DRIVER RESPONSE TO RAINFALL ON THE GARDINER EXPRESSWAY

by

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A thesis
presented to the University of Waterloo
in the fulfillment of the
thesis requirement for the degree of
Master of Environmental Studies
in
Geography

Waterloo, Ontario, Canada, 2004

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

Adverse weather conditions can increase travel risk. Understanding how drivers react to adverse weather, such as rainfall, can aid in the understanding of road safety patterns and traffic operations. This information can in turn be used to improve driver education as well as highway operation through improved signing or the introduction of intelligent highway systems.

Hourly rainfall data collected from the Pearson International Airport weather station and City of Toronto traffic data collected at the study site on the Gardiner expressway were used to create event and control pairs. In total, 115 hours with rainfall were matched to control data one week before or after the rainfall event. The traffic sensor at the study site collected speed, volume, and occupancy data at 20-second intervals, which was aggregated to five minutes. In addition, speed deviation and headway data at the 5-minute interval were used for analysis purposes.

Two methods were used to test the effects of rainfall on traffic variables and the relationships between them. Matched pair t-tests were used to determine the magnitude of change between event and control conditions for the volume, speed, speed deviation, and headway variables for congested and uncongested traffic conditions. In addition, stepwise multiple linear regression was used to test the effects of rainfall on speed-volume and volume-occupancy relationships.

Results of the matched pair t-tests indicated that volumes, speeds, and speed deviations dropped in event conditions, while headways increased slightly. Changes tended to be greater for congested than uncongested conditions. Linear regression results indicated that changes in speed were sensitive to volume conditions, and changes in volume were sensitive to occupancy, although only to a limited extent.

Overall, drivers' respond to rainfall conditions by reducing both speed and speed deviations, and increasing headway. Reductions in speed are larger in congested conditions, while increases in headway are smaller. Taken in combination, drivers are taking positive steps in order to either maintain or improve safety levels.

ACKNOWLEDGMENTS

There is no way to quantify the amount I have learned and the number of wonderful giving people I have met in the process of completing this thesis.

As I was nearing the end of this thesis, I was told a number of times to “Look at the forest Dan, you are focusing too much on the trees.” I would like to thank my advisor Dr. Jean Andrey for helping me both see the trees and the forest. Besides the lack of bubble tea trips and sushi trips, you have been a great help, a great support in this process.

I would also like to thank Dr. Frank Saccomanno for agreeing to take part in my committee. Additionally, I would like to thank Dr. Saccomanno, Dr. Bruce Hellinga, and Chris Lee for providing the traffic data used in this thesis.

I also couldn’t have reached the set goals for this thesis without weather data. For this, I would like to thank Brian Mills for the data and help in understanding the idiosyncrasies of the data set.

Acknowledgements also must be made to the Institute for Catastrophic Loss Reduction. They provided funding so that I could afford to complete this thesis.

Which brings me to the true funders of this venture. Without the help and support of my parents, the path to this thesis would have been a much more tumultuous and uncertain one.

Finally, I would acknowledge Candace Newman. There is so much that could be written here, but I want to limit these acknowledgements to one page. You have made me think of things I’ve never thought of before. You’ve also allowed me to feel things I never have before. I thank you, more than you know.

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1 INTRODUCTION

1.1 PROBLEM STATEMENT

In the driving environment many complex interactions occur between drivers, vehicles, and roads. Some of these interactions can increase risk and lead to traffic accidents resulting in injuries or fatalities. One such risk factor is the onset of adverse weather conditions such as rainfall. Increases in collisions, injuries, and fatalities have in fact been observed to increase in periods of wet weather (Brodsky and Hakkert, 1988; Andrey et al., 2001; Andrey et al., 2003; Eisenberg, 2004).

How a driver responds to the changing environment due to precipitation plays a key role in understanding safety levels. Previous studies into the effects of rainfall on traffic conditions have tended to focus on the operations side, including analysis on speed-flow and flow-occupancy relationships. Driver behaviour impacts have also been mostly limited to statements focusing solely on speed reductions for certain traffic conditions and highway types. The lack of information on urban highways and varying traffic conditions has resulted in a gap in our understanding of how drivers react to rainfall.

1.2 STUDY OBJECTIVES

The purpose of this thesis is to contribute to our understanding of the effects of rainfall on both driver behaviour and traffic operations. These contributions will be made through three specific objectives, which are:

1. Estimate the magnitude of volume, speed, speed deviation, and headway differences between rainfall and "normal" conditions.
2. Examine the speed-volume-occupancy relationships in order to determine how wet weather affects these relationships.
3. Explore the differential effects of rainfall on uncongested versus congested conditions.

The purpose of the first objective is to determine how drivers are altering their behaviour by monitoring changes in four variables through the use of t-test procedures. The second objective is to determine the effects of rainfall on relationships such as speed-volume and volume-occupancy relationships. The third and final objective is to expand the knowledge of rainfall effects from just uncongested periods to congested and uncongested periods. The results of this section will illustrate how these variables interact, and how drivers may change their behaviour as traffic conditions change in wet weather.

In order to meet the objectives of the study, data were collected from a station along the Gardiner Expressway in the downtown area of Toronto. These traffic data were matched with Environment Canada weather data from Pearson Airport, to create a set of event-control pairs for analysis.

1.3 CONTRIBUTIONS OF THE STUDY

Past research into the effects of rainfall on both driver behaviour and traffic operations in wet weather primarily focused on uncongested high speed and rural expressways (speed limits over 100 kph). Given the location and type of expressway, the following research will attempt to fill the knowledge gap regarding weather-related driver and traffic effects in congested conditions, and on an urban highway.

This thesis will also contribute to the general knowledge of the effects of rainfall on driver compensation in terms of volume, speed, speed deviation, and headway using both t-test and multiple linear regression results. Previous research into some of these variables focused on either one of these methods, but did not use both. It is hoped that by combining the results of the two tests, a more robust set of results will be achieved.

1.4 THESIS OUTLINE

Chapter Two provides an introduction to several topics relevant to the thesis. It begins with a discussion on general road safety statistics and concepts, and is followed by a discussion on general concepts relating to driver behaviour. The focus of the chapter then moves to previous research into the effects of weather on road safety and traffic operations. The behavioural responses to inclement weather are then discussed. The chapter ends with a review of several traffic operations relationships.

Chapter Three begins by introducing the spatial and temporal context of the study. The site selection process is discussed and the unit of analysis is justified. The weather data for the study period is then characterized by comparing it with previous years and the 30-year normal. Finally, the methods used for analysis are introduced.

Chapter Four introduces the events selected for analysis. This is followed by a discussion on traffic data issues such as temporal aggregation, data quality, and direction of travel differences. The traffic data set is then split into congested and uncongested conditions, which are then characterized by speed, speed deviation, volume, and headway variables. The chapter concludes with an analysis of the amount of difference between travel directions.

Chapter Five presents results for each of the objectives, beginning with results from the matched pair t-test analysis. The results of the regression analysis are discussed and briefly compared with a previous study using similar methods.

The thesis concludes with chapter six where conclusions of the study are discussed, and recommendations for further research are made.

2 RESEARCH CONTEXT

This chapter provides an introduction to road safety measurements and trends in Canada, as well as an overview of some of the theories that inform our understanding of driver behaviour generally and driver responses to situational risks more specifically. The chapter ends with a review of our state of knowledge of the effects of one situational risk factor—weather—on safety outcomes and driver behaviour, as well as the introduction of various traffic relationships used to characterize traffic operations.

2.1 ROAD SAFETY

> "No one who lives in a motorized society can fail to be concerned about the enormous human cost of traffic crashes." (Evans, 1991, 1)

The safety of motorized travel can be quantified in many ways. Various measures of economic loss, loss of life, and casualties are seen in safety literature, and each tells a somewhat different story about the magnitude of the problem and how it has changed over time.

Estimates of the economic costs vary with the methods used to calculate them, with more comprehensive assessments providing estimates that are up to an order of magnitude higher than simple accounting of crash-related property damage. For example, based on the willingness-to-pay approach, Vodden et al. (1994) estimated the total social costs of motor vehicle crashes in Ontario to be $9 billion, of which $1.5 billion was associated with property damage. Given that Ontario represents approximately one-third of the Canadian population, and allowing for inflation since 1994, this would lead to a first estimate of approximately $30 billion for the country as a whole. Other methods provide somewhat different values. For example, Achwan and Rudjito (1999) state that the cost to the economy is approximately one percent of a country's gross domestic product, which for the year 2002 would translate into $11.5 billion. Another estimate, as stated in Elvik (2000), is that the total cost to a developed economy, including lost quality of life ranges, from 0.5 to 5.7% of gross national product, depending on the industrialized country. The Elvik does not provide data on Canada, but using the range from above, an estimate of between $5.6 billion and $64.3 billion is arrived at for the year 2002. As can be seen, regardless of the estimate, the costs to the society are staggering.

In addition to financial costs, human costs are also borne by society. Over the past 60 years, a clear trend in both fatalities and injuries has occurred. As seen in figure 2-1, both fatalities and injuries increased markedly from 1945. The number of fatalities in Canada peaked in the mid-1970s, while the number of injuries peaked more recently in the early 1990s. Since their peak, the number of fatalities has decreased by over half, while injuries have decreased by roughly a fifth. Despite these reductions, the downward trends appear to be stalling, with both the number of fatalities and the number of injuries remaining constant in the late 1990s and in the early 2000s. In addition to focusing on the actual number of injuries and fatalities, road safety literature often focuses on the rate of increase or decline. This type of metric, using the "per billion vehicle kilometres travelled", also illustrates a decrease in both fatalities and injuries in the 1980s and 1990s (Andrey, 1990).

FIGURE 2-1: ROAD SAFETY TRENDS IN CANADA, 1945-2002

Many factors can affect the frequency and severity of road accidents. These factors can be classified into three broad categories labelled as driver, vehicular, and environmental (social and physical) (Wambold and Kulakowski, 1990; Abdel-Aty and Radwan, 2000; Norris et al., 2000; Smiley, 2000; Wouters and Bos, 2000). By studying these factors in all phases of a crash (pre-event, event, and post-event), steps can be taken to reduce the severity or even the occurrence of accidents. A common way to conceptualize these interventions is to display them in a Haddon matrix (table 2-1)—a framework that was developed in the 1960s for use in injury prevention studies (Fowler, 2002).

TABLE 2-1: HADDON MATRIX

	Human	Vehicle	Road Environment
Pre-Event	• Impaired Driving Training • Graduated Licensing	• Anti-Lock Brakes • Adaptive Cruise Control	• Median Installation • Paved Shoulders
Event	• Seat Belt Legislation • Child Restraints	• Air Bags	• Removal of Roadside Obstacles • Introduction of Break-away Signs and Poles
Post-Event			• Improved Emergency Medicine

Sources: Edwards 1996; Evans 1991; Hoedemaker and Brookhuis 1998; Transport Canada 2004

Previous attempts to improve safety have been effective, which is reflected in the decrease in fatalities and injuries, even as the number of vehicles and distance travelled continues to increase. However, the true effects of individual interventions are hard to gauge. The introduction of a single technology such as seat belts can decrease the number of fatalities. However, the introduction of such a technology may lead to drivers taking more chances on the road due changes in their perceived safety or vulnerability (Elvik, 2000). In his 1991 book *Traffic Safety and The Driver* Evans attempted to determine the cumulative effects of a various vehicle improvements aimed at occupant safety. He calculated that measures ranging from head restraints to the structure of vehicles led to an overall decrease in fatalities of 11.43%.

Although a comparable assessment into the effects of safety interventions in the driving environment has not been made, general inferences can be made from piecemeal evidence. For example, Evans (1991) states that much higher fatality rates on two lane roads are associated with head-on crashes and with automobiles striking fixed objects near the roadway. However, in multi-lane roadways, these effects are mitigated by the installation of median barriers and fewer roadside objects. Although travel and driving patterns differ for both of these roadways, Evans (1991) also states that differences in fatality numbers illustrate that roadway characteristics affect overall fatality rates.

A similar type of study was performed by Noland (2003) into the effects of general medical technology on fatality counts. It was determined that these advances in medical treatment and technology have reduced traffic fatalities in developed countries in the past 20-30 years.

Even with a century's worth of improvements in the human, vehicle, and road environments, collisions still occur, and the vast majority of these accidents are attributable in whole or in part to driver errors and human behaviour (Wouters and Bos, 2000). Since driver behaviour directly affects the three essential tasks of driving – navigation, guidance, and control (Ogden, 1997) it is generally considered the most complex factor in accident prevention. Although the road environment and the vehicle environment are important in the safety equation, ultimately the driver must respond and react to changes in the road environment, otherwise known as behavioural adaptation (Rubin-Brown and Noy, 2002).

2.2 Driver Behaviour

In *Traffic Safety and the Driver*, Leonard Evans (1991) makes a distinction between driver performance and driver behaviour, with the former referring to drivers' perceptual and motor skills and the latter referring to "what the driver in fact *does* do" (p. 133). The focus in this review is on driver behaviour.

There is general agreement in the road safety community that psychological characteristics play important roles in explaining driver behaviour and safety outcomes (Evans, 1991). However, there is no single psychological theory that can be used to explain the complex actions of drivers. Rather a variety of theories have been developed and used as partial explanations for various driver behaviours. For example, Aberg et al. (1997) cite the theory of reasoned action where driver attitudes and subjective norms affect driver intention. In the study on vehicle speed and perception of speed of others, the effects of the social traffic environment were tested. It was determined that drivers tended to overestimate others' speeds by up to 50%, which led to an increase in speed due to a drivers' desire to travel at the same speed as others.
Parker et al. (1992) and Elliott et al. (2003) used an extension of this theory, the theory of planned behaviour, to further explain drivers' compliance with speed limits. They found that attitude, perceived control, and subjective norms play a larger role in speed compliance than demographic variables.

One of the central concepts in much of the driver behaviour research is that of risk and how three aspects of risk—objective, subjective and acceptable—relate to one another (Wang et al. 2002). The first, objective risk is usually defined as the product of an event's occurrence and the magnitude of the consequences if the event were to occur. Second is the idea of subjective risk, which refers to how a driver perceives risk, which can greatly affect behaviour and, in turn, safety levels. Finally, acceptable risk refers to the amount of risk that society or an individual is willing to accept in exchange for a certain level of mobility.

Various theories integrate these three aspects of risk in an attempt to explain risk-taking behaviour. Central to several such theories is the process of risk compensation, which is the idea that drivers adapt to driving situations in order to bring their perceived level of risk into line with their acceptable level of risk. Examples of related theories include Summala's zero risk theory, first put forward in the 1970s. The main premise of this theory is that drivers adapt to risk in a traffic situation in order to reduce their subjective risk to zero (Summala, 1996). This theory implies that drivers will alter their behaviour rapidly, for example by adjusting the gap between their own vehicle and the vehicle in front of them, if the driving situation changes. A second theory, risk homeostasis, was first articulated by Gerald Wilde (1982). This theory states that unless drivers' target levels of risk are reduced, people will adjust their driving behaviour in order to maintain their perceived risk at a relatively constant level—that which is acceptable to them. The implication of the risk homeostasis theory is that many safety interventions, particularly those that are based on engineering approaches, may have limited effectiveness because of the dynamic nature of driver behaviour.

Of all the driver behaviour theories, none has received the scrutiny that risk homeostasis has. Some empirical results suggest that the theory has some validity. One example of such a study reports on research testing the effectiveness and safety gains of airbags, where it was found that the introduction of airbags in cars lead to more aggressive driving (Peterson et al., 1995). Additionally, a study by Janssen (1994) found that drivers who had these safety devices compensated by driving faster and closer to vehicles in front of them. However, other studies call into question the adequacy of this driver behaviour theory. For example, Lund and Zador (1984) focussed on driving behaviour and seatbelt use in Newfoundland. They found that after the law was enacted, seatbelt use increased from 16% to 77% and there was no major difference in following distance, speed, stops at intersections during the yellow phase of operations, and turning left in front of traffic. Similarly, using the example of airbag introduction, Williams et al. (1990) state that if drivers were to maintain risk levels with the introduction of airbags, they would have to reduce their use of seat belts, but they did not. Finally, Wilde and Robertson (2002) discussed the issue of traffic accident fatalities. The authors observe that between 1964 and 1990, occupant death rates in passenger cars per distance travelled fell by almost two thirds in the United States due mainly to vehicle improvements. In summary, therefore, while there is some evidence of a risk compensation mechanism, the link between perceived and acceptable risk, and the way this link plays out in driver decision making, remains elusive.

In other driver behaviour research, the focus is on the driver's attitude. Research has shown that even though driver skill levels may be high, a poor attitude will increase the risk of being in collision (Assum, 1997). Other psychological characteristics such as hostility, poor self-esteem, and irresponsible attitude can also reduce the effectiveness of measures taken to increase safety levels on roadways (Assum, 1997; Norris et al., 2000). For example, Norris et al. (2000) quote Beirness et al. (1993) who found that crash-involved drivers tended to have lower levels of self-confidence than drivers who were not involved in a crash.

Another theme in driver psychology relates to drivers' desire for control and their estimation of their own skill levels. A driver with a high desire for control not only tends to drive faster and pull into smaller gaps, but also tends to believe that he or she has a large degree of control over chance events (Hammond and Horswill, 2002). Similarly, drivers who drive faster tend to be more confident and have a higher opinion of their driving skill (Parker et al., 1995). Both skill assumptions and desire for control can be used to define a driver's attitude, which in turn, influences a driver's behaviour. Assum (1997 found that drivers with the 'right' attitude had 2.5 fewer accidents per million kilometres than drivers who had the 'wrong' attitude.

As illustrated in the preceding paragraphs, driving psychology is an active area of theoretical research. At this time however, these theories are insufficient to accurately predict the direction and magnitude of driver responses to various external stimuli, such as weather. The alternative approach to using driver psychology theory to predict driver behaviour is to proceed with empirical analyses that permit the estimation of behavioural responses through comparisons of traffic conditions during rainfall versus dry, seasonal conditions. The next section provides a review of the methods and findings of studies that have adopted a similar empirical approach.

2.3 Empirical Research on Weather, Road Safety and Traffic Operations

Based on available information from the literature, the most important situational risk factors for road safety include the roadway characteristics, traffic conditions and weather (Hijar et al., 2000). Relevant roadway characteristics are geometry, surface condition, shoulder and median width, and lane width (Stamatiadis et al., 1999; Abdel-Aty and Radwan, 2000; Karlaftis and Golias, 2002). Traffic conditions are also important, as higher volumes have been associated with increased collision rates, while fatality numbers decrease (Brodsky and Hakkert, 1983; Abdel-Aty and Radwan, 2000; Norris et al., 2000;). Finally, weather conditions, such as precipitation and fog, affect roadway friction and driver visibility levels, leading to changes in both collision-involvement rates and the frequency of collisions of different severities. Evidence of such a link was found by Andrey et al. (2001) in a study focusing on the effects of precipitation on road safety in urban areas of Canada. That research showed that precipitation led to an increase in traffic collisions and related injuries. The rest of section 2.3 focuses on weather as a situational risk factor. The discussion focuses initially on safety outcomes (section 2.3.1) and then on driving behaviour as they may relate to these outcomes (section 2.3.2).

2.3.1 WEATHER AND ROAD SAFETY

Most research into the relationship between weather conditions and road safety indicates that adverse weather is associated with an increase in the total number of accidents. Typically, property damage collisions increase the most during periods of adverse weather. In a series of empirical studies on weather-related risk, Brodsky and Hakkert (1988) found that rainfall can increase the total number of accidents during periods of rain by 50%. In conclusions made by Hankins (1977), wet weather accident rates are generally 2 to 3 than compared to total rates, and in some cases 10 times higher than normal accident rates. Another study by Eisenberg (2004) focusing on the effects of precipitation on traffic crashes found that a one cm increase in precipitation led to a 1.15% increase in fatal accidents. Results from his analysis on snowfall amounts also saw a 0.9% increase in fatal accidents with an additional centimetre of snow. Another study into the effects of winter weather on accident rates by Rama (1999) found that the risk of an accident can be 20 times higher than under good road conditions. In terms of absolute number of crashes, Knapp (2001) found that on average, there were two crashes during each winter storm, whereas only 0.65 crashes occured in a non-storm period.

The increased collision rate has been observed for both snowfall and rainfall, although these two forms of precipitation have different implications for crash severity patterns. The results for rain-related studies indicate collisions of all severities are more frequent during rain events relative to dry conditions. For example in a rain event-control matched pair study, Andrey et al. (2003) found that collisions during rainfall in Canadian cities increased by 75 percent, on average, and injury rates increased by 45 percent overall. In another study previously quoted, Brodsky and Hakkert (1988), using US Safety Board data, found that the risk of a fatal accident on wet pavement was 3.9 to 4.5 times greater than on dry pavement.

For snowfall, property damage and injury rates increase, but the situation for fatal collisions is less clear. For example, in one study, Khattak and Knapp (2001) found that while crash rates increased during snow events, the number of fatalities tended to be fewer. They suggested that the reduction in fatalities may have been the result of snow playing a protective role by lessening the impact with stationary objects, if snow banks exist. In another study by Knapp (2001), severe injury rates on roads with snow and ice were seen to be several times greater than at any other time of year. In a study quoted by Knapp (2001), Perry and Symons (1980) found that while total number of injuries and fatalities increased by 25% on snowy days, the rate of injuries and fatalities increased by 100%. Brorsson et al. (1988), studying the effects of snow depth on single vehicle crashes; found that a one-centimetre increase in snow depth saw crashes with occupant injury and with severe or fatal injury increase by 3% and 3.5%, respectively. It was also found that the number of crashes with only property damage is higher during the winter as compared with non-snow seasons.

There are many variables that can affect the frequency and number of accidents during periods of inclement weather. Some of these relate to the characteristics of the weather event itself. For example, road risk is found to increase above 'normal' rain risk levels when the rain event was preceded by an extended dry period (Brodsky and Hakkert, 1988). There are two related explanations for such a situation. The first is that there is typically an increased amount of oil and brake dust on the roadway after an extended dry period, which may reduce the amount of friction when rain does occur. The second is that drivers may become used to driving under dry conditions and, when a rain event does occur, they do not adjust sufficiently to the change in friction and visibility. Other weather variables that have been found to affect collision risk include rain intensity, distribution of raindrop size, and the depth of water on the road. Both rain intensity and distribution of raindrop size affects the visibility levels, and thus the ability of drivers to navigate the roadway (Bhise et al., 1981). Finally, the duration of the rainfall was identified as being important in a study by Brodsky and Hakkert (1988), but a subsequent study by Andrey et al. (1993) found that as soon as rainfall ends, accident risk returns to normal levels.

The amount of risk a driver is exposed to on a roadway during periods of rainfall is also dependent on factors such as traffic volume and traffic patterns, as noted by Brodsky and Hakkert (1988). Higher traffic volumes during a period of rainfall may increase the chance of impacting another vehicle. Additionally, in periods of higher volume, an increased number of lane changes may also adversely affect risk levels. These issues are discussed further in the next section.

Whether a roadway is located in a rural or urban area can also affect the number and severity of accidents. In a 2001 traffic trend report of accidents between 1988 and 1997 Transport Canada found that of all accidents that occurred in Canada, only 34.4% of fatal accidents occurred on urban roadways. Conversely, 71.4% of all injury accidents occurred in urban areas. This difference in fatal accidents is the result of higher speeds, more head-on collisions and cars striking trees and other objects in rural areas (Evans, 1991). Due to design standards, most of these hazards have either been removed along urban expressways, or minimized through measures such as breakaway signs (Transportation Research Board, 2000). The lower speeds but greater potential for traffic conflicts on urban streets further explains these severity differences.

There is a fair amount of research on the effects of precipitation on either rural or urban roadways. However, very little research exists that directly compares the two. However, a 1980 study by Bertness into the effects of rain on transportation-related activities compared crashes in Chicago with those in northwest Indiana. It was found that crash severity during rainfall increased in rural areas but not in urban areas, but no explanation was provided by the author.

2.3.2 BEHAVIOURAL RESPONSES TO INCLEMENT WEATHER

Weather conditions also affect traffic operations. For example, both rain and snow reduce the amount of available friction on the road as well as changing the appearance of the road (Brodsky and Hakkert, 1983). These two factors can reduce the speed, and thus flow of a roadway.

Although little is known about how individual drivers respond to inclement weather, there is some evidence that some measures are taken in order to mitigate weather-related risks. For example, in a study of self-reported driver adjustments, various types of inclement weather were found to result in various degrees of trip cancellation, speed reduction, increased following distance and increased caution generally (Andrey and Knapper, 2003). Overall, the proportion of respondents who indicated adjustment was lowest for “steady rain” and higher for “heavy wet snow”, “morning fog” and “freezing rain”. Other studies into the effects of adverse weather on traffic operations have used variables such as traffic flow, mean speed, speed deviation, occupancy, and headway to monitor changes in behaviour.

Traffic flow or volume measurements illustrate macroscopic changes that occur in traffic patterns. Adverse weather can result in the rescheduling of trips in order to avoid poor road conditions in the short term, or the outright cancellation of the trip. When measuring for such a change in volume, these two reasons are most commonly cited; however, a recorded reduction in volume may actually be the result of increased vehicle spacing (May, 1990) or reduced speed. In a study by Ibrahim and Hall (1994), maximum observed flows decreased during precipitation, with the drop increasing as the weather worsened. Volumes were observed to drop 48% in periods of heavy snow and 20% in periods of heavy rain, both of which are partially explained by lower speeds and larger headways. In a similar study, Knapp (2001) states that volume reductions during snow events were smaller during peak travel hours and on weekdays. This volume reduction may suggest that, in addition to speed and headway changes, trip cancellation actually occurs during times of discretionary driving. As a complement to studies using traffic data from automated stations, studies by Doherty and Andrey (1993) and Andrey and Knapper (2003) provide self-reported data of what drivers do in response to various weather scenarios. Their results suggest that speed reductions are a common response, but that trip cancellation is relatively rare except in extreme conditions.

As suggested above, the speed of the traffic is also greatly affected by road conditions during periods of adverse weather. Weather characteristics that can affect speed, much like volume, include the type, intensity, and duration of precipitation, as well as the state of visibility. Beginning with visibility, Liang et al. (1999) found that fog events reduced highway mean speed by 8 km/h. Rain can also reduce visibility by increasing the amount of spray in the air or causing the windshield to be covered in water. The reduction in mean highway speed during normal periods of rain was measured in one study to be roughly 10 km/h (Brilon and Ponzlet , 1996). Another highway study by Ibrahim and Hall (1994) during free flow conditions found that light rain reduced mean speeds by 2 km/h and heavy rain saw reduction of 5 to 10 km/h. Snow events appear to reduce the mean speed of vehicles the most, which may be explained by a greater reduction in visibility in combination with the deposition of ice and snow on the road surface. This deposition of snow would both reduce the amount of friction and the visibility of lane and shoulder pavement marks. Several studies have shown quite a large range of mean speed reductions. The study by Ibrahim and Hall (1994) saw reduction in mean speeds of 13 km/hr in periods of light snow, and up to 60 km/hr in periods of heavy snow. Other studies show an 18% to 42% reduction in mean speed on two-lane roadways, and 13% to 22% reductions in speed on freeways (Padget et al., 2001).

Perhaps the most important and least studied variable when it comes to driver behaviour, safety, and inclement weather is standard deviation of speed. Closely related to the mean speed variable, speed deviation can characterize how vehicles are interacting with each other. A high speed deviation is thought to increase the risk of being in a collision (Padget et al., 2001). The exact threshold where speed deviations become dangerous is somewhat contested. In the Padget et al. study (2001), a West and Dunn (1971) study is quoted where crash probability remains low for vehicles within 24.2 km/h of the average vehicle speed. However, the results of the study state that for every 1 km/h a vehicle deviates from the average, there was a 2% - 3.5% increase in the probability of being involved in an accident. In inclement weather, when mean vehicle speeds are typically reduced, the standard deviation has been found to increase by as much as two to three times above normal conditions (Liang et al., 1999, Padget et al., 2001).

Also closely related with speed and general safety levels, headway can be used to portray both driver behaviour as well as a driver's risk taking behaviour (Evans and Wasielewski, 1982). Like speed, headway distances are dependent on both a drivers' experience and behavioural tendencies. Short following distances allow for less time to react if the lead vehicle brakes or if an obstacle is encountered. Even if a headway distance gap were to remain static, a corresponding increase in speed would result in reduced time for reaction before a collision. For this reason, short headways are connected with increased accident risk (Rajalin et al. 1997). In another study by Evans and Wasielewski (1982), it was found that there is a correlation between traffic safety and a driver's choice of headway. Specifically, it was concluded that the size of a driver's headway can be used as a predictor of accident involvement.

The actual headway that is determined to be 'safe' is not clearly established. A safe headway is seen as a function of a driver's reaction time and a vehicle's braking ability (Boer, 1999; Taieb-Maimon and Shinar, 2001). In addition to the reaction time and vehicle capabilities, it is suggested that an additional safety margin be introduced to allow for a safe headway buffer (Nilsson, 2000). The method for depicting this headway safety margin differs as much as the actual safety margin itself. In the 1940's, a safe headway was assumed to be one second, and by 1954, the American Association of State Highway Officials assumed a safe headway of 2.5 second for all design speeds (Fambro et al., 1999). Recent research has put the time much lower at somewhere between 0.6 seconds and 0.8 seconds (Taieb-Maimon et al., 2001). Other methods for illustrating this safety margin are more variable. It is thought by some that a driver sets up a mental distance threshold between cars and that this threshold is constantly being approached and then being moved away from (Brackstone and McDonald, 1999). Yet another method of illustrating this concept of a safe headway distance uses a distance measurement such as one car length for every 16 km/hr travelled (Taieb-Maimon and Shinar, 2001).

2.4 Relationships Between Traffic Variables, and the Effects of Weather

The relationship between traffic variables such as flow, speed, and occupancy are used to portray the characteristics of a roadway, or certain sections of a roadway. Flow signifying the number of cars passing a point, speed – the mean speed of the vehicles, and occupancy, the amount of time a road sensor is occupied. Much research has been done on the effects of roadway conditions and external variables such as free flow conditions (Transportation Research Board, 2000), congested conditions (Zhou and Hall, 1999), and environmental effects such as precipitation (Hall and Barrow, 1988; Ibrahim and Hall, 1994)

The most commonly cited relationship in literature is the speed-flow relationship. In this relationship, as seen in figure 2-2, there are three distinct periods of traffic conditions. The first, uncongested, occurs in uncongested traffic conditions. The second is a period of congestion, or "within a queue". This period is made distinct by the much lower speeds. The third period is "queue discharge", or the transitions period between congested and uncongested conditions.

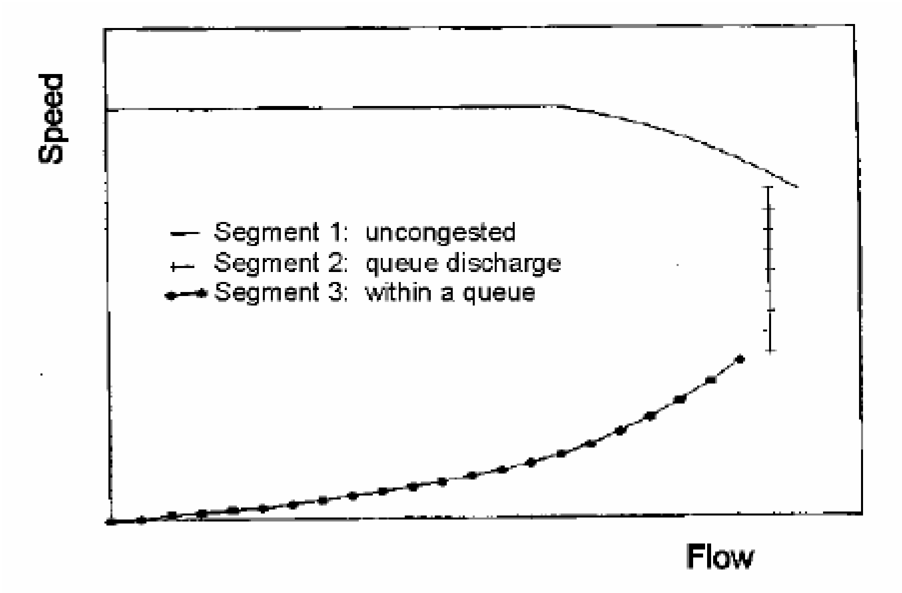


FIGURE 2-2: GENERALIZED SHAPE OF SPEED-FLOW CURVE FROM (HALL ET AL., 1992, 14)

Another commonly cited relationship is the one between flow and occupancy, or the number of vehicles passing over a point on the roadway and the amount of time that point is occupied. A sample of a flow-occupancy relationship is seen in figure 2-3. The points at the lower end of the curve, represented by lower flows and occupancies, occur during uncongested periods. Points that occur at higher flows and higher occupancies occur during periods of congestion.

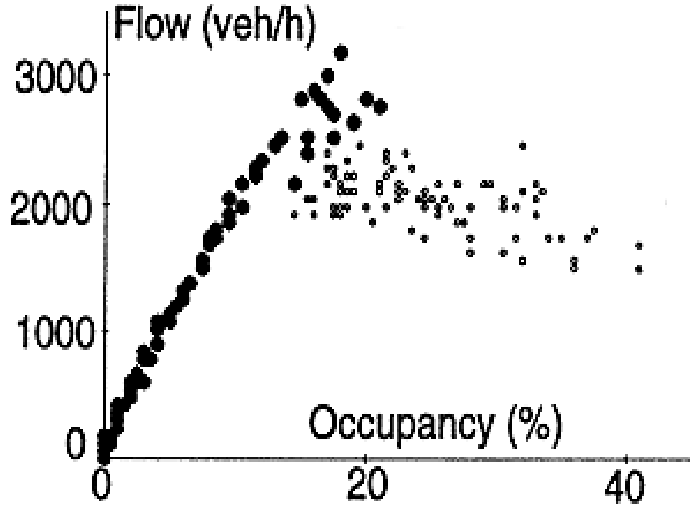


FIGURE 2-3: FLOW-OCCUPANCY RELATIONSHIP FROM (DAGANZO ET AL., 1999, 369)

A recent study by Ibrahim and Hall (1994) used both the speed-flow and flow-occupancy curves to determine the effects of both snow and rainfall on traffic operations on a limited access highway in southern Ontario. A slightly different study examined the effects of both snow and rainy weather on the flow-occupancy relationship (Hall and Barrow, 1988). The Ibrahim and Hall (1994) and Hall and Barrow (1988) results found that light and heavy rain reduced the slope of the flow-occupancy functions.

In addition to the speed-flow and flow-occupancy relationship, the speed-occupancy relationship is sometimes used to characterize the operations of a highway. This measure is sometimes used in combination with the other two relationships in a three dimensional model (Gilchrist and Hall, 1989). However, in a recent conference presentation, Nair et al. (2001), used the speed-occupancy relationship to illustrate different traffic conditions. In figure 2-4, two examples of the speed-occupancy relationship are provided. The first relationship (A) illustrates conditions in uncongested periods, while the second relationship (B) shows periods in congested conditions. In figure 2-4A, i.e. uncongested conditions, the relationship forms a straight line, while in congested conditions, a flattened out S-curve is present. This was confirmed in the Gilchrist and Hall (1989) study.

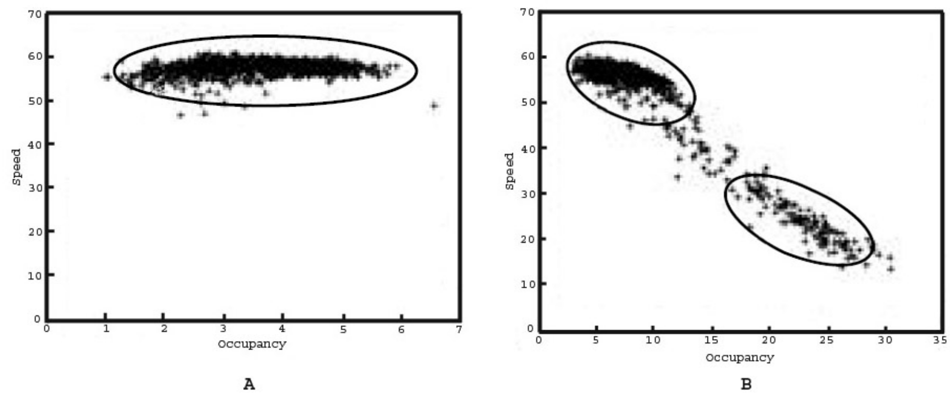


FIGURE 2-4: SPEED-OCCUPANCY PLOTS FROM (NAIR ET AL., 2001, 2)

A fourth relationship that is sometimes used to summarize traffic characteristics focuses on the concept of headway. In the 2000 Highway Capacity Manual, the frequency of headways on an expressway in Long Island illustrates that the distribution of time headways for each lane is slightly different (figure 2-5).

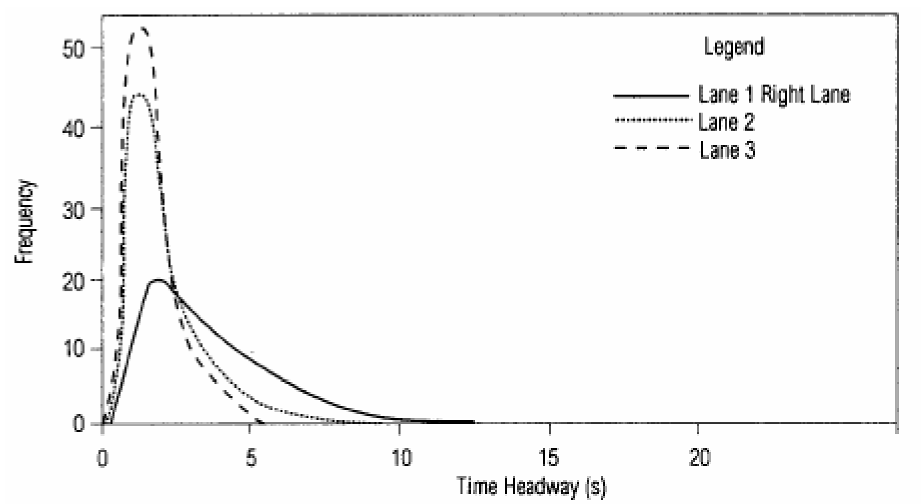


FIGURE 2-5: TIME HEADWAY DISTRIBUTION FROM (HCM, 2000, 8-26)

The relationship between headway and speed has been researched by Banks (2003) in conditions of congested freeway flow. His research, focusing on two highways in North America (San Diego and Mississauga), found that in congested conditions, headways are essentially constant with respect to speed. His observations from the study site in San Diego, as illustrated in figure 2-6, show that during congested periods, where lower speeds typically occur, headways are constant, even though scatter does occur. A similar relationship was plotted for the Mississauga study site in the Banks study which held the same basic pattern. As speeds increase and free flow conditions occur, the time headways increase greatly.

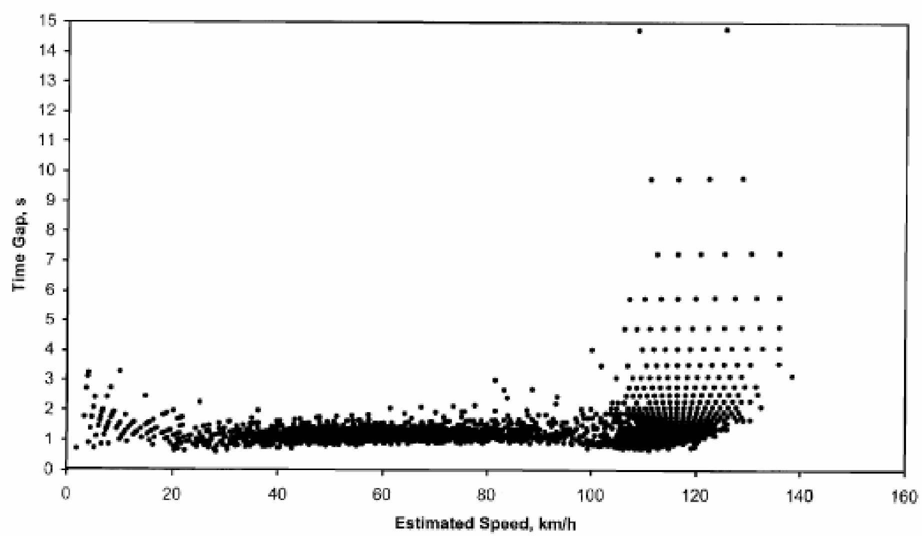


FIGURE 2-6: SPEED VS TIME GAP OBSERVATIONS FROM (BANKS, 2003, 543)

The research into the speed-occupancy and speed-headway relationships focused primarily on traffic conditions. Specifically, the effects of congested and uncongested conditions were researched. In the speed-occupancy relationship, speeds remained constant in uncongested conditions, and fell in congested conditions, as would be expected. In the speed-time gap relationship, time gaps were constant in congested conditions, and increased as speeds increased as would be experienced in uncongested conditions. For both of these relationships, the effects of external conditions such as weather have not been researched.

3 METHODS

Through the statistical analysis of empirical data, the effects of rain on traffic characteristics are examined. Variables including volume, speed, and headway can aid in the understanding of how driver behaviour changes. A matched-pair approach using rain periods and control periods is used to isolate changes in traffic conditions due to rain events while controlling for other factors such as time of day. In order to narrow the scope of the study, only weekdays were included in the analysis data set.

The study site is located along the Gardiner Expressway in Toronto, Ontario. As an urban expressway, weekday drivers are primarily commuters and stable traffic patterns are observed from week to week (Dadson et al., 1999). The monitoring site that was chosen is located on a straight section of highway and is some distance from on-and off-ramps, to minimize the effects of roadway geometrics and merging traffic on the results.

3.1 SPATIAL AND TEMPORAL CONTEXT OF THE STUDY

The City of Toronto has a population of approximately 2.5 million people (Statistics Canada, 2001) and a highly developed road network with over 5300 kilometres of roadway (City of Toronto, 2004), including several urban expressways. With an average annual daily traffic count of 90,000 vehicles (Dadson et al., 1999), the Gardiner Expressway is used to access the core areas of the city. The expressway, designed as a limited access roadway, has six lanes of traffic, three moving east and three moving west, and has a posted speed limit of 90 kilometres per hour, which is strictly enforced (City of Toronto, 2004). Traffic conditions are continually monitored using a double-loop monitoring system, which provides traffic information to city engineers and the motoring public.

The City of Toronto has a moist continental mid-latitude climate that experiences warm summers, cold winters, and receives ample precipitation throughout the year (Strahler and Strahler, 2002). According to Environment Canada 30-year normal records (2004), average temperatures range from a monthly minimum of -11^{o}C in January, to a monthly maximum of 26.8^{o}C in July. Typically, snow falls during the months of October to April and rainfall occurs in all months of the year. Within the period of 1991-2000, 88% of all snowfall occurred from December to March and 80% of all rainfall from April to November (Environment Canada, 2004). The mean number of precipitation days varies from month to month, with an average of at least 10 precipitation days per month from April to November, and fewer than five precipitation days in the month of February (World Meteorological Organization, 2004).

The focus of this study is on rainfall-induced changes in traffic patterns. This sole focus on rainfall has several justifications. First, rainfall typically occurs in all 12 months of the year. Secondly, the data collection methods for snow result in six-hour totals, in contrast to a one-hour total for rain. When trying to pinpoint the exact time of rain or snow, the finer temporal resolution for rainfall data makes the analysis of changing traffic conditions more viable. Finally, research with respect to rainfall is of relevance to every major city, since every city would receive some amount of rainfall.

3.2 Traffic Data and Site Selection

In order to disseminate traffic data to the public, the City of Toronto maintains a network of double-loop detector stations along the Gardiner Expressway, of which the westbound sensors can be seen in figure 3-1. These detectors function much like the induction loop detectors at traffic lights. When a vehicle passes over the sensor, a circuit is completed and several pieces of information in regards to vehicle characteristics and operation are recorded. The information, collected in 20-second intervals, includes speed, flow, occupancy, and vehicle length. The network of stations along the Gardiner Expressway consists of 21 matched pairs of stations, one in each direction of travel.

In order to maintain an accurate data set for analysis, certain criteria in regards to data quality and station location were applied to the site-selection process. In this way, external forces on driver behaviour and traffic characteristics such as road geometry and weaving sections were minimized. The first criterion required each pair of stations to have high-quality data. The second criterion related to distances from on and off-ramps, and was intended to minimize the effects of merging and diverging traffic movements. The third criterion, road geometry, was used so that the station would not be located on a portion of roadway that had a high degree of curvature and/or a change in grade that exceeded three percent.

The application of the first criterion resulted in the removal of all double-loop stations east of Yonge Street. Of the remaining stations west of Yonge Street, listed in table 3-1, data quality issues are also evident at several sites (C. Lee, personal communication, October 20, 2003). In fact, only five sites had adequate data quality (dw010, dw060, dw070, dw120, and dw130) in order to be considered for the next phase of site selection.

TABLE 3-1: STATION DATA QUALITY

Site Number	Data Quality		Distance from ramp	
	East	**West**	**East**	**West**
dw010	Good	Good	Over 450m	Under 450m
dw020	Poor	Poor	Over 450m	Over 450m
dw030	Good	Poor	Under 450m	Under 450m
dw040	Poor	Good	Over 450m	Over 450m
dw050	Poor	Poor	Under 450m	Over 450m
dw060	Good	Good	Over 450m	Over 450m
dw070	Good	Good	Over 450m	Over 450m
dw080	Poor	Good	Over 450m	Over 450m
dw090	Good	Poor	Over 450m	Over 450m
dw100	Poor	Poor	Over 450m	Under 450m
dw110	Good	Poor	Over 450m	Over 450m
dw120	Good	Good	Over 450m	Over 450m
dw130	Good	Good	Over 450m	Over 450m
dw140	Poor	Poor		Over 450m

The second site-selection criterion pertains to the effects of merging and diverging traffic due to the presence of on-ramps and off-ramps. Specifically, for a station to be included in the study, its location must be at least 450 metres from the merge or diverge area of a ramp. This is the minimum distance from an on- or off-ramp where the effects of merging and diverging traffic with its associated weaving manoeuvres are minimized (HCM, 2000). Application of this criterion resulted in the removal of dw010 from the list of potential study sites.

The final criterion related to the amount of curvature of the road. Due to the presence of a large curve in the expressway, sites dw120 and dw130 were removed from further consideration. As a result, only two sites could be used for analysis. Of these two sites, dw060 and dw070, dw060 was chosen for analysis as its location was furthest from all on- and off-ramps.

MAP SOURECE: MAPQUEST.COM

FIGURE 3-1: TRAFFIC MONITORING STATIONS ALONG THE GARDINER EXPRESSWAY

3.2.1 Variable Selection

The Gardiner Expressway double-loop detectors are intended to measure four different variables in 20-second intervals, 24 hours a day, 365 days a year. The first variable, flow, is the equivalent hourly rate of vehicles passing over the sensor. The flow variable is different from volume, which is the total number of vehicles passing over the sensor per time interval. Speed, is the average speed of all vehicles passing over the sensor in the same 20-second interval. The third variable, occupancy, is defined as the percentage of time the sensor is occupied by vehicles passing over the sensor. The final variable, average vehicle length was not used in the analysis. However, the variance of this variable over 24 hours can be seen in figures 4-5 and 4-6. These figures illustrate that the overall vehicle length is constant throughout the day, with slightly longer average vehicle lengths occurring in the early morning hours, likely due to a higher percentage of trucks on the road. Because of the lack of temporal variation, the vehicle length variable is not used in the current study. Another variable used in further analysis, headway, is not collected by the traffic sensors. Headway, which can be defined as the "difference in times that a common point on successive vehicles pass a point" (Banks, 2003, 540), is calculated using the flow variable as explained below[1].

The next step was to decide how to represent flow/volume, speed, occupancy and headway variables in the current study. Review of the literature indicates that a number of different statistical measures have been used in studies of road safety and freeway operations. Three types of studies are of relevance to the current thesis: relationships between traffic characteristics and safety; relationships between weather and traffic characteristics; and relationships among various traffic characteristics. For each, summary comments are made about how traffic is characterized. Key studies are summarized in table 3-2.

- In terms of relationships between traffic characteristics and safety, many studies have shown that speed affects both collision frequency and severity. Two aspects of speed are of importance –"typical" speed and variation of speed. Typical speed is usually

[1] Headway is not to be confused with time gap, which is defined by Banks (2003, 540) as "the difference between the times that the rear of one vehicle and the front of the next pass a point." Headway was calculated instead of time gap because the data-capture time per vehicle is so small (<1 second for all the selected data based on the length of the sensor and observed sensor speeds), and because the distance between the back of one vehicle and the front of the following vehicle cannot easily be determined, since the sensor captures the length of the frame only—not the total vehicle length including bumpers and plastic mouldings. The equation to calculate the average headway comes from the 2000 Transportation Research Board Highway Capacity Manual (2000, 7-5): Flow rate (veh/h) = 3600/Headway(s/veh). Therefore, Headway = 3600/Flow.

represented as mean speed, but sometimes as median speed. Speed variation is usually represented as standard deviation.

- Traffic flow appears to affect both collision frequency and severity, although the number of relevant studies is fairly limited. Typically, flow is represented as either flow or volume. Headway is also thought to affect collision frequency, although again the amount of empirical evidence is limited. As stated in the footnote #1, headway is usually represented as headway or timegap.
- In terms of relationships between weather and traffic characteristics, there is some evidence that speed, flow, and headway are affected by the presence of rain, snow, or other conditions that reduce visibility or friction or both. In the few such studies that exist that are not survey-based, the operational variables have been volume, occupancy, mean speed, and speed deviation (Ibrahim and Hall, 1994; Kockelman, 1998; Banks, 2002).
- Finally, in terms of studies on relationships among traffic variables, much attention has been focussed on the relationship between average speed and flow, since this has implications for highway capacity. Other studies have considered the flow-occupancy relationship (Ibrahim, 1992; Transportation Research Board, 2000)

TABLE 3-2: VARIABLE USE IN PREVIOUS STUDIES TABLE

	Literature				
	Ibrahim and Hall, 1994.	Ma & Kockelman, 2004	Edwards, J.B., 2002	Liang et al., 1999	Banks, 2003
Variable Used in Analysis	Flow (volume), Mean Speed, Occupancy	Mean Speed and Speed Deviation	Mean Speed	Mean Speed and Speed Deviation	Mean Headway
Study Focus	To determine the effects of rainfall and snowfall on flow-occupancy and speed-flow relationships.	Investigate the effects of factors such as traffic characteristics, weather conditions, vehicle characteristics on accident severity.	To establish if drivers compensate for additional risks due to rainy weather by reducing speed.	Effects of environmental variables on driver speed.	Determine average time gaps in congested flow.
Study Location	Urban Freeway in Mississauga	Southern California Highways	M4 Motorway, South Wales, U.K.	Rural Interstate Highway	San Diego and Mississauga Freeway
Methods	Multiple Linear Regression Modelling	Ordered Probit Model	Data Survey of Vehicle Speeds	Multiple Regression Analysis	Variation and Relationship of Headway
Findings	Both rainfall and snowfall have an effect on the relationships.	Current traffic conditions and design characteristics were valuable in determining accident severity.	Drivers marginally slow down in wet weather.	Reduced visibility and high winds were the primary factors affecting driving speed.	Average time gap is constant with respect to speed in congested flow.

From above, five traffic variables have been found to be important in all three types of studies, and were used in this study. These variables include flow, occupancy, mean speed, standard deviation of speed, and mean headway. For volume, the measured hourly flow was converted to volume for each 20-second interval. The standard deviation of speed was chosen over the coefficient of variation of speed, because the mean speeds are relatively similar in different time periods. The coefficient of variation of speed is typically used when means differ radically (Burt and Barber, 1996). Finally, as noted above, flow data were used to calculate the headway variable. Therefore, these two variables are not truly independent.

3.3 WEATHER DATA

Weather data including rainfall amounts have been recorded in the Toronto area for many years. In the City of Toronto, eight stations collect different types and qualities of weather information year round (Environment Canada, 2004). For the purposes of this study, the selected weather station must be located as near as possible to the traffic station, as well as provide reliable year-round hourly precipitation. Accordingly, three study sites were evaluated using these two criteria. The City Centre Airport is the closest to the study site at 1.1 kilometres (table 3-3). However, this site does not keep automated records of hourly rainfall data.

TABLE 3-3: WEATHER STATION DISTANCE TO STUDY SITE

Station	Distance (km)
City Centre Airport	1.1
Bloor Street Station	3.1
Pearson Int. Airport	16.1

Instead of hourly rainfall totals, the Toronto Island weather station records hourly weather observations of intensity made by a trained observer. Specifically, at the top of every hour, the observer makes a qualitative assessment and records the intensity of any rainfall that may be occurring at the time. For several reasons, these data are not adequate for characterizing precipitation events. First and most important, precipitation totals for each hour are not available. Secondly, the observation only applies to the period of time the observer is actually looking at the sky, not the entire hour. Finally, the Toronto Island weather site does not conform to World Meteorological Organization standards for temperature and precipitation data collection (Environment Canada, 2004). Indeed, both Bloor Street and Pearson International Airport are the only stations in Toronto that do.

The second closest station, Toronto (Bloor Street), is located 3.1 kilometres from the study site. However, as the station only collected hourly precipitation totals from the months of April to September, this station could not be used.

Pearson International Airport is the next closest precipitation-monitoring site. Although the distance from the traffic-monitoring site is 16.1 kilometres, previous research has shown that distances up to 35 km can still provide reliable data (Andrey and Olley, 1990). However, due to a sensor error, no precipitation data exist for the months of June and December 1998.

A comparison of the Bloor Street site and the Pearson station found little difference between the two sites in terms of total precipitation. Additionally, the hourly precipitation data from the Pearson International Airport weather station was compared with hourly data from the Bloor Street weather station for the months of April, May, July, August, and September. For these periods, there was only a difference of 15 mm of rainfall between the two sites. A matched pair t-test found that both the mean and standard deviation's for the two sites were similar, with only a .0042 mm difference in means. The correlation for the two data sets was 0.696 with a 0.000 significance. Therefore, Pearson data were used for January through May and September through November. For the month of June, data from the Bloor Street station were substituted for the Pearson station. However, for the month of December, neither the Bloor Street nor Pearson site recorded hourly precipitation data. Therefore, no analysis was performed for this month.

To test the spatial representativeness of the Pearson weather station data for the Gardiner Expressway, the hourly precipitation ordinal data from the City Centre Island Airport station were compared with the hourly accumulation data from the Pearson site for 1998. These data, as summarized in a contingency table (table 3-4), indicate that a majority of the entries match. In total, only 482 of the 8760 observations differ. Of these differences, 278 hours (58%) did not match due to unshared short (less than two hours) rainfall events or short events that differed by one hour in length. Another 17% of the non-matching entries can be attributed to unshared events that last longer than two hours. The remainder of the differing observations can be attributed to events that differed due to intensity or the presence of a break in precipitation. The one area of concern, however, relates to the relatively poor match between the two sites for moderate and heavy precipitation, a theme that will be addressed further chapter four.

TABLE 3-4: STATION COMPARISON - COUNT OF HOURS WITH SPECIFIED PRECIPITATION

	Toronto Island City Centre Airport				
Pearson	No Rainfall	Light	Moderate	Heavy	Total
No Rainfall	7789	173	13	5	7980
0.1 - 2.4 mm	225	474	31	6	736
2.5 - 7.4 mm	3	17	15	3	38
7.5 + mm	2	3	1	0	6
Total	8019	667	60	14	8760

3.3.1 NORMAL WEATHER CONDITIONS

With weather conditions in southern Ontario varying from year to year, it is important to explore whether 1998 was a typical year in comparison with the 30-year normal. The 30-year normal data (1971-2000), taken from the Environment Canada online archives, lists many variables, including monthly and yearly average rainfall levels. Additionally, the study year is also compared with previous years (1995-1997).

Overall, the study year of 1998 had slightly lower rainfall totals than the 30-year normal, as indicated in table 3-5. In addition, month-to-month rainfall totals are slightly lower. In particular, with the exception of January, June, and December (18.4mm, 8.5mm, and 2.9mm excess rainfall), every month had a lower rainfall total than the 30-year normal, indicating that 1998 was a drier year. By comparison with the three preceding years for which detailed data were acquired, the monthly rainfall is less for 1998 than 1995 and 1996, with the one exception of June, which would appear to be a slightly wetter month for 1998. In general, the first half of 1998 appears to be approximately normal, while the second half appears to be much drier than the 30-year average. The study year of 1998 closely compares with 1997, which had 15 mm less rainfall.

TABLE 3-5: MONTHLY RAINFALL TOTALS (mm)

Month	1995	1996	1997	1998	30 yr
January	108.9	44.4	11.8	43.3	24.9
February	2.8	12.6	59.5	0.0	22.3
March	41.0	1.4	7.3	8.0	36.7
April	71.4	81.2	24.0	57.0	62.4
May	84.1	89.6	65.2	71.8	72.4
June	51.5	116.2	50.2	82.7	74.2
July	55.4	97.2	29.8	44.5	74.4
August	132.3	48.2	71.9	26.7	79.6
September	27.3	167.1	48.1	38.0	77.5
October	130.3	74.5	32.2	23.3	63.4
November	66.9	21.9	35.3	32.5	62.0
December	1.8	59.9	15.1	37.6	34.7
Total	773.7	814.2	450.4	465.4	684.5

Further comparison of 1998 rainfall events with proceeding years was accomplished by examining individual rainfall events. Specifically, hourly precipitation data were used to compare both precipitation amounts and events from year to year. As in Andrey and Yagar (1991), an event is defined by a period of rainfall with at least a two-hour buffer between rainfall occurrences. This time buffer allows for the assumption that the pavement may dry in-between events, thereby resulting in the commencement of a new event after drying.

Preliminary analysis of the event data for 1995 through 1998 confirms that 1998 was a drier year with a lower number of rainfall events. With the exception of January and November, the total number of events was much lower than in the years 1995 -1997 (figure 3-2). On the event level, the late spring months (April to June) of 1998 had many fewer events, which was the main reason for lower precipitation totals.

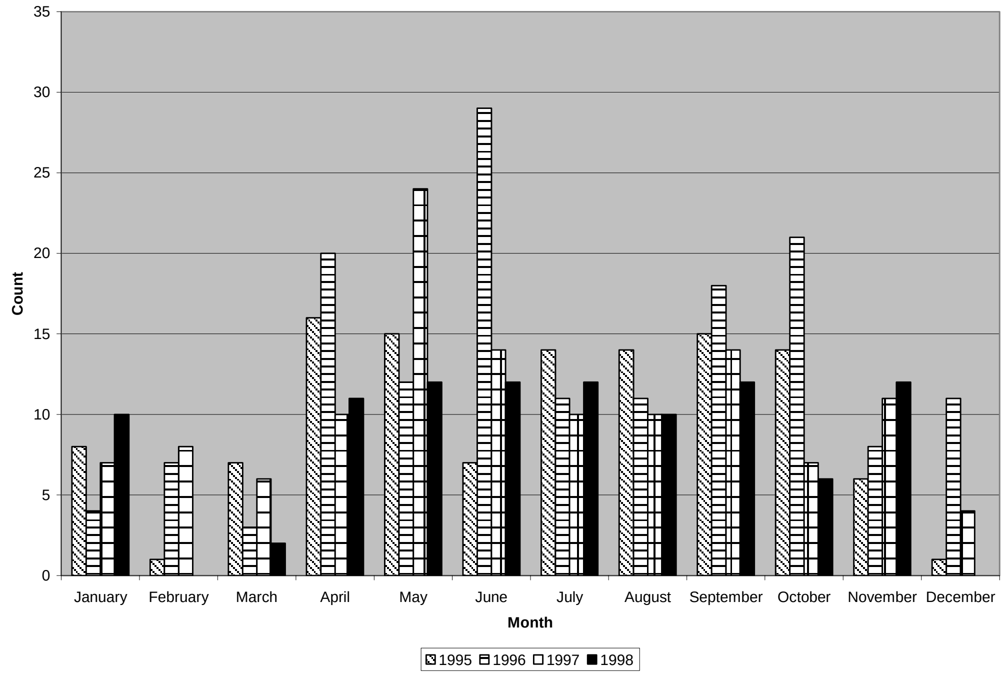


FIGURE 3-2: TOTAL EVENTS PER MONTH

However, analyses of all rainfall events for each year show that, although the total rainfall for 1998 was lower, the event-length breakdown was reasonably similar to previous years. The largest differences between 1998 and the other years is a lower number of one-hour events, as well as a smaller number of events that lasted 4-5 hours. Additionally, 1998 saw fewer events lasting over 20 hours (table 3-6). Overall, however, the data set from 1998 provides a reasonably representative set of weather events for detailed analysis.

TABLE 3-6: TOTAL NUMBER OF EVENTS

Length (hours)	1995	1996	1997	3-year % Frequency	1998	1998 % Frequency
1	44	55	43	36	35	35
2-3	31	37	41	27	38	38
4-5	19	24	20	16	8	8
6-7	7	13	7	7	5	5
8-9	7	8	7	6	6	6
10-11	4	6	3	3	2	2
12-13	0	4	2	2	1	1
14-15	1	2	0	1	0	0
16-17	2	2	1	1	2	2
18-19	0	1	1	1	1	1
20-21	2	1	0	1	0	0
22-23	1	1	0	1	0	0
24-25	0	1	0	0	0	0
26-27	0	0	0	0	1	1
Sum	118	155	125	100	99	100

3.4 Analysis Methods

Two separate techniques were used to test the effects of rainfall on traffic variables at the selected study site. The first technique, the t-test, has been used in previous weather and safety related traffic studies in a matched pair approach. In a pair of studies by Edwards (1999, 2002), the effects of wet weather on mean speed and the effects of asphalt type in wet weather on mean speed were monitored. In both of these studies, significant differences between the event and control data illustrated that mean speed drops in wet weather. In a publication by Hijar et al. (2000), different highway traffic accident risk factors were assessed by using several methods including t-tests for continuous variables in a case-control setup. Another study by Oh et al. (2000) used t-tests to test the difference between normal traffic conditions and those leading up to an accident.

The second technique used for analysing the traffic variables in this thesis was linear regression. Many examples of such an approach have been used in the past as already reviewed in section 2.4.

The two methods make it possible to test if differences exist in traffic variables for rainfall versus dry periods. The paired t-test returns a t-statistic that can be used to determine if statistically significant differences between event and control periods exist in the volume, speed, speed deviation, and headway means. The linear regression method allows for determining how relationships between volume, speed, occupancy, and headway change in response to rainfall. Analyses were done separately for eastbound congested, eastbound uncongested, westbound congested, and westbound uncongested traffic.

4 RESULTS OF PRELIMINARY ANALYSIS OF TRAFFIC DATA

This chapter provides an overview of the events selected for analysis, as well as preliminary results from a first look at the event and control traffic data. The first section, as mentioned, focuses on the events used for analysis, and how these events compare to previous years' precipitation events. This is followed by a description of how the 20-second traffic loop data were analysed and cleaned of bad data points. The methods used to aggregate these data are then discussed. The final section of chapter four defines the periods of congestion for the study site. The average speed, speed deviation, volume, and headway characteristics of congested and uncongested time for both travel directions are discussed.

4.1 WEATHER CHARACTERISITICS AND EVENT SELECTION

The selection of time periods for subsequent analysis of traffic patterns was dependent on both the availability of traffic data as well as the availability of matched event and control pairs, as defined by weather conditions. Traffic data were only available for 177 days in 1998. Weather data were available for 154 of these 177 days, with the remaining 23 days of traffic data occurring in the month of December, which had no available hourly rainfall data.

The first step in the analysis was to define event-control pairs. Using hourly precipitation amounts, a total of 99 variable-length rainfall events were identified, as shown in table 4-1. Then, events were removed if they lasted only a single hour (35 removed) because in such a short event there are most likely as many dry minutes as wet minutes. Additionally, events were removed if traffic data were unavailable (32 events removed, 23 of which occurred in December). Additional events were removed if there was a traffic accident during the event period at the sensor location, or within one sensor location in either direction (3 events removed). Finally, a check was made for matching control periods defined as one week before or after the rain event day (5 events removed). This left 24 event-event control pairs, or a total of 230 hours for study—115 during rainfall and 115 during matched control periods (table 4-2).

TABLE 4-1: RAINFALL EVENT SUMMARY TABLE

Length (hours)	Yearly Average 1995-1997	1998	Selected Events	Percentage Included
1	47	35	0	0
2-3	36	38	19	50
4-5	21	8	0	0
6-7	9	5	0	0
8-9	7	6	3	50
10-11	4	2	0	0
12-13	2	1	1	50
14-15	1	0	0	0
16-17	2	2	0	0
18-19	1	1	1	100
20-21	1	0	0	0
22-23	1	0	0	0
24-25	0	0	0	0
26-27	0	1	0	0
Sum	132	99	24	

TABLE 4-2: EVENT SAMPLE WEATHER SUMMARY

Event	Start Date	Start Time	Day Of Week	Number of Breaks	Total Length	Total Rainfall	Peak Intensity	Mean Vis.	Peak Vis.	Mean Wind	Min Temp	Max Temp	Days Last Precipitation
1	02/04/1998	5	Thursday	0	3	1.5	1.1	10.2	12.9	0.7	5.1	6	0.1
2	02/04/1998	18	Thursday	0	2	1.9	1.4	21.7	24.1	1.8	7	7.2	0.4
3	08/04/1998	13	Wednesday	0	3	2.8	1.3	16.1	19.3	2.7	6.2	8.9	5.7
4	11/05/1998	19	Monday	0	3	2	1	13.4	19.3	1.2	13.8	15.2	0.1
5	19/05/1998	17	Tuesday	0	3	7.4	6.8	16.6	19.3	0.9	18.6	27.5	7.3
6	02/06/1998	16	Tuesday	0	2	4.4	3.4	13.7	16.1	3.3	20.9	24.9	2.3
7	11/06/1998	22	Thurs., Fri.	0	9	20.7	6.7	4.3	8	2	15.8	17.2	1.3
8	26/06/1998	2	Friday	0	2	13.2	12.8	9.7	11.3	2.2	20.7	22.2	2.6
9	06/07/1998	18	Monday	0	2	0.6	0.4	25.8	32.2	1.1	18.8	18.8	2.1
10	06/07/1998	23	Mon., Tues.	2	16	12.7	7.1	8	19.3	1.2	16	18.2	0.1
11	07/07/1998	21	Tuesday	0	2	0.4	0.2	3.8	4	0.8	18.5	18.7	0.2
12	08/07/1998	5	Wednesday	0	3	1.5	1.1	1.9	2.4	0.7	18.9	19.2	0.3

TABLE 4-2 CONT'D: EVENT SAMPLE WEATHER SUMMARY

Event	Start Date	Start Time	Day Of Week	Number of Breaks	Total Length	Total Rainfall	Peak Intensity	Mean Vis.	Peak Vis.	Mean Wind	Min Temp	Max Temp	Days Last Precipitation
13	06/08/1998	3	Thursday	1	18	11.8	2	3.5	4.8	1.7	20.1	22.1	6.6
14	07/08/1998	3	Friday	0	8	8.4	2.2	3.3	4	1.1	19.6	20.9	0.3
15	02/09/1998	1	Wednesday	0	2	0.6	0.3	19.3	32.2	0.8	16.2	16.4	7.6
16	02/09/1998	23	Wed., Thurs.	0	2	1.2	0.9	24.1	24.1	0.7	15.6	17.5	0.4
17	14/09/1998	23	Mon., Tues.	0	2	0.8	0.6	12.1	12.9	1.1	19.3	19.8	8
18	15/09/1998	6	Tuesday	1	3	1.3	1.1	4.4	6.4	0.7	19.7	20	0.1
19	15/09/1998	19	Tuesday	0	2	1.3	1.1	8.9	9.7	1.7	20.9	21.3	0.5
20	01/10/1998	24	Thursday	0	2	8	5.7	9.7	12.9	1.7	11.8	12.1	4.8
21	28/10/1998	11	Wednesday	0	2	0.8	0.5	5.2	6.4	2.6	14.9	16	13.9
22	10/11/1998	5	Tuesday	0	3	0.8	0.4	8.6	9.7	1.9	6.5	7.2	0.8
23	10/11/1998	10	Tuesday	1	12	14.5	5.6	6.8	11.3	2.9	6.8	12.5	0.1
24	16/11/1998	8	Monday	0	9	5.7	1.3	8.8	24.1	0.7	2.4	3.3	1.7

An analysis of rainfall events lasting two or more hours by weekday and month shows that selected events are spread out across all weekdays and across seven months. Each weekday is represented with two to five events, with Tuesdays being the most common rain day with seven events (table 4-3). The inclusion of four multi-day events is similar to the overall proportion of multi-day events in 1998. In total, 13 of the 99 rainfall events in 1998 were multi-day events.

TABLE 4-3: SAMPLE RAINFALL EVENTS BY DAY OF WEEK

Day	Events	Sample	% Included
Sunday	4	0	0
Monday	9	3	33
Tuesday	13	7	54
Wednesday	10	4	40
Thursday	6	4	67
Friday	3	2	67
Saturday	6	0	0
Multi-day	13	4	31
Sum	64	24	

The monthly breakdown shows that events occurring only between the months of April to November were included for analysis (table 4-4). Weather data for the month of December did not exist, and there were no rainfall events in the month of February. The remaining months of January and March saw few rainfall events and either no traffic data or no matched control days.

TABLE 4-4: SAMPLE RAINFALL EVENTS BY MONTH

Month	Events	Sample	% Included
January	8	0	0
February	0	0	0
March	1	0	0
April	9	3	33
May	6	2	33
June	10	3	30
July	8	4	50
August	3	2	67
September	8	5	63
October	4	2	50
November	7	3	43
Sum	64	24	

The duration of selected events is also comparable to the overall durations of rainfall that took place in 1998 and the comparison years of 1995-1997 (table 4-1). Although not all rainfall events are included for analysis, the selected events account for roughly one-third of all rain events lasting longer than one hour in 1998. The events comprise just over 32% of the total hours of measurable precipitation and 55% of total hours of events that last longer than one hour. Included in the sample of events are several short two-hour events, and the second longest rain event of 1998 spanning 18 hours. The total precipitation occurring during the sample events is also roughly one-third of the yearly total. However, if one-hour event precipitation amounts are removed, this percentage increases to 55% of the year's total precipitation. Clearly, one-hour events provide a significant portion of rainfall over the year. However, although numerous at 35 events in the year, their average precipitation is small at 0.8 cm per rainfall event. Therefore, the full effects of such rain events on traffic operations would be difficult to determine, given the state of available existing weather information. Excluding the one-hour events, the remainder of events experience an average rainfall amount of 6.3 cm. The sample event average is smaller with 4.5 cm of rainfall falling during each event, on average.

Data on hourly precipitation rainfall amounts for each year are displayed in table 4-5. As shown here, hours with light rainfall account for 80%-90% of all rainfall hours. For the study period, 105 of the total 115 rainfall hours (91%) that comprise the 24 events listed in Table 4-3 are light rainfall events, nine are moderate rainfall events (8%), and one hour can be classified as having heavy rainfall (1%). Because of (a) the small number of moderate and heavy rainfall hours, (b) the fact that these rainfalls occurred mainly during early morning hours when traffic is unusually light, and (c) heavy rains at Pearson do not necessarily coincide temporally with heavy rains in downtown Toronto, as discussed in chapter three, the moderate and heavy precipitation hours were removed from analysis. Thus the analysis in the thesis is based on 105 hours of rainfall associated with 24 different rainfall events.

TABLE 4-5: HOURLY PRECIPITATION AMOUNTS BY YEAR

	1995	1996	1997	1998	Sample Data
Light (0.1mm - 2.4 mm)	345	530	362	299	105
Moderate (2.5 mm - 7.4 mm)	65	81	37	35	9
Heavy($\leq$ 7.5mm)	17	9	3	4	1
Total Number of Rainfall Hours	427	620	402	338	115

The weather characteristics for all of the 24 sample events are summarized in table 4-2. As might be expected, the weather variables differ considerably from month to month, with temperatures peaking in the summer months. Large variability in the length of time before last rainfall is also evident.

4.2 Traffic Data Preparation and Aggregation

4.2.1 Data Quality and Aggregation

As noted earlier, the traffic loop data provide recordings every 20 seconds. While some of the exploratory analysis and graphing is based on 20-second data, most of the statistical analysis is performed on data that have been aggregated to five-minute intervals because the aggregated 5-minute data have the following advantages:

1. Noise is removed,
2. Distributions are more normal,
3. Observations are paired,
4. Standard deviation of speed cannot be calculated at the 20-second interval,
5. Flow and headway variables are essentially redundant at the 20-second interval,
6. At points of further aggregation, some temporal variability is lost.

The plots of 20-second, 5-minute, 15-minute, and 30-minute data across a sample day in September 1998 can be seen in figures 4-1 through 4-4. As larger intervals are used, noise is reduced and the detail of temporal variability is lost.

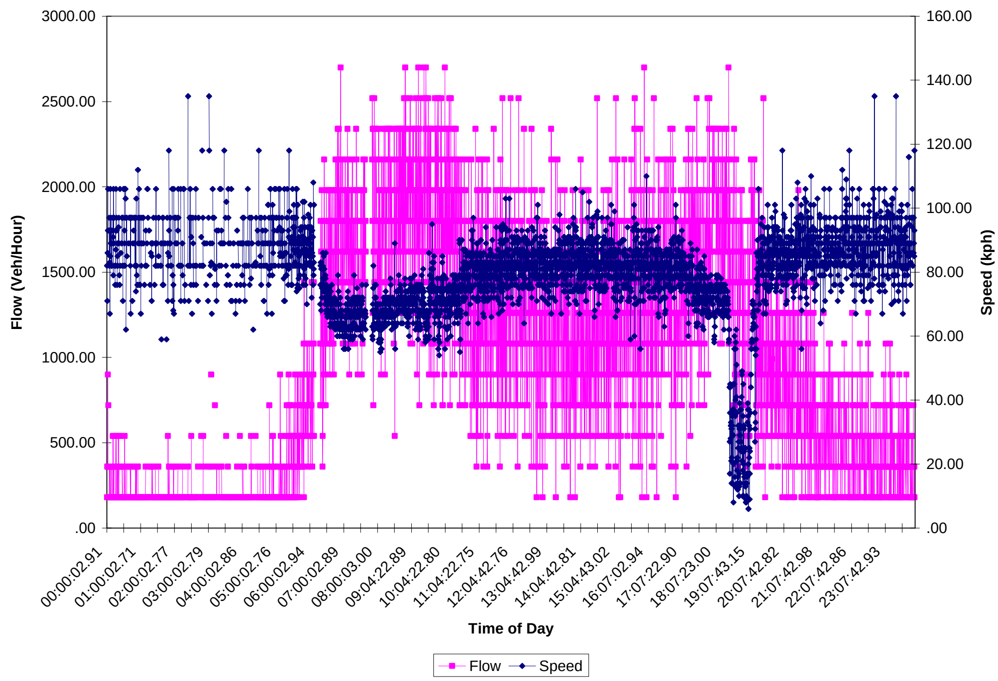


FIGURE 4-1: INTERVAL ANALYSIS - 20-SECOND DATA

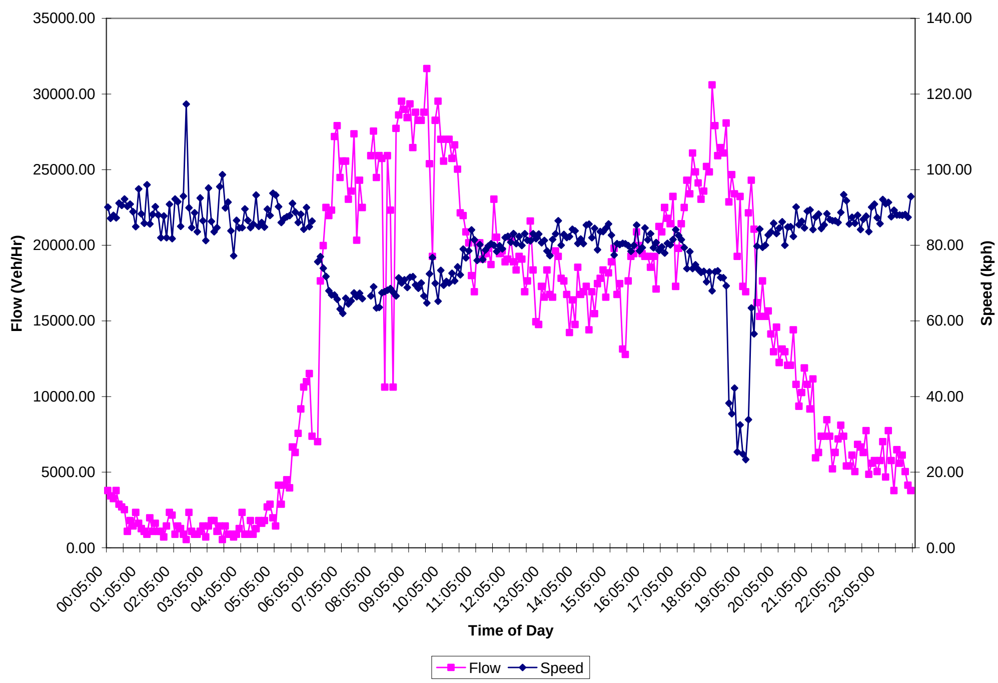


FIGURE 4-2: INTERVAL ANALYSIS - 5-MINUTE DATA

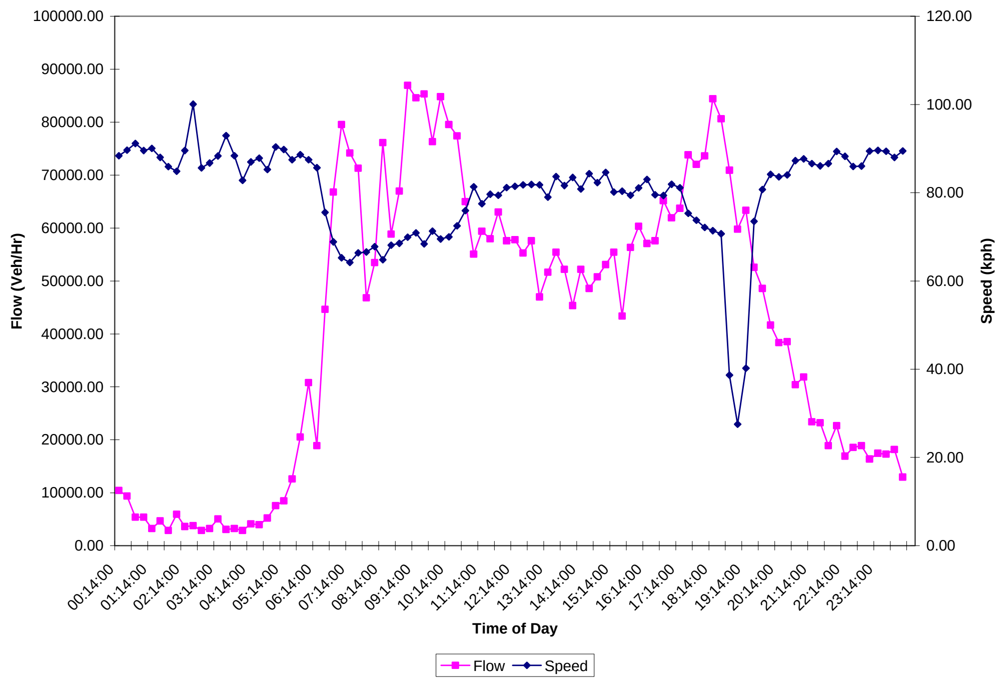


FIGURE 4-3: INTERVAL ANALYSIS - 15-MINUTE DATA

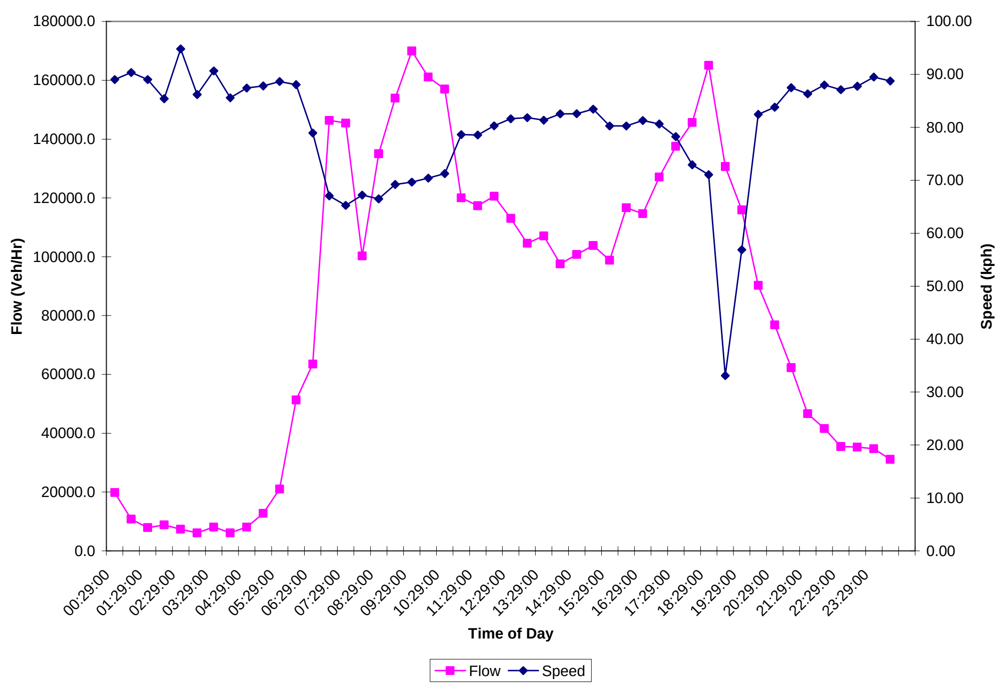


FIGURE 4-4: INTERVAL ANALYSIS - 30-MINUTE DATA

In addition to using the plots to determine an optimal time period for analysis, a search of previous traffic studies found that time intervals ranging from 20-30 seconds to periods longer than an hour have been used. The two most common intervals used include the automated data collection interval (20-30 seconds) and the 5-minute interval. The data collection interval is typically used to preserve data detail in order to aid in incident detection. Results of analysis that used both the 30-second and 5-minute intervals (Ibrahim and Hall, 1994) indicated that no significant differences existed between them. In the case of Cassidy and Mauch (2001), 30-second data were used for some analysis, but 5-minute moving averages were used to smooth temporal fluctuations. In fact, many studies make use of the 5-minute interval (Liang et al., 1998; Nair et al., 2001). Table 4-6 lists several studies that have used a variety of time periods, as well as the benefits of their time period selection.

TABLE 4-6: TIME INTERVAL SELECTION IN PREVIOUS STUDIES

	Objective	Time Period(s)	Benefit of Time Period Selected	Conclusions
Hall and Agyemang-Duah, 1991.	To determine the effects of a queue on freeway capacity.	30-second, 5-minute, full peak period.	30-second data used to determine the beginning of the queue.	Capacity drops occur in bottlenecks.
Hall and Barrow, 1988.	To determine the effects of weather on the flow occupancy relationship on freeways.	30-second & 5-minutes.	30 second data used to preserve detail for incident detection.	Weather reduces the slope of the flow-occupancy curve.
Zhou and Hall, 1999.	To investigate the relationship between speed and flow in congested conditions.	5-minute	Reduce the random variation of 20-second data.	The speed-flow relationship increases rapidly in congested conditions.
Ibrahim and Hall, 1994.	To determine the effects of adverse weather on the speed-flow-occupancy relationships.	30-second & 5-minte.	Regression results indicate that significant differences did not exist between the two data sets.	Rain and Snow lead to speed and flow reductions.
Cassidy and Mauch, 2001.	Analyze the relationship between vehicle accumulation and flow.	30-second & 5-minute	30-second data were used for analysis.	Vehicle densities decrease and speed decrease as you move from the queue to the bottleneck.

The first step in consolidating the 20-second data to 5-minute data was to examine and remove spurious data points. Spurious data points consisted of either "NULL!" or negative values. As seen in table 4-7, the eastbound direction had more spurious data points than the westbound direction.

TABLE 4-7: MISSING 20-SECOND INTERVAL DATA IN EVENT AND CONTROL PERIODS

	East	West
Event	5.4%	0.9%
Control	7.5%	3.0%
Event & Control	6.5%	1.9%

In order to preserve the integrity of the calculated 5-minute interval data, 5-minute periods were removed from analysis if five or more 20-second intervals were missing. Examination of the missing data revealed a certain pattern which applied to both travel directions. Typically missing data occurred as a single 20-second interval, or for longer intervals of 10-20 minutes. For this reason, the missing 20-second intervals were split into two separate groups in order to better monitor the type of missing data. The first group of missing data consisted of one to four missing 20-second intervals per 5-minute time period. The second group consisted of time periods with five or more 20-second consecutive intervals with missing or spurious data. A majority of the missing data occurred in time periods similar to those in the second group. With 5-minute intervals removed (table 4-8) due to ten or fewer 20-second valid observations, the total amount of missing data falls to 2.1% in the eastbound direction and 1.6% in the westbound direction (table 4-9).

TABLE 4-8: FIVE MINUTE INTERVALS REMOVED DUE TO INSUFFICIENT DATA POINTS

	Eastbound Direction	Westbound Direction
Event Periods	75 (5.4% of total)	10 (.7% of total)
Control Periods	65 (4.7% of total)	6 (.4% of total)

TABLE 4-9: MISSING 20-SECOND INTERVAL DATA BY TYPE

	1-4 20-Second Intervals Missing		5+ 20-Second Intervals Missing	
	Eastbound	Westbound	Eastbound	Westbound
Event Periods	0.9%	0.6%	4.5%	0.3%
Control Periods	3.3%	2.6%	4.2%	0.4%
Event & Control Periods	2.1%	1.6%	4.4%	0.3%

The final step in 5-minute interval aggregation was to calculate the values for each of the variables of interest. The volume variable was a simple sum for each 5-minute interval. Both the mean speed and mean headway were calculated using a weighted mean to account for the differences in volume across the fifteen 20-second intervals that comprise each 5-minute value. The weighted standard deviation of speed based on the 15 observations for each 5-minute period was then calculated for each 5-minute interval.

4.2.2 TRAFFIC DATA ACCORDING TO DIRECTION OF TRAVEL

Next, the data were analysed in order to gain a better understanding of traffic patterns on the Gardiner Expressway. The first step was to determine if the two sides of the road (Eastbound vs. Westbound) displayed temporal differences in their respective travel patterns as well as notable differences in their observed values. The average of all the control periods, using the 5-minute data, can be seen in figures 4-5 and 4-6.

The eastbound traffic into the core of Toronto displays two clear peak volume periods, one in the morning, and one in the late afternoon. Associated with these periods, there is an overall drop in average speed and an associated increase in occupancy. The only variable that does not seem to respond to this congestion period is the headway variable, which stays essentially constant from 7 am to 8 pm. The vehicle length patterns illustrate the possible presence of longer trucks in early morning hours, but in the rest of the day, the traffic mix seems to be dominated by smaller vehicles such as passenger cars.

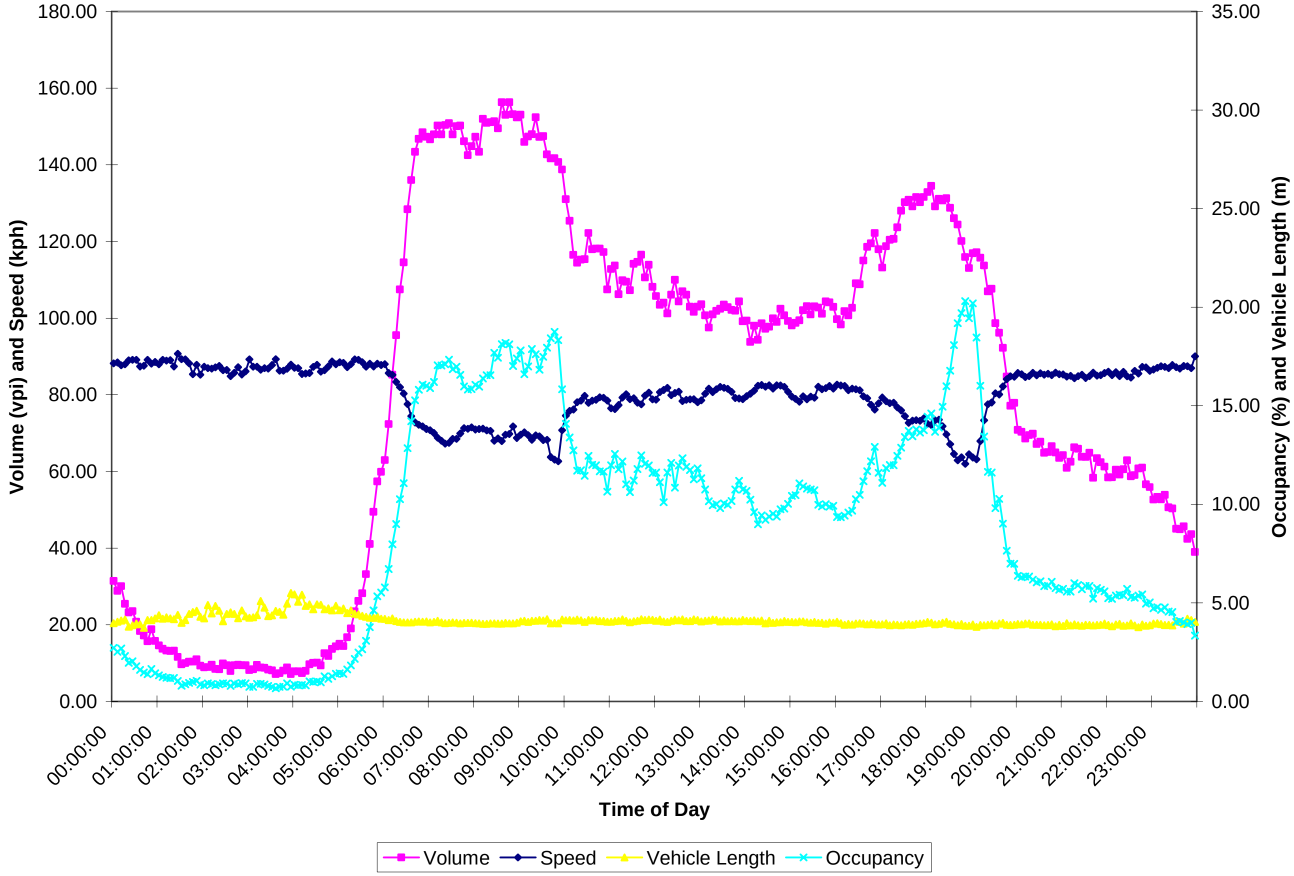


FIGURE 4-5: EASTBOUND TRAFFIC PATTERNS - 5-MINUTE AGGREGATION

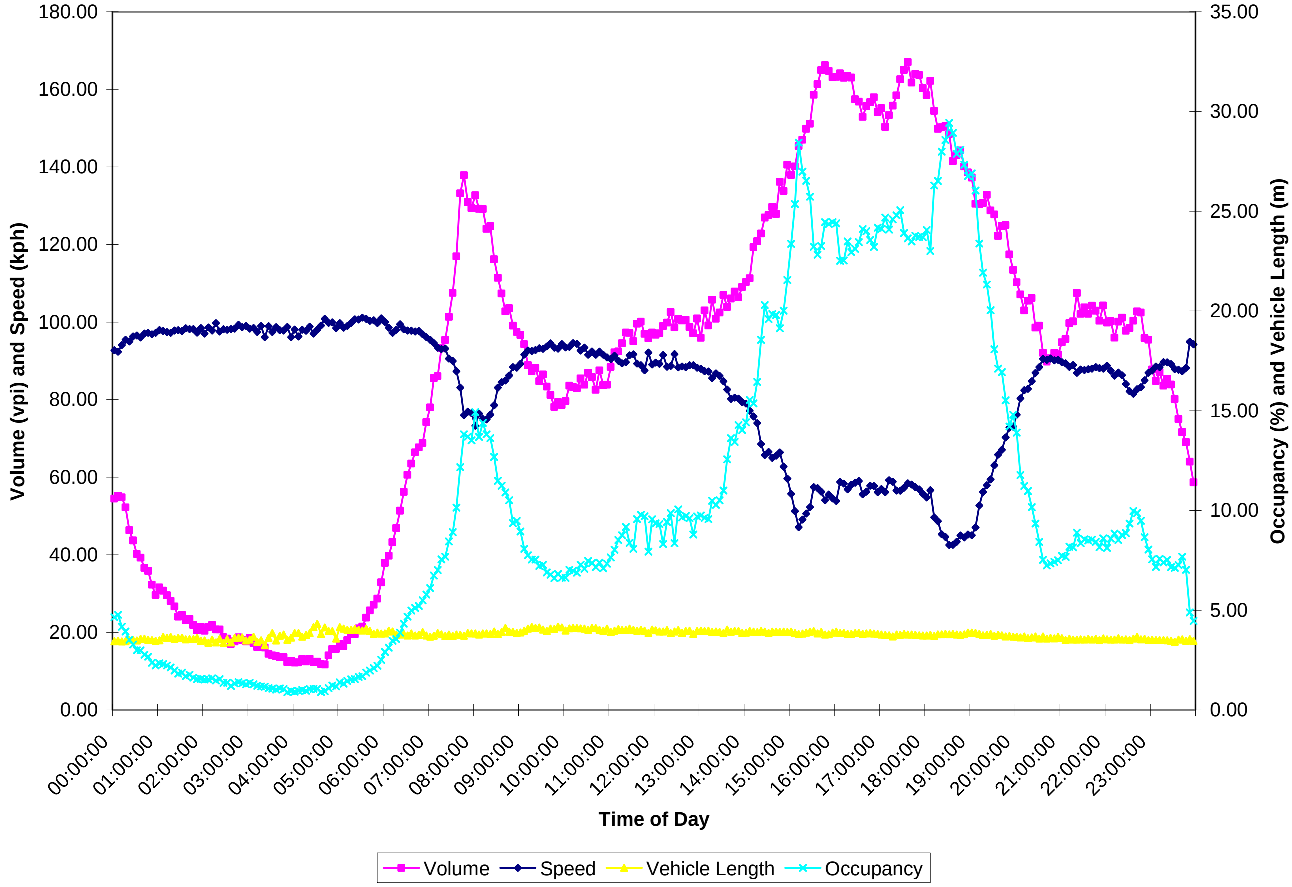


FIGURE 4-6: WESTBOUND TRAFFIC PATTERNS - 5-MINUTE AGGREGATION

The westbound traffic out of the core of Toronto exhibits slightly different patterns than the eastbound direction. Although it does display the same associated drops in speed and increase in occupancy in peak periods, obvious differences in traffic patterns exist. The morning peak period is much shorter, while the afternoon peak period involves higher volume numbers over a longer period of time. There is also a much greater drop in average speed that is associated with the afternoon rush-hour. The pattern for vehicle length is much the same, however, with longer vehicle such as trucks in the early morning hours, and passenger cars in the rest of the day.

As a result of the preliminary analysis, differences in the temporal pattern of traffic variables as well as observed values were evident and the two sides of the road were separated for further analysis as seen in section five. These differences are further discussed in sections 4.3.2 and 4.4.

4.3 Congested Versus Uncongested Conditions

4.3.1 Defining Periods of Congestion

Traffic flows during periods of congestion are quite different than in uncongested periods. During congestion, the average speeds of vehicles are reduced and occupancies are increased, as visible in figure 4-5 and 4-6. However, for the purposes of analysis, the periods of congestion have to be well defined, which is not possible from a simple trends graph (figures 4-5 and 4-6). In order to determine a more precise period of congestion, speed-flow and flow-occupancy graphs were created. In a previous study by Ibrahim (1992), uncongested periods were defined as lying on the left hand side of the flow-occupancy graph. Similar plots using 5-minute data derived from all of the control days were created, the results of which can be seen in figures 4-7 and 4-8. The eastbound flow-occupancy graph shows that there is a natural break around the 1000 vehicles per hour (vph) flow rate. A similar type of break also occurred in the westbound lane. Thus, as a first approximation, it appears that congestion on the Gardiner is associated with flows greater than 1000 vehicles per hour.

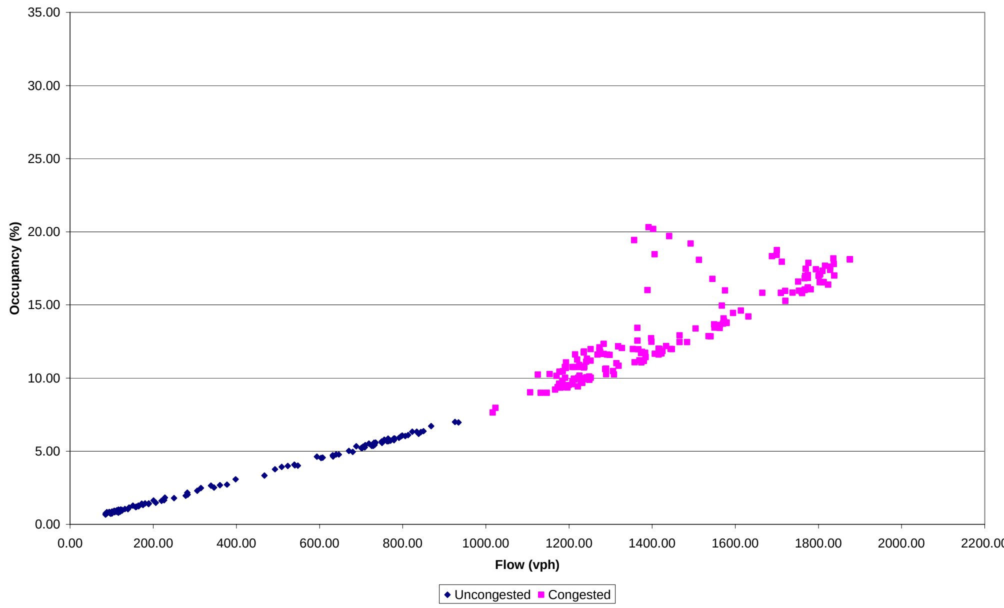


FIGURE 4-7: FLOW VS. OCCUPANCY CONGESTION GRAPH - EASTBOUND

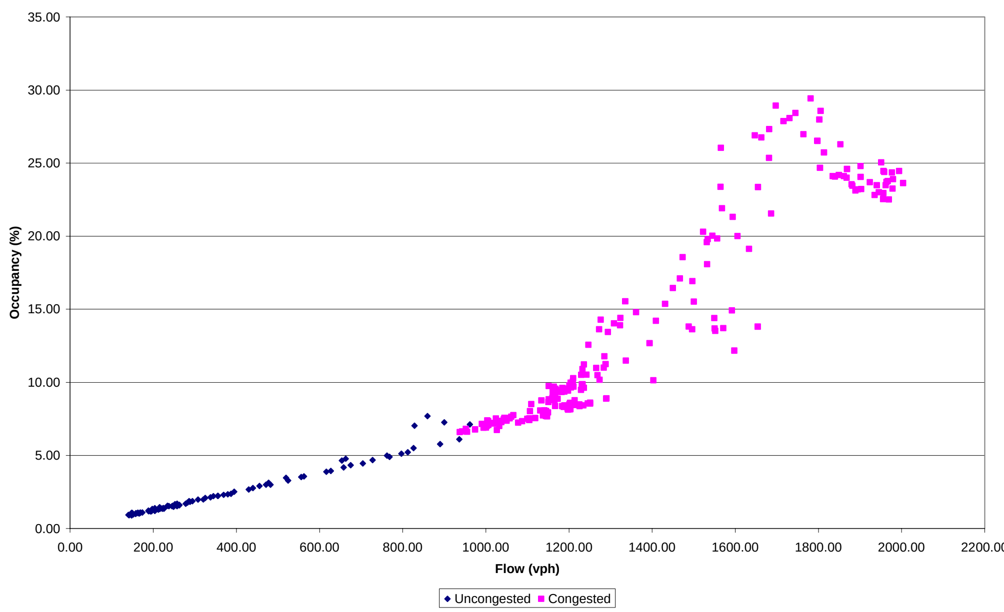


FIGURE 4-8: FLOW VS. OCCUPANCY CONGESTION GRAPH - WESTBOUND

To further confirm the point at which congestion occurs, the speed vs. flow relationship was then plotted (figures 4-9 and 4-10). According to the Highway Capacity Manual (2000), and a traffic flow theory monograph from the Transportation Research Board (Gartner et al. eds. (1992), there are no periods of congestion in the control data. In fact, according to those publications, no congested conditions exist in the eastbound direction and only a short period exists in the westbound direction.   In addition to the 5-minute speed-flow information in figures 4-9 and 4-10, a 20-second plot was created (figure 4-11). Given the information from both the speed-flow and flow-occupancy plots, it was decided that congested periods would be classified as shown in the figures 4-9 and 4-10. Specifically, the right hand portions of both relationships were classified as congested. In terms of the speed-flow plot, the left hand portion may be classified as uncongested (figure 2-2) and the right hand portion of the plot defined as congested for this study.

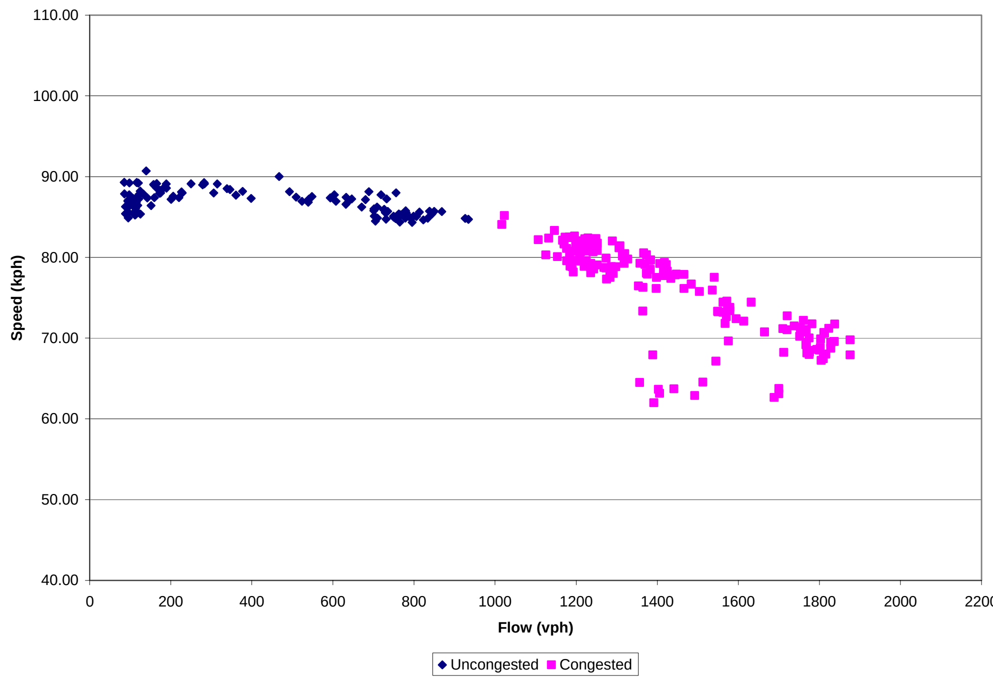


FIGURE 4-9: SPEED VS. FLOW PLOT - 5-MINUTE INTERVAL - EASTBOUND

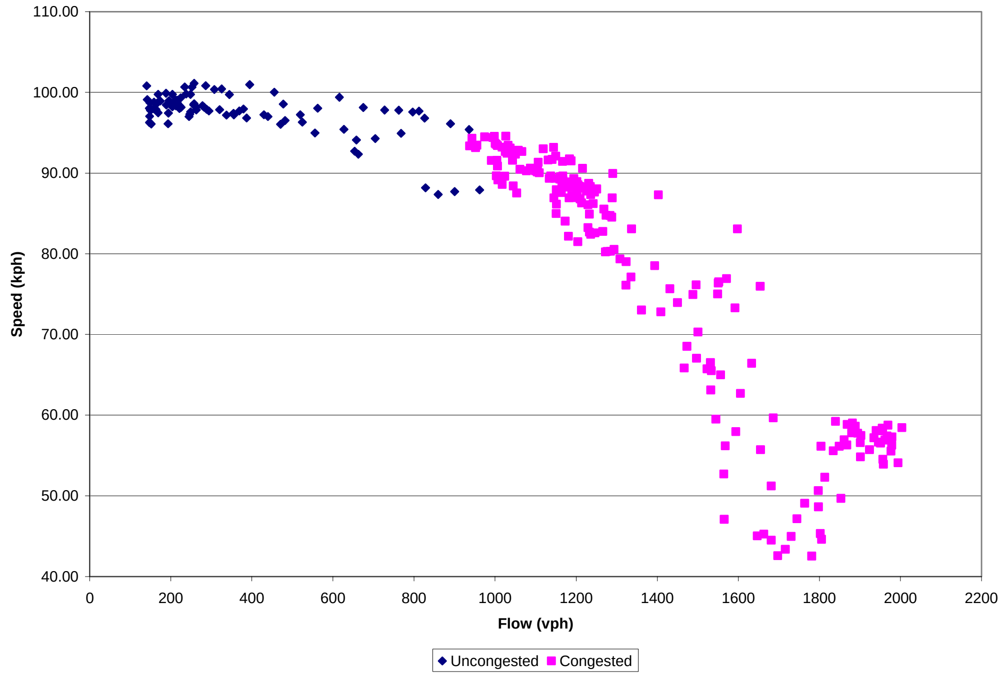


FIGURE 4-10: SPEED VS. FLOW PLOT - 5-MINUTE INTERVAL - WESTBOUND

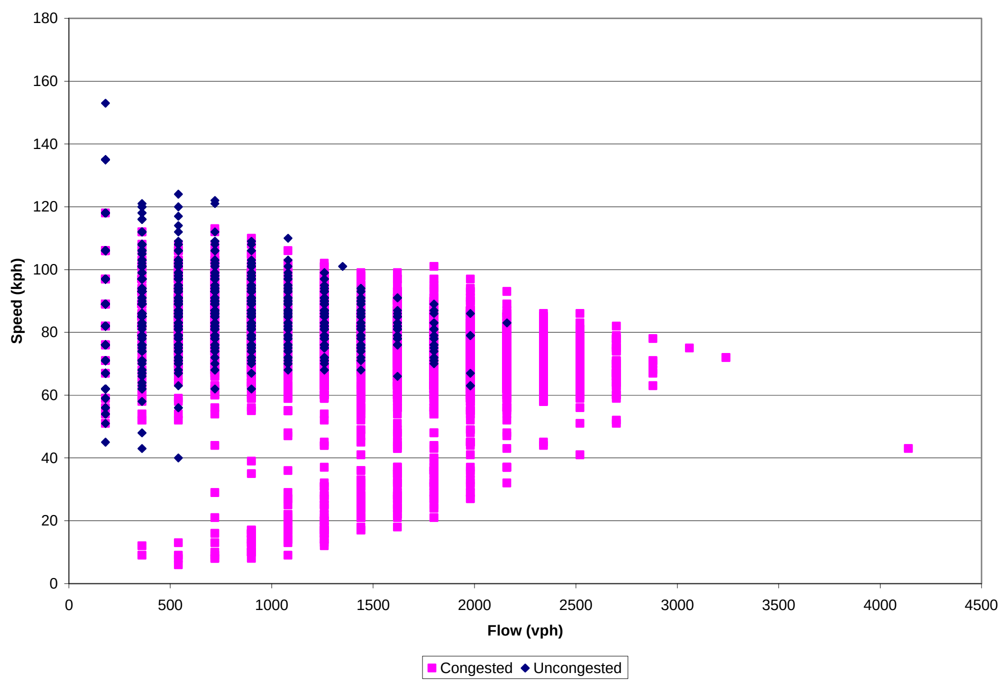


FIGURE 4-11: SPEED VS. FLOW PLOTS - 20-SECOND INTERVAL - EASTBOUND

4.3.2 CONGESTED PERIOD CHARACTERISTICS

The preliminary analysis of traffic conditions on control days reveals that the travel direction affects congestion onset, duration, and intensity. Analysis of the time-series plots and traffic data illustrate that the congestion begins in eastbound lanes much earlier than the westbound lanes. However, due to an increased duration of congestion, westbound congestion ends much later (table 4-10). The nature of these differences can be seen in figures 4-12 and 4-13.

TABLE 4-10: CONGESTION TIMES

	Start	End
Eastbound	6:10 AM	7:50 PM
Westbound	7:05 AM	11:30 PM

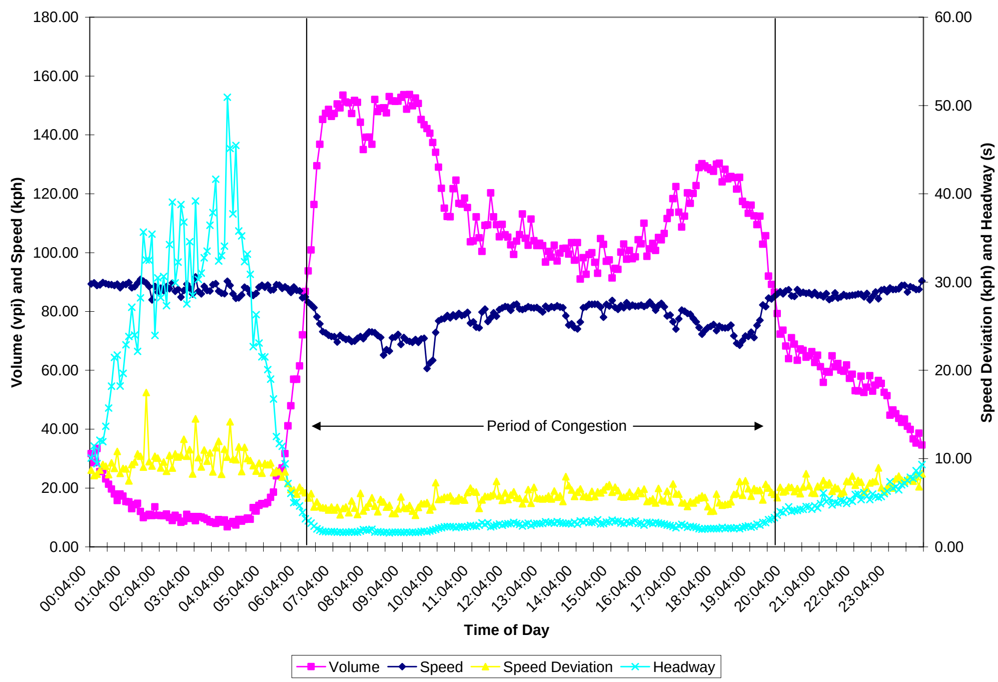


FIGURE 4-12: EASTBOUND DIRECTION TRAVEL PATTERNS

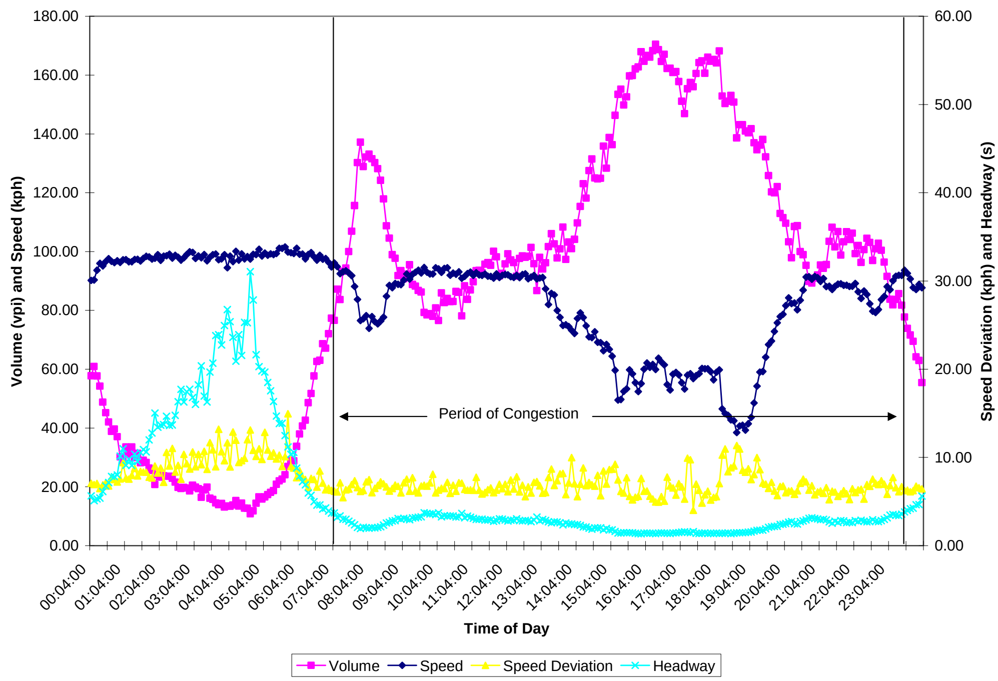


FIGURE 4-13: WESTBOUND DIRECTION TRAVEL PATTERNS - 5-MINUTE INTERVALS

The above data illustrate the average traffic patterns for each travel direction across the 24 control days. Across the control days, there is some variation of traffic patterns. But, for both the east and westbound travel directions, the commencement of congestion is almost identical, varying by only 5 to 10 minutes from day to day. However, the time at which congestion ends is different for east and westbound travel directions. The eastbound direction had four days where congested conditions lasted longer than the 7:50 pm end time. Otherwise, the other 20 days had congested periods ending within ten minutes of that time. The westbound travel direction with its much longer congested periods had more variation in the end times, with up to two hours variation from day to day. Even though the flow numbers may differ from day to day, all of the control days exhibit the same trend of falling flows at the end of the day or congestion period.

The presence of the reduced congestion period in the westbound lanes from 9:30am to 11:00am resulted in the drop in flow numbers seen in figure 4-13. However, this period does not see consistently lower flows for every control day during this period. Rather, there are sporadic ten to fifteen minute intervals of lower volumes throughout this time period, not enough to consider it a true uncongested period.

4.4 A Further Look at Differences by Direction of Travel

Given the differences and timing of uncongested and congested conditions, this section explores some specific differences between the two directions of travel. Rather than just focusing on the four sensor variables, the focus now shifts to five key variables used for further analysis (volume, speed, speed deviation, occupancy, and headway).

4.4.1 Uncongested Periods

In uncongested control periods, differences exist between travel directions in volumes, speeds, speed deviations, occupancies, and headways. The differences are as follows:

1. Mean volumes in the eastbound direction are slightly lower than the westbound direction (table 4-11). The eastbound direction has a larger proportion of 5-minute intervals with volumes between 0 and 25 vehicles.

TABLE 4-11: VOLUME CHARACTERISTICS - UNCONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean	
			Lower	Upper
Eastbound	565	29.5	27.7	31.3
Westbound	517	32.5	30.7	34.2

2. Mean speeds during uncongested conditions are lower in the eastbound direction than in the westbound direction (table 4-12). Additionally, the standard deviation of the hundreds of mean speed values is also lower for the eastbound direction, indicating speeds are more uniform across time periods.

TABLE 4-12: SPEED CHARACTERISTICS - UNCONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean		St. Dev	85th
			Lower	Upper		
Eastbound	565	87.4	87.1	87.7	3.9	91.1
Westbound	517	97.8	97.5	98.2	4.2	101.8

3. The speed deviations calculated for each 5-minute interval are similar for both directions (table 4-13).

TABLE 4-13: SPEED DEVIATION CHARACTERISTICS - UNCONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean	
			Lower	Upper
Eastbound	564	8.4	8.1	8.7
Westbound	517	8.8	8.5	9.1

4. Occupancies for uncongested conditions were almost identical for each travel direction (table 4-14). The only differences between the sides were the minima and maxima, which were slightly higher for the westbound direction.

TABLE 4-14: OCCUPANCY CHARACTERISTICS - UNCONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean		Min	Max
			Lower	Upper		
Eastbound	565	2.8	2.7	3.0	0.1	8.8
Westbound	517	2.8	2.7	3.0	0.5	10.2

5. In uncongested conditions, mean headway is slightly larger in the eastbound direction at 10.3 seconds than the westbound direction at 9.3 seconds (table 4-15). However, the minimum and maximum headways are virtually identical.

TABLE 4-15: HEADWAY CHARACTERISTICS - UNCONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean		Min	Max
			Lower	Upper		
Eastbound	565	10.3	9.9	10.7	3.1	20.0
Westbound	517	9.3	9.0	9.6	3.2	20.0

4.4.2 Congested Conditions

In congested periods, differences between each of the variables are typically larger. These differences can be seen in tables 4-16 to 4-20, and can be described as follows:

1. During congestion, volumes are typically higher for the westbound direction than the eastbound direction. Although the westbound direction has a lower mean volume per 5-minute interval, it does have a larger dispersion of volumes, and also a higher number of 5-minute intervals with volumes exceeding 120 vehicles.

TABLE 4-16: VOLUME CHARACTERISTICS - CONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean	
			Lower	Upper
Eastbound	821	117.6	115.9	119.3
Westbound	921	111.9	109.8	114.0

2. The mean speeds in congested conditions are virtually identical for eastbound versus westbound travel (table 4-17). However, the standard deviation across time periods is much higher for the westbound direction than the eastbound direction. This is the result of a larger number of 5-minute periods with speeds less than 60 kph, in addition to a larger number of speeds in excess of 100kph.

TABLE 4-17: SPEED CHARACTERISTICS - CONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean		St. Dev	85th
			Lower	Upper		
Eastbound	819	75.8	75.1	76.5	10.0	83.7
Westbound	921	76.0	74.5	77.4	22.0	93.6

3. The speed deviation within each 5-minute interval in congested conditions is also higher for the westbound direction (table 4-18). This further confirms that not only is there higher scatter in speeds from 5-minute interval to 5-minute interval, but there is a larger scatter of speeds from 20-second interval to 20-second interval.

TABLE 4-18: SPEED DEVIATION CHARACTERISTICS - CONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean Lower	Confidence Intervals of Mean Upper
Eastbound	819	5.5	5.3	5.6
Westbound	921	6.9	6.7	7.0

4. In congested conditions, occupancies are slightly higher in the westbound direction in terms of the mean and the maximum (table 4-19). Although the lower volumes and higher speeds would appear to indicate that mean occupancy should be lower than the eastbound direction, the presence of a larger number of speeds below 60 kph would drive occupancies higher.

TABLE 4-19: OCCUPANCY CHARACTERISTICS - CONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean Lower	Confidence Intervals of Mean Upper	Min	Max
Eastbound	821	12.9	12.5	13.2	6.2	41.2
Westbound	921	14.4	13.8	15.1	3.5	51.7

5. In congested conditions, the time headways for eastbound and westbound directions are very similar, with only 0.2 seconds variation occurring between the means (table 4-20). Differences, however, do exist when the minima and maxima are considered. Although it has a lower mean, the eastbound direction has lower and higher headways.

TABLE 4-20: HEADWAY CHARACTERISTICS - CONGESTED CONDITIONS

	# of 5-Minute Intervals	Mean	Confidence Intervals of Mean Lower	Confidence Intervals of Mean Upper	Min	Max
Eastbound	821	2.6	2.6	2.7	1.4	7.4
Westbound	921	2.8	2.8	2.9	1.6	6.0

5 EFFECTS OF WEATHER ON TRAFFIC CONDITIONS

5.1 TESTING THE EFFECTS OF WEATHER USING T-TESTS

As noted in Chapter 1, the main objectives of the thesis are to determine the effects of rainfall on traffic conditions using two methods of analysis, t-tests and linear regression. This chapter reports on the findings related to these objectives.

The results of the t-tests indicate that drivers are compensating for light rainfall, as summarized in tables 5-1 to 5-4. Generally speaking, rainfall resulted in lower volumes, speeds, and speed deviations, as well as increased headways, although there are some differences based on travel direction and prevailing traffic conditions (i.e. congested vs. uncongested).

The results of the t-tests, as shown in table 5-1, indicate that there is a drop in volume in periods of light precipitation in both uncongested and congested periods. Although not statistically significant at the .05 level, the difference in means for eastbound uncongested periods resulted in an average drop in volume of 2.6%. The westbound direction experienced a larger drop in volumes of 5.9%. For congested periods, the reductions in volumes were reversed, with the eastbound direction experiencing a larger drop (4.3%) than the westbound direction (1.8%).

TABLE 5-1: T-TEST RESULTS FOR THE VOLUME VARIABLE

Volume			Eastbound		Westbound	
			Control	Light Rainfall	Control	Light Rainfall
Uncongested	Mean		30.2	29.4	33.7	31.7
	% Diff.		-2.6		-5.9	
	n		451		426	
	p	t	.083	-1.7	.000	-4.5
Congested	Mean		117.0	112.0	111.8	109.8
	% Diff.		-4.3		-1.8	
	n		671		819	
	p	t	.000	-5.6	.012	-2.5

The reductions in volume in both uncongested and congestedconditions during periods of light precipitation are most likely the result of a combination of reduced speeds and increased headways, which will be discussed later in this chapter, The results of the speed t-tests (table 5-2) show that average speeds are reduced during rainfall in both uncongested and congested conditions. For uncongested conditions in, speeds drop 5.2% in eastbound traffic, and 3.3% in westbound traffic. In periods of congestion, speeds drop to a larger degree with an 8.6% drop in eastbound traffic and a 7.5% drop in westbound traffic.

TABLE 5-2: T-TEST RESULTS FOR SPEED VARIABLE

Speed			Eastbound		Westbound	
			Control	Light Rainfall	Control	Light Rainfall
Uncongested	Mean		87.2	82.7	98.0	94.7
	% Diff.		-5.2		-3.3	
	n		451		426	
	p	t	.000	-14.9	.000	-10.9
Congested	Mean		76.5	69.9	76.0	70.3
	% Diff.		-8.6		-7.5	
	n		669		819	
	p	t	.000	-15.3	.000	-9.7

The higher speed reductions in congested conditions seem to indicate that drivers are more sensitive to precipitation and wet roads when volumes are high. Additionally, these speed reductions in congested conditions would affect more vehicles due to the interactions that occur between vehicles. These interactions would be fewer in uncongested conditions due to larger following distances.

In addition to reductions in mean speed, rainfall is also associated with reduced speed variability. These differences are larger in congested conditions than in uncongested conditions (table 5-3). These reductions in speed deviation may not play a large role in volume reductions. However, they do indicate that, in periods of rainfall, drivers not only reduce their speed, but they also travel at more uniform speeds, thus increasing safety levels.

TABLE 5-3: T-TEST RESULTS FOR SPEED DEVIATION VARIABLE

Speed Deviation			Eastbound		Westbound	
			Control	Light Rainfall	Control	Light Rainfall
Uncongested	Mean		8.5	8.1	8.9	8.9
	% Diff.		-4.7		0.0	
	n		449		426	
	p	t	.039	-2.1	.880	-0.2
Congested	Mean		5.5	4.9	6.9	6.4
	% Diff.		-10.9		-7.2	
	n		669		819	
	p	t	.000	-5.8	.000	-4.8

Headways increase in rainfall conditions in both congested and uncongested periods. Although the largest percent differences generally occur in congested conditions, it is during uncongested periods that time headways increase the most. Given the small headways in congested periods in control periods, any minor change would result in a higher percent difference as compared to uncongested conditions. However, with time headways increasing for uncongested periods ranging from 0.2-0.5 seconds, the actual time increase is larger.

TABLE 5-4: T-TEST RESULTS FOR HEADWAY VARIABLE

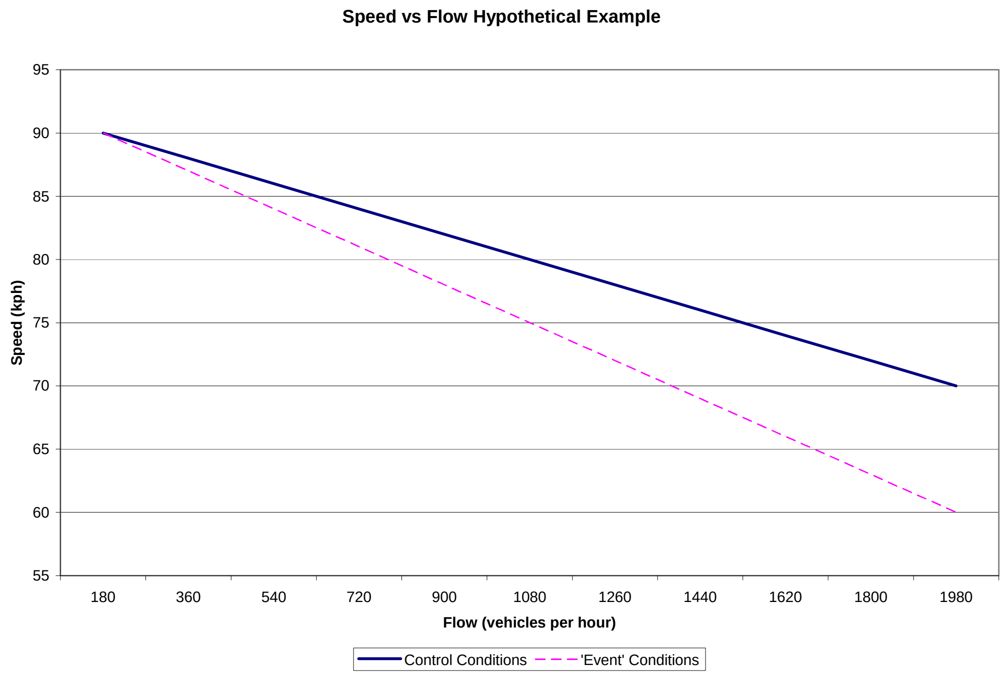
Headway			Eastbound		Westbound	
			Control	Light Rainfall	Control	Light Rainfall
Uncongested	Mean		10.2	10.7	9.4	9.9
	% Diff.		+4.9		+5.3	
	n		451		426	
	p	t	.000	4.6	.000	4.3
Congested	Mean		2.6	2.8	2.8	2.9
	% Diff.		+7.7		+3.6	
	n		671		819	
	p	t	.000	5.1	.000	6.3

5.2 PRELIMINARY REGRESSION ANALYSIS

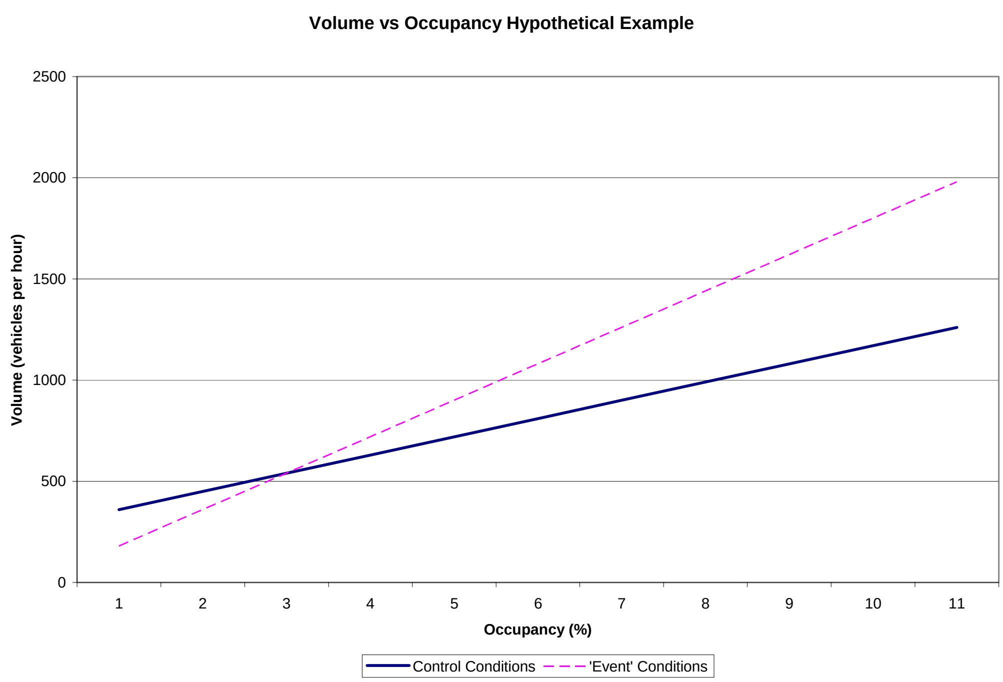
The results of the t-tests in section 5.1 show that differences between the variables exist in periods of rainfall versus normal dry conditions. However, these differences do not illustrate how changes in one variable relate to changes in another. One way to monitor and determine changes in these interactions is to use regression analysis. Common relationships that are used to monitor these changes in traffic include speed-flow and flow-occupancy relationships. A previous study which used both of these relationships to monitor the effects of rain and snow on traffic operations was performed by Ibrahim (1992). The study specifically focused on uncongested conditions on a major inter-urban Ontario highway.

The two relationships, as seen earlier in section 2.4, figures 2-2 and 2-3, illustrate how speeds, volumes, and occupancies change in association with one another, and in particular how periods of congestion are markedly different than uncongested periods. The first relationship of speed vs. flow is a measure of how speeds of vehicles changes with volume, and the second relationship, flow vs. occupancy is a measure of how volume changes with the time the traffic sensor are occupied, as seen in figure 2-3. This figure can be split into two regions, with congestion shown as the linear relationship showing volume increasing with occupancy. Congested conditions in this figure occur on the right hand portion of the curve. Typically, this is represented as a region not a line.

These relationships not only show how variables change in response to one another, but they also provide an insight into traffic operations and road safety. As previously stated, each of the relationships show at what point congested and uncongested conditions occur. Additionally, figure 2-2 illustrates that the point at which a queue forms can be determined from the speed-flow relationship. The safety aspects of the relationships can be determined primarily from the speed-flow relationship. For example, as seen in figure 5-1A, a relationship exists between speed and flow conditions under control conditions. As volume increases, speed drops. In ‘event’ conditions, a similar relationship exists; however, speeds reduce faster as volumes increase, thus, increasing safety levels. For the volume-occupancy relationship (figure 5-1B), if volumes increase at a slower rate in ‘event’ conditions, fewer cars are getting through in the same amount of time, most likely confirming a drop in speed, increasing safety levels.



A



B

FIGURE 5-1: SPEED-FLOW-OCCUPANCY EXAMPLES

5.2.1 Model Selection

The first step in regression analysis was to select a model for speed-volume and volume-occupancy relationships. The results of this regression analysis using control data only can be found in tables 5-5 and 5-6. Both linear and quadratic regression equations were tested.

Evidence of differences between travel directions can be seen in the coefficients of the regression analysis. Although the slopes are similar for east and westbound travel in uncongested conditions for the linear term, the intercept is much lower (88.51 kph) for the eastbound direction. In congested conditions, the intercept for the eastbound direction is also lower than the westbound direction. This is most likely the result of a much longer defined congested period, and sporadic periods of lower volumes and higher speed in the mid-morning hours.

$$\text{Linear: Speed} = \text{Intercept} + \beta_1 * \text{Volume}$$
$$\text{Quadratic: Speed} = \text{Intercept} + \beta_1 * \text{Volume} + \beta_2 * \text{Volume}^2$$

TABLE 5-5: COEFFICIENTS FOR CONTROL DAY DATA -- SPEED VS. VOLUME RELATIONSHIPS

	Uncongested		Congested	
Linear	Gardiner East	Gardiner West	Gardiner East	Gardiner West
Intercept	88.51	100.623	97.814	125.65
Volume (β_1)	-0.04	-0.08	-0.18	-0.45
R	0.239	0.334	0.466	0.639
R^2	0.062	0.112	0.217	0.409
F Stat	28.18	53.37	200.71	570.52
F Sig.	0.000	0.000	0.000	0.000
Quadratic	Gardiner East	Gardiner West	Gardiner East	Gardiner West
Intercept	87.33	95.19	81.48	160.066
Volume(β_1)	0.06	0.27	0.11	-1.06
Volume^2 (β_2)	-0.001	-0.004	-0.001	0.003
R	0.279	0.489	0.476	0.649
R^2	0.078	0.239	0.226	0.421
F Stat.	19.537	66.58	105.52	299.24
F Sig.	0.000	0.000	0.000	0.000

The results of the volume-occupancy preliminary regression analysis are summarized in table 5-6. For both the uncongested and congested periods, results indicated that the quadratic term improved the goodness of fit as in the speed-volume relationship. For this reason, the quadratic term was used in the subsequent analysis.

$$\text{Linear: Volume} = \text{Intercept} + \beta_1 * \text{Occupancy}$$
$$\text{Quadratic: Volume} = \text{Intercept} + \beta_1 * \text{Occupancy} + \beta_2 * \text{Occupancy}^2$$

TABLE 5-6: COEFFICIENTS FOR CONTROL DAY DATA -- VOLUME VS. OCCUPANCY RELATIONSHIPS

	Uncongested		Congested	
Linear	Gardiner East	Gardiner West	Gardiner East	Gardiner West
Intercept	0.39	14.11	80.26	83.18
Occupancy(β_1)	10.26	6.89	2.98	1.98
R	0.978	0.781	0.590	0.617
R^2	0.957	0.609	0.348	0.381
F Stat.	10337.76	662.69	387.07	508.21
F Sig.	0.000	0.000	0.000	0.000
Quadratic	Gardiner East	Gardiner West	Gardiner East	Gardiner West
Intercept	-1.66	0.63	-8.22	22.89
Occupancy (β_1)	12.07	12.97	14.06	10.45
Occupancy^2 (β_2)	-0.25	-0.27	-0.29	-0.20
R	0.979	0.934	0.900	0.898
R^2	0.959	0.872	0.811	0.806
F Stat.	5400.81	1446.17	1548.97	1794.37
F Sig.	0.000	0.000	0.000	0.000

In comparison with the 1992 Ibrahim study where 30-second loop data were used to determine the optimal regression equations, there are obvious differences. Due to the higher volumes associated with the aggregated 5-minute data, the slopes of the volume-occupancy relationship are much greater, although the same general direction is preserved. The intercepts for this relationship are surprisingly similar with only small differences existing between the two data sets. A major difference, however, exists in the classification of uncongested periods in the two different highways. In the Ibrahim study, volumes of 25 vehicles in one 30-second interval are used to illustrate the effects of the relationship on uncongested conditions. An equivalent volume on the Gardiner expressway would be 17 vehicles in a 20-second, which is classified as congested conditions. The largest difference in the speed-volume relationship exists in the size of intercept values. However, this is most likely the result of the differences in the highway type (urban vs. inter-urban) and the differences in the posted and enforced speed limits (90 kph vs. 100 kph). Preliminary analysis of the clear weather days illustrate that the functions governing the highways appear to be similar. In addition to intercept values, the R^2 results for both the volume-occupancy and speed-volume relationships were similar. Although Ibrahim (1992) did no use quadratic equations for the speed-volume relationship, a single test was performed and was found not to increase the goodness of fit significantly. However, in the case of the Gardiner data, larger differences were observed.

As stated previously, the quadratic functions were used to determine the effects of precipitation on the two relationships, much like Ibrahim (1992). However, unlike the Ibrahim (1992) study, it was decided to treat the control and event data separately, rather than use a dummy variable and interactive term setup. Due to the nature of these functions, issues with collinearity arise in quadratic regression terms.

5.3 Effects of Weather Conditions – Regression Analysis

5.3.1.1 Uncongested Conditions - Speed Versus Volume Relationship

The results of the regression analysis where speed is the dependent variable can be found in table 5-7. The table shows that in both eastbound and westbound directions, precipitation does affect speed levels. Coefficients that were not returned as significant are shown in shaded cells. As in the control data regression analysis in section 5.2.1, the eastbound direction has a lower speed intercept than the westbound data, as is visible in the speed-volume plots in figure 5-2 and 5-3. Using the minimum, maximum, median, upper, and lower quartiles, a regression line was plotted for each result. Additionally, the plots for each of the regression equations with their associated scattergrams can be seen in appendix A.

TABLE 5-7: UNCONGESTED CONDITIONS - SPEED-VOLUME REGRESSION RESULTS

	Eastbound		Westbound	
	Control	Light Rainfall	Control	Light Rainfall
Intercept	88.51	81.13	95.19	96.60
Volume	0.06	0.16	0.27	-0.06
Volume^2	0.001	-0.002	-0.004	0.000
R	0.279	0.193	0.489	0.284
R^2	0.078	0.57	0.239	0.081
F Stat.	19.54	8.658	66.58	18.586
F Sig.	0.000	0.000	0.000	0.000
n	465	450	425	424

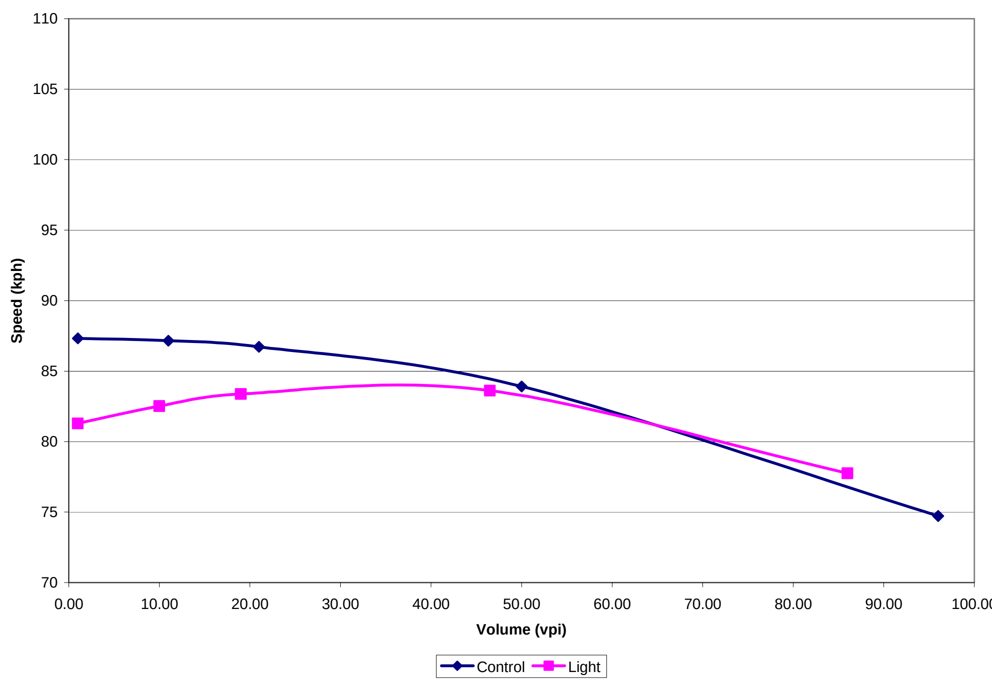


FIGURE 5-2: EASTBOUND UNCONGESTED SPEED VS. VOLUME PLOTS

The results of the eastbound plots (figure 5-2) indicate that in control conditions, speeds decrease as volume increases, while in light rainfall conditions, speeds slightly increase as volumes increase and then decrease, much like control conditions. In volumes higher than roughly 65 vehicles per 5-minute interval, speeds are higher in rainfall than in control conditions. This indicates that, in low volumes, drivers are adjusting for rainfall by slowing down in the eastbound direction, but, as volumes increase rainfall has little affect on speed choice–which is already lower.

The westbound regression plot for uncongested conditions is different than that of the eastbound direction. In general, the intercepts are larger in westbound conditions as well as the minimum speed at high volumes. For control conditions, speeds increase in low volumes, and then begin to decrease at the 40 vehicles per interval point. The light rainfall regression results indicate that speeds are lower at low volumes, but at roughly the 55 vehicles per 5-minute interval point. The light rainfall results also indicate that compensation does occur, but, it not affected by changes in volume, unlike the eastbound direction

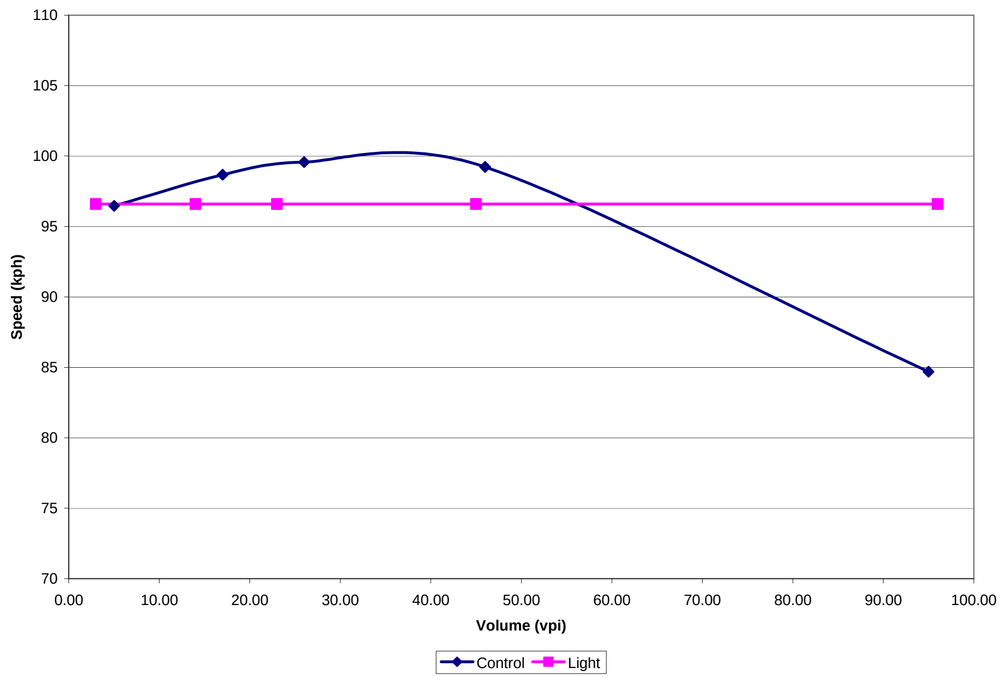


FIGURE 5-3: WESTBOUND UNCONGESTED SPEED VS. VOLUME PLOTS

5.3.1.2 UNCONGESTED CONDITIONS - VOLUME VERSUS OCCUPANCY RELATIONSHIP

Results of the volume-occupancy regression analysis add to the results of both the t-test analysis, and speed-volume regression analysis. Specifically, as occupancies increase, volumes increase at a faster rate in times of precipitation. This effect is most pronounced in the westbound direction (figure 5-4 and 5-5), where volumes increase fastest in light precipitation, and at a less rapid rate in moderate precipitation. The results from the eastbound direction indicate, that in periods of light precipitation, volumes increase at a slightly faster rate than in control conditions, and at a slower rate in periods of moderate precipitation.

TABLE 5-8: UNCONGESTED CONDITIONS - VOLUME-OCCUPANCY REGRESSION RESULTS

	Eastbound		Westbound	
	Control	Light Rainfall	Control	Light Rainfall
Intercept	-1.66	-1.54	0.63	0.51
Occupancy	12.07	11.61	12.97	12.85
Occupancy^2	-0.25	-0.16	-0.27	-0.09
R	0.979	0.988	0.934	0.990
R^2	.0959	0.977	0.872	0.979
F Stat.	5400.81	9488.73	1446.172	10040.31
F Sig.	0.000	0.000	0.000	0.000
n	465	450	425	424

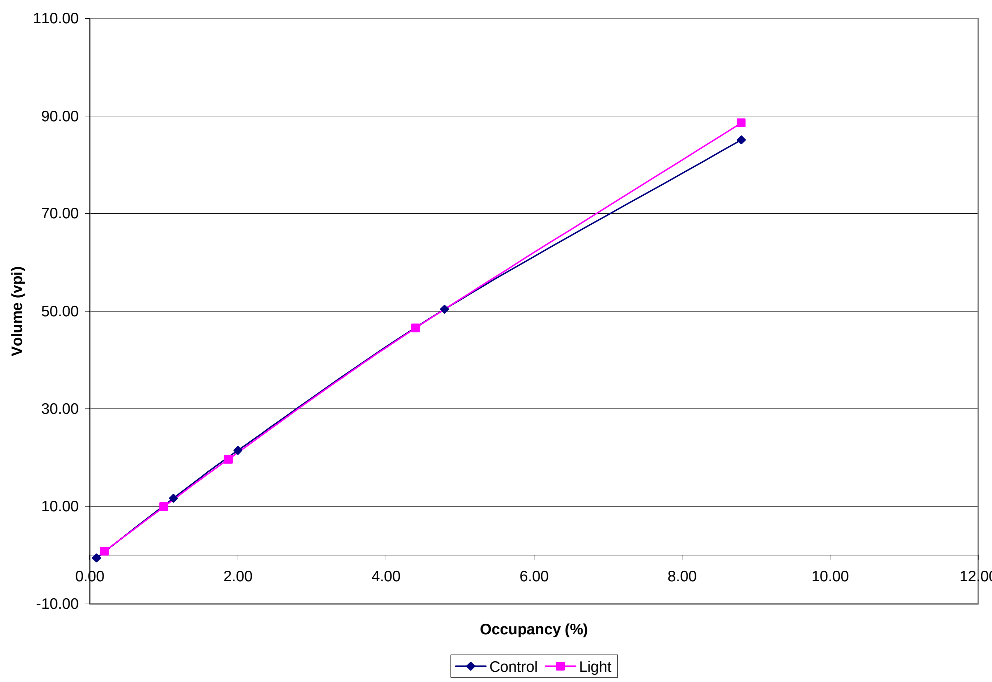


FIGURE 5-4: EASTBOUND UNCONGESTED VOLUME VS. OCCUPANCY PLOTS

The results of the volume vs. occupancy relationship for the eastbound direction (figure 5-4) indicate that there is little difference between control and light rainfall conditions. Only slight differences can be seen at higher occupancies, and this difference only amounts to 3.5 vehicles per 5-minute interval. The results for the westbound direction indicates that as occupancies, or densities, increase, volumes increase at a faster rate in light precipitation than in control conditions.

As stated in Hall and Barrow (1988), the slope of both eastbound and westbound volume vs. occupancy curves in light precipitation indicate that maximum flows are higher than in control conditions, which is similar to the results of Ibrahim and Hall (1994).

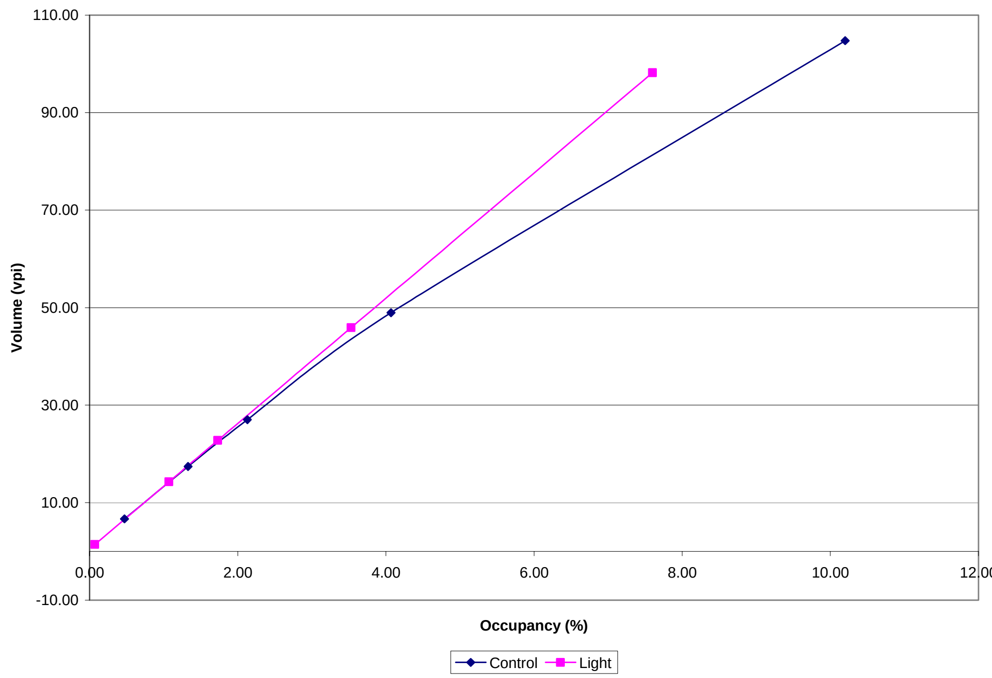


FIGURE 5-5: WESTBOUND UNCONGESTED VOLUME VS. OCUPANCY PLOTS

5.3.1.3 UNCONGESTED CONDITIONS - HEADWAY VERSUS SPEED RELATIONSHIP

Although a commonly used relationship like flow-occupancy and speed-flow relationship does not exist for the headway variable, analyses of the variation of headway typically does make use of the speed variable. However, previous attempts to determine the relationship of speed with headway have been performed by Banks (2003). For this reason, the headway versus speed relationship was tested. However, a plot of the speed and headway values reveals that no such relationship is possible given the distribution of the data (figures 5-6 and 5-7).

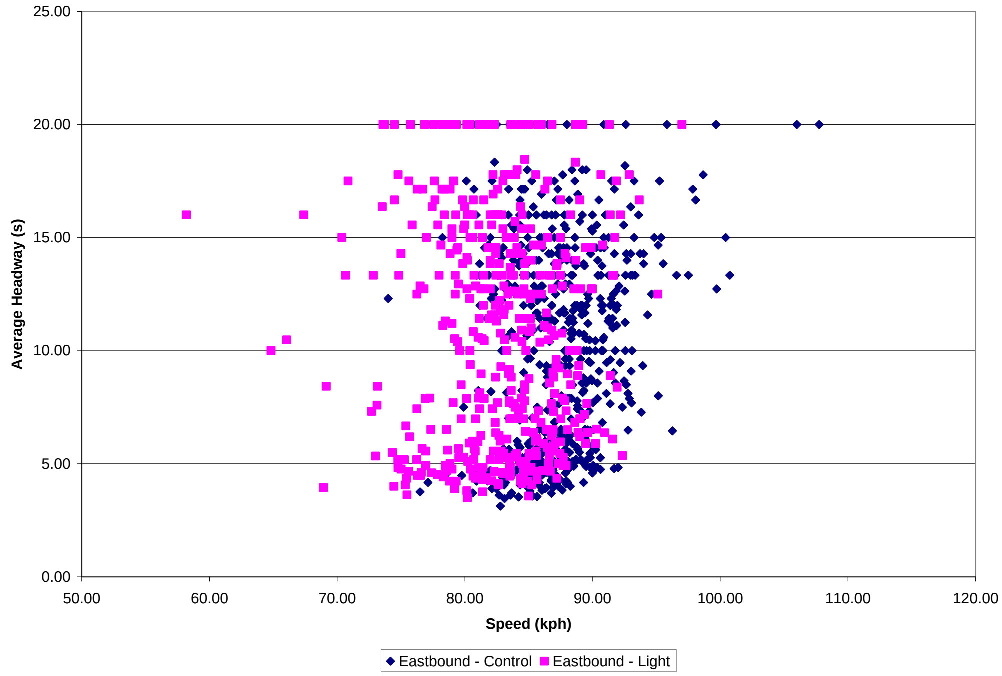


FIGURE 5-6: UNCONGESTED CONDITIONS - EASTBOUND SPEED VS. HEADWAY PLOT

Results of the two plots (figures 5-6 and 5-7) show that in addition to speed reductions, there is a slightly higher proportion of larger headways under light conditions than under control conditions. Similar statements can be made about the moderate precipitation results, even though the number of points in this category is limited.

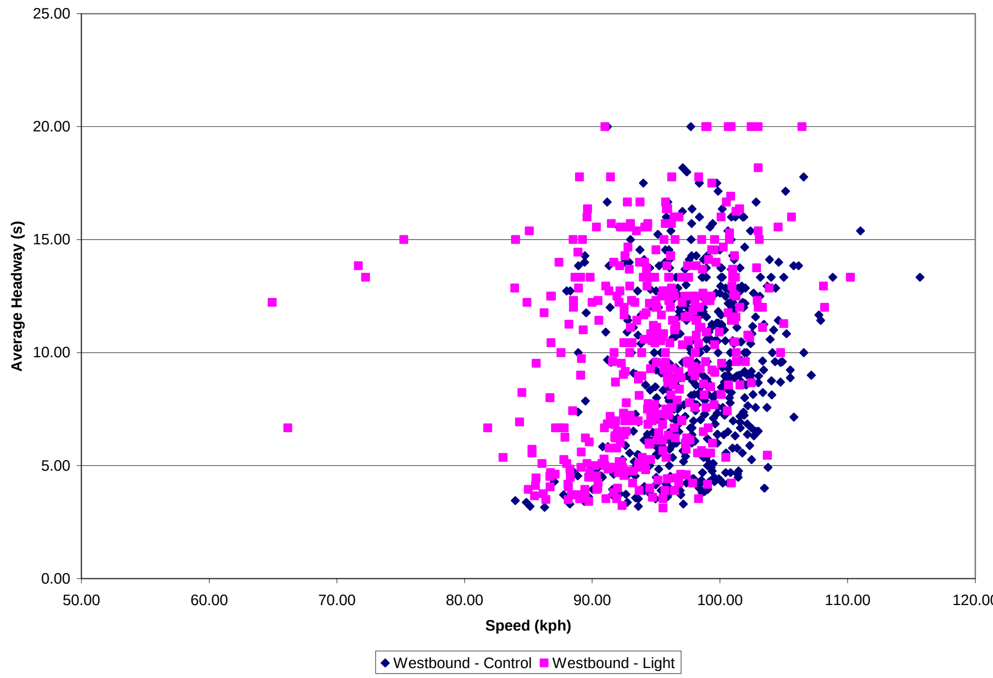


FIGURE 5-7: UNCONGESTED CONDTIONS - WESTBOUND SPEED VS. HEADWAY PLOT

5.3.1.4 UNCONGESTED CONDITIONS - SAFETY IMPLICATIONS OF REGRESSION RESULTS

In combination, all of the regression relationship results indicate that drivers are responding to precipitation events. However, this compensation appears to be minimal when speeds, volumes, and headways are considered. In the eastbound direction, drivers are compensating for precipitation by reducing their speeds as shown in figures 5-2 and 5-3. However this speed reduction is minimal in the westbound direction, which could be the result of uncongested period timing occurring mainly in the early morning hours. Additionally, it appears that drivers are compensating for light rain by increasing their headway. However, an overall reduction in volumes does not seem to be occurring.

5.3.2.1 CONGESTED CONDITIONS - SPEED VERSUS VOLUME RELATIONSHIP

The results of the speed vs. volume regression results for congested conditions were similar to those of uncongested conditions (table 5-9, figure 5-8 and figure 5-9). In general, speeds dropped as volumes increase.

TABLE 5-9: CONGESTED CONDITIONS - SPEED-VOLUME REGRESSION RESULTS

	Eastbound		Westbound	
	Control	Light Rainfall	Control	Light Rainfall
Intercept	81.48	74.71	160.07	123.13
Volume	0.11	0.056	-1.06	-0.49
$Volume^2$	-0.001	-0.0001	0.003	0.000
R	0.476	0.367	0.649	0.717
R^2	0.226	0.135	0.421	0.514
F Stat.	105.52	56.72	299.24	410.619
F Sig.	0.000	0.000	0.000	0.000
n	723	731	825	823

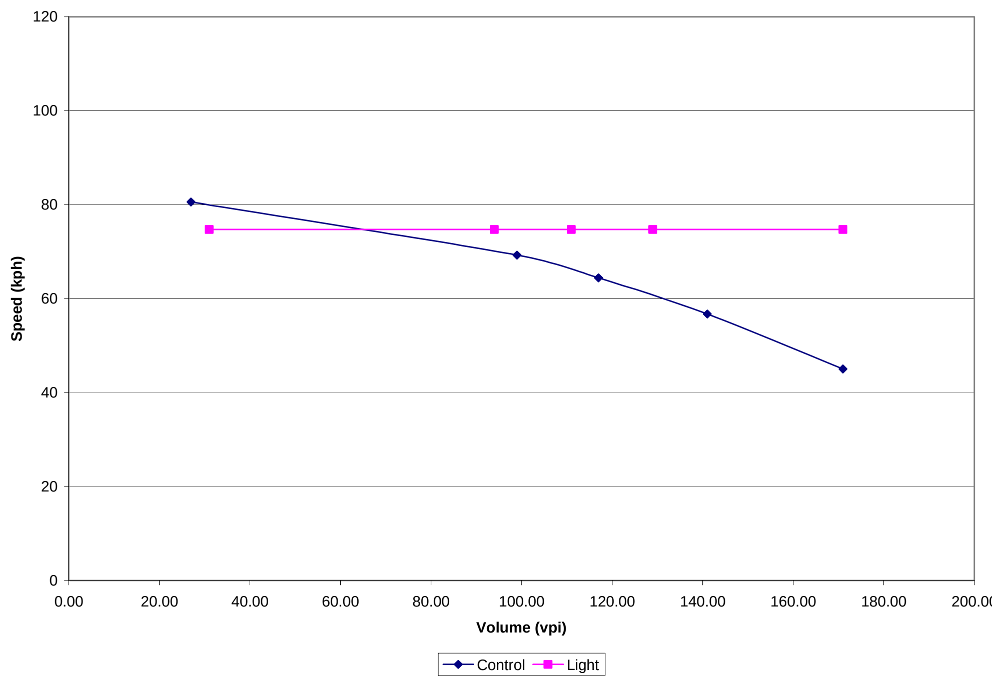


FIGURE 5-8: EASTBOUND CONGESTED CONDITIONS - SPEED VS. VOLUME PLOTS

For the eastbound direction (figure 5-8), the regression results indicate that compensation during congested conditions is minimal at lower volumes, and that speeds are not reduced in periods of higher volumes. However, in the westbound direction, speeds are lower in all volumes. This confirms the fact that different processes are occurring when focusing on travel direction.

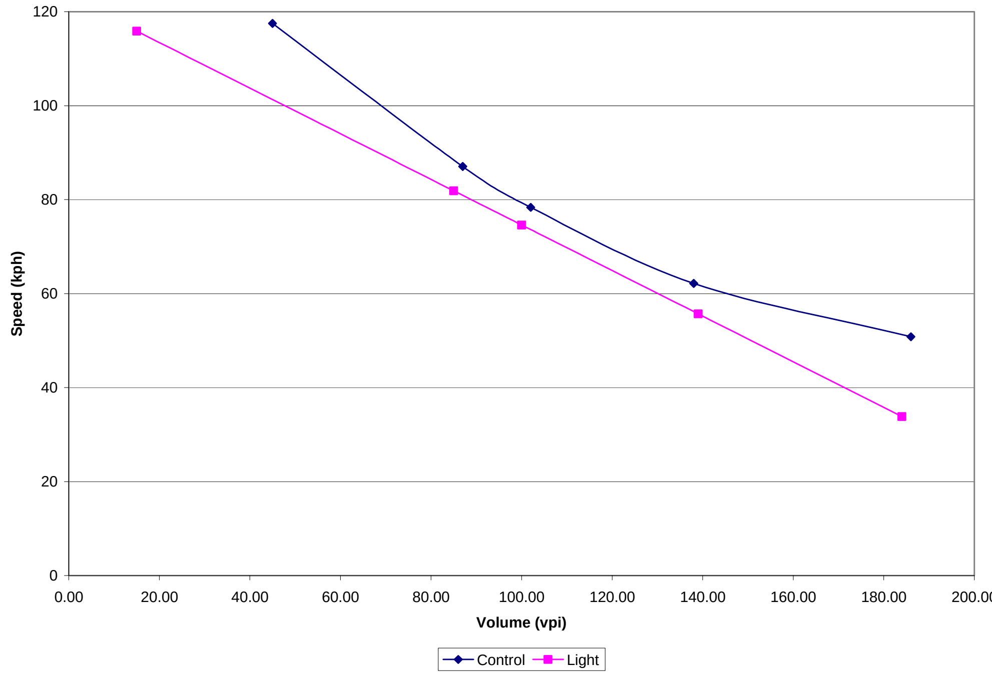


FIGURE 5-9: WESTBOUND CONGESTED CONDITIONS - SPEED VS. VOLUME PLOTS

5.3.2.2 CONGESTED CONDITIONS VOLUME VERSUS OCCUPANCY RELATIONSHIP

Results of the volume vs. occupancy regression analysis (table 5-10, figure 5-10 and figure 5-11) indicate that in periods of light rainfall, volumes are lower for similar occupancies in both the eastbound and westbound direction, indicating a reduced maximum flow, which would be expected in congested conditions. Additionally, these results follow the same trends as previous examples of the volume-occupancy relationship as seen in figure 2-3.

TABLE 5-10: CONGESTED CONDITIONS – VOLUME-OCCUPANCY REGRESSION RESULTS

	Eastbound		Westbound	
	Control	Light Rainfall	Control	Light Rainfall
Intercept	-8.22	-6.93	22.89	22.41
Occupancy	14.06	13.23	10.45	10.03
$Occupancy^2$	-0.29	-0.29	-0.20	-0.19
R	0.900	0.846	0.898	0.915
R^2	0.811	0.716	0.806	0.838
F Stat.	1548.97	918.73	1794.372	2119.869
F Sig.	0.000	0.000	0.000	0.000
n	725	731	825	823

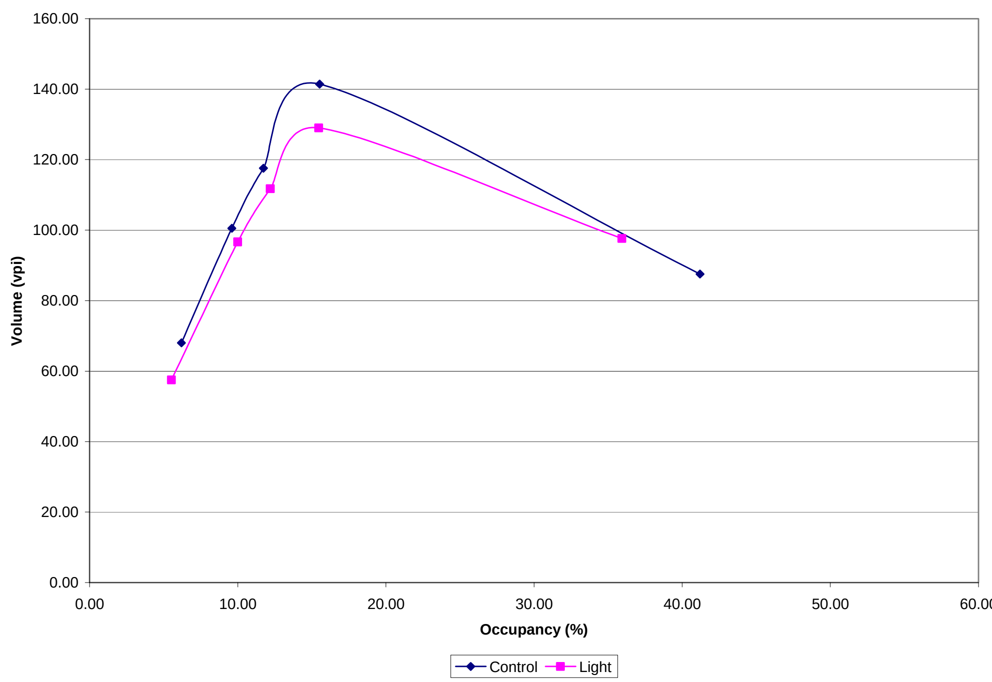


FIGURE 5-10: EASTBOUND CONGESTED CONDITIONS - VOLUME VS. OCCUPANCY PLOTS

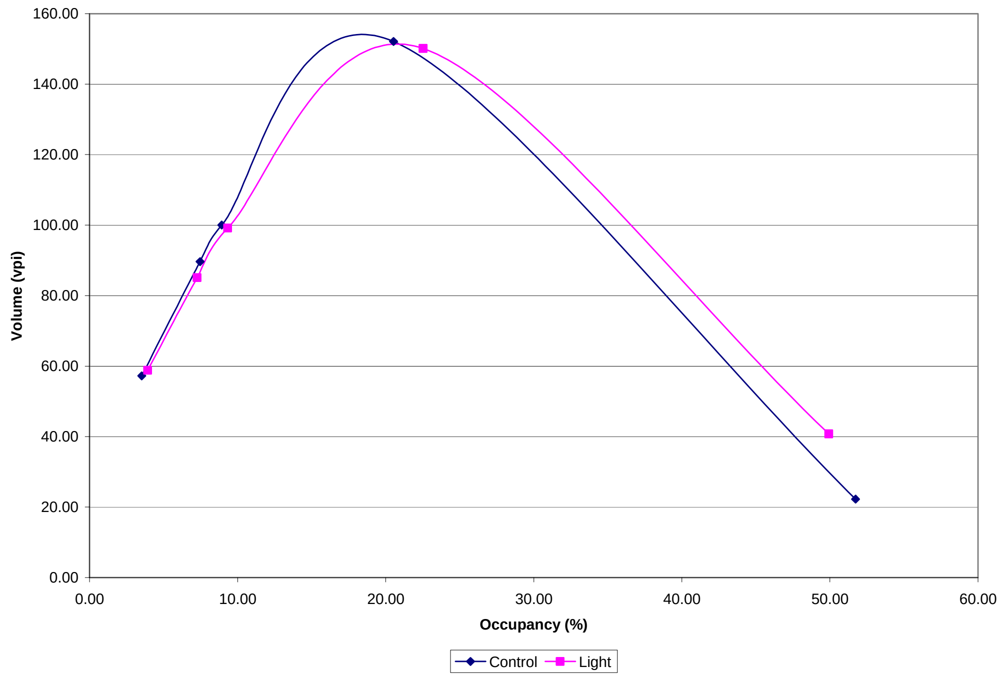


FIGURE 5-11: WESTBOUND CONGESTED CONDITIONS – VOLUME VS. OCCUPANCY PLOTS

5.3.2.3 CONGESTED CONDITIONS SPEED VERSUS HEADWAY RELATIONSHIP

The distribution of headways in congested conditions is different than that of uncongested conditions. An increased number of lower headways during periods of lower speeds are present, which is characteristic of congested conditions, as described by Banks (2003). In his conclusions Banks states that in congested conditions, headways can be expected to be constant. The results of the speed-headway plots for eastbound and westbound congested control conditions appear to confirm these results.

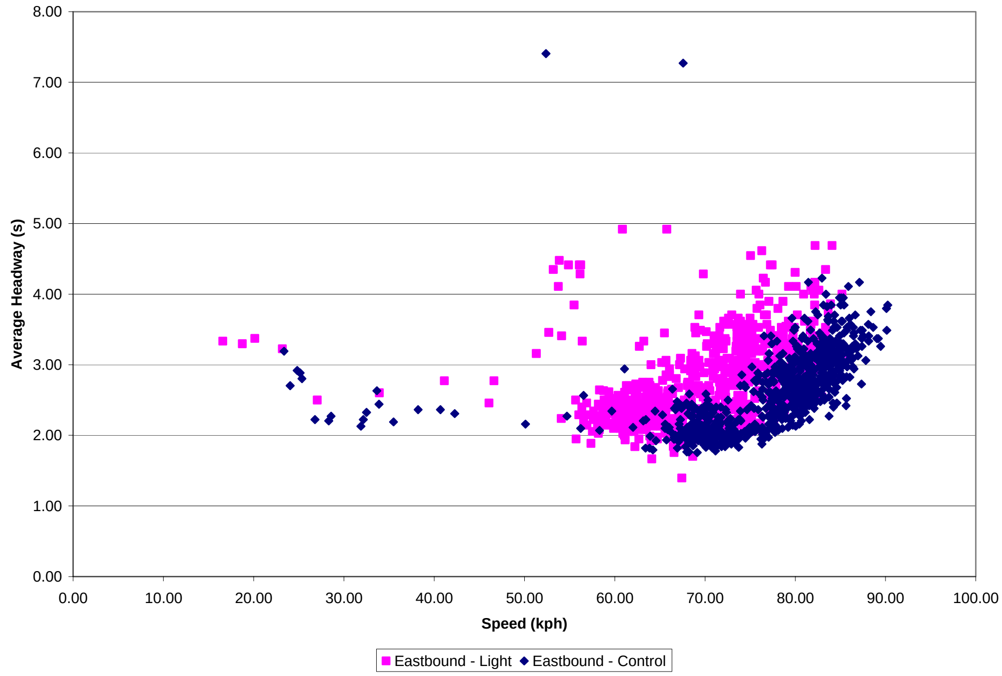


FIGURE 5-12: CONGESTED CONDITIONS - EASTBOUND SPEED VS. HEADWAY PLOT

In addition to the reduction of speeds, which are visible in the speed vs. headway plots, light precipitation also appears to slightly increase average headways, which is confirmed by the headway t-test results. This effect is greatest in the westbound direction of travel. Additionally, the westbound direction has a much higher proportion of speeds below 60 kph, and associated small average headways of 1.5 – 2.5 seconds.

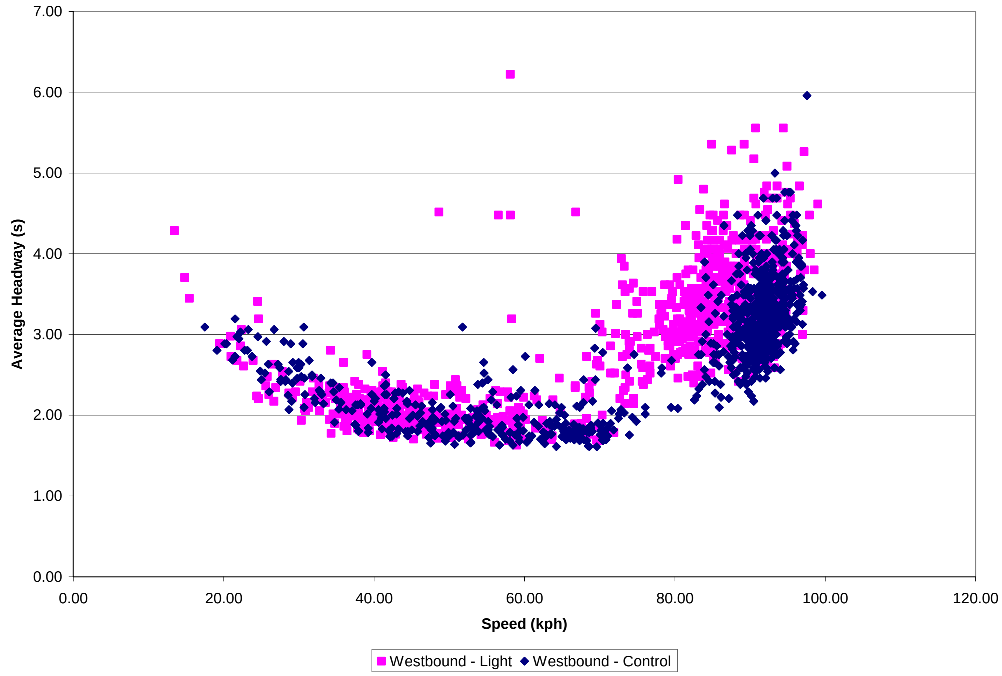


FIGURE 5-13: CONGESTED CONDITIONS - WESTBOUND SPEED VS. HEADWAY PLOT

5.3.2.4 CONGESTED CONDITIONS - SAFETY IMPLICATIONS OF REGRESSION RESULTS

The results of the regression analysis again illustrate that drivers tend to compensate for rainfall. However, the compensation during congested periods is different than that during uncongested periods. The eastbound direction, with a shorter, less intense congested period, experiences slightly increased volumes, decreasing speeds, and increasing headways. The rate at which these variables change show that in periods of light precipitation drivers slow down more than in periods of clear weather. Additionally, headways are much higher in light precipitation for similar speeds. In combination, drivers are increasing their safety levels by reducing their speeds and increasing their headways. In the westbound direction speed reductions are greater, which could partly explain the higher volumes at similar occupancies to control conditions.

5.4 Summary of Regression and T-Test Results

The results of both the t-test and regression analysis indicate that drivers are reacting to precipitation events as they occur. In general, this reaction results in decreased speeds for both congested and uncongested conditions. Results from the t-test also indicate that volumes are reduced in periods of light rainfall. In congested periods, volume also experiences an overall decrease, as indicated by t-test results. However, the results of regression analysis indicate that as occupancy increases, volume increases at a faster rate in congested and uncongested conditions. The average headways during periods of both light and moderate precipitation increase slightly, indicating that drivers tend to leave a little more space in between vehicles.

6 CONCLUSIONS

The purpose of this thesis was to contribute to the understanding of the effects of rainfall on traffic operations and driver behaviour. The following three objectives were identified:

1. Using t-test data, estimate the magnitude of volume, speed, speed deviation, and headway changes between control and event data.
2. Examine the speed-volume-occupancy relationships in order to determine how wet weather affects these relationships.
3. Explore the differential effects of rainfall on uncongested and congested conditions.

The first objective was to determine the magnitude and direction of change in volume, speed, speed deviation, and headways between event and control data. The results indicated that volumes drop in periods of light rainfall in both congested and uncongested periods. Speed reductions occurred in both directions and traffic conditions. The largest speed reductions occurred in congested periods for both the east and westbound direction with smaller reductions in uncongested periods.

T-test results for both speed deviations also saw similar trends for uncongested and congested periods, with the largest reductions occurring in congested periods. The headway variable, however, was slightly different, with the largest increases in headway occurring in uncongested periods, and only marginal, but statistically significant increases in congested conditions ranging from 0.1-0.2 seconds.

In combination, these results indicated that drivers did tend to compensate for the occurrence of precipitation. The largest compensation occurred with the reductions in speed, and subsequent reductions in speed deviation. The increase in headway of 0.5 seconds in uncongested light precipitation periods was the largest, most likely due to the lower volumes and lower speeds. The small reduction in headways for congested conditions indicated that although drivers slowed down more, they also increased their following distance greatly.

The second objective focused on the use of regression equations to determine the effects of the precipitation events on speed-volume and volume-occupancy relationships. It was determined that both the intercepts and slopes are different for periods of precipitation, signifying a change in driving behaviour in both uncongested and congested conditions. However, this change appears to be limited mostly to changes in speed.

The results from the t-test and linear regression analysis indicate that drivers are altering their driving behaviour in response to precipitation events. Regardless of traffic conditions and precipitation amount, results indicate that drivers reduce their speed and increase their following distance. Additionally, the speed deviations are reduced during periods of precipitation indicating that drivers select speeds that are more uniform in periods of precipitation. These adjustments however, are slightly larger in congested periods than in uncongested periods.

The third objective was intended to provide new insight into the effects of rainfall during both uncongested, and previously overlooked congested conditions. The results of the analysis indicated that drivers tended to compensate differently in congested conditions than in uncongested conditions in periods of rainfall. More specifically, results indicate that although higher, volumes do not drop as much as in uncongested periods as in congested periods. However, speeds and speed deviations were seen to drop to a greater degree. Finally, headway times increased in both congested and uncongested periods, but to a smaller degree in congested conditions.

6.1 Opportunities for Future Research

There are several opportunities for continued research that have arisen from this study. The investigation taken on by this study has found that drivers do alter their behaviour in periods of precipitation; however, the data set was limited in that only light precipitation was used, and the effects of time of day and night time conditions were not considered. Further investigation into other sites of the Gardiner expressway might lead to a better understanding of the effects of precipitation on the driving population using this highway. Specifically, the reactions of drivers may differ according to the location of the study site (i.e. merging or diverging traffic vs. a straight section of highway).

A second opportunity for future research exists in the opportunity to include other increased rainfall events and additionally weather conditions in the analysis, including snow, visibility, and wind speeds to name a few. This would expand the understanding of how weather in general affects driver behaviour and traffic conditions. A third opportunity that could be pursued would be the additional of accident data into the data set to determine risk levels in relation to weather conditions and site location.

Another opportunity for further research into the effects of weather on traffic operations stem from the classification of traffic conditions. Under the criteria of this study, only two periods were used for analysis (uncongested and congested). However, this limited the ability of this researcher to conclude what the true effects of rainfall on congested conditions were. However, if each time period were further subdivided into smaller categories of flows and times, further conclusions on the effects of rainfall on different traffic conditions could be reached. For example, separate categories could be used to separate out the peak flows from congestion, or the extremely low flows of early morning from uncongested periods, allowing for more additional conclusions on the effects of weather on driver behaviour and traffic operations.

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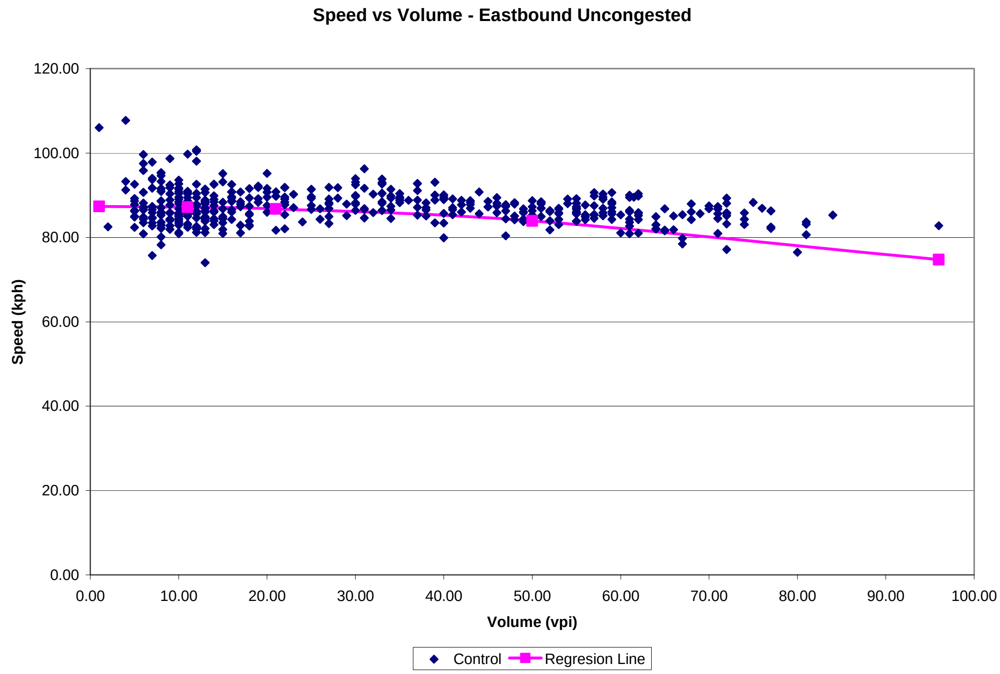
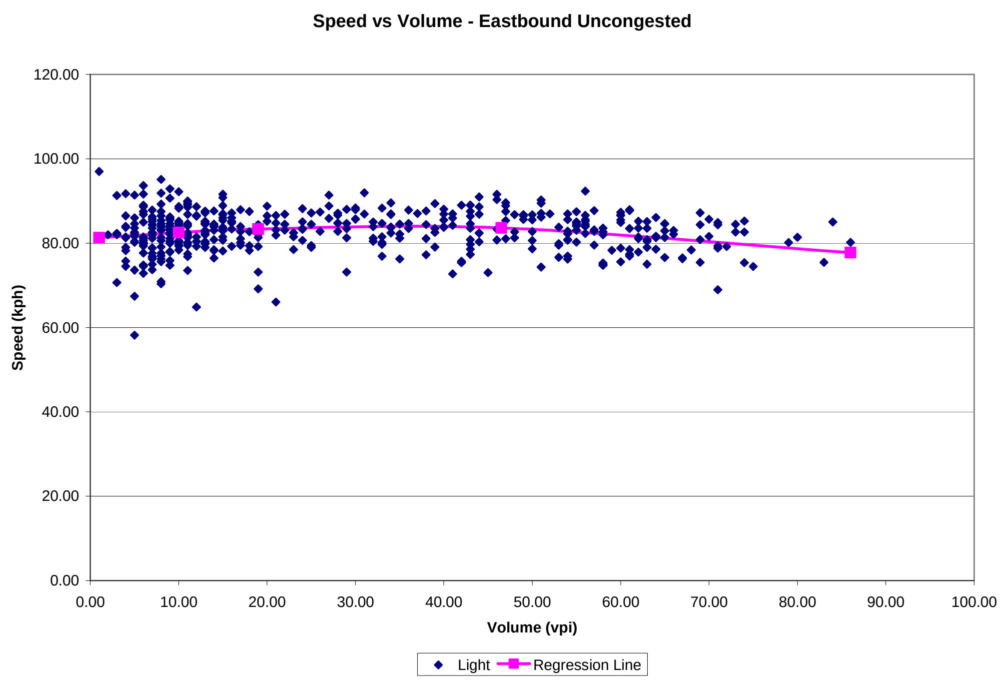
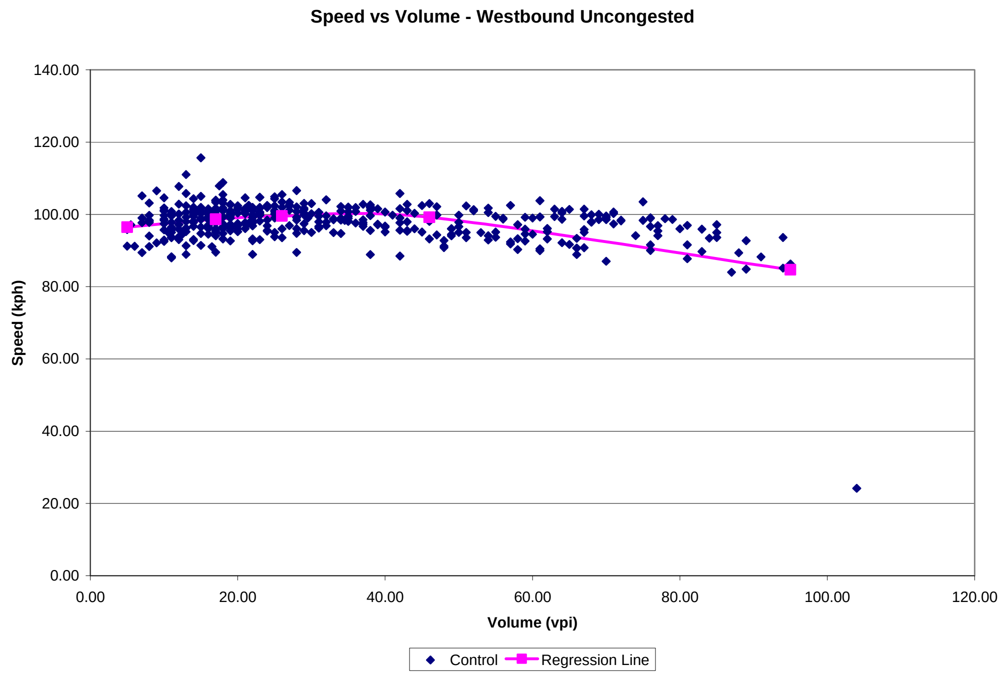
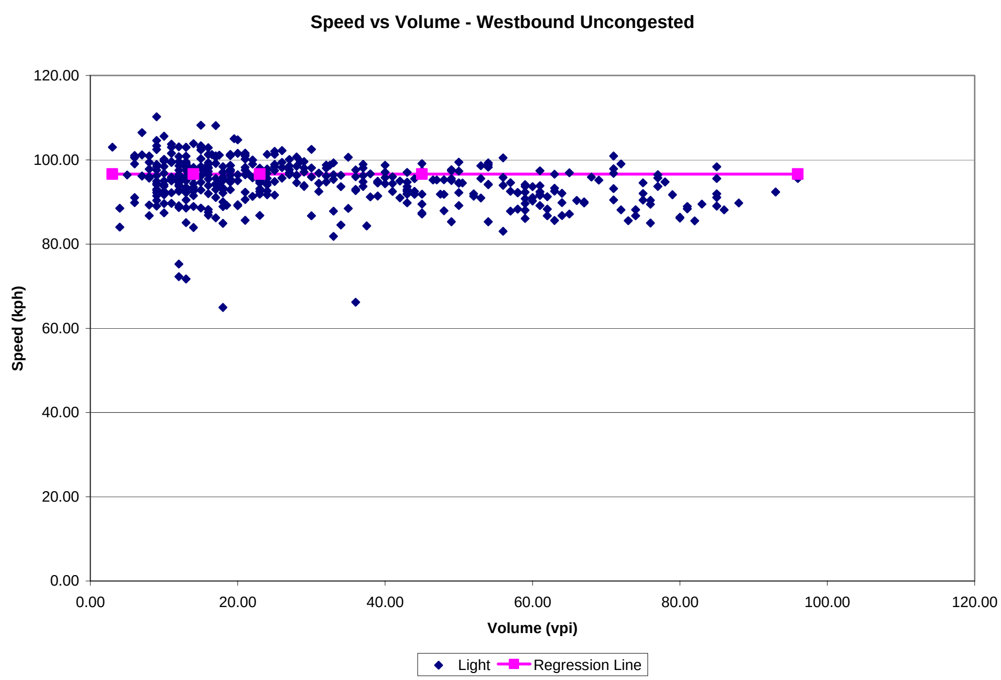
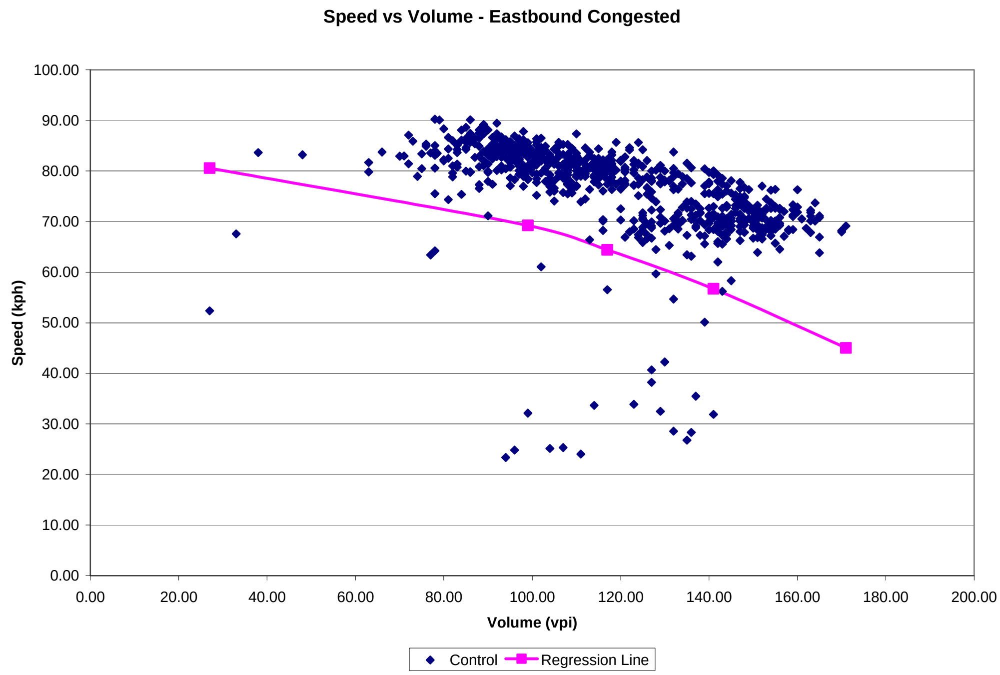
Appendix A: Regression Plots and Associated Scattergrams

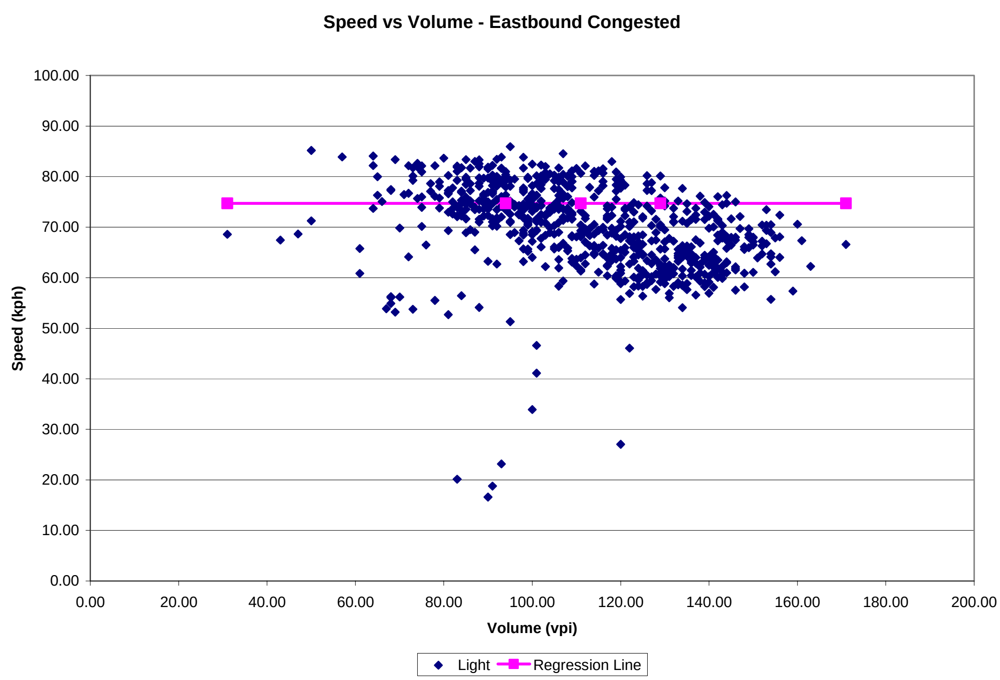




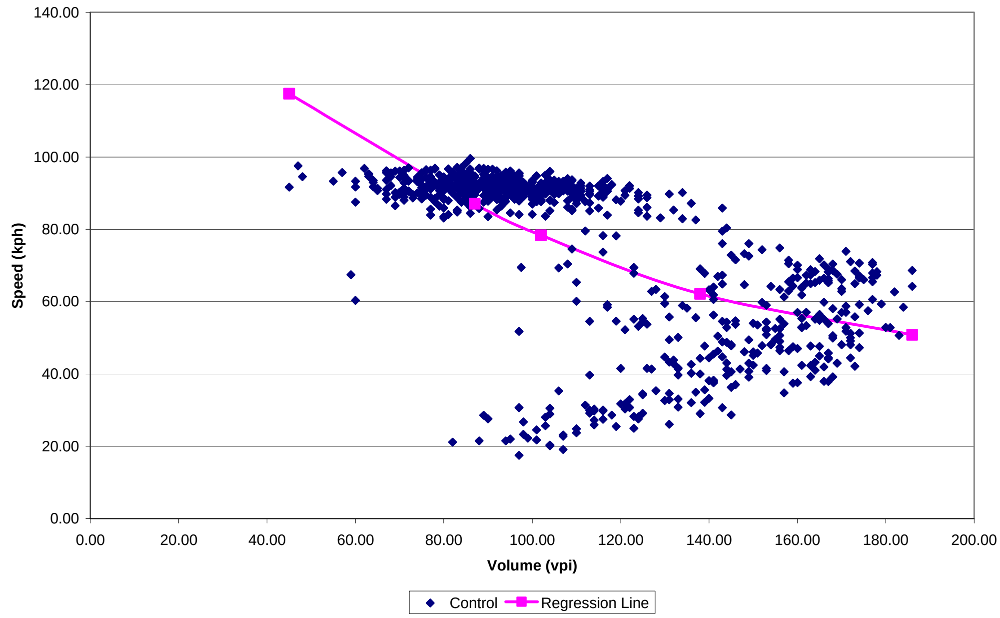

Speed vs Volume - Westbound Uncongested
Speed (kph)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Volume (vpi)
Control
Regression Line


Speed vs Volume - Westbound Uncongested
Speed (kph)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Volume (vpi)
Light
Regression Line

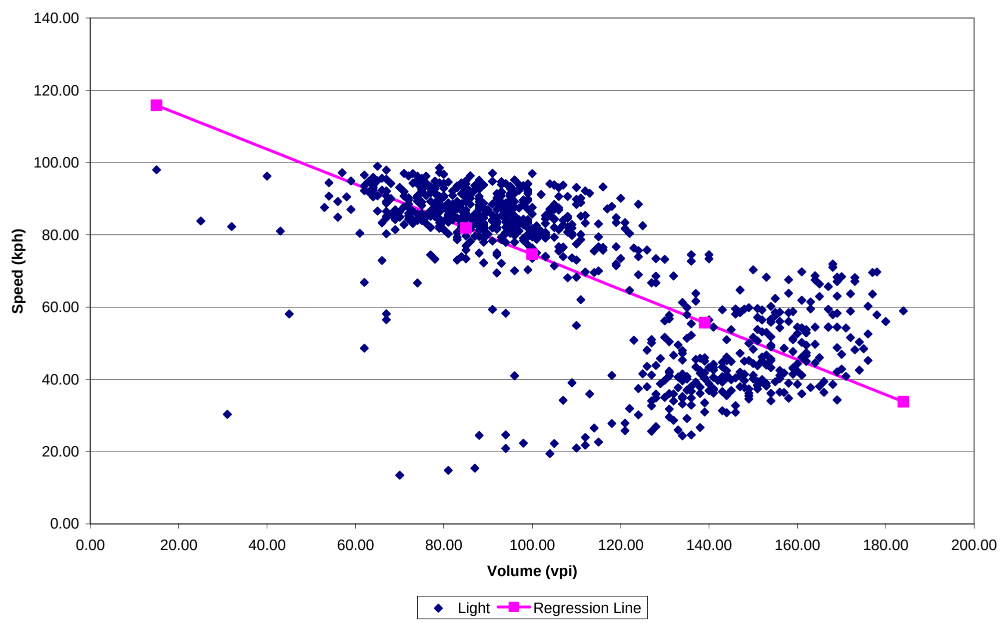

Speed vs Volume - Eastbound Congested
Speed (kph)
Volume (vpi)
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
Control
Regression Line


Speed vs Volume - Eastbound Congested
Speed (kph)
Volume (vpi)
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
Light
Regression Line

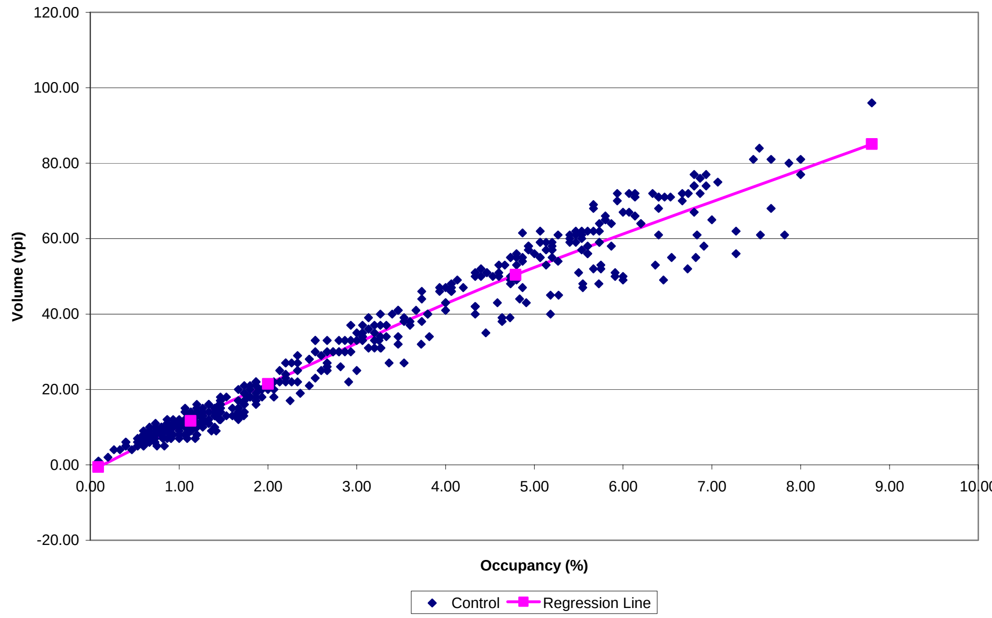
Speed vs Volume - Westbound Congested



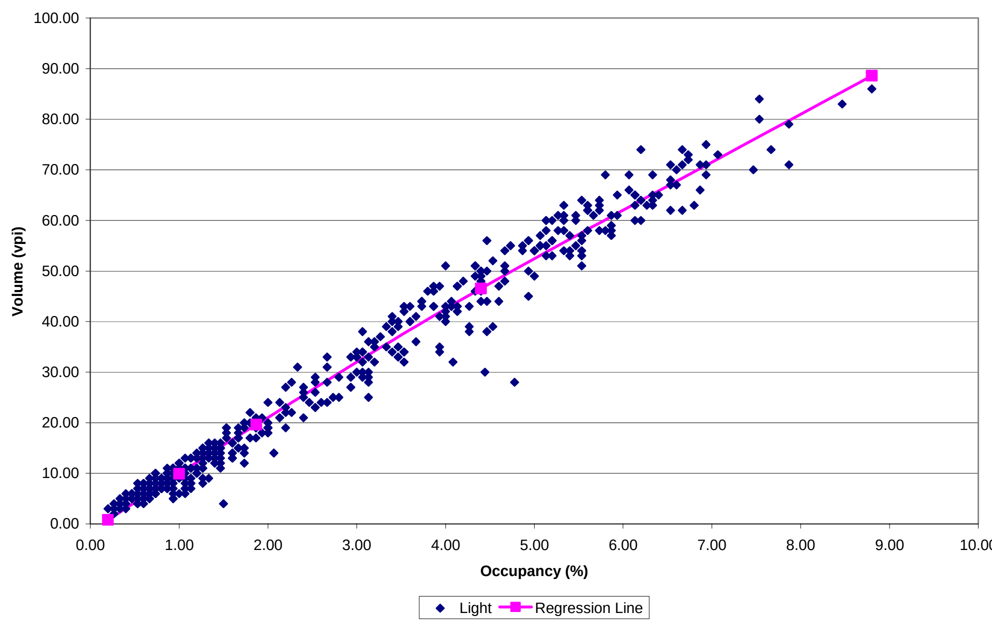
Speed vs Volume - Westbound Congested

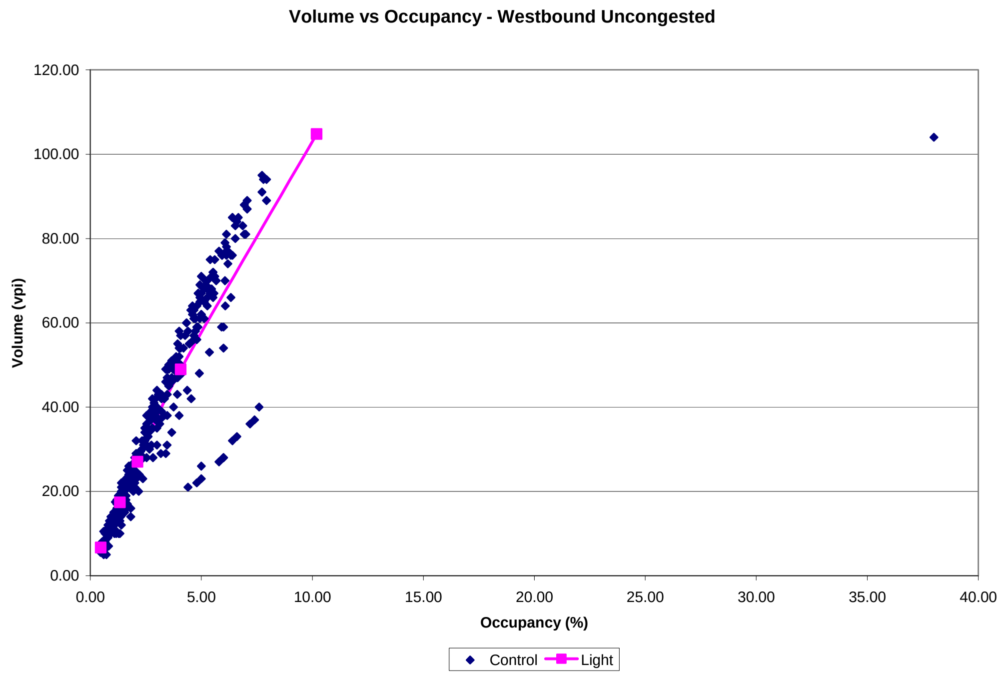


Volume vs Occupancy - Eastbound Uncongested

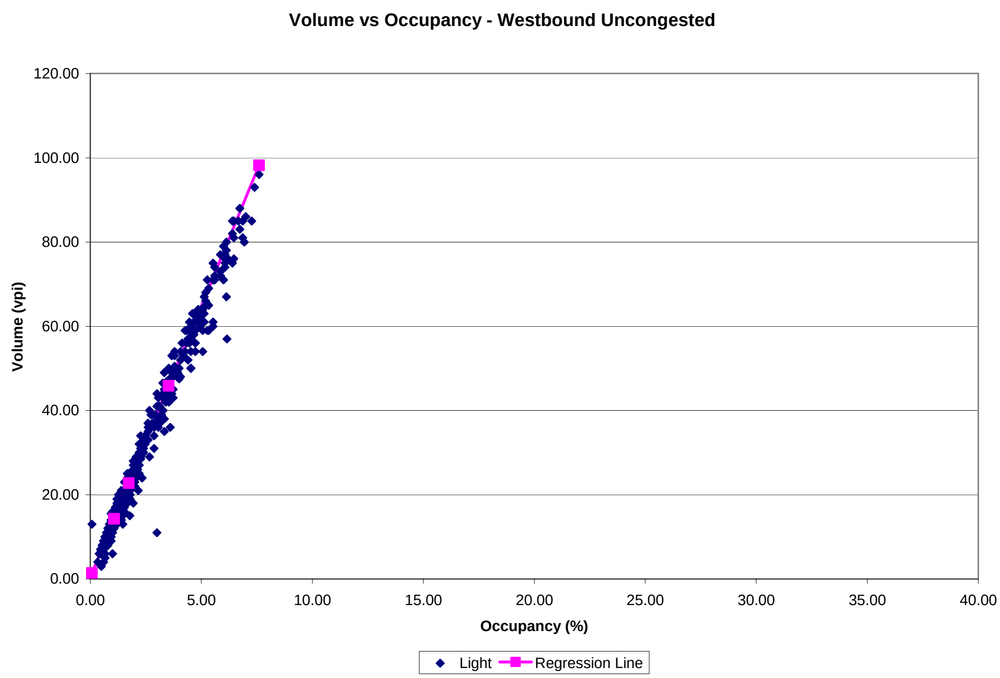


Volume vs Occupancy - Eastbound Uncongested



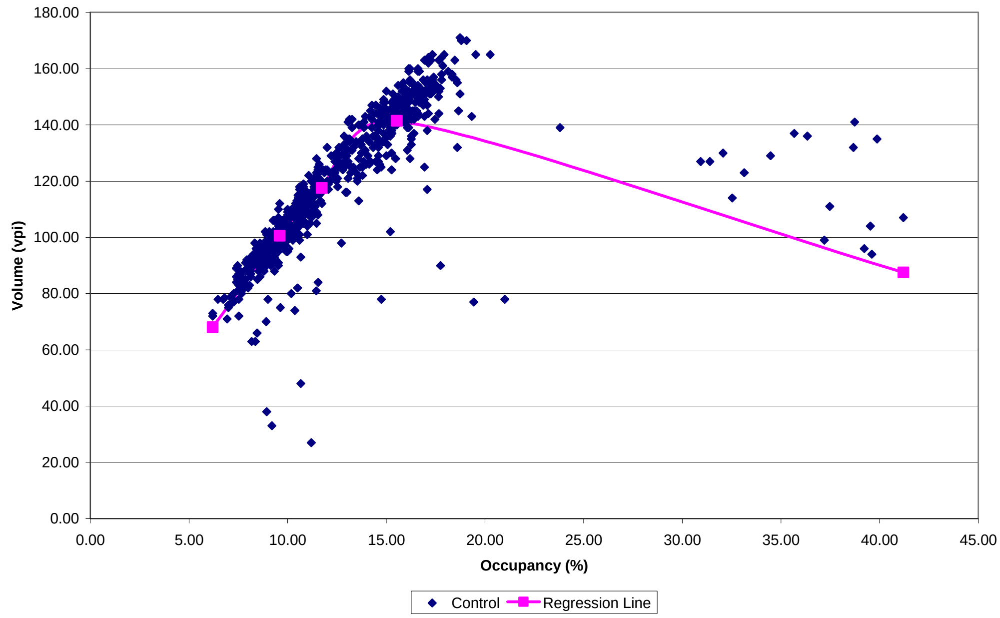


Volume vs Occupancy - Westbound Uncongested
Volume (vpi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Occupancy (%)
Control
Light

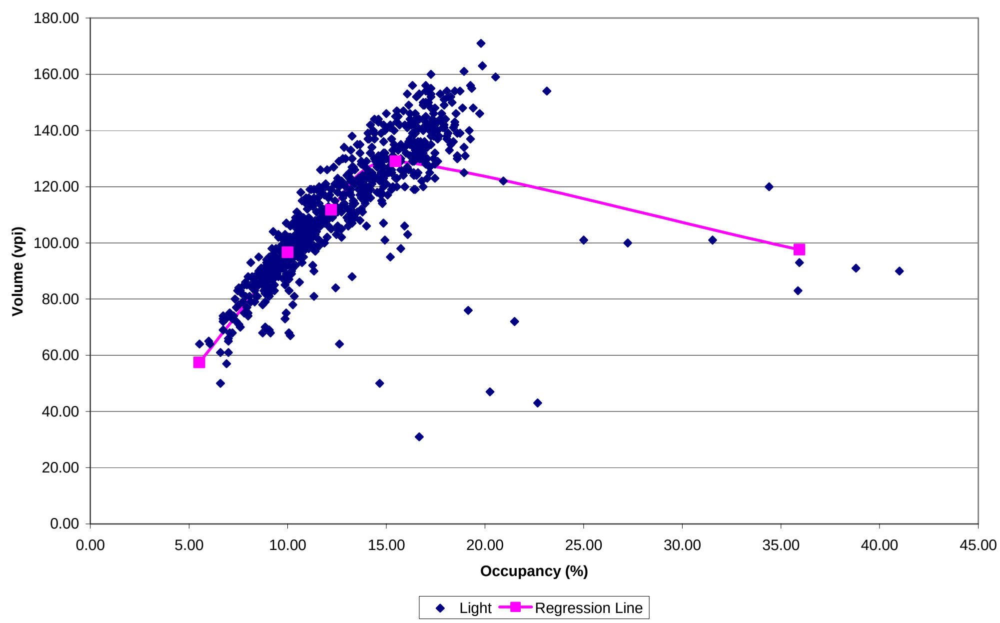


Volume vs Occupancy - Westbound Uncongested
Volume (vpi)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Occupancy (%)
Light
Regression Line

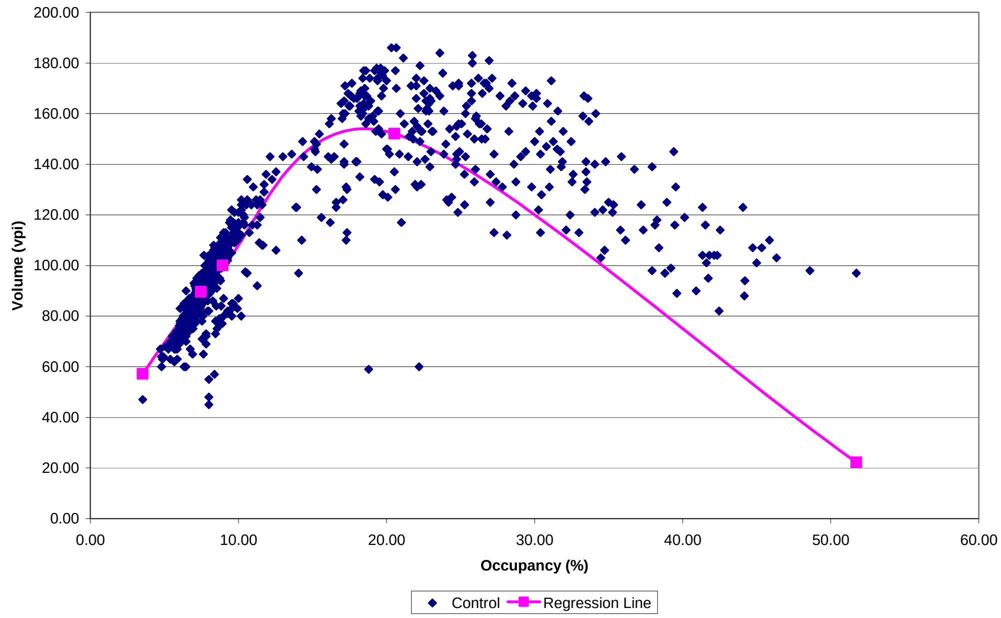
Volume vs Occupancy - Eastbound Congested



Volume vs Occupancy - Eastbound Congested



Volume vs Occupancy - Westbound Congested



Volume vs Occupancy - Westbound Congested