DRIVER RESPONSE TO RAINFALL ON AN URBAN EXPRESSWAY

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ABSTRACT

This paper models the effects of light rainfall on urban freeway operations in order to improve our understanding of both road safety and speed-flow-occupancy relationships during suboptimal weather. The paper also addresses three broader issues: What is the form of the relationship between various traffic variables during rain relative to dry conditions? Are the safety implications of driver adjustments during the rain different for day versus night? How should speed variation be measured in ecological studies? Both the volume-occupancy and speed-volume relationships are affected by rainfall. In particular speeds are reduced and there is a stronger dependency of speed on volumes in the rain. In nighttime uncongested conditions, speeds are reduced and time gaps are increased in the rain, though only minimally. In daytime, when traffic volumes are typically high, speeds are reduced substantially during rainfall and, because of the interaction between traffic variables, volumes also decrease. Physical time gap also increases marginally while speed variability within the traffic stream is reduced. For congested daytime conditions, light rainfall is not associated with any changes in volume or time gap, but speeds are reduced. Finally, safety-related information on speed deviation can be derived from traffic-loop data by calculating the variability of travel speeds within small time units.
INTRODUCTION

Driver behavior research is important for designing safety interventions as well as determining transport system performance. Driver behavior is the outcome of both personal variables as well as factors related to the driving environment. A key environmental variable that affects both collision risk and traffic operations is weather. However, our understanding of driver responses to weather is limited, in part because of the difficulty of obtaining relevant and accurate data. In fact, much of what is known about driver adjustments to weather is inferred from either collision analyses or psychological theory, with only a handful of empirical studies that model changes in driver behavior.

This paper models the effects of rainfall on freeway operations in order to improve our understanding of both road safety and speed-flow-occupancy relationships during inclement conditions, in both congested and uncongested periods. The main objective is to quantify the extent to which traffic characteristics change during rainfall relative to dry conditions, focusing especially on travel speed and the time gap between successive vehicles. Secondarily, the article addresses three broader issues: What is the form of the relationship between various traffic variables during rain relative to dry conditions? Are the safety implications of driver adjustments during the rain different for day versus night? How should speed variation be measured in ecological studies?

BACKGROUND

Past research has established that inclement weather increases collision risk, suggesting that drivers’ adjustments to weather are insufficient to completely offset the hazards associated with reduced road-tire friction and poorer visibility. However, weather-related increases in risk are not consistent for all collision severities; rather the increase is higher for property damage collisions than for more serious crashes, suggesting that driver compensation does occur (1,2).

Various driver adjustments might be taken to reduce risk during inclement weather. One potential response is to cancel or defer a trip, which reduces exposure to risk and affects traffic density, both of which have implications for safety outcomes (3). In studies using aggregate data, vehicle counts recorded in fixed periods (from 20-second to one-day intervals) have been used to monitor changes over time (4-7). Results indicate that traffic levels are typically reduced during inclement conditions, with only minor changes during light rain and light snow but with reductions of 20 percent or more during heavy precipitation. However, it is reasonable to infer that much of the observed change in volume is due to lower travel speeds rather than to trip rescheduling; indeed driver surveys confirm that trip cancellation is rare except in extreme weather, such as freezing rain (8).

While trip cancellation may be rare, empirical studies indicate that travel speed adjustments during rain and snow are commonplace. Nevertheless speed adjustments are typically small, again except during extreme weather. For example, Ibrahim and Hall (6) found that, during free-flow conditions, mean expressway speeds were reduced by 2 kph during light rain and 5 to 10 kph during heavy rain. Similar speed adjustments were observed by Brilon and Ponzlet (9) and Edwards (10) for wet and/or foggy conditions. Studies of snowfall suggest much greater reductions in average speed—in the order of 20 kph (7,11). As a complement to studies using traffic data from automated stations, some studies (8) provide self-reported data of what drivers do in response to various weather scenarios. They also found that speed adjustments
during wet weather were minimal, but that the magnitude of the change increased as weather severity increased.

Also related to average speed and of more importance to safety is the variation in travel speed across drivers. A high speed deviation is thought to increase the risk of collision because the potential for vehicle conflicts is increased (12). Indeed, there are examples where serious crash events have been associated with high speed deviation during inclement weather (e.g., the 87-vehicle collision on Highway 401 in Canada on September 3, 1999) and studies that document how the standard deviation of speed actually increases during poor weather (11,12). However, it is difficult to infer individual risk from ecological studies using aggregate data (13), and this raises the question as to how one might use aggregate data to gain some understanding of the potential for conflict that arises because of speed variation in the traffic stream.

Closely related to speed is the time gap between vehicles, which is one measure of the level of caution being taken by drivers. Like speed, time gap is dependent on drivers’ experience levels and behavioural tendencies, but may also be affected by environmental conditions such as weather, lighting and traffic. Short time gaps allow for less time to react if the lead vehicle brakes or if an obstacle is encountered. For this reason, short headways are associated with increased crash risk (14). Although driver surveys suggest that drivers do leave more space during inclement weather (8), relatively little effort has gone into measuring following distances in different weather conditions.

In summary, previous research suggests that drivers compensate for weather. However, most of the past research has focussed on extreme weather and its effects during free-flow conditions on rural highways. As a complement to this body of literature, the current study examines data for an urban expressway that connects the downtown of major metropolitan city to its western edge. Also, the analysis is based on data for both uncongested and congested conditions, and focuses on light rainfall—a condition that occurs between five and fifteen percent of the time in most parts of North America.

DATA AND METHODS

Traffic Data

The study is based on data from the Gardiner Expressway, a six-lane, limited-access highway that provides access to the core of Canada’s largest city, Toronto, with a population of approximately two and a half million. The highway has a speed limit of 90 kph and an annual average daily vehicle count of 90,000 vehicles. Traffic data for the study are for the year 1998, because of pre-processing of the data which occurred for other research purposes (15).

Traffic conditions on the Gardiner are continually monitored using a double-loop system, which provides information in 20-second intervals for four variables: traffic flow (vehicle count); average speed (kph); occupancy (the percent time that the sensor is occupied, which is an indication of traffic density); and average vehicle length (m). For the current study, data for the first three variables were used. All information was aggregated to 5-minute intervals in order to reduce the degree of scatter in the data and for consistency with previous studies (16). Traffic volume and average speed were used directly as two indicators of traffic conditions. The standard deviation of the 20-second average speeds was also calculated for each 5-minute interval (i.e., each standard deviation was based on the 15 speed readings) and used as a measure of the relative variability of speed in a traffic stream. Volume, average speed and occupancy
were used together to derive physical time gap (i.e., the time separation between the rear of the lead vehicle and the front of the following vehicle) as in Banks (17). Average vehicle length was not used because preliminary analysis indicated that it was fairly constant through time.

Along the Gardiner Expressway, there are 21 matched pairs of stations, one in each direction of travel. However, many of the sites are either near an on- or off-ramp or are associated with a large number of missing data points. Thus the decision was made to focus the initial analysis on one site with nearly complete data that would minimize the effects of external factors such as road curvature, grade, and merging maneuvers. Site dw0060, located on the western portion of the Gardiner, near the cross street, Strachan Avenue, was chosen.

Other operational decisions made for the study were with regards to lanes of traffic and days of the week. For the purposes of analysis, only the median lane, or the lane closest to the center median, was included for each direction of traffic. Due to the dynamics of the highway, and prevailing traffic laws, this is the lane with the least amount of truck traffic. Also, the analysis includes weekdays only (Monday through Friday) for which there are predictable morning and afternoon peak periods.

Data from the four sensor variables are provided in Figures 1 and 2 for a subset of dry weekdays during the study period. As illustrated here, median-lane flows are above 1200 vph (100 vehicles per 5-minute interval) throughout much of the day—from before 7 a.m. to after 7 p.m. in both directions. Because of the location of the monitoring site west of the downtown, westbound traffic has a more pronounced afternoon peak than does eastbound traffic.

![FIGURE 1 General traffic characteristics in Eastbound direction.](image-url)
FIGURE 2  General traffic characteristics in Westbound direction.

Weather Data and Event Selection

Data from three weather stations were considered for the study: City Centre Airport, Bloor St. Station and Pearson International Airport, located 1.1, 3.1 and 16.1 km from the study site, respectively. However, the City Centre site does not provide hourly precipitation amounts, and the Bloor St. location provides such information for the summer months only. Therefore, Pearson Airport was used as the principal site for weather data; these records were supplemented with data from Bloor St. where Pearson data were missing. To test the appropriateness of Pearson data for the current study, the hourly precipitation observations taken at the City Centre Airport were compared with hourly accumulation data for Pearson. In total, only five percent (482 of the 8769 hourly observations) differed in terms of their recordings of whether or not rainfall occurred. However, it was evident that the timing of heavier rainfall did not always correspond between the two sites; this was considered in the definition of the sample set, as explained in the following paragraph.

Using hourly rainfall totals, rainfall events were defined based on the starting and ending times of measurable rainfall. After removing events that lasted only a single hour or for which traffic data were not available, only 32 rainfall events remained. Additional events were removed from the sample set if a traffic accident occurred near the study site during precipitation (3 events removed) or if a time-matched control period (with no notable weather) one week before or after the event was not available (5 events removed). Of the 24 remaining events, there were a total of 230 hours of observations — 115 hours of rainfall and 115 matched control hours. Of these 115 hours of rainfall, 105 were classified as light (0.1 – 2.4 mm total accumulation), using The Meteorological Service of Canada’s definition. The 105 hours are from 21 separate events. The remaining hours were classified as moderate or heavy. A decision was made to
focus on light rainfall only because of the relatively small sample for heavy rainfall and uncertainty about the exact timing of heavier rain at the highway monitoring site. Also, the heavier rainfalls for the study period occurred mostly in the early morning hours introducing a time-of-day bias. For longer events where hourly rainfall totals varied considerably, the hours of light rainfall were included, allowing a two-hour buffer around times of heavier rainfall to ensure that any delayed effects of heavier rain on traffic were removed.

Analysis

The direction and extent of drivers’ adjustments to periods of light rainfall were estimated by comparing rainfall conditions and paired “normal” conditions. More specifically, each 5-minute time interval with rainfall was matched with the same clock time either one week before or after the period of rainfall, but when conditions were dry. Initially, eastbound traffic was considered separate from westbound traffic, because of differences in traffic volumes and travel speeds by time of day, although in the end they were combined to form a composite data set.

The first step in the analysis was to explore the relationships between speed, volume and occupancy in order to create subsets of observations according to traffic regime—undersaturated (uncongested), oversaturated and queue discharge. As would be expected, most of the observations occurred during uncongested conditions, when average speed was largely unaffected by volume and occupancy increased linearly with volume. In order to identify those time periods characterized by oversaturation or queue discharge, each individual event or control was examined separately, by highway direction, using three graphs. The first graph depicted how volume and average speed varied over time. In the second and third, the speed-volume-occupancy relationships were graphed. Periods of congestion were identifiable by either an abrupt drop in speed and/or volume or by changes in the speed-volume-occupancy relationships.

Once all of the events and controls were examined in this way, the 5-minute observations for all the events and controls were combined in order to create the following data subsets:

- Uncongested 5-minute periods during light rain (n=1823)
- Uncongested 5-minute periods during dry controls (n=1792)
- Congested (oversaturated) 5-minute periods during light rain (n=236)
- Congested (oversaturated) 5-minute periods during dry controls (n=269)

A small number of data points were not included in any of the four categories, including 18 observations where queue discharge was clearly occurring, and 22 observations where traffic changed abruptly for only for a single observation before recovering.

Then the speed-volume-occupancy relationships were modeled for each of the four datasets. These provide insight into the nature of uncongested and congested operations on freeways, the latter of which has received only limited attention. The models also illustrate the effect of rainfall on these relationships.

In order to obtain an estimate of the safety implications of light rainfall, the data were re-assembled as follows:

- All of the event-control pairs where both members occurred in uncongested conditions during the daytime (n=885)
- All of the event-control pairs where both members occurred in uncongested conditions during the nighttime (n=611)
All of the event-control pairs where both members occurred in oversaturated conditions during the daytime (n=86).

For each set of observations, summary statistics were calculated for traffic volume, average speed, speed deviation and time gap. Where one member of the pair belonged to one traffic regime and the partner to a different traffic regime, these data points were excluded. Similarly, the 30 minutes before and after dawn and dusk, which were labeled as twilight in the first-stage analysis, were omitted.

RESULTS

As a starting point, it is useful to examine the volume-occupancy graphs shown in Figures 3 and 4, which are based on data for 21 dry events and 21 matched days with light rain. A linear model was fit through the uncongested and congested data separately. For uncongested conditions, the resultant $R^2$ values are .97 for dry conditions and .96 for light rainfall. For congested conditions, the $R^2$ are considerably lower at .45 for dry conditions and .30 for light rain. The poorer model fit reflects the fact that both volumes and speeds change rapidly and frequently during congestion, consistent with Hall et al’s (16) assertion that the relationship between flow and occupancy within congestion is highly complex. The equations are as follows where $X$ represents 5-minute volume:

Average Speed During Dry, Uncongested Conditions = $9.12X + 11.02$ (1)

Average Speed During Light Rain, Uncongested Conditions = $7.91X + 14.64$ (2)

Average Speed During Dry, Congested Conditions = $-1.68X + 188.28$ (3)

Average Speed During Light Rain, Congested Conditions = $-1.14X + 173.64$ (4)

The graphs also give a good indication of the transition volumes between uncongested and congested flow. These volumes are approximately 160 vehicles/5-minute interval during dry conditions, and slightly lower during light rainfall.
FIGURE 3 Volume-Occupancy relationship in dry conditions in both congested and uncongested conditions.

FIGURE 4 Volume-Occupancy relationship in light rain conditions in both congested and uncongested conditions.
Figures 5 and 6 illustrate the speed-volume relationships for the same data; however, based on the values identified above, the models were fit only for those data where volumes were less than 160 vehicles per interval in dry conditions and 155 in rainfall. As illustrated in the graphs, there is a fair degree of scatter between volume and average speed, as would be expected given the combination of data from 21 days into a single graph. For uncongested conditions, a quadratic curve was fit to the data, first for dry conditions and then for light rainfall. The $R^2$ of these models are .55 for dry conditions and .52 for light rainfall; the equations are as follows where $X$ represents 5-minute volume:

**Average Speed During Dry Uncongested Conditions**

$$\text{Average Speed During Dry Uncongested Conditions} = -0.0018X^2 + 0.1265X + 91.302 \text{ (5)}$$

**Average Speed During Light Rain, Uncongested Conditions**

$$\text{Average Speed During Light Rain, Uncongested Conditions} = -0.0018X^2 + 0.0744X + 89.286 \text{ (6)}$$

It is worth noting that the $R^2$ values obtained here for dry conditions are considerably higher than in Ibrahim and Hall’s paper (6), part of which may be explained by the use of 5-minute rather than 30-second data but possibly also due to the nature of the traffic on the two highways.

For congested conditions, the $R^2$ are lower at .44 and .42 for dry conditions and light rainfall, respectively, and the equations are as follows, where $X$ represents 5-minute volume:

**Average Speed During Dry Congested Conditions**

$$\text{Average Speed During Dry Congested Conditions} = 8.6518e^{0.117X} \text{ (7)}$$

**Average Speed During Light Rain, Congested Conditions**

$$\text{Average Speed During Light Rain, Congested Conditions} = 7.581e^{0.121X} \text{ (8)}$$

![FIGURE 5 Speed-Volume relationship in dry conditions in both congested and uncongested conditions.](image-url)
FIGURE 6 Speed-Volume relationship in light rain conditions in both congested and uncongested conditions.

The four curves are plotted on the same graph in Figure 7. Of note is the shape of the congestion curve, which is similar to what has been found for other Ontario data (16); for congestion, the speed-volume curve aims toward, though does not join, the uncongested curve at the peak of pre-queue flows. Also, although the difference in intercept for uncongested conditions is only 1.5 kph, consistent with Ibrahim and Hall (6), there is a stronger dependency of speed on volumes in the rain than in dry conditions. Finally, during congested conditions, speeds are only marginally lower in the rain than in dry periods and the shape of the speed-volume relationship is essentially unchanged.
FIGURE 7  Speed-Volume relationships in dry and light rain conditions during congested and uncongested periods.

The tendency toward lower speeds in the rain and other driver behaviour changes are summarized Table 1 for three different situations—nighttime uncongested, daytime uncongested and daytime congested. At night in uncongested conditions, average speed is reduced by only 2.5 kph (<3%) in light rain, and physical time gap increases by only 0.4 seconds. However, volumes drop by more than 5%, which seem to suggest that some trip rescheduling or cancellation may occur, although it is very minor.

For daytime uncongested conditions, light rainfall is associated with an average speed reduction of 8 kph (~10%) and a marginal increase in the physical time gap (2.7 to 2.8 seconds). Traffic volume also decreases by 3.6%, but, this change can most likely be attributed to the lower average speed, which reduces throughput. Thus the principal driver adaptation to light rainfall during daytime uncongested conditions on the Gardiner Expressway is reduced travel speed.

For congested daytime conditions, light rainfall is not associated with any changes in volume or time gap, but speeds are reduced by 5.7 kph. The relatively large change in speed perhaps reflects the sensitivity of high-volume, urban highways to environmental conditions, especially during congestion.
TABLE 1 Comparisons of Traffic Variables in Rain versus Dry Conditions

<table>
<thead>
<tr>
<th></th>
<th>Night Uncongested</th>
<th>Day Uncongested</th>
<th>Day Congested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rain (kph)</td>
<td>Dry (kph)</td>
<td>Rain (kph)</td>
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<tr>
<td>Minimum</td>
<td>48.6</td>
<td>65.6</td>
<td>51.4</td>
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<td>Lower Quartile</td>
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<td>85.7</td>
<td>68.9</td>
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<td>Median</td>
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<tr>
<td>Upper Quartile</td>
<td>94.8</td>
<td>96.6</td>
<td>85.1</td>
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<tr>
<td>Maximum</td>
<td>110.2</td>
<td>115.7</td>
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<tr>
<td>Weighted Mean</td>
<td>85.2</td>
<td>87.7</td>
<td>75.4</td>
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<tr>
<td>Minimum</td>
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<td>1.7</td>
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<tr>
<td>Lower Quartile</td>
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<tr>
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<tr>
<td>Maximum</td>
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<td>149.8</td>
<td>19.0</td>
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<tr>
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<tr>
<td>Minimum</td>
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<td>Weighted Mean</td>
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</table>

The lower section of the table summarizes the findings for speed deviation, calculated as the standard deviation of the 15 20-second average speeds for each observational period. As noted here, speed deviation drops in all three situations described above, again indicating behavioural adaptation in the direction of safety. The proposed measure, which considers those vehicles following one another in a traffic stream, seems an appropriate measure of conflict potential.

GENERALIZABILITY OF RESULTS

In order to explore the extent to which the results can be generalized to other sites, the analyses were repeated for two other sites on the same expressway: sites dw0030 and dw0090, which are located approximately 1.5 km east and 2 km west of the original study site. These two sites represent situations where the traffic stream is affected by the presence of ramps and lane changes, leading to merging and diverging traffic. For the dw0030 site, data were used for the eastbound lanes only due to poor data quality for the westbound lanes; the eastbound traffic is affected by an off-ramp located approximately one-half km before the detector and a decrease from three to two lanes approximately 300 m past the detector. For the dw0090 site, data are...
available for both directions of travel. Eastbound traffic is affected by two on-ramps, one located on either side of the detector at distances of less than 100 m. The westbound direction is affected by an off-ramp approximately 200 m before the detector and an on-ramp approximately 250 m after the detector.

Figure 8 shows the speed-volume relationship for these two sites combined. For uncongested conditions, again it is clear that speeds are lower during the rain relative to dry conditions, regardless of the volume, and speed adjustments increase as volumes increase. The shape of the speed-volume relationship is also similar to that found for the original study site. For congested conditions, the speed-volume relationship is somewhat different than that found for the original study site, but the overall implication for safety is similar: travel speeds are very low, and speed adjustments in the rain are minimal. In terms of the other two variables of interest, physical time gap and speed deviation, again findings were quite similar across the sites: physical time gap changed very little and speed deviations were lower in the rain than during dry conditions. This provides some evidence that the direction and magnitude of driver adjustments are transferable across sites of the same highway, even across sites that have different characteristics. Nevertheless, further studies on other highways are recommended to better understand the extent to which these findings can be generalized.

FIGURE 8 Speed-Volume relationships in dry and light rain conditions during congested and uncongested periods for sites with merging and diverging traffic.

CONCLUSIONS

Light rainfall is a condition that occurs frequently. Although previous studies have documented the implications of this environmental condition for safety outcomes, little attention has been given to understanding how driver behaviour changes in the rain. The primary adaptation to
light rain is to reduce speeds. On urban expressways, where traffic volumes are frequently high, the nature of the speed reductions and their implication for traffic operations varies from one traffic regime to another.

In nighttime uncongested conditions, traffic volumes are low and travel speeds in dry conditions approximate the speed limit. During light rain, speeds are reduced and time gaps increased, though only minimally. From a safety perspective, the degree of change is quite small—although it would seem that the low density of traffic would provide sufficient time for safe stopping in most cases.

In daytime conditions, traffic volumes are typically high and time gaps are short—in the neighbourhood of 3 seconds. When rain occurs, speeds are reduced by approximately 10% (lesser at lower volumes and more at higher volumes) and because of the interaction between traffic variables, volumes also decrease. Physical time gap also increases marginally and speed variability within the traffic stream is reduced. All of these driver adaptations are in the direction of safety, but it is clear that in these high-volume situations, the modified speeds and time gaps would be insufficient to provide a safe stopping distance given the reduced friction on wet roads.

Finally, in congested conditions that typically coincide with the morning and afternoon peak periods, the shape of the speed-volume relationship is similar for dry versus rainfall conditions. Again, speeds are somewhat reduced in the rain, despite the fact that travel speeds are already typically below 60 kph. Physical time gaps are unchanged, and are short at less than 2 seconds on average. However, speed deviation does drop to some extent, indicating that vehicles following one another tend to be more uniform in speed as they move along in queue.

While some previous studies noted that the standard deviation of speed (as measured with data for various time periods) increases in the rain, it is argued here that variability within small time units is a better measure of speed variability from a safety perspective. Still, it is clear that more attention should be given to understanding vehicle conflict potential in different circumstances.

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