop management strategies to mitigate the impacts of weather on traffic safety, traffic demand, and traffic flow.

The second important conclusion of the work reported here is that if RWIS environmental sensors are going to be of significant value to traffic managers, then they must more reliably collect different data elements. Clearly, intensity of precipitation matters and the majority of RWIS stations do not currently collect intensity data. Also, visibility data are not currently commonly collected and visibility is important. Lastly, when working with wind direction and wind speed data from the RWIS stations, we found these data misleading and hypothesized that erroneous measurement of wind direction and speed might be a result of the interaction between the measurement device (anemometer) and the vehicles on the roadway.

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