AN INVESTIGATION INTO THE IMPACT OF RAINFALL ON FREEWAY TRAFFIC FLOW

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ABSTRACT

Transportation agencies are seeking to integrate weather data into traffic operations in order to improve system efficiency. In order to do so, it is essential that transportation professionals have a solid understanding of the impact of various weather conditions on traffic flow. The purpose of this research effort was to investigate the impact of rainfall, at varying levels of intensity, on freeway capacity and operating speeds.

The findings of this study, derived from traffic and weather data collected in the Hampton Roads region of Virginia, add to the guidance currently available to professionals in the *Highway Capacity Manual*. The findings are summarized below.

- Light rain (intensity of 0.01 - 0.25 inches/hour) decreases freeway capacity by 4-10%
- Heavy rain (intensity of 0.25 inches/hour or greater) decreases freeway capacity by 25-30%.
- The presence of rain, regardless of intensity, results in approximately a 5.0-6.5% average decrease in operating speeds.

These findings indicate that the impact of rain is more significant than currently reported in the *Highway Capacity Manual*, and therefore indicate the need to carefully examine freeway operations strategies during rainfall events.

INTRODUCTION

It is widely accepted that weather plays a significant role in the performance of the surface transportation system. Certainly, extreme weather events, such as snow or thick fog, can bring traffic to a standstill. However, beyond these extreme conditions, more common weather events, such as rainfall, have also been shown to impact traffic conditions. As the transportation profession continues to seek to operate transportation facilities at the highest possible level of efficiency, it is necessary to take into account the impact of weather.

In a recent article entitled "Weather: A Research Agenda for Surface Transportation Operations," Nelson and Persaud argue that "people who manage highway operations must seek new techniques and intelligent transportation systems that complement the amazing systems of weather-information collection, analysis, and forecasting" *(1).* There are a number of examples of system configurations that can meet this challenge. For example, a freeway ramp management and control system could be designed to automatically modify metering rates based on changes in effective mainline capacities due to weather conditions. However, in order to effectively integrate traffic operations with weather information, one must have a solid understanding of the impact of weather conditions on key traffic parameters such as capacity and operating speed.

The purpose of this research effort was to investigate the impact of rainfall, categorized by intensity, on freeway traffic flow. In particular, this research expands on the limited guidance in this area currently presented to freeway operations personnel in the *Highway Capacity Manual*. This guidance, as well as previous research in this area, is summarized in the next section.

LITERATURE REVIEW

In Chapter 22, "Freeway Facilities", the *Highway Capacity Manual (2)* addresses the impact of rain on freeway capacity and operating speeds. The manual first references the research of Lamm, Choueiri, and Mailaender *(3),* who concluded that operating speeds are not affected by wet pavement until visibility is also impacted, and therefore light rain does not impact operating speeds, while heavy rain does. The manual goes on to cite the research of Ibrahim and Hall *(4)* to provide quantitative information on the impact of light and heavy rain on operating speeds and maximum observed flow rates. For light rain, the manual states that one can expect a 1.2 mile/hour reduction in operating speeds during free flow conditions, and a 4 to 8 mile/hour reduction in operating speeds at a flow rate of 2400 vehicles/hour. Furthermore, the manual states that there is no reduction in capacity during light rain. For heavy rain, it is stated that there is a 3 to 4 miles/hour reduction in operating speeds during free flow conditions and an 8 to 10 miles/hour reduction in operating speeds at a flow rate of 2400 vehicles/hour. Finally, it is stated that there is a 14-15% reduction in capacity during heavy rain.

A key area of concern, however, is that the *Highway Capacity Manual* does not define the rainfall intensity ranges associated with the categories heavy and light rain. Given the significant difference in the impact of rain based on its intensity, freeway operators are forced to attempt to classify a rainfall event without a strong basis to support this classification. This weakness of the current *Highway Capacity Manual* is even more significant when one considers that road-weather information systems will provide detailed rainfall intensity measures to freeway operators.

Given that the information provided in the *Highway Capacity Manual* is based on the work of Ibrahim and Hall *(4)*, this research was examined in more detail. The data used in this study were collected by the Queen Elizabeth Way Mississauga freeway traffic management system. Dummy variable multiple regression analysis techniques were used to test for significant differences in operating speeds and maximum observed flow rates under different weather conditions (including snowfall). The authors did address the issue of defining light versus heavy rain in the statement, “the rate of fall was used to identify the intensity of rain.” However, the rainfall intensity threshold between the categories of heavy and light rain is not provided in the paper. The researchers limited traffic data considered in this study to the hours of 10:00 am – 4:00 pm in order to avoid the impact of darkness. Six days worth of “clear” data was utilized, and only two days worth of “rainy” data was used. The authors did note that their results were consistent with those of researchers in the 1970’s – most notably Jones and Goolsby *(5)*. Finally, in their conclusion, the researchers stated that regional factors could play a significant role in the results, based on an area’s “driver’s familiarity with driving in the rain and snow.”

Clearly, the Ibrahim and Hall study is a very significant piece of work in that it provides quantitative information concerning the impact of rain on operating speeds and capacity (and therefore, is included in the *Highway Capacity Manual*). However, an analysis of the work points to the following areas warranting further research.

- There is a need to relate measures of rainfall intensity (beyond the categories of light and heavy) to traffic flow.
- There is a need to investigate the impact of rainfall using a larger set of data to minimize the potential impacts of the inherent variability of traffic data.
- There is a need to conduct the research in a different region than Toronto in order to investigate potential regional impacts.

Finally, a number of other researchers have addressed the impact of weather conditions on traffic flow. Often, researchers consider rain as a binary (yes/no) variable without addressing the intensity of rainfall, such as in Kockelman’s research *(6)* that illustrated that continuum traffic flow models are significantly impacted by rainy conditions. Other researchers have focused exclusively on ice and snow, such as Chin, et. al. *(7)*. Others have focused on pavement condition, visibility, and wind speeds on level-of-service analyses, such as Kyte, etl al. *(8)*. While all of these perspectives are important and have significant transportation implications, the focus of the research described in this paper was to address the needs described above to more fully explore the impact of rainfall on freeway traffic flow.

METHODOLOGY

In order to investigate the impact of rain on freeway traffic flow, detailed traffic and weather data was collected in Hampton Roads, Virginia – an urban region in the southeast corner of the state. The following subsections describe the methodology.

Data Collection & Preprocessing

The Smart Travel Laboratory at the University of Virginia archives all freeway traffic flow data collected by the Hampton Roads Smart Traffic Center, the region's freeway management system. This data includes volume, time mean speed, and occupancy at 2-minute intervals on a per-lane basis. For this study, two freeway links (defined as an aggregate of all lanes in one direction at a particular sensor location) were selected (stations 69 and 123) for analysis. The detectors at these links have been determined to collect accurate data and provide high data availability. These 3-lane freeway links experience heavy commuter and recreational traffic. Finally, the stations are within 3 miles of the weather station used in the study, which is located at the Norfolk International Airport.

Traffic and weather data were compiled for a one-year period, from August 1999 – July 2000. Average speed and flow rate of vehicles were compiled for the two links in 15-minute intervals, totaling 26,598 available intervals. A 15-minute interval was used to minimize the "noise" resulting from shorter interval traffic measurements. The rainfall data collected at the Norfolk International Airport, obtained from the Virginia State Climatology Office, was available on an hourly basis. This data provided rainfall intensity measures in units of inches/hour. For the purpose of this study, it was assumed that the rainfall intensity was the same for every 15-minute interval over the course of the hour.

A challenge of this research was to distinctly classify rainfall intensities as either light or heavy. This was done using information from the Cooperative Institute for Meteorological Satellite Studies and the Philippine Atmospheric Geophysical and Astronomical Services Administration. The rainfall intensity categories defined based on these sources are shown in Table 1.

Finally, as has been the case in previous weather/traffic impact studies, traffic and weather records during times of darkness were removed. The times of sunrise and sunset were determined for Hampton Roads over the given time period from the U.S. Naval Observatory. Since the precipitation data is only available by the hour, the sunrise and sunset times (which are given by the minute) had to be rounded.

Create and Examine Speed-Flow Plots

Speed-flow plots were created for each station, for each rainfall category (none, light, heavy). Note that the plots were used primarily for preliminary analyses. These plots were examined to gain the following information:

- To obtain a rough estimate of link capacity at the maximum point in the curve where traffic is transitioning from the uncongested to congested regime.
- To verify that travel demand reached capacity of the link by identifying the presence of the maximum point.
- To consider the change in speed as higher demand levels were experienced.

Estimate and Compare Capacity Based on Rainfall Level

In order to estimate freeway link capacity under varying rainfall intensities, the research team elected to use the maximum observed throughput approach. This approach, described by Chen et. al. *(9)* is based on the notion that effective capacity is best estimated by observing the maximum values of throughput that the link could sustain. As Chen et. al. noted, this is different from the *Highway Capacity Manual's* approach to estimating capacity. In this research, it was assumed that the mean of the highest 5% of flow rates observed on a link would represent the effective capacity. This accounts for noise in the data and sensor malfunctions. Finally, given that the purpose of the research is to determine percentage changes in capacity due to rainfall, it is reasonable to assume that percentage changes computed based on the research team's definition of effective capacity are roughly equivalent to percentage changes observed using other capacity estimation techniques.

Figure 1 illustrates the process of estimating capacity at Station 123 under light rain conditions. In this case, the top 5% of observed flow rates (the larger dots on the plot) were averaged to produce an estimated capacity of 2,300 vehicles/hour/lane, as represented by the line.

To complete this step of the methodology, a statistical test was used to determine if the percentage changes in capacity based on rainfall intensity were significant. The research team chose to use Sheffe's Test given that the sample sizes from each population were not equal. The test was conducted at the 0.05 significance level.

Estimate and Compare Operating Speeds Based on Rainfall Level

Research in traffic flow theory has noted that the upper "half" of the speed-flow curve (i.e. the uncongested region) is essentially flat. In other words, speed is relatively insensitive to increasing flow rates until congestion sets-in. Therefore, in order to consider the impact of rain on operating speeds, the research team assumed that operating speed is constant in the uncongested region, unaffected by flow rate. Based on this assumption, the research team simply calculated the mean speeds for each station/weather combination in the uncongested region (in this case defined as cases with speed values of greater than 40 miles/hour). Then, percent changes in operating speeds based on different rainfall intensities were tested for statistical significance.

RESULTS

The results of this research are presented in two sections – capacity reduction and operating speed reduction.

Capacity Reduction

Capacity reduction was evident at each link as rainfall intensity became greater. The results are summarized below in Table 2.

The results of the Sheffe's Test indicate that the capacity reduction at each rainfall intensity level is statistically significant.

Operating Speed Reduction

Operating speed reductions were not as dramatic as was the case with capacity reductions. The results are summarized below in Table 3.

The results of the Sheffe's tests indicate that there is a significant reduction in operating speed when rain of any intensity is compared to no rain. However, the tests also indicate that different intensity levels of rainfall do not have a significant impact on operating speed. In other words, heavy rain does not impact operating speed any more than light rain.

COMPARISON TO *HIGHWAY CAPACITY MANUAL*

Given that the purpose of this research effort was to investigate the area of rainfall impact on freeway traffic in order to provide further guidance to freeway operators, it is important to compare the results to the current information found in the *Highway Capacity Manual*. The comparisons are presented in Table 4 (capacity impact) and Table 5 (operating speed impact). Note that the comparison assumes that the definition of light versus heavy rainfall adopted in this research is consistent with the classification in the *Highway Capacity Manual*.

Based on this comparison, the following key conclusions are reached:

- This research found that rainfall, particularly at heavy intensities, has a significantly greater impact on capacity than is currently presented in the *Highway Capacity Manual*.
- The results indicate that the impact of rainfall on operating speeds is described at a reasonable level in the *Highway Capacity Manual.*
- This research indicates that the impact of heavy rain on operating speed may be overstated in the *Highway Capacity Manual.*

CONCLUSIONS

Rainfall has a significant impact on freeway capacity and operating speed. Furthermore, in the case of capacity, the impact of rainfall is a function of its intensity. Given that the results of this research are in many cases inconsistent with the *Highway Capacity Manual*, and thus indicate the possibility of poor freeway management decisions given weather data, there is a need to replicate this study in a number of regions to determine if the impact of weather is region-specific.

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Table 1. Rainfall Intensity Classifications

Rain Intensity	**Rainfall ($^{1}/_{100}$ inch per hour)**
None	**< 1**
Light	**1 - 25**
Heavy	**> 25**

Table 2. Summary of Capacity Reduction at Each Station

	Station 69				**Station 123**		
	No Rain	**Light**	**Heavy**		**No Rain**	**Light**	**Heavy**
$^{1}/_{100}$ in/hr	**0**	**<10 - 25**	**>25**		**0**	**<10 - 25**	**>25**
Sample size	614	43	6		619	44	6
Max Volume	1729	1559	1224		2340	2246	1742
% Reduction	0.00	9.88	29.22		0.00	3.99	25.55

(Using the average of the top 5% of the data points for each intensity at each station)

Table 3. Summary of Operating Speed Reduction at Each Station

	Station 69				**Station 123**		
	No Rain	**Light**	**Heavy**		**No Rain**	**Light**	**Heavy**
$^{1}/_{100}$ in/hr	**0**	**<10 - 25**	**>25**		**0**	**<10 - 25**	**>25**
Sample size	12176	813	114		12349	837	115
Avg Speed (mi/h)	58.77	55.18	55.00		59.97	57.08	56.72
% Reduction	0.00	6.11	6.41		0.00	4.82	5.43

(Using mean of speeds greater than 40 mph)

Table 4. Comparison of Capacity Impact

	% Reduction in Capacity	
	Light	Heavy
HCM	0	14 - 15
This Study	4 - 10	25 - 30

Table 5. Comparison of Operating Speed Impact

	Reduction in Speed (%)		Reduction in Speed (mph)	
	Light	Heavy	Light	Heavy
HCM	2 - 14	5 - 17	1.2	3 - 4
This Study	5 – 6.5	5 – 6.5	3 - 4	3 - 4

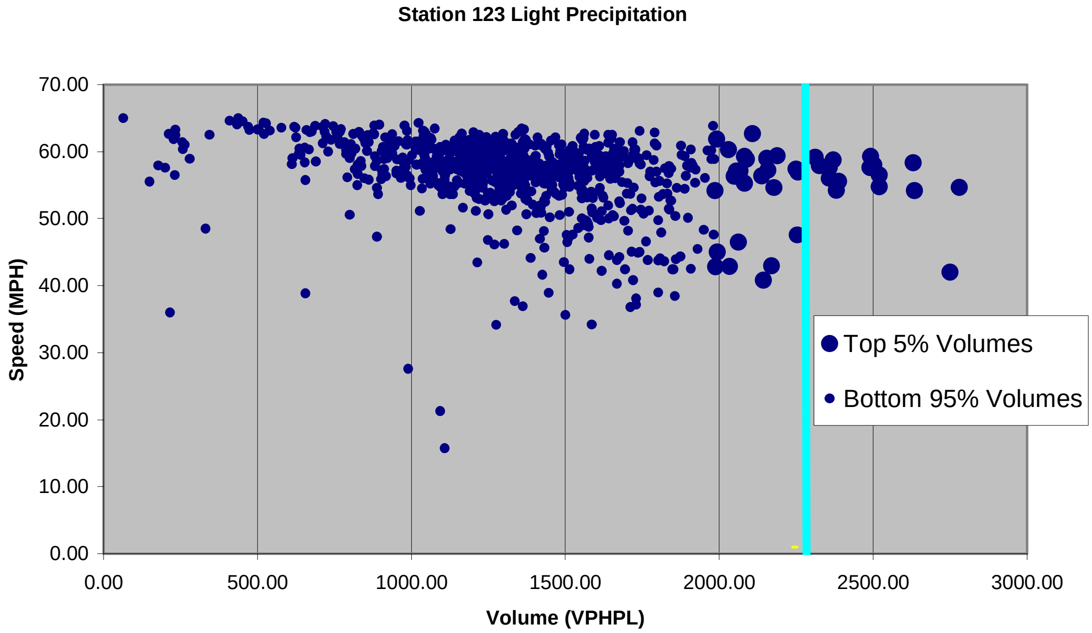

Figure 1. Estimation of Effective Capacity