INVESTIGATING SPEED-ACCIDENT RELATIONSHIP AT URBAN SIGNALIZED INTERSECTIONS USING ACCIDENT PREDICTION MODELS

by

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ABSTRACT

Motor vehicle speed is a key risk factor contributing to many road accidents. Historical data shows that speed-related accidents account for a significant proportion of all the fatal and serious injury accidents and result in considerable social and economic costs. The objective of this thesis is to understand and quantify the relationship between traffic speed and accident frequency at urban signalized intersections in the city of Edmonton and Vancouver, Canada. This objective is achieved by developing accident prediction models which relate accident frequency to speed variables and other intersection characteristics. Road accident, traffic speed, traffic flow and road geometric data were obtained from the two cities for the purpose of the models development. The generalized linear modelling techniques are used to develop the accident prediction models assuming negative binomial error structure. A total of 15 models are developed relating accident frequency with five speed variables: average speed, mode speed, 85th percentile speed, speed standard deviation and percent of vehicles speeding. The results show that all five speed variables are positively correlated with accident frequency. A quantitative relationship between the change in the value of speed variables and the change in accident frequency is derived from the developed models.

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1 INTRODUCTION

1.1 THE ROAD SAFETY PROBLEM

Since the start of the automobile age, road transportation has brought considerable benefits to society by facilitating the movement of people and goods. However, the increase in road transportation has resulted in a severe traffic safety problem in terms of increased road accidents which place a significant burden on public health and have adverse impacts on economic and social development of a nation. Worldwide, approximately 1.3 million people are killed in road accidents annually — representing over 3,000 deaths every day (WHO, 2008a). Vulnerable road users such as pedestrians, cyclists and motorcyclists account for almost half of road traffic deaths (Penden et al., 2004). Moreover, the impacts of road traffic injuries are more noticeable on young people aged between 5 to 44 years than on other age groups. Statistics show that road accidents are the second leading cause of death for people in 5-29 age group and the third leading cause of death for 30-44 age group (WHO, 2009). In addition to the huge number of people killed in road accidents, it is estimated that accidents cause are between 20 to 50 million non-fatal injuries every year (WHO, 2008b). As well, it has been forecasted that, unless increased prevention efforts are taken, the number of road accident fatalities and injuries will increase by about 65% by 2020 (Murray and Lopez, 1996; Kopits and Cropper, 2003). Moreover, it is expected that road accidents will rise from the ninth to the fifth leading cause of death by 2030 (Penden et al., 2004).

Road accidents not only impact people's health in terms of consequence such as deaths or injuries, but also have significant impact on the economy. The main cost of road accidents consists of the loss of current resources such as property damage, medical care and administrative costs, and it also includes the loss of future resources caused by the loss of accident victim's potential production capacity or output. It is estimated that the losses due to road accidents account for 1% to3% of a country's gross national product and the total annual costs of road accidents worldwide are over US$ 500 billion (Jacobs, Aeron-Thomas, & Astrop, 2000).

In Canada, significant efforts have been made to improve road safety leading to a drop in road accidents and casualties that began in the 1970s and has started to level off in recent years (WHO, 2009). In 2001, Transport Canada reported the trends in road accident statistics for the period between 1988 and 1997. According to that report, the number of accidents resulting in a fatality dropped from 3,160 to 2,647 during the 10-year period, with fatalities decreasing from 4,154 to 3,064 in the same time period. The percent reduction in the number of fatal accidents and deaths during these 10 years was 26.2% and 26.7% respectively (Transport Canada, 2001). The latest Canadian motor vehicle traffic accident statistics show that there were 2,767 people killed in 2,469 fatal accidents in 2007 (Transport Canada, 2010). This indicates that in the 11-year time period (from 1997 to 2007) the number of deaths and fatal accidents were reduced by only 9.6% and 6.7%, which are much less than the percent reduction in fatalities and fatal accident during the previous time period from 1988 to 1997. These figures demonstrate that extra efforts should be taken by Canadian Authorities to further reduce road traffic accidents.

In addition to the social costs of road accidents, the economic impacts are also significant and very costly. In Canada, it has been estimated that the annual losses due to road accidents were CDN$ 63 billion (Vodden, Smith, Eaton, & Mayhew, 2007). The average cost for each fatality collision was estimated at CDN$ 13.6 million. The average costs for each major and minor injured person were CDN$ 280 thousand and CDN$ 48 thousand, respectively (Vodden et al., 2007).

Recognizing the growing public health problem and the considerable losses to society and economy caused by road accidents, many road authorities have established road safety improvement programs (RSIPs) which aim at minimizing the suffering and losses due to road accidents. The main objectives of these RSIPs are: 1) identifying areas that may have safety problems; 2) understanding the situation or identifying the factors contributing to the safety issues; and 3) developing countermeasures for mitigating the safety problems and evaluating the effectiveness of these remedial measures. A large and growing body of scientific research on road safety play an important role in achieving these objectives.

Identifying contributing factors for road traffic accidents is an essential step in improving road safety by providing evidence or clues to effective and efficient countermeasures to reduce the number of road accidents and consequent casualties. Among a range of contributory factors in road accidents, the speed of motor vehicle is a well-documented risk factor which contributes to as much as one-third of fatal accidents (Fildes and Lee, 1993; Bowie and Walz, 1994; Frith, Strachan, & Patterson, 2006). A brief introduction on how speed affects road safety will be given in the next section.

1.2 SPEED AND ROAD SAFETY

The increased accident risk from motor vehicle speed generally refers to "excessive speed" and "inappropriate speed". Excessive speed means that a vehicle is travelling above the posted speed limit, while inappropriate speed refers to driving too fast or unsuitable for the prevailing conditions (Penden et al., 2004). In general, when vehicles are travelling at higher speeds, the probability or risk of being involved in a road accident will be greater for the following reasons:

- A higher speed increases the likelihood of losing control of the vehicle and running off the road especially when the driver negotiates horizontal curves;
- A higher speed leads to a longer distance to be travelled during the time period when the driver responds or reacts to a hazard;
- A higher speed significantly increases the braking distance.

The choice of driving speed does not only affect the risk of a road accident, but also the likelihood of being seriously injured which increases with higher speeds. The amount of energy released in an accident is directly correlated with the square of the pre-accident speed. The higher the speed, the more energy is released and mainly absorbed by the vehicle occupants or other road users involved in the accident and thus may result in a more severe injury.

Apart from the aforementioned reasons explaining why speed is related to the risk and severity of road accidents, historical accident data also show that speed is a contributing factor to accident occurrence and consequent injuries. According to a Transport Canada's report, which examined the data for speed-related accidents occurring from 2002 to 2004, there are on average over 700 deaths and over 3,500 serious injuries caused by speed-related accident annually in Canada — representing approximately 25% of people killed and 20% of people seriously injured in all the vehicle accidents (Transport Canada, 2008). In the province of British Columbia, there were over 10,000 speed related traffic accidents occurred in 1995 (accounted for 37% of all fatal accidents and 15% of all injury accidents in British Columbia) which resulted in 184 fatalities and more than 8,000 injuries in that year (Chen, Meckle, & Wilson, 2000). In 15 member states of the European Union, the annual loss caused by 1.24 million injury accidents occurred in 1995 was about €162 billion and a significant proportion of which caused by speed related accidents (Baruya, 1998).

The social and economic costs caused by speed related accidents have attracted the attention of many researchers and several empirical studies have been conducted to investigate the relationship between speed and accident occurrence. Generally speaking, these studies can be classified into three groups. The first group of studies examined the relationship between accident occurrence and individual vehicle speed or average speed of the traffic. Studies that focused on the individual vehicle speed attempted to quantitatively relate the speed of a vehicle to its accident involvement rate or the risk of accident involvement. Studies that examined the relationship between average traffic speed and accidents were intended to link the average speed of the traffic on a road section to the accident rate or accident frequency of that road.

The second group of studies focused on another important speed characteristic influencing accident occurrence, namely speed dispersion or speed variation in traffic flow. The reason for considering speed dispersion as a risk factor to road safety is that the higher speed dispersion the larger the speed differentials among vehicles in the traffic stream, which is likely to lead to more overtaking manoeuvres and thus may raise the level of accident risk. As well, higher rear-end accident potential can result from higher variability in vehicle speeds.

The third group of studies evaluated the effectiveness of speed management countermeasures in reducing speed and consequently road accidents. Speed and accident data are collected before and after the implementation of speed management measures. This group of studies is considered as an indirect approach to investigate the speed-accident relationship. A detailed review of all three groups of studies will be given in Chapter 2.

It should be noted that most of the previous studies on speed-accident relationship mainly focused on rural areas rather than urban areas. This is surprising given the fact that the majority of road accidents occur on urban roads. Therefore, there is a recognized need to understand and quantify the relationship between speed and accident occurrence in urban areas.

1.3 OBJECTIVE OF THE THESIS

The main objective of the present thesis is to investigate the relationship between traffic speed and accident frequency at urban signalized intersections in two cities in Canada:

Edmonton in the province of Alberta and Vancouver in the province of British Columbia. The study attempts to quantify the impact of two important speed characteristics on accident occurrence, namely the absolute speed (e.g., average traffic speed) and the speed dispersion. To achieve this study objective, a number of accident prediction models are developed which quantitatively relate the frequency of accidents to speed-related variables and other characteristics such as traffic flow and road geometry. The change in accident frequency associated with the change in speed is estimated based on the developed model by changing the values of speed-related variables while holding other independent variables in the model constant.

1.4 THESIS STRUCTURE

This thesis is made up of six chapters. Chapter 1 introduces the thesis and the objectives of the research. Chapter 2 reviews previous work related the speed-accident relationship. The theory, procedure and results of developing accident prediction models, as well as investigating the speed-accident relationship, are given in Chapter 3 for Edmonton models and Chapter 4 for Vancouver models respectively. Chapter 5 draws conclusions from this research and Chapter 6 provides recommendations for future research directions.

2 LITERATURE REVIEW

This chapter contains two sections. The first section provides a review of previous studies which investigated the effect of vehicle speed on road safety and reviews studies focusing on the effect of speed on the environment. In the second section, studies on the effectiveness of variety speed management countermeasures or treatments are reviewed. A total of six speed management measures are introduced and their effectiveness on managing vehicle speeds are discussed in the second section.

2.1 EFFECTS OF SPEED

Over the past several decades, significant improvements have been made to road systems. At the same time, more motorised vehicles were being manufactured which are able to travel at higher speeds. Having an efficient transportation system is an essential ingredient in the economic development of any country by providing greater mobility, allowing shorter journey times for goods and passengers movement, and generating travel time savings. However, higher speeds have some adverse impacts in terms of road accidents with severe consequences including deaths, injuries, and property damage. In addition, higher speeds also have an adverse effect on the environment. It contributes to the increase in fuel consumption, vehicle emissions and noise which can lead to environmental problems such as air pollution, noise pollution, and global climate change. The literature review in this section provides an overview of the adverse effect of speeding. The first subsection is the primary section which focuses on the effect of speed on road safety (road accidents). Effect of speed on the environment, including fuel consumption, emission and noise, is illustrated in the second subsection.

2.1.1 SPEED EFFECT ON ROAD SAFETY

2.1.1.1 Speed Effect on Accident Involvement and Accident Frequency

The earliest and best known study that attempted to examine the relationship between vehicle speed and the risk of accident involvement was conducted by Solomon in late 1950s in the United States and the results were published in 1964. In the study, Solomon analyzed accident records (between 1954 and 1958) of nearly 10,000 accident-involved drivers and compared them with the speed of 29,000 vehicles not involved in accidents. The study was conducted on 600 miles of main rural highways comprising 35 sections in 11 states. The 35 sections of rural highways were made up of 75% of two-lane highways and 25% of four-lane highways, which were representative of United States rural highways composition. The speeds of 29,000 vehicles not involved in accidents were measured during 1957 and 1958 at each of the sites. Vehicle speeds at data collection locations represented the average speed for the entire section (e.g., data collection sites were away from entrances or intersections). All of the 10,000 accidents reported in the study occurred on the 35 sections and their data were obtained from police accident reports. Unlike the speeds of 29,000 vehicles, the pre-accident speeds of these accident-involved vehicles could not be measured directly and therefore were estimated based on the police reports which recorded the pre-accident speed estimate by police officers, drivers or witness.

Solomon (1964) produced a figure to illustrate the relationship between vehicle speed and accident involvement for daytime and night-time accidents. In the figure, the daytime and night-time accident-involvement rates took the same form of a U-shaped curve with speed values at approximately 60mph having the lowest involvement rate while higher rates associating with both slow and fast traveling speed. In other words, the probability of being in an accident decreased as speed increased up to around 60mph, and then increased at speeds higher than 60mph.

A few years after the Solomon's study, Cirillo (1968) examined the relationship between vehicle speed and accident involvement. In the study, Cirillo used a similar method to analyze the accident data of 2,000 accident-involved vehicles on rural and urban sections of interstate freeways. The accident data were limited to daytime same direction accident involving two or more vehicles such as rear-end accidents, angle accidents and sideswipe accidents. The results of Cirillo's study confirmed the findings of Solomon that the relationship between speed and the risk of accident involvement represented a U-shaped curve.

The two studies by Solomon and Cirillo have been extensively reviewed and critiqued by many researchers (Fildes and Lee, 1993; Kloeden, McLean, Moore, & Ponte, 1997; Stuster and Coffman, 1998; Shinar, 1998). Several shortcomings were identified. First, the pre-accident speeds of vehicles involved in accidents were estimated based on police reports, driver's reports or witness, which were probably inaccurate. Second, the fact that vehicles travelling at slow speed had high accident involvement rate were questioned by many researchers. It was argued that many of the accidents involving slow moving vehicles occurred at entrances or intersections of the highway where vehicles were forced to slow down to make a turn, enter or exit the highway rather than traveling at slow and free-flow speed. However, it is important to note that vehicle speeds data were collected at locations that represented the average speed for the entire section. In other words, accidents involving turning vehicles were included in the study but speed data of vehicles turning, entering, exiting the road were not included. The accident involvement rate of vehicles with slower traveling speed would be overestimated due to these problems. Third, Kloeden et al. (1997) cited a paper by the Insurance Institute for Highway Safety which stated that single vehicle accidents are likely to be related to high speed and these accidents represent more than 50% of fatal accidents on interstate highways. Whereas, in Cirillo's study accidents involving two or more vehicles were included, which may result in underestimation of accident involvement rate associated with high speed. Finally, it is criticized that these two studies were conducted in 1950s with very different road conditions, vehicle design and traffic control devices. It has been argued that the study results are probably not relevant to today's condition (Fildes and Lee, 1993).

A more recent study by Fildes et al. (1991) was conducted on both rural and urban highways in Australia. Two rural road sections and two urban road sections were selected as study sites and the vehicle speed data were collected unobtrusively on each site. Vehicles travelling at excessively fast and slow speeds (i.e., travelling at speeds below 15th percentile and above 85th percentile) were of particular interest and were stopped at the roadside in order to interview the drivers. More than 700 divers participated in the interview to answer questions about their accident history in the past 5 years. Contrary to the findings of early studies by Solomon and Cirillo, Fildes et al. failed to obtain a U-shaped curve relationship between accident involvement and vehicle speed. Rather, the results showed that for both rural and urban sections the relationship between accident involvement rate and vehicle speed was linear or slightly curvilinear: drivers travelling at excessive high speed were likely to have higher accident involvement rate than those travelling at mean speed, while drivers travelling slowly were likely to have lower accident involvement rate.

However, there were a number of shortcomings associated with Fildes et al.’s (1991) study. First, the accident data was collected from drivers’ self-reports which suffer from the potential of underestimation of accident involvement rate for high speed accidents. Drivers in high speed accidents are less likely to survive than drivers of low speed accidents and only drivers who survived the past accidents can be included in the study. The second shortcoming of this study is that the sample size is relatively small (e.g., Solomon’s study included 10,000 accident-involved drivers) and vehicles travelling at extreme speed were rarely observed, thus the relationship between accident involvement rate and very slow or very high driving speed cannot be derived from the limited data.

Kloeden et al. (1997) applied a different method than Fildes et al.’s study to examine the relationship between travelling speed and the risk of casualty accident involvement. The method is known as case-control method which compares the speeds of casualty accident involved vehicles (i.e., case vehicles) with the speeds of vehicles passing through the accident location and not involved in accidents (i.e., control vehicles). Kloeden et al.’s study was conducted on urban roads within 60km/h speed limit zones in the Adelaide metropolitan area, South Australia, and a total of 151 case vehicles and 604 control vehicles were involved. The pre-accident speeds of case vehicles were reconstructed by experts using computer-aided reconstruction techniques while the control vehicles' speeds were randomly measured using a laser speed meter. Control vehicles were selected based on the criteria that the vehicles were travelling at free flow speed in the same site, same direction, and same day of week and time of day as the case vehicles. Researchers finally obtained a positive relationship between travel speed and risk of involvement in a casualty accident: at speed higher than the speed limit of 60km/h, vehicle's risk of casualty accident involvement steadily increases – with each 5km/h increase in speed the risk doubles. However, at travelling speeds below 60km/h the risk of being involved in casualty accident was found to be very low.

The results by Kloeden et al. (1997) were based on data collected on urban roads. In order to extend the results to rural roads, Kloeden et al. (2001) conducted a similar case-control study to examine the relationship between travel speed and the risk of accident involvement on rural roads with speed limit of 80km/h or higher. Eighty-three case vehicles were compared with 830 control vehicles. It was concluded that the relationship between travel speed and the risk of accident involvement can be represented by an exponential function, i.e. the risk of accident involvement increases when the vehicle is travelling at increasing speed above the average speed and vice versa. As a follow up to this study, Kloeden et al. (2002) re-analyzed the data collected on urban roads in their earlier study (Kloeden et al., 1997) and developed an exponential function representing the relationship between travelling speed and risk of accident involvement.

Maycock et al. (1998) and Quimby et al. (1999) conducted studies in the U.K. using the self-report method (through questionnaires sent to drivers) and developed accident models reflecting the relationship between measured driving speed and driver's accident liability in the past 3 years. Both studies found that the relationship follows a power function i.e., increase in driving speed is associated with considerable growth in accident liability. However, the extent to which the increasing speed can change the accident liability is different between the two studies. With every 1% increase in the driving speed, Maycock et al. (1998) found that the increase in the accident liability is 13.1%, while Quimby et al. (1999) obtained a smaller figure of 7.8%.

Nilsson (2004) presented a 'Power Model' to represent the relationship between the number of injury accidents, number of fatal accidents and average traffic speed. The 'Power Model' was developed on the basis of before and after study to examine the effect of changed speed limits on road safety. It is illustrated by the model that the number of injury accidents, fatal & serious injury accidents, and fatal accidents is related to the second, third and fourth power of the average traffic speed. The equations for the 'Power Model' have three forms as follows:

For all injury accidents:

$$y_1 = \left(\frac{v_1}{v_0}\right)^2 y_0 \tag{2.1}$$

For fatal accidents and serious injury accidents:

$$y_1 = \left(\frac{v_1}{v_0}\right)^3 y_0 \tag{2.2}$$

For fatal accidents:

$$y_1 = \left(\frac{v_1}{v_0}\right)^4 y_0 \tag{2.3}$$

In the above equations, y_0 and y_1 denotes the number of accidents before and after the change of speed limit, while v_0 and v_1 is the average speed before and after the change, respectively. According to these models, Nilsson (2004) concluded that when the average speed increases by 5%, the number of all injury accidents will increase about 10% and the number of fatal accidents will rise by approximately 20%.

Finch et al. (1994) reviewed a wide range of before and after studies conducted in a number of countries. These studies mainly examined the change in road safety before and after a speed limit change. Researchers attempted to summarize the findings of all these studies and identify the general relationship between speed and accidents. Finally a conclusion was drawn by the authors. Generally speaking, every increase (reduction) of 1mph in the average traffic speed can result in 5% increase (reduction) in the number of accidents.

All the studies reviewed so far attempted to obtain a one-to-one relationship between accident occurrence and vehicle speed. These studies can be divided into two groups. The first group investigated the relationship between individual vehicle speed and accident involvement, such as the study by Solomon (1964), Cirillo (1968), Fildes et al. (1991), Kloeden et al. (1991, 2001, 2002), Maycock et al. (1998), and Quimby et al. (1999). The second group focused on the effect of average traffic speed on accident frequency, such as the study by Finch et al. (1994) and Nilsson (2004). It should be noted that the one-to-one relationship between the average traffic speed and accident frequency ignores the impacts of other factors influencing the speed-accident relationship, such as traffic volume and other road characteristics. These factors may mask the true relationship between traffic speed and accident. A study by Baruya (1998) attempted to include such factors in addition to speed and accident. A brief description of this study is given below.

Baruya (1998) investigated the speed-accident relationship on European roads based on the speed, accident, traffic flow and other road geometric data obtained from four European countries: Netherlands, Sweden, Portugal and UK. The Generalized Linear Modelling (GLM) was applied to develop an accident prediction model, called EURO model, to describe the speed-accident relationship which can be applied in the European Union. The form of the EURO model is as follows:

$$E(Y) = 5.663V^{0.748}L^{0.847}M^{-2.492}P^{0.114}\exp\left(0.038NI - 0.056W + 0.023S\right) \tag{2.4}$$

The symbols used in the model are: *E(Y)*, the predicted accident frequency; *V*, traffic flow; *L*, road section length; *M*, mean speed; *P*, proportion of speeders; *NI*, number of minor intersections; *W*, road width; *S*, posted speed limit. The model reveals that the proportion of vehicles travelling above the speed limit (P) and speed limit (S) have positive effect on accident occurrence. However, it can be seen from the model that the exponent of mean speed (*M*) is a negative value, indicating that higher mean speeds are associated with fewer accidents. Baruya (1998) explained that this negative relationship between mean speed and accidents is probably due to the effect of poor road design and geometry rather than the mean speed itself. Apart from the EURO model, Baruya (1998) also obtained a quantitative relationship between mean speed and accident frequency based on the relationship between the mean speed (*M*) and the proportion of speeders (*P*): reduction of 1km/h in the mean speed (*M*) impacted by the reduction in proportion of speeders (*P*) would let the accident frequency fall by (153.6/*M*) percent. For instance, if the mean speed is 60, 70 and 80km/h, the reductions of accident frequency will be 2.56%, 2.19% and 1.92% respectively.

In summary, this section reviewed several previous studies that examined the relationship between individual vehicle speed and road accidents. The approaches applied in these studies were mainly based on the self-report method and case-control method. As for the relationship between accident involvement rate and speed, earlier studies conducted in 1950s by Solomon (1964) and Cirillo (1968) found a U-shaped curve relationship, i.e. speed values at around mean traffic speed having the lowest involvement rate while quite high rates associating with the travel speed that is much slower or faster than the average speed. However, more recent studies by Fildes et al. (1991) and Kloeden et al. (1997, 2001, 2002) obtained different results. Fildes et al. found that the relationship between accident involvement rate and vehicle speed is linear or slightly curvilinear, i.e. drivers travelling at excessive high speed are likely to have higher accident involvement rate than those travelling at mean speed, while drivers travelling slowly are likely to have lower accident involvement rate. Studies by Kloeden et al. (1997, 2001, 2002) showed that the relationship between travelling speed and the risk of accident involvement is exponential, i.e. the risk of accident involvement increases when the vehicle is travelling at increasing speed above the average speed while at speed below the average speed, the decreasing speed is associated with lower risk. A power function was proposed by Maycock et al. (1998) and Quimby et al. (1999) to capture the relationship between vehicle speed and accident liability.

Other studies reviewed in this section investigated the relationship between traffic speed and the accident frequency. Although different functions were established to represent the relationship between accident frequency and speed, it was generally found that the increase (or reduction) in traffic speed is associated with the increase (or reduction) in accident frequency. Nilsson (2004) showed that the relationship follows a power function while Finch et al. (1994) obtained a linear function. Unlike the study by Finch et al. and Nilsson which showed the one-to-one relationship between traffic speed and accident frequency, the study by Baruya (1998) obtained a multiple regression model relating accident frequency with traffic speed and other road and traffic characteristics.

2.1.1.2 Effect of Speed Dispersion on Accidents

The studies reviewed in the previous section examined the effect of speed on accidents. This section summarizes the results of studies that show that accidents can be related not only to individual vehicle speed and average speed of traffic, but also to speed dispersion or speed variation in traffic flow.

As stated previously, Solomon (1964) conducted a study on rural highways to investigate the relationship between vehicle speed and the risk of accident involvement and concluded that the relationship followed a U-shaped curve. Solomon also found that the relationship between accident involvement and the variation from average speed again followed a U-shaped curve. Involvement rate was highest when vehicles travelling at 35mph below the average speed or slower, lowest when vehicle speeds at approximately 5mph above the average and then increased as the variations above the average speed increased.

A study similar to Solomon's was conducted by Cirillo (1968) on interstate freeways and the results confirmed Solomon's findings. As for the relationship between speed dispersion and accident involvement, Cirillo established a similar U-shaped curve. However, unlike the study by Solomon, Cirillo found that the accident involvement rate was lowest for vehicles travelling at around 12 mph (rather than 5 mph found by Solomon) above the average speed.

Lave (1985) measured the effect of average speed and speed variance on the fatality rate based on regression analyses of data from 48 states in United States. Data were obtained from the U.S. Department of Highways and consisted of fatality rate (fatalities per 100 million vehicle miles traveled), average speed and 85th percentile speed on each of the six types of highways (i.e., rural and urban Interstates and arterials, urban freeways and rural collectors) in the years 1981 and 1982. Speed variance was roughly measured by the difference between the 85th percentile speed and the average speed. Finally, 12 regression equations were developed, each for six types of highways for two separate years. The results showed that most regression coefficients of average speed are negative while the regression coefficients of speed variance are mainly positive. Furthermore, when speed variance is held constant, no significant relationship is found between fatality rate and average speed or between fatality rate and three other speed measures (percentage of vehicles exceeding 55mph and 65mph, and 85th percentile speed) for any type of highway. Based on the above evidence, Lave concluded that reducing the speed variance, not the speed, plays the most important role in reducing fatalities. “Variation kills, not speed.” (Lave 1985, p 1159)

A US study that examined the relationship between speed variance and accident rates was conducted by Garber and Gadirau (1988). A total of 36 study sections were selected from six types of highway in Virginia including urban and rural Interstates, freeways, urban and rural arterials, and rural major collectors. Traffic data recorder was used to collect hourly volumes and individual vehicle speeds at each section, while the design speed and accident data were obtained from available database. Several regression models were then developed to quantify the relationships between accident rate and different variables including average speed, speed variance, design and posted speed. In addition, the relationship between different speed variables was also investigated through the models. It was suggested from the regression models that the relationship between speed variance and the difference between design and posted speeds can be represented by U-shaped function with the lowest speed variance occurring when the posted speed is 5-10mph lower than design speed. In addition, the correlation between average speed and accident rate was found to be non-significant based on the data and thus the authors concluded that higher average speed is not necessarily correlated with higher accident rate. Another important result of the study was that the accident rate is positively related to speed variance for all types of roads. Therefore, when the difference between design speed and the posted speed is 5-10mph, it can be concluded that the speed variance is minimum and thus the accident rate is lowest. As a result, the researchers recommended that the posted speed limit should be set 5 or 10mph lower than the design speed in order to reduce speed related accidents.

More recently, a cross-sectional study conducted in UK by Taylor et al. (2000) confirmed the findings from Garber and Gadirau (1988) that the speed variance is an important factor influencing accident occurrence. In addition, they concluded that both the average traffic speed and speed variance can impact accidents and that they cannot be substituted for each other. In their study, traffic flow, road geometry and vehicle speeds data were collected, while the accident statistics were obtained from official database. Based on the data collected, a statistical model was developed to investigate the relationship between speed and accident frequency. Based on the results of the urban accident model, the researchers indicated that the relationship between average speed and accident frequency is positive and the accident frequency rise approximately with the second power of average traffic speed. Furthermore, the analysis revealed that the measure of speed dispersion is positively related to the accident frequency and the relationship can be represented by exponential function. An urban model was established to demonstrate the impact of both average speed and speed dispersion on accident frequency, the model is given by the following equation:

$$\mathrm{AF} = 0.000435\,\mathrm{V}^{2.25}\mathrm{e}^{5.893\mathrm{C_v}} \tag{2.5}$$

where:

AF – accident frequency per year;

V – average traffic speed, miles per hour;

Cv – coefficient of variation of speed, i.e., the ratio of speed standard deviation to the average traffic speed (V).

In summary, the studies that were reviewed in this section examined the relationship between speed dispersion and accident rate. The results indicate that larger speed dispersion is associated with higher accident rate. Although earlier studies found that the correlation between average speed and accident rate is not strong when compared to the relationship between speed dispersion and accident rate (Lave, 1985; Garber and Gadirau, 1988), a more recent study indicated that both the average speed and speed variance can influence accident occurrence and that they cannot be substituted for each other (Taylor et al., 2000).

2.1.1.3 Effect of Speed on Accident Severity

The effect of speed on accident severity is more straightforward than on accident involvement. Once an accident has occurred, the level of severity is highly related to the pre-accident speed. The amount of energy released in an accident depends on the mass of accident-involved vehicles and the impact speed (i.e., speed change from pre-accident travelling speed to zero) in the accident. The energy can be given by the following equation:

$$\mathrm{E} = \frac{1}{2}\mathrm{mv}^2 \tag{2.6}$$

where:

E – kinetic energy;

m – mass of vehicle;

v – impact speed.

It can be stated that the higher speed at which the accident-involved vehicles are travelling, the more kinetic energy will be released in the accident. The released kinetic energy is mainly absorbed by the occupants in the vehicle or other road users involved in the accident and thus can result in injuries. Therefore, the likelihood and severity of injury is correlated with the kinetic energy released and absorbed in the accident and thus with the impact speed. For example, if the impact speed in an accident increases from 50 to 60 mph, which is a 20% increase in impact speed, the released kinetic energy will increase by 44%. Studies that investigated the effect of speed on accident severity are reviewed below.

The study by Solomon in 1964 examined the relationship between speed and accident severity by showing the fatality and injury rates at different levels of speed. The data used in the study showed that the relationship between speed and fatality and injury rates follows U-shaped curve with the high rates associated with both relative low and high speed. However, Kloeden et al. (1997) argued that the high rates at low speed were subject to error because of the inaccuracy in pre-accident speed estimates. In addition, accidents at low speed were more likely to occur at intersections or entrances of highways where vehicles are forced to slow down. Therefore, the high involvement rates at low speed were probably overestimated. Apart from the U-shaped curve representing the relationship of speed to fatality and injury rates, Solomon also found that the fatality rate increases sharply at higher speed. For example, it was shown that the fatality rate rises from 2 to 118 persons killed per 100 million vehicle miles when the speed increases slightly by approximately 7%. This indicates the strong correlation between higher level of severity and higher impact speed and Solomon has drawn a conclusion that the increase of injury severity was dramatically rapid at travel speeds exceeding 60mph (Shinar, 1998; Stuster and Coffman, 1998).

Bowie and Walz (1994) examined the relationship between impact speed and the risk of being injured by analysing the accident data from the National Accident Sampling System in seven-year period of time from 1982 to 1989. The level of injury severity was described by Abbreviated Injury Scale (AIS). Both the risk of injury for AIS2 and AIS3 injuries were included in the analysis. There are six scales of AIS ranging from 1 (minor injury) to 6 (un-survivable injury), and AIS2 and AIS3 injury indicates moderate and serious injuries, respectively. The risk of injury is expressed as the percentage of injured (for AIS2 or AIS3 injury) among the total number of occupants. Bowie and Walz (1994) concluded that the risk of AIS2 and AIS3 injury increases substantially as the impact speed increases. For instance, when the impact speed ranges from 1 to 10 mph the risk of AIS2 injury is less than 5% while this figure rises dramatically to nearly 70% at impact speed higher than 50 mph.

The Power Model developed by Nilsson (2004) represents the relationship between the number of injury accidents, number of fatal accidents and speed. The model shows that when the average speed increases by 5%, the number of all injury accidents will increase by approximately 10% and the number of fatal accidents will increase by approximately 20%. In addition, Nilsson presented equations that illustrate the relationship between speed and the number of fatalities and injured persons per injury accident. To validate the Power Model, Elvik et al. (2004) conducted a meta-analysis for a total of 98 relevant studies that have shown the effect of speed change on road safety (expressed either by the number of accidents or injured persons). As a result, Elvik et al. (2004) presented a modified version of the Power Model with the value of the speed exponents as follows:

- Fatalities: 4.5
- Serious injuries: 3.0
- Slight injuries: 1.5
- All injuries: 2.7
- Fatal accidents: 3.6
- Serious injury accidents: 2.4
- Slight injury accidents: 1.2
- All injury accidents: 2.0
- Property damage only accidents: 1.0

Compared to the occupants of accident involved vehicles, it is clear that pedestrians or cyclists are more likely to be severely injured when they collide with motorised vehicles since they are the most vulnerable group of road users. Furthermore, the fatality risk of a pedestrian in a car accident is correlated with the impact speed. Rosén and Sander (2009) conducted a study to examine the relationship between the probability of pedestrian fatality in a car accident and the impact speed based on pedestrian accidents data in Germany in the time period from 1999 to 2007. The study analysed 490 pedestrians that were struck by the front of a passenger car and developed a model to quantify the effect of impact speed on the probability of pedestrian fatality. The study concluded that the probability of pedestrian fatality is much less than what was previously found by other studies but is strongly correlated with the impact speed. At an impact speed of 50km/h, the probability of fatality is more than five times larger than the probability at 30km/h.

In conclusion, all the studies reviewed in this section confirm the finding that the accident severity is positively related to the impact speed. The increase in the impact speed was found to lead to an increase in the level of accident severity. In addition, when vulnerable road users such as pedestrians are involved in motor vehicle accident, they are more likely to be severely injured than the vehicle occupants and their level of injury severity is more strongly related to the impact speed.

2.1.2 SPEED EFFECT ON ENVIRONMENT

The previous section highlighted the adverse impacts of vehicle speed on road safety (i.e., accident involvement, frequency, and severity). This section discusses how vehicle speed influences the environment (i.e., the effect of speed on the level of emissions, fuel consumption, and noise).

Emissions from motor vehicles make up a major portion of air pollution in most metropolitan areas (Mayer, 1999). The major pollutants associated with vehicle emissions are: carbon monoxide (CO), hydrocarbons (HC) or voltaic organic compounds (VOC), and oxides of nitrogen (NO_x). The amounts of emissions for these pollutants are highly related to the vehicle speed. Generally speaking, high emission levels appear when vehicles are travelling at either very low or high speeds, while emissions are relatively lower at medium speeds. Specifically, carbon monoxide (CO) and hydrocarbons (HC) have the highest emission levels at very low speed and then increase again at high speed, while the emission of oxides of nitrogen (NO_x) rises gradually with increase in speed and being highest at steady high speed with engine operation in high temperatures (TRB, 1995).

Speed is also known to have an effect on the exterior noise emitted by vehicles. There are mainly two sources of exterior noise associated with vehicles travelling on the road: a) operation of engine; and b) frictional noise from the interaction between tires and pavement. The relationship between speed and the tyre to road noise follows the rule that the doubling of speed is associated with 12 dB of increase in the level of noise (Robertson, Ward, Marsden, Sandberg, & Hammarström, 1998). In addition, the tyre to road noise dominates at higher speeds (i.e., above 20~40km/h for new cars and 30~60km/h for new trucks) while the noise from the engine dominates only at low speed (Robertson et al., 1998).

The influence of speed on fuel consumption is similar to that on the level of vehicle emissions. The fuel consumption increases when the vehicle speed is either very low or high and declines at medium speed. A U.S. Department of Energy study depicts the relationship between fuel economy (miles per gallon) and driving speed through a figure.

According to that figure, the fuel economy is very low at driving speed of 5-10mph. When the driving speed increases, the fuel economy increases and peaks at speed of around 55mph, then it declines when vehicles travel at higher speed. Therefore, reducing the speed of vehicles travelling at excessive speed can have benefits to reduce its adverse effect on the environment.

2.2 SPEED MANAGEMENT

2.2.1 SPEED LIMIT

Setting an appropriate speed limit is an important part of any speed management system. As described in previous sections, speed has considerable impacts on accident involvement and severity. Setting appropriate speed limits takes these impacts into account in order to ensure road users' safety. In addition, when setting the speed limit it is important to consider the environment since speed influences the level of emissions and fuel consumption, and it also considers the quality of life of people who live along the roadway due to the effect of speed on the level of noise emitted by vehicles. As an essential component of any speed management system, the speed limit effectiveness on driving speed and road safety is of great interest to researchers and many studies have been conducted on this topic. This section begins with an introduction on setting appropriate speed limits and concludes by providing a review of studies evaluating the effectiveness of speed limit.

2.2.1.1 Setting Speed Limit

There are two kinds of speed limits that need to be distinguished from each other, namely; general speed limit and local speed limit (or speed limit in speed zones). The general speed limit is set within the legislative framework and is applied on a nation-wide or state-wide basis. On the other hand, the local speed limit in a speed zone is usually set by local road authorities and applied to a section of a road. Typically, setting general speed limit takes into consideration certain aspects such as: to appropriately reflect the safety and mobility requirements on a particular category of highway (e.g., motorway/freeway, urban arterial road, rural road, etc.). Therefore, adopting a general speed limit is not recommended for all roads or all road sections and thus setting local speed limit is sometimes necessary. Local speed limit is often determined by local road authorities based on an engineering study that takes into account the local roadway environment, specific traffic, and/or weather conditions.

During the process of establishing general speed limits, different considerations are given for different road categories based on the road function and design characteristics. Generally, travel efficiency or mobility is considered more important when establishing speed limits for main roads (i.e., motorways and rural main roads) than for other road categories. Moreover, local roads or residential roads are expected to have lower speed limits since more consideration is given for the safety of vulnerable road users.

Draskóczy and Mocsári (1997) conducted a survey to collect information regarding the general speed limits on four categories of roads (i.e., motorways, motor roads, rural rods and built-up areas) from all European countries. Motorways, which are the highest-standards road category, are generally the safest roads and the speed limits are generally set between 110 to 130km/h in most countries. As another road category, motor roads lie between two categories of roads (i.e., rural roads and motorways) with limited access to motor vehicles that are only able to exceed certain driving speed. General speed limits on motor roads are often set between the speed limits on rural roads and motorways: mainly between 90 and 110km/h. The rural roads are generally less safe than motor roads and motorways due to their restrictive roadway geometry such as sharp curves, hills, and narrow lanes. Therefore, lower speed limits are expected on this category of roads in order to offset such poor or dangerous roadway conditions. According to the survey, speed limits on rural roads usually vary from 80 to 100km/h with 80 km/h being a common value in most of European countries. Road conditions in built-up areas (or urban areas) are very complex. The risk of a vehicle being involved in an accident is high due to high traffic density, number of intersections, and roadside development and activities. In addition, there is a wide range of road users on urban roads including motorised vehicles and other vulnerable users such as bicyclists and pedestrians. Therefore, safety instead of travel efficiency should be given priority when determining speed limits in built-up areas and lower speed limits are appropriate in order to provide safety for all road users. General speed limits in built-up areas are more homogenous than on other categories of road in European countries – nearly all the countries apply 50km/h speed limit.

In addition to road categories, vehicle types are also taken into account when determining general speed limits. A mix of different categories of vehicles with different operating characteristics impacts on road safety. Heavy trucks that have lower performance characteristics than passenger cars such as longer stopping distances and more limited mobility may increase the probability of accidents. As well, the heavy weight of trucks may increase the severity of accidents. Consequently, lower speed limits may be established for trucks due to their different performance characteristics than passenger cars. The survey conducted by Draskóczy and Mocsári (1997) revealed that in most European countries, lower speed limits are set for heavy and light trucks as well as buses: 10~30km/h lower than the limit for passenger cars on rural roads and motor roads while 30~50km/h lower on motorways.

As indicated earlier, there is a need to determine the local speed limit when the general speed limit is inappropriate for a specific length of road or inconsistent with the local environment. Two approaches are usually used to establish local speed limits. One approach is to set the speed limit first at the 85th percentile speed and then make modifications to this value on the basis of other factors including accident history, roadside conditions, and roadway geometry (Fitzpatrick et al., 1997). Earlier studies by Solomon (1964) and Cirillo (1968) that examined the relationship between speed and road safety are considered as support for setting speed limit at the 85th percentile speed. Both studies showed that the accident probability was lowest when vehicles were travelling near 85th percentile speed. However, this rule was found to be only applicable to certain classes of roads such as freeways and major arterial highways. Therefore, the 85th percentile speed may not be an appropriate speed limit for all classes of roads particularly on urban roads or residential streets.

The second approach to set a local speed limit is to use speed limit setting models based on some computer procedure (e.g. the LIMITS programme). The LIMITS program is a computer-based programme that takes into account several factors to establish speed limits. Several countries have developed speed limit setting models such as: QLIMITS, NLIMITS and VLIMITS in Australia; USLIMITS in United States; and NZLIMITS in New Zealand. Factors that are usually considered during the process of speed limit setting include: a) road environment (e.g., road function); b) roadway factors (e.g., number of lanes); c) road user activity (pedestrian, bicyclists, etc.); d) accident history. Information regarding these factors is entered into the model and the output is a recommended speed limit value. Models based on the LIMITS programme are particularly useful on roads where the speed limit set at the 85th percentile speed is inappropriate.

2.2.1.2 Effectiveness of Speed Limit

When speed limits have been set or changed, their effectiveness of managing speed is usually of interest to researchers and is examined by investigating the change in actual speed, speed distribution and road safety before and after the change in speed limits. This section provides reviews of studies which examined the effectiveness of speed limits change in the United States and other countries worldwide.

In1974, the year following the oil crisis in 1973, the U.S. Congress established 55mph National Maximum Speed Limit (NMSL) on all U.S. highways in order to conserve fuel consumption. In 1987, states were allowed to raise the NMSL on rural freeways to 65mph from 55mph and a total of 40 states raised speed limits accordingly between 1987 and

1988. Several studies were conducted to investigate the effect of increased speed limits on road safety in one single state or for the whole nation. Table 2.1 summarizes these studies by outlining their major findings. Most of the studies found an increase in the fatalities or fatal accidents after the implementation of 65mph speed limit, with the amount or percentage of increase varying among studies. The study by Ossiander and Cummings (2002) also found that the increased speed limit leads to increase in the average speed, 85th percentile speed, and speed dispersion on rural interstates.

Table 2.1: Summary of Studies on Effect of 65mph Speed Limit

Author(s)	**Location**	**Major Findings**
Baum et al., 1989	U.S.	In states that raised speed limit to 65mph: fatalities increased by 15% on rural interstates; In states that remained at 55mph speed limit: fatalities were 6% lower than expected on rural interstates.
Garber and Graham, 1989	40 U.S. states	The median effect of increased speed limit of 15% increase in fatalities on rural interstates and 5% increase in fatalities on rural non-interstates.
NHTSA, 1989	U.S.	In states that raised speed limit to 65mph: 19% increase in fatalities on rural interstates; In states that remained at 55mph speed limit: 7% increase in fatalities on rural interstates.

Author(s)	Location	Major Findings
McKnight and Klein, 1990	U.S.	In states that raised speed limit to 65mph: fatal accidents increased by 27% on rural interstates; In states that remained at 55mph speed limit: fatal accidents increased by 10% on rural interstates.
Lave and Elias, 1994	U.S.	In states that raised speed limit to 65mph: total state-wide fatality rates fell 3.4%~5.1%.
Wagenaar et al., 1990	Michigan State	On rural limited access highways where speed limit is raised to 65mph: 19.2% increase in fatalities, 39.8% increase in serious injuries and 25.4% increase in moderate injuries; On rural limited access highways with speed limit remained at 55mph: 38.4% increase in fatalities.
Pant et al., 1992	Ohio State	Fatal accident rates had not significantly changed on rural interstates posted at 65 or 55mph, nor on rural non-interstates posted at 55mph.
Rock, 1995	Illinois State	Fatalities, injuries and accidents significantly increased on both 65mph and 55mph rural highways.

Author(s)	**Location**	**Major Findings**
Ossiander and Cummings, 2002	Washington State	Fatal accident rate increased on rural freeways with rate ratio 2.1; total accident rate did not change substantially on rural freeways; 5.5mph and 6.6mph increase in average speed and 85th percentile speed, and the speed variance consistently increased on rural interstates.

Apart from the United States, studies that evaluated the effectiveness of speed limit were also conducted in many other countries worldwide. A number of studies are reviewed and their major findings are summarized in Table 2.2. Unlike the American studies that investigated the effect of a raised speed limit from 55 to 65mph, all the international studies listed in Table 2.2 evaluated the effect of lowered speed limit on residential streets (Engel and Thomsen, 1992; Vis, Dijkstra, & Slop, 1992), urban streets (Hollo 199, 2004; Hoareau, Newstead, & Cameron, 2006), and motorways (Johansson, 1996). The results from these studies generally indicated that the decrease in speed limits led to significant reduction in fatalities and injuries, accidents, as well as the traffic speeds. It can be concluded from these results that the lowered speed limits have positive effect on road safety, particularly in urban areas.

Table 2.2: Summary of Studies on Effect of Speed Limits

Author(s)	**Country**	**Description**	**Major Findings**
Engel and Thomsen, 1992	Denmark	Speed limits in residential streets were lowered to 30km/h or 15km/h; Evaluate the safety effect of lowered speed limit.	24% and 45% reduction in the number of accidents and casualties; 11km/h reduction in the mean speed.
Vis et al., 1992	Netherlands	Evaluate the safety effect of 30km/h zones in built-up areas.	20% reduction in 85th percentile speed; 25% reduction in injury accidents; 5% reduction in all accidents.
Johansson, 1996	Sweden	Examine the effect of lowered speed limit (from 110km/h to 90km/h) on the number of accidents on motorways and other major highways.	Statistically significant reduction in the number of minor injury and vehicle damage accidents; No significant reduction in the number of fatal and serious injury accidents.
Ragnøy, 2004	Norway	Examine the effect of the changes in speed limits (from 80 to 70km/h, and from 90 to 80km/h) on speed and accidents.	On roads that speed limits lowered from 80 to 70km/h: 2.1~4.1km/h of reduction in mean speed, and significant reduction in the number of accidents, fatalities and injuries; On roads that speed limits

Author(s)	Country	Description	Major Findings
			lowered from 90 to 80km/h: 1.6~2.8km/h of reduction in mean speed, no reduction in the number of accidents, fatalities and injuries.
Hollo, 1999; 2004, cited in OECD/ECMT , 2006	Hungary	Evaluate the safety effect of lowered speed limit (from 60 to 50km/h) in the built-up areas and the effect of raised speed limit by 10km/h outside the built-up areas.	Inside built-up areas: 18.2% reduction in fatalities; Outside built-up areas: considerable increase in fatalities.
Hoareau et al., 2006	Australia	Evaluate the impacts of 50km/h default urban speed limit on road safety.	12% reduction in all casualty accidents; 25%~40% reduction in fatal and serious injury accidents involving pedestrians; 2~3km/h of reduction in average and 85th percentile speed.

2.2.2 SPEED ENFORCEMENT

2.2.2.1 Introduction

Speed limits are established by taking into consideration several factors such as road safety, travel efficiency, and the environment in order to achieve appropriate vehicle speeds on the road. However, setting appropriate speed limits is insufficient to manage speeds since there will always be drivers who do not obey the speed limit and drive at a much faster speed. Excessive speed is a common feature throughout the world. The proportion of drivers above the speed limit varies among countries from 10% up to 80% (European Commission, 1998). Both motorways and urban streets are especially affected by speeding and urban streets should be given more concern because of the complex traffic conditions and the presence of vulnerable road users such as pedestrians and bicyclists (European Commission, 1998). Therefore, speed enforcement plays an important role in ensuring the compliance to the speed limits.

Speed enforcement is based on the principle of deterrence to make drivers try to comply with the speed limits in order to avoid the penalty. The effectiveness of speed enforcement is closely related to the subjective risk of apprehension perceived by drivers (OECD/ECMT, 2006). In other words, in order to achieve the desirable effectiveness of speed enforcement, it is important to make drivers believe that there is a significant probability of being penalized. There are some measures to increase this subjective risk including increase in the intensity of actual level of enforcement and, very importantly, publicity campaigns that ensure the enforcement activities to be well-publicised (OECD/ECMT, 2006).

There are mainly two methods of speed enforcement. The first method is known as conventional or manual speed enforcement which can be further divided into two forms:

stationary enforcement and mobile patrol enforcement. Stationary enforcement involves a stationary visible or invisible police car equipped with a speed measurement device such as speed radar and another apprehension unit downstream of the identified speeding car to stop the offenders and issue a fine. Mobile patrol enforcement is conducted in an unmarked police car moving around the enforcement area. The speed is detected by radar/laser and video camera installed in the patrol car. When speeding drivers are identified, they will be followed and stopped by the police car. There are some advantages of conventional speed enforcement. First, the speeders are immediately stopped by the police and the reasons for enforcing speed can be explained directly by the police officer. Second, the apprehension occurs alongside the road where it is clearly noticed by other drivers. This indirectly increases the probability of being caught subjectively perceived by other drivers (TRB, 1998). The main disadvantage of conventional speed enforcement is its labour-intensive nature, this situation is even worse for mobile patrol enforcement because of its smaller chance of identifying speeding behaviour than stationary enforcement (TRB, 1998).

The second method of speed enforcement is automated speed enforcement which is performed without police presence. The core equipment of automated speed enforcement is a speed camera which generally consists of a speed measuring device to detect speed offenders and a camera to record the information of speeders. The violation notification or speeding ticket is issued and sent by mail to the identified drivers. The automated speed enforcement can be conducted on specific road sections where speeding is a major road safety problem and where conventional speed enforcement cannot be conducted safely and effectively. Advantage of automated speed enforcement is that it can be operated without the presence of police which frees the rather limited traffic enforcement resources for other traffic enforcement activities (TRB, 1998).

A relatively new form of automated speed enforcement is average speed control which is also called section control or point-to-point control. Under this speed enforcement method, the average speed over a section of road is measured. Specifically, each vehicle is identified twice when travelling on the road section under section control: once at the start point and the other at the end point of the enforcement section. The time interval between these two points is recorded and the average vehicle speed on the section is calculated. The advantage of this new method of speed enforcement is its high probability of apprehension since every vehicle travelling on the enforcement section is identified with its speed being measured (OECD/ECMT, 2006).

2.2.2.2 Effectiveness of Speed Enforcement

The preceding section provides a brief introduction of speed enforcement methods that are commonly used in practice, namely, conventional or manual speed enforcement and automated speed enforcement. The introduction includes the process of conducting each speed enforcement method and discussion on the advantages and disadvantages of the different speed enforcement methods. However, as a speed management strategy, how these enforcement methods are effective in managing speed needs to be investigated. Studies that examined the effectiveness of these methods are reviewed in this section.

Studies that examined the effectiveness of conventional speed enforcement generally concluded that this enforcement method is effective in reducing vehicle speeds and accidents. An early study by Hauer et al. (1982) found that the average traffic speed is markedly reduced and is close to the posted speed limit at the enforcement sites. Holland and Conner (1996) conducted another study on urban roads in northern England to investigate the effect of intensive police intervention on the number of drivers exceeding the posted speed limits and the intension of drivers to exceed speed limits. The results showed that the intervention was effective in reducing the number of speeders and some groups of drivers (female under 25 and male over 25 who tended to break the limit by small amounts) showed a reduction in their intention to speeding. A recent study by Goldenbeld and Van Schagen (2005) in Netherlands evaluated the effect of targeted speed enforcement on speed and road accidents. Researchers found reductions in both the mean speed (reduced by 4km/h) and percentage of drivers exceeding the speed limits (reduced by 12%) on enforced roads. Moreover, researchers estimated that the speed enforcement project can lead to a 21% reduction in injury accidents and serious casualties.

A network-wide random enforcement, also known as Random Road Watch (RRW), can be considered as a specific type of conventional enforcement which is performed randomly anytime and anywhere in the entire road network. A Random Road Watch programme was undertaken in Queensland, Australia and its safety effect was evaluated by Newstead, Cameron, & Leggett (2001). It was estimated that fatal accidents decreased by 31% on roads covered by the RRW programme. In addition, 15% reduction in fatal accidents and 12% reduction in all injury accidents were estimated in the third year of the programme.

Many studies have evaluated the effectiveness of automated speed enforcement. Although most of the studies found positive effect on road safety, the actual effectiveness varied largely among individual studies since many factors can influence the study results, such as the intensity of enforcement, initial level of road safety and speeding, and type of road (Elvik and Vaa, 2004). A meta-analysis, reported by Elvik and Vaa (2004), was performed over 10 studies conducted during the period from 1984 to 1996 on effectiveness of fixed and mobile cameras. The results showed that automatic speed cameras can generally lead to 15%~20% of reduction in accidents, with 28% and 18% reduction on urban and rural roads respectively.

In the U.K., a national safety camera programme was introduced and the effectiveness was analyzed over 4-year period between 2000 and 2004 by Gains et al. (2005). It was concluded that the proportion of speeding vehicles decreased by 70% at fixed camera sites and 18% at mobile sites. The injury accidents dropped by 22% while fatalities and severe injuries reduced by 42% after the programme was introduced.

An automatic speed camera programme was introduced in France (OECD/ECMT, 2006). The safety effect was evaluated and found to be positive: 40% and 65% reduction in injury and fatal accidents at enforcement sites. On other French roads, a 5km/h reduction in average speed and 30% reduction in fatalities were observed, which can be attributed to the spillover effect of the programme.

Few studies have been conducted to evaluate the effect of average speed control because this enforcement method is relatively new and has not been widely applied yet. An average speed control system was implemented in a motorway tunnel in Austria and its effectiveness was observed in the first year of operation. It was estimated that the number of fatalities and serious injuries would drop by 48%, while the reduction in the number of injury accidents was estimated at 33% after two years of operation (Stefan, 2006).

2.2.3 EDUCATION AND INFORMATION CAMPAIGNS

Education and information campaigns in the media play an important role in speed management. They are usually launched with other speed management measures such as speed limits and speed enforcement aiming at garnering public support. This provides road authorities that are familiar with the implemented speed management measures an opportunity to explain the reasons for employing such measures. Another objective of information campaigns and education is to influence drivers' opinions and attitudes and thus change their unsafe behaviour.

The effect of education and information campaigns in reducing speed and accidents is not intensively evaluated because it is difficult to isolate the effect of information and education from combined measures in speed management programs. There are a number of studies, however, examined the effect of overall road safety campaigns consisting of education, information campaign, as well as enforcement and rewards. A meta-analysis over 35 studies on effectiveness of road safety media campaigns concluded that the number of accidents reduced by 8.5% on average during the campaign period and 14.8% after the campaign was completed (Delhomme et al., 1999). Another meta-analysis on 87 evaluated mass media road safety campaigns was conducted by Elliot (1993, cited in Delaney et al., 2004) who estimated that the average reduction in the outcome measure of effect was 7.5%. Although the safety effect estimated from the above two studies cannot be attributed to education and information alone but to all elements of campaigns, the positive effect of information and education cannot be neglected since they are crucial to obtaining public awareness and support for speed management programs and can enhance the positive safety effect of other speed management strategies (European Commission, 1998).

2.2.4 TRAFFIC CALMING

Traffic calming is an alternative approach for speed control which reduces vehicle speeds through the use of a wide range of physical measures. This approach is primarily applied in low-speed residential areas where the safety of pedestrians and other road users is a major concern. Traffic calming techniques generally fall into four categories: vertical deflections (e.g., speed humps, cushions, etc.), horizontal deflections (e.g., chicanes), road narrowing, and safety islands.

The effectiveness of traffic calming measures on speed and accident reduction has been evaluated in a large number of studies (Fildes and Lee, 1993; Zein et al., 1997; TRB, 1998). Harvey (1992) did a review of several traffic calming techniques and their effect on reducing vehicle speeds. It was found that vertical shifts in the carriageway such as road humps were most effective for reducing vehicle speeds among all the six traffic calming techniques examined in the study. Furthermore, as concluded by Harvey (1992), up to 40% of reduction in accident levels can be achieved through traffic calming.

Zein et al. (1997) evaluated the safety effect of traffic calming by reviewing 4 local traffic calming projects in the Greater Vancouver area, as well as a total of 85 traffic calming case studies from Europe, Australia, and North America. For the 4 local traffic calming projects, the study found that the accident frequency was reduced by 40% on average, with a range of 18% to 60% reduction. The reduction in accident frequency determined from 85 international case studies ranged from 8% to 100%. When the authors analyzed only 15 studies with more than 5 accidents/year of accident frequency before the operation of traffic calming, the range of reduction in accident frequency was 8% to 95%. Finally, Zein et al. (1997) aggregated all the 85 international case studies with the 4 road traffic calming projects in Greater Vancouver area and determined the effect of a variety of traffic calming measures on reducing accident frequency. The results showed that the reduction in accident frequency caused by traffic calming measures ranged from 30% to 83%.

2.2.5 SIGNS, SIGNALS AND ROAD MARKINGS

Variable message signs (VMSs) with variable speed limits are used to convey information to travellers about the real time hazardous road conditions such as traffic congestion, accidents, and adverse weather conditions. In addition to letting travellers know about the road conditions, variable speed limits could be changed accordingly in order to be consistent with both the roadway and overall road conditions. Rämä (2001) investigated the effect of variable message signs for slippery road conditions and weather-controlled sign system message signs on speed and driver behaviour. The results for variable message signs for slippery road conditions showed that the mean speed of free flow traffic has decreased by 1.2km/h on average with steady display sign and decreased by 2.1km/h on average with flashing sign. As for the weather-controlled sign system, it was found that changing the variable speed limit from 100km/h to 80km/h resulted in 3.4km/h of reduction in the mean speed in winter. In the summer season, changing the variable speed limit from 120km/h to 100km/h decreased mean speed on average by 5.1km/h.

Road markings are installed on the surface of roadways to guide the drivers by keeping them on the correct path or to provide regulatory warning information. Road markings that are commonly used as a speed management measure include transverse and chevron road markings since they create an illusion to the drivers that they are travelling faster. Voigt and Kuchangi (2007) reviewed several studies on the effectiveness of chevron road markings in Japan, U.K., and U.S. These studies generally reported a reduction in vehicle speeds and accidents, though the exact amount of reduction has varied among the studies. The Japanese study found that no accidents occurred during the period of six months after the implementation of chevron road markings, compared to 10 accidents recorded in the period of one year before the implementation. In the U.K., a 1995 study showed that the installation of chevron road markings resulted in 40% reduction in multi-vehicle accidents and 56% reduction in all types of accidents. Voigt and Kuchangi (2007) also reviewed three American studies on the effect of chevron markings on reducing vehicle speeds, and it was found that the percentage of reduction in mean speed varied from 11% to 23%. In addition to reviewing previous studies, Voigt and Kuchangi (2007) also investigated the effectiveness of converging chevron road markings on freeway-to-freeway ramps. The results showed that the markings were effective in reducing vehicle speeds whereas the reduction in average speeds varied among different classes of vehicle and curve locations. The maximum reduction of 4mph in average speed was found for heavy trucks travelling at upstream location of the curve.

Martons et al. (1997) reviewed several studies that evaluated the effect of road markings including transverse road markings on managing speed. It was concluded that transverse road markings are generally effective in reducing speed on roadway segments, especially on the approach to a dangerous site such as a sharp curve, a dangerous crossing, and a roundabout.

In addition to transverse and chevron road markings, there are other special road markings used to reduce traffic speed. Retting and Farmer (1998) conducted an experiment to evaluate the effectiveness of a road marking treatment installed before a sharp left curve on a suburban two-lane secondary road in North Virginia. The road marking consisted of the word “SLOW” and a left arrow mark. Results showed that there was a 6% overall decrease in traffic speed and significant reduction in the percentage of vehicles exceeding 40mph.

Retting et al. (2000) examined the effect of another special road marking treatment on reducing speeds. This road marking was deployed on freeway exit ramps in Virginia and New York. The road marking treatment narrowed the lane width of both the curve and tangent section by widening the gore area and moving the edge line gradually inward. The results indicated a general effectiveness of this road marking in reducing speeds of passenger cars and large trucks and a significant reduction in the percentage of vehicles exceeding posted off-ramp advisory speed limits.

In addition to signs and road markings, signals are another speed management measure particularly in urban areas. An example of reducing vehicle speeds through the use of traffic signals is “moderating” the green wave with shorter cycle time and green times (i.e., bandwidths) and lower coordination speed. The moderating green wave was introduced in French towns and its effectiveness was studied. It was found that the average speed decreased by approximately 10% to 20%, and the 85th percentile speed decreased by 15% to 25% (Chauvin 1999, cited in OECD/ECMT 2006).

2.2.6 OTHER TECHNOLOGIES OF SPEED MANAGEMENT

Application of advanced technologies in vehicles and road networks is considered as another approach in speed management systems. This section describes a number of these technologies and their impacts on speed control and road safety.

Speedometers were originally introduced to solve the problem that drivers are unable to accurately judge their travelling speed. Allowing for an instrument error between the speed indicated by speedometer and the actual speed (i.e., the actual speed is lower than speed shown on speedometer) can have positive impact on safety. There are mainly two types of speedometer: analogue and digital speedometer. The main advantage of digital speedometer is that drivers can read the speed faster and more accurately than analogue speedometer, while the merit of analogue speedometer is that it ideally shows the changing speeds with moving needle and makes it easier for drivers to maintain a set speed (OECD/ECMT, 2006). A relative new technology, heads-up display speedometer, has been applied in passenger vehicles. The heads-up speedometer displays speed information through the windshield and thus drivers do not need to periodically check the dashboard which is out of drivers' normal fields of view (TRB, 1998).

Vehicle control technologies provide another way of managing speed. Conventional Cruise Control (CCC) enables drivers to maintain the set speed by continuously adjusting the power unit accordingly to the road environment. Adaptive Cruise Control (ACC) system is a more advanced vehicle control technology than CCC system. It enables drivers to select a cruising speed while allowing the vehicle to follow a vehicle ahead within a safe following distance. This new function is achieved through the use of sensors to detect forward vehicles (TRB, 1998).

Chira-Chavala and Yoo (1994) evaluated the safety impact of Adaptive Cruise Control by analyzing the change in road accidents and traffic operation characteristics. Accident data analyses indicated that Adaptive Cruise Control potentially lead to a 7.5% reduction in traffic accidents. The study results showed that the speed variation could be reduced.

Intelligent Speed Adaptation (ISA), also known as Intelligent Speed Assistance, is included under the Intelligent Transportation System (ITS) programme. ISA refers to an advanced system that continuously detects vehicle speeds and posted speed limit and conveys the information to the driver. When the vehicle speeds exceed the speed limits, drivers will be warned, or an intervention system will automatically reduce the vehicle speeds. The ITA system can be divided into three different types based on how the system intervene the driving task (Carsten and Tate, 2005; OECD/ECMT, 2006):

- Advisory ISA: displays the speed limit and warns the driver when exceeding the speed limit;
- Voluntary ISA: displays the speed limit and allows the driver to activate the automatic vehicle control;
- Mandatory ISA: automatic vehicle control is activated all the time.

Another criterion for categorizing ISA systems is the type of speed limit being informed to drivers (Carsten and Tate, 2005; OECD/ECMT, 2006):

- Fixed: only posted speed limits are informed to drivers;
- Variable: both posted and variable speed limits are informed to drivers;
- Dynamic: posted speed limit, variable speed limits, and any speed limits implemented based on weather and traffic conditions are informed to drivers.

Carsten and Tate (2005) conducted simulation research in U.K. to evaluate the effect of different types of ISA on reducing fatal and injury accidents. It was estimated that the fixed mandatory ISA can result in 20% reduction in injury accidents and 37% reduction in fatal accidents. In addition, the estimated reduction in accidents caused by dynamic mandatory ISA is 36% for injury accidents and 59% for fatal accidents.

2.2.7 SUMMARY

A range of speed management measures were described in Section 2.2.1 to Section 2.2.6, in which the studies that evaluated the effectiveness of speed managing were reviewed. Speed limits represent the backbone of the speed management systems, while other speed management strategies including enforcement, education and information campaigns, traffic calming, traffic control (signs, road markings and signals) and other advanced technologies (e.g., Adaptive Cruise Control and Intelligent Speed Adaptation) could be used to control the traffic speed. Although these measures can be used individually, they are commonly used in combinations of two or more measures in order better control speeds and consequently reduce accidents.

3 SPEED-ACCIDENT MODELS FOR EDMONTON

Chapter 2 reviewed previous studies on vehicle speed. These studies mainly fell into two areas i) investigating the relationship between speed and road accidents and ii) the effectiveness of different speed management techniques. In the first area, researchers generally developed various models to mathematically express the effect of speed on road accidents; however, different methods of data collection and model development were used among the studies. In the second area, the effectiveness of speed management measures was examined based on before-and-after studies. In these studies vehicle speed, accident records and other traffic conditions data were collected both before and after the period of implementing speed management tactics. The change in vehicle speed and accident frequency at study sites from “before” to “after” period was taken to represent the effectiveness of the specific countermeasure.

The research presented in this thesis can be classified into the first study area. The main objective is to investigate the relationship between vehicle speed and accident frequency. According to the literature review (in Chapter 2), previous studies focusing on the effect of speed on accidents can be divided into two groups. The first group of studies investigated the relationship between individual vehicle speed and accident involvement, such as the study by Solomon (1964), Citillo (1968), Fildes et al. (1991), Kloeden et al. (1997, 2001, 2002), Maycock et al. (1998), and Quimby et al. (1999). The second group of studies focused on the effect of average traffic speed on accident frequency, such as the study by Finch et al. (1994) and Nilsson (2004). All the aforementioned studies attempted to obtain a one-to-one relationship between the speed and accident occurrence. It should be noted that a one-to-one relationship between the average traffic speed and accident frequency ignores the influence of other factors, such as the traffic volume, road geometry and so on. Therefore, a proper relationship between traffic speed and accident frequency may be masked by the effects of these factors. This problem calls for attempts to develop multiple regression models which relate accident frequency to traffic speed and other road and traffic characteristics. Baruya (1998) developed a multiple regression model based on the accident, traffic speed, flow and geometric data obtained from European countries.

The approach applied in this study is similar to that in Baruya's study. To be more specific, this study attempts to establish a multiple regression relationship rather than a one-to-one relationship between traffic speed and accident frequency. It is intended to develop accident prediction models based on accident, traffic speed, volume and geometric data. Using these models, the effect of speed on accident frequency can be investigated quantitatively by relating the accident frequency to speed and other factors.

It should be emphasized that this research focuses on investigating the speed-accident relationship in urban areas. The literature review in Chapter 2 shows that most of the previous studies on speed-accident relationship mainly focused on rural areas rather than urban areas. This is surprising given the fact that the majority of road accidents occur on urban roads. Therefore, there is a recognized need to understand and quantify the relationship between speed and accident occurrence in urban areas.

Six sections are included in this chapter. Section 3.1 describes the data used to develop the accident prediction models. Section 3.2 introduces the basic theory and procedure for model development. The modeling results are presented in Section 3.3 and the major findings of the speed-accident relationship are stated in Section 3.4. In Section 3.5, the research findings are compared with that of previous studies. The final section, Section 3.6, describes two applications of the accident prediction models: identification and ranking of the accident-prone locations.

3.1 DATA DESCRIPTION

The data used in this case-study was obtained from the City of Edmonton. Traffic speed data were collected from speed surveys conducted on urban roads. Speed data collection sites were selected at locations where the free-flow speed can be measured. The travel speed of each vehicle passing the data collection site was measured and collected for each road lane and for both directions of the road section. The average speed, mode speed, and 85th percentile speed of the traffic on each road section were recorded in the dataset. Other available data include: traffic volume on road sections, records of historical road accident occurred at intersections, as well as the traffic control (i.e., signalized or un-signalized intersection) and the number of legs for each intersection (i.e., four-leg or three-leg intersection).

The accident prediction models developed in this case-study are specific to urban intersections. It is necessary to relate the speed data collected on road sections to the number of accidents occurring at intersections. The two adjacent intersections connected by the road section where the speed survey was conducted are treated as study intersections.

Traffic speeds for two directions of the road section are considered as vehicle speeds approaching the two adjacent intersections. In this manner, the speed can be introduced into the intersection accident prediction model.

A total of 67 signalized intersections, consisting of 58 four-leg intersections and 9 three-leg intersections, are investigated to develop accident prediction model relating the accident frequency at signalized intersections to their traffic volume, geometric characteristic, and most importantly, traffic speed. The response variable of the model is the number of accidents occurring at the study intersection over a three-year period from 2006 to 2008. The explanatory variables consist of: a) average value of three years' (2006~2008) annual average daily traffic (AADT) for major and minor approaches for each study intersection, b) average speed, mode speed, and 85th percentile speed of the traffic approaching the study intersection, and c) dummy variable indicating whether the study intersection is a four-leg intersection.

3.2 METHODOLOGY FOR MODEL DEVELOPMENT

3.2.1 MODEL FORM

The model development is based on the work of Sayed and Rodriguez (1999) and Sawalha and Sayed (2006). The functional form of an accident prediction model should satisfy certain conditions (Sawalha and Sayed, 2006). Firstly, the accident frequency predicted by the model should not be a negative number. Secondly, the model should lead to zero predicted accident frequency when the values of exposure variables (e.g., traffic volume) are zero. However, the predicted number of accidents is not expected to be zero if other explanatory variables have zero values (e.g., number of bus stops, number of pedestrian crosswalks, and so on). Thirdly, in order to use generalized linear regression modelling approach, which is used almost exclusively for the accident prediction model development, a known link function must exist which can linearize the model form. The following model form, which satisfies all of the above-mentioned conditions, is used in this study:

$$E(Y) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp \textstyle\sum_j \beta_j x_j \tag{3.1}$$

where,

$E(Y)$ – predicted accident frequency at an intersection during a specific time period;

V_1 – major road annual average daily traffic (AADT);

V_2 – minor road annual average daily traffic (AADT);

x_j – other variables;

α_0, α_1,α_2, β_j – model coefficients.

In this study, the speed-related variables are introduced into the model as other variables (i.e., x_j in Equation 3.1) in addition to major and minor road AADT. There are three speed-related variables (i.e., average speed, mode speed and 85th percentile speed) and each of them is used to develop a separate model. Apart from the speed-related variables, a dummy variable indicating the type of intersection is added into the model. In order to examine the effect of speed on the severity of road accidents, three types of models were developed: a) fatal and injury accidents, b) property damage only (PDO) accidents, and c) total accidents, respectively. Therefore, a total of 9 models will be developed and their model form can be expressed mathematically as follows:

Model 1(Total Accidents-Average Speed Model):

$$E(Y) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 Avg + \beta_2 FL) \tag{3.2}$$

Model 2 (Fatal and Injury Accidents-Average Speed Model):

$$E(Y_1) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 Avg + \beta_2 FL) \tag{3.3}$$

Model 3 (PDO Accidents-Average Speed Model):

$$E(Y_2) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 Avg + \beta_2 FL) \tag{3.4}$$

Model 4 (Total Accidents-Mode Speed Model):

$$E(Y) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 Mode + \beta_2 FL) \tag{3.5}$$

Model 5 (Fatal and Injury Accidents-Mode Speed Model):

$$E(Y_1) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 Mode + \beta_2 FL) \tag{3.6}$$

Model 6 (PDO Accidents-Mode Speed Model):

$$E(Y_2) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 Mode + \beta_2 FL) \tag{3.7}$$

Model 7 (Total Accidents-85th Percentile Speed Model):

$$E(Y) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 S_3 + \beta_2 FL) \tag{3.8}$$

Model 8 (Fatal and Injury Accidents-85th Percentile Speed Model):

$$E(Y_1) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 S_3 + \beta_2 FL) \tag{3.9}$$

Model 9 (PDO Accidents-85th Percentile Speed Model):

$$E(Y_2) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp(\beta_1 S_3 + \beta_2 FL) \tag{3.10}$$

where,

E(Y) – total number of accidents at intersection per 3 years (number of accidents/3 years);

$E(Y_1)$ – number of fatal and injury accidents at intersection per 3 years (number of accidents/3 years);

$E(Y_2)$ – number of PDO accidents at intersection per 3 years (number of accidents/3 years);

V_1 – major road AADT (vehicles/day);

V_2 – minor road AADT (vehicles/day);

Avg – average traffic speed approaching the study intersection (km/h);

Mode – mode speed of the traffic approaching the study intersection (km/h);

S_3 – 85th percentile speed of the traffic approaching the study intersection (km/h);

FL – indicator variable for four-leg intersection (equal to 1 if intersection is four-leg intersection; equal to 0 if intersection is three-leg intersection);

α_0, α_1,α_2, β_j – model coefficients.

3.2.2 ERROR STRUCTURE

As stated by Sawalha and Sayed (2006), it is common to assume that the error structure of the accident prediction model is Poisson or negative binomial. If the accident frequency at an intersection during a time period, as denoted by *Y,* is assumed to follow a Poisson distribution, the mean of *Y*, denoted by Λ, is usually assumed to be gamma distributed with shape parameter κ and scale parameter κ/μ. Then the accident frequency *Y* around $E(\Lambda)=\mu$ follows a negative binomial distribution, with probability density function of:

$$P(Y = y) = \frac{\Gamma(\kappa+y)}{\Gamma(\kappa)y!}\left(\frac{\kappa}{\kappa+\mu}\right)^{\kappa}\left(\frac{\mu}{\kappa+\mu}\right)^{y} \tag{3.11}$$

The expected value and variance of Y is:

$$E(Y) = \mu \tag{3.12}$$

$$Var(Y) = \mu + \frac{\mu^2}{\kappa} \tag{3.13}$$

As shown by the two equations, under the assumption of negative binomial distribution for the error structure, the variance of accident frequency is generally greater than its expected value (except for the case when κ goes to infinity, the value of variance becomes equal to the mean). This assumption of negative binomial distribution for the error structure is more realistic than assumption of Poisson distribution (the variance is equal to the mean) since it has been shown that most accident data is over-dispersed (i.e., variance is greater than the mean) (Kulmala, 1995).

3.2.3 ASSESSING MODEL GOODNESS OF FIT AND PARAMETER SIGNIFICANCE

The criterion to assess the statistical significance of the coefficient estimates is whether the *t*-ratio of estimated coefficient is significant at a given level of confidence such as 90% or 95%. The *t*-ratio of estimated coefficient is calculated as the ratio of the value of the estimated coefficient relative to its standard error. The coefficient estimate is assessed as statistical significant when its *t*-ratio is greater than the *t*-statistics at a specific confidence level. For example, the value of *t*-statistics at 90% confidence level is 1.64, therefore an estimated coefficient is statistical significant at 90% confidence level if its *t*-ratio is greater than 1.64.

The goodness of fit of the model is assessed using two statistical measures. The first measure is to test whether the Pearson χ^2 statistic is significant at a given confidence level. The definition of Pearson χ^2 is expressed as:

$$Pearson\ \chi^2 = \sum_{i=1}^{n} \frac{[y_i - E(Y_i)]^2}{Var(Y_i)} \tag{3.14}$$

where,

y_i – observed accident frequency at intersection *i*;

$E(Y_i)$ – predicted accident frequency at intersection *i* as obtained from the model;

$Var(Y_i)$ – variance of the accident frequency for intersection *i*.

The second criterion for assessing the model's goodness of fit is to test whether the scaled deviance is significant at a given confidence level. When the error structure of the model follows negative binomial distribution, the scaled deviance is defined as:

$$SD = 2\sum_{i=1}^{n} \left[y_i ln\left(\frac{y_i}{E(Y_i)}\right) - (y_i + \kappa)\ln\left(\frac{y_i + \kappa}{E(Y_i) + \kappa}\right)\right] \tag{3.15}$$

Both Pearson χ^2 and the scaled deviance follow the χ^2 distribution with *n-p* degrees of freedom, where *n* is the number of data points and *p* is the number of model coefficients. Let *m* be the given level of confidence, the model can be assessed as having an acceptable fit to the data if both the value of its Pearson χ^2 statistic and the scaled deviance are less than the value of the test statistic $\chi^2_{(1-m,\ n-p)}$.

3.3 RESULTS OF MODEL DEVELOPMENT

The statistical software SAS version 9.2 was used to estimate the model's parameters. The GENMOD procedure is used to estimate the model coefficients (α_0, α_1, α_2, β_j) and the dispersion parameter (inverse of the shape parameter κ) using the maximum likelihood based on the negative binomial error structure and 'log' link function.

Nine accident prediction models as described in Section 3.2.1 were developed. The Pearson χ^2 was significant at 95% confidence level for all of the nine models. The *t*-ratios of the parameter estimates for the intercept, major, and minor traffic volume were significant at 95% confidence level for all the models. However, the scaled deviance was significant at 95% confidence level for only six models while insignificant for three models which are developed for PDO accidents (i.e., Model 3, 6, and 9). The *t*-ratios for the coefficient estimates of speed-related variables were significant for four models at 95% confidence level (Model 3, 6, 7, and 9) and two models at 90% confidence level (Model 1 and Model 4). For the dummy variable *FL*, the *t*-ratio of its estimated coefficient was insignificant at 95% confidence level for all the nine models while significant at 90% confidence level for five models. A detailed statistical test results for the scaled deviance, *t*-ratios of coefficient estimates of speed-related variables and *FL* are listed in Table 3.1.

The goodness of fit results suggest that the data set might have some outliers; these are a few unusual or extreme data points. Data sets usually contain some outliers since mistakes or errors could happen during the process of data collection and recording. The 67 data points were reviewed to check and remove any outliers that might exist in the data set. The outlier analysis revealed that one of that data points was obviously unusual, with major and minor road AADT of over 20,000 and 4,000 vehicles per day with zero accidents occurring in the past three years. This data point was identified as an outlier and removed from the dataset. A new set of models were developed based on the remaining 66 data points.

Table 3.1: Statistical Test Results for Models (67 data points)

Number of data points used: 67		Statistical significant?				
		SD (95%)	Speed		FL	
Model No.	Description		95%	90%	95%	90%
1	Total accidents-average speed	Yes	No	Yes	No	No
2	Fatal&injury accidents-average speed	Yes	No	No	No	No
3	PDO accidents-average speed	No	Yes	Yes	No	Yes
4	Total accidents-mode speed	Yes	No	Yes	No	Yes
5	Fatal&injury accidents-mode speed	Yes	No	No	No	No
6	PDO accidents-mode speed	No	Yes	Yes	No	Yes
7	Total accidents-85th percentile speed	Yes	Yes	Yes	No	Yes
8	Fatal&injury accidents-85th percentile speed	Yes	No	No	No	No
9	PDOaccidents-85th percentile speed	No	Yes	Yes	No	Yes
Note: SD – Scaled deviance; Speed – Speed-related variable in each model; FL – Dummy variable for four-leg intersection; 95%, 90% – Confidence level.						

Table 3.2: Statistical Test Results for Models (66 data points)

Number of data points used: 67		Statistical significant?				
		SD (95%)	Speed		FL	
Model No.	Description		95%	90%	95%	90%
1	Total accidents-average speed	Yes	No	Yes	No	Yes
2	Fatal&injury accidents-average speed	Yes	No	No	No	No
3	PDO accidents-average speed	Yes	Yes	Yes	Yes	Yes
4	Total accidents-mode speed	Yes	No	Yes	Yes	Yes
5	Fatal&injury accidents-mode speed	Yes	No	No	No	No
6	PDO accidents-mode speed	Yes	No	Yes	Yes	Yes
7	Total accidents-85th percentile speed	Yes	Yes	Yes	Yes	Yes
8	Fatal&injury accidents-85th percentile speed	Yes	No	No	No	No
9	PDOaccidents-85th percentile speed	Yes	Yes	Yes	Yes	Yes
Note: SD – Scaled deviance; Speed – Speed-related variable in each model; FL – Dummy variable for four-leg intersection; 95%, 90% –Confidence level.						

For the new models, the Pearson χ^2 and the *t*-ratios of the coefficient estimates for the intercept, major and minor AADT were significant at 95% confidence level for the nine models. Table 3.2 shows that the scaled deviance was significant at 95% confidence level for all models. For the dummy variable *FL*, the *t*-ratio of its estimated coefficient was significant at 95% confidence level for only five of the models. Overall, there were three models (Model 3, 7, and 9) in which the *t*-ratios of all the estimated model coefficients were significant at 95% confidence level and had a good fit to the data (i.e., both values of their scaled deviance and Pearson χ^2 were significant at 95% confidence level). It should be noted that the *t*-ratios of coefficients for speed-related variables and dummy variable *FL* were insignificant for the three models that relate the speed variables to fatal and injury accidents (Model 2, 5, and 8). This suggests that the speed-related variables and dummy variable *FL* cannot be retained in these models. Therefore, only the models that relate the speed variables to total accidents and property damage only accidents are listed in Table 3.3 to Table 3.8. The symbols used in the tables are a) $E(Y)$, total number of accidents at intersection per 3 years; b) $E(Y_2)$, number of property damage only (PDO) accidents at intersection per 3 years; c) V_1 and V_2, major and minor road annual average daily traffic (AADT) in vehicles per day; d) *Avg*, average traffic speed approaching the study intersection in kilometers per hour; e) *Mode*, mode speed of the traffic approaching the study intersection in kilometers per hour; f) S_3, 85th percentile speed of the traffic approaching the study intersection in kilometers per hour; g) *FL*, dummy variable indicating if the study intersection is four-leg intersection or not (equal to 1 if it is four-leg intersection; 0 otherwise).

Table 3.3: Accident Prediction Model 1 (Total Accidents-Average Speed)

Model form: $E(Y) = 0.0001051\, V_1^{0.6090} V_2^{0.6952}\, exp\,(0.0099\, Avg + 0.2911\, FL)$					
SD=70.7207 Pearson χ^2=66.5913 Degree of freedom=61 $\chi^2_{(0.05,\,61)}$=80.2 $t_{(0.05,\,61)}$=1.96 $t_{(0.10,\,61)}$=1.64 κ =6.911					
Variable	*Constant*	V_1	V_2	*Avg*	*FL*
Coefficient	0.0001051	0.6090	0.6952	0.0099	0.2911
***t*-ratio**	6.898^{**}	4.407^{**}	9.682^{**}	1.768^{*}	1.929^{*}
Note: ** – significant at 95% confidence level; * – significant at 90% confidence level.					

Table 3.4: Accident Prediction Model 2 (PDO Accidents-Average Speed)

Model form: $E(Y_2) = 0.00004307\, V_1^{0.6306} V_2^{0.7237}\, exp\,(0.0116\, Avg + 0.3107\, FL)$					
SD=76.9279 Pearson χ^2=65.0129 Degree of freedom=61 $\chi^2_{(0.05,\,61)}$=80.2 $t_{(0.05,\,61)}$=1.96 $t_{(0.10,\,61)}$=1.64 κ =6.789					
Variable	*Constant*	V_1	V_2	*Avg*	*FL*
Coefficient	0.00004307	0.6306	0.7237	0.0116	0.3107
***t*-ratio**	7.336^{**}	4.428^{**}	9.547^{**}	2.071^{**}	2.012^{**}
Note: ** – significant at 95% confidence level; * – significant at 90% confidence level.					

Table 3.5: Accident Prediction Model 3 (Total Accidents-Mode Speed)

Model form: $E(Y) = 0.0001251\, V_1^{0.5961} V_2^{0.6951} exp\,(0.0093\, Mode + 0.3083\, FL)$					
SD=70.9574 Pearson χ^2=67.3126 Degree of freedom=61 $\chi^2_{(0.05,\,61)}$=80.2 $t_{(0.05,\,61)}$=1.96 $t_{(0.10,\,61)}$=1.64 κ =6.887					
Variable	*Constant*	V_1	V_2	*Mode*	*FL*
Coefficient	0.0001251	0.5961	0.6951	0.0093	0.3083
***t*-ratio**	6.873**	4.338**	9.601**	1.632*	1.997**
Note: ** – significant at 95% confidence level; * – significant at 90% confidence level.					

Table 3.6: Accident Prediction Model 4 (PDO Accidents-Mode Speed)

Model form: $E(Y_2) = 0.0000525\, V_1^{0.6156} V_2^{0.7242}\ exp\,(0.0110\, Mode + 0.3309\, FL)$					
SD=77.2280 Pearson χ^2=65.7692 Degree of freedom=61 $\chi^2_{(0.05,\,61)}$=80.2 $t_{(0.05,\,61)}$=1.96 $t_{(0.10,\,61)}$=1.64 κ =6.757					
Variable	*Constant*	V_1	V_2	*Mode*	*FL*
Coefficient	0.0000525	0.6156	0.7242	0.0110	0.3309
***t*-ratio**	7.296**	4.347**	9.479**	1.897*	2.097**
Note: ** – significant at 95% confidence level; * – significant at 90% confidence level.					

Table 3.7: Accident Prediction Model 5 (Total Accidents-85th Percentile Speed)

Model form: $E(Y) = 0.00008408\, V_1^{0.6052} V_2^{0.6947}\, exp\,(0.0119\, S_3 + 0.3145\, FL)$					
SD=70.7215 Pearson χ^2=66.3980 Degree of freedom=61 $\chi^2_{(0.05,\, 61)}$=80.2 $t_{(0.05,\, 61)}$=1.96 $t_{(0.10,\, 61)}$=1.64 κ =7.163					
Variable	*Constant*	V_1	V_2	S_3	*FL*
Coefficient	0.00008408	0.6052	0.6947	0.0119	0.3145
***t*-ratio**	7.341**	4.574**	9.953**	2.288**	2.108**
Note: ** – significant at 95% confidence level; * – significant at 90% confidence level.					

Table 3.8: Accident Prediction Model 6 (PDO Accidents-85th Percentile Speed)

Model form: $E(Y_2) = 0.0000338\, V_1^{0.6251} V_2^{0.7243}\, exp\,(0.0137\, S_3 + 0.3352\, FL)$					
SD=77.0705 Pearson χ^2=65.0823 Degree of freedom=61 $\chi^2_{(0.05,\, 61)}$=80.2 $t_{(0.05,\, 61)}$=1.96 $t_{(0.10,\, 61)}$=1.64 κ =7.128					
Variable	*Constant*	V_1	V_2	S_3	*FL*
Coefficient	0.0000338	0.6251	0.7243	0.0137	0.3352
***t*-ratio**	7.841**	4.613**	9.854**	2.635**	2.210**
Note: ** – significant at 95% confidence level; * – significant at 90% confidence level.					

3.4 EFFECT OF SPEED ON ACCIDENT FREQUENCY

Tables 3.3 to 3.8 summarize the parameter estimates and goodness of fit statistics for all the developed models. The regression coefficients for speed variables were all positive, indicating that average speed, mode speed, and 85th percentile speed are positively associated with the number of property damage only accidents and total accidents occurred at signalized intersections.

The effect of speed on accident frequency can be quantified by changing the values of speed-related variables while holding all the other independent variables in the model constant. Based on this principle, the developed accident prediction models can be converted to equations which correlate the change in the accident frequency with the change in the value of average speed, mode speed and 85th percentile speed. The relationship could be expressed mathematically as:

$$P_1 = exp(0.0099 \times \Delta Avg) - 1 = 1.0099^{\Delta Avg} - 1 \tag{3.16}$$

$$P_2 = exp(0.0116 \times \Delta Avg) - 1 = 1.0117^{\Delta Avg} - 1 \tag{3.17}$$

$$P_1 = exp(0.0093 \times \Delta Mode) - 1 = 1.0093^{\Delta Mode} - 1 \tag{3.18}$$

$$P_2 = exp(0.0110 \times \Delta Mode) - 1 = 1.0111^{\Delta Mode} - 1 \tag{3.19}$$

$$P_1 = exp(0.0119 \times \Delta S_3) - 1 = 1.0120^{\Delta S_3} - 1 \tag{3.20}$$

$$P_2 = exp(0.0137 \times \Delta S_3) - 1 = 1.0138^{\Delta S_3} - 1 \tag{3.21}$$

where,

P_1 – percentage of the increase or decrease of total accident frequency at signalized intersection per 3 years;

P_2 – percentage of the increase or decrease of PDO accident frequency at signalized intersection per 3 years;

ΔAvg – increase or decrease of average traffic speed (km/h);

$\Delta Mode$ – increase or decrease of mode speed (km/h);

ΔS_3– increase or decrease of 85th percentile speed (km/h).

The results show that when the average, mode, and 85th percentile speeds of the traffic approaching the signalized intersection decrease by 1km/h, the number of total predicted accidents at an intersection will be reduced by approximately 1.0%, 0.9% and 1.2% respectively. The reduction in PDO accident frequency associated with the 1km/h reduction of average, mode, and 85th percentile speeds is 1.2%, 1.1% and 1.4% respectively, which is slightly greater than the reduction in total accident frequency.

Furthermore, when the reduction of average, mode, and 85th percentile speeds is 5km/h, the total accident frequency will consequently drop by 5.0%, 4.7% and 6.1%, while the number of PDO accidents will decrease by 6.0%, 5.7% and 7.1%, respectively. The relationship between the percent of change in total accident frequency and change in average speed, mode speed, and 85th percentile speed at signalized intersection is shown in Figure 3.1. Figure 3.2 depicts the change in PDO accidents frequency that is associated with the change in three speed-related variables. Figure 3.3, 3.4 and 3.5 compare the change in total accidents with the change in PDO accidents caused by the change in average, mode, and 85th percentile speed, respectively.

Figure 3.1: Relationship between Change in Average Speed, Mode Speed and 85th Percentile Speed and Percentage of Change in Total Accident Frequency

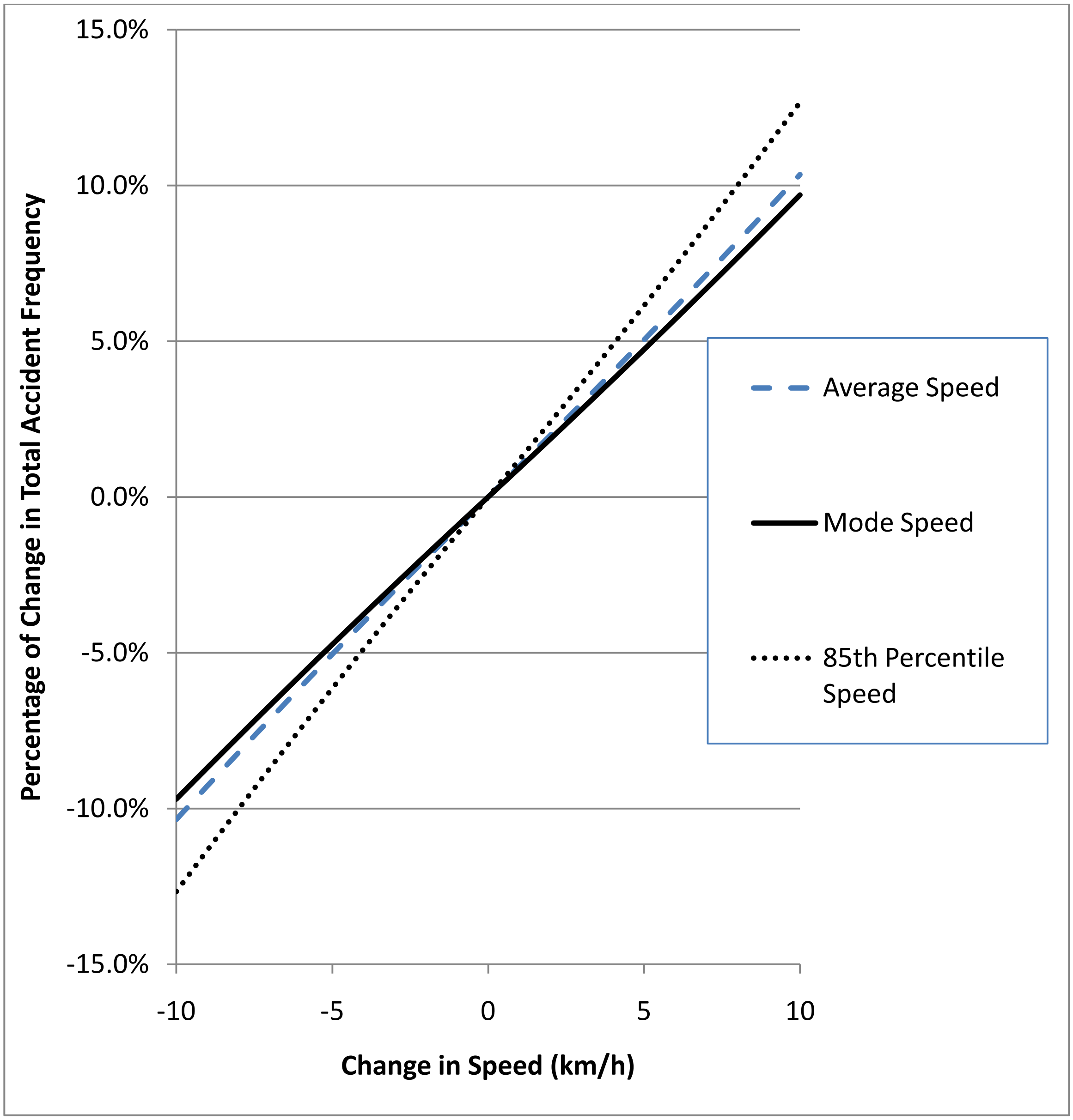


Figure 3.2: Relationship between Change in Average Speed, Mode Speed and 85th Percentile Speed and Percentage of Change in PDO Accident Frequency

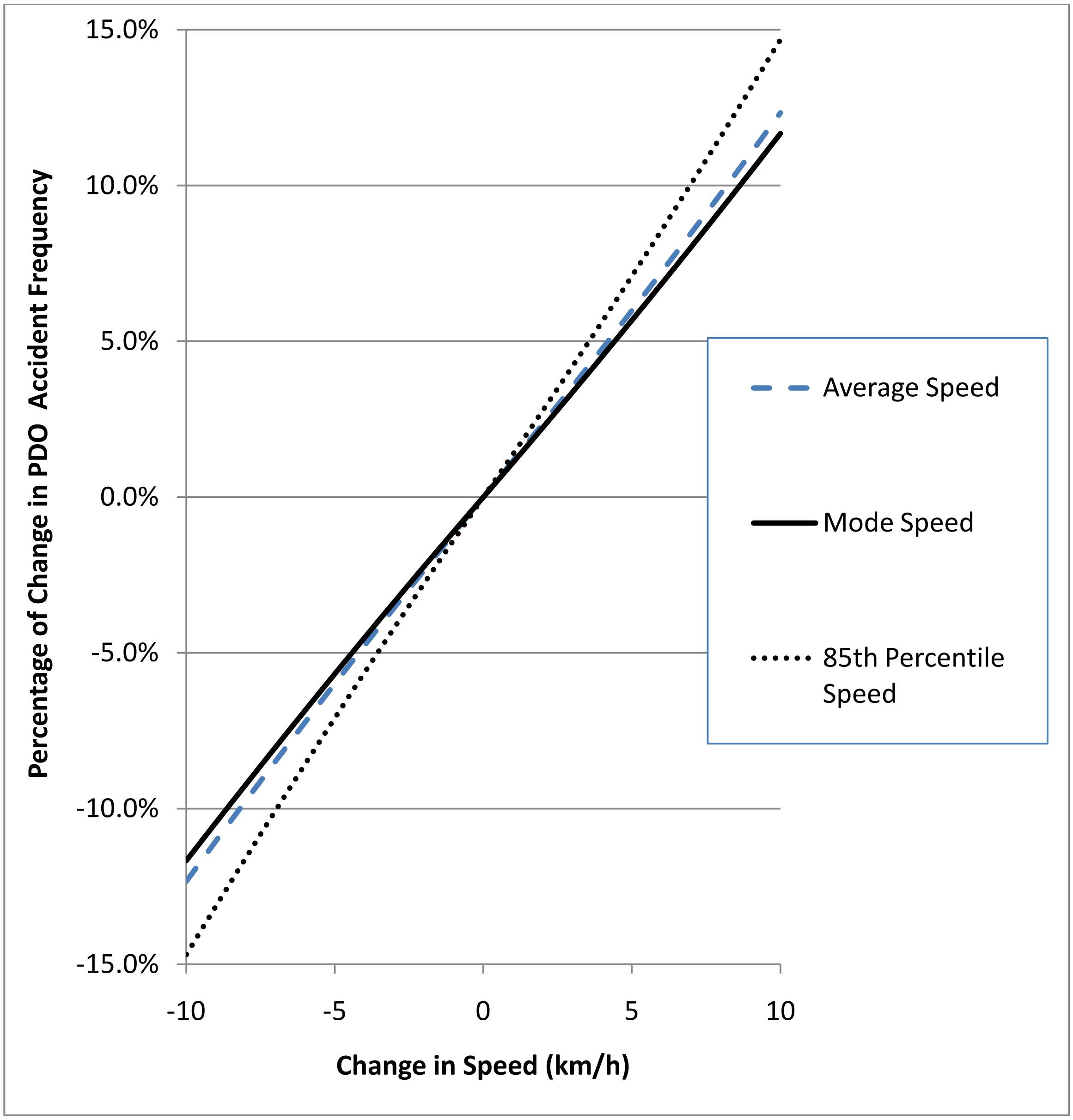


Figure 3.3: Relationship between Change in Average Speed and Percentage of Change in Total and PDO Accident Frequency

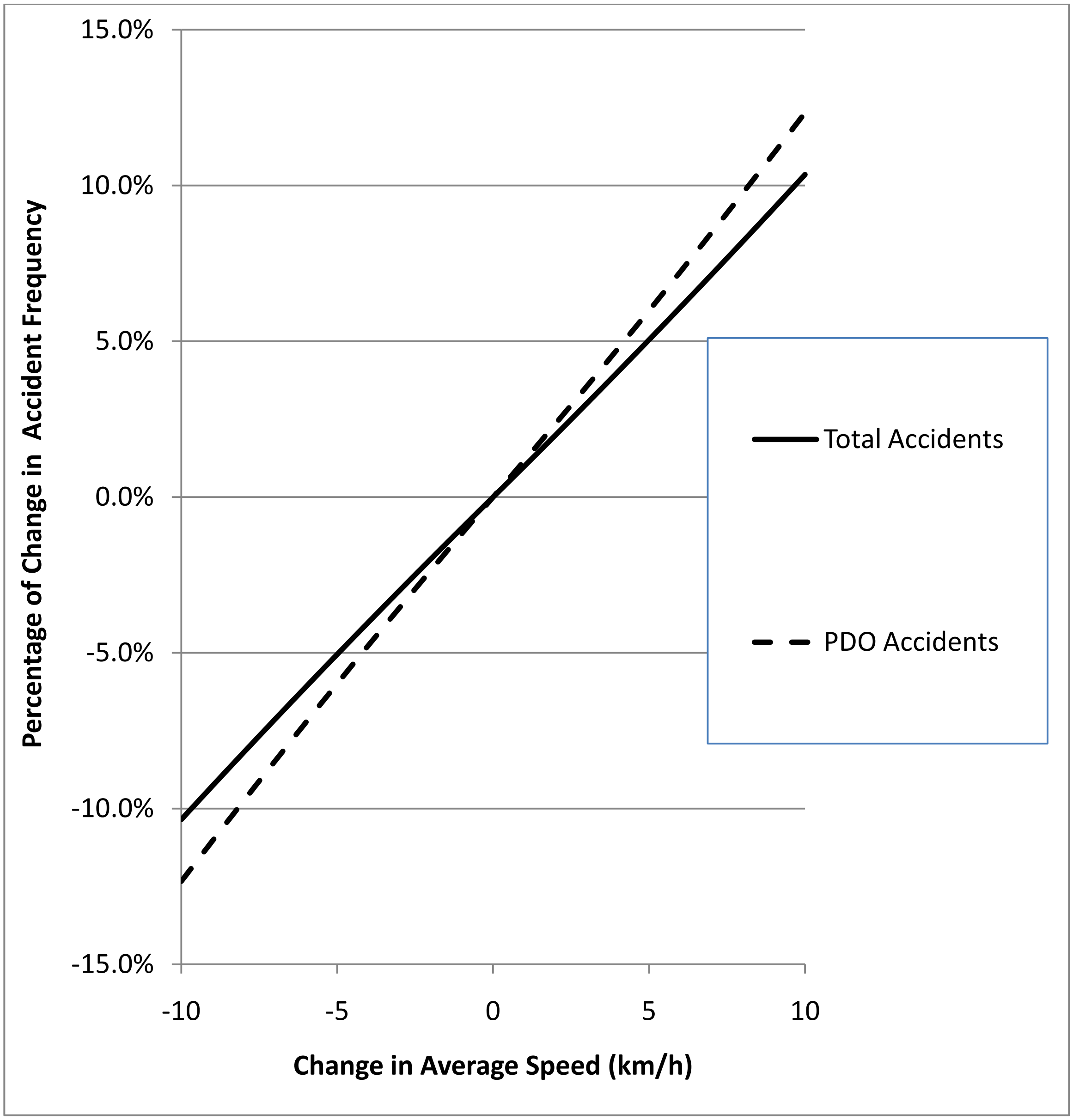


Figure 3.4: Relationship between Change in Mode Speed and Percentage of Change in Total and PDO Accident Frequency

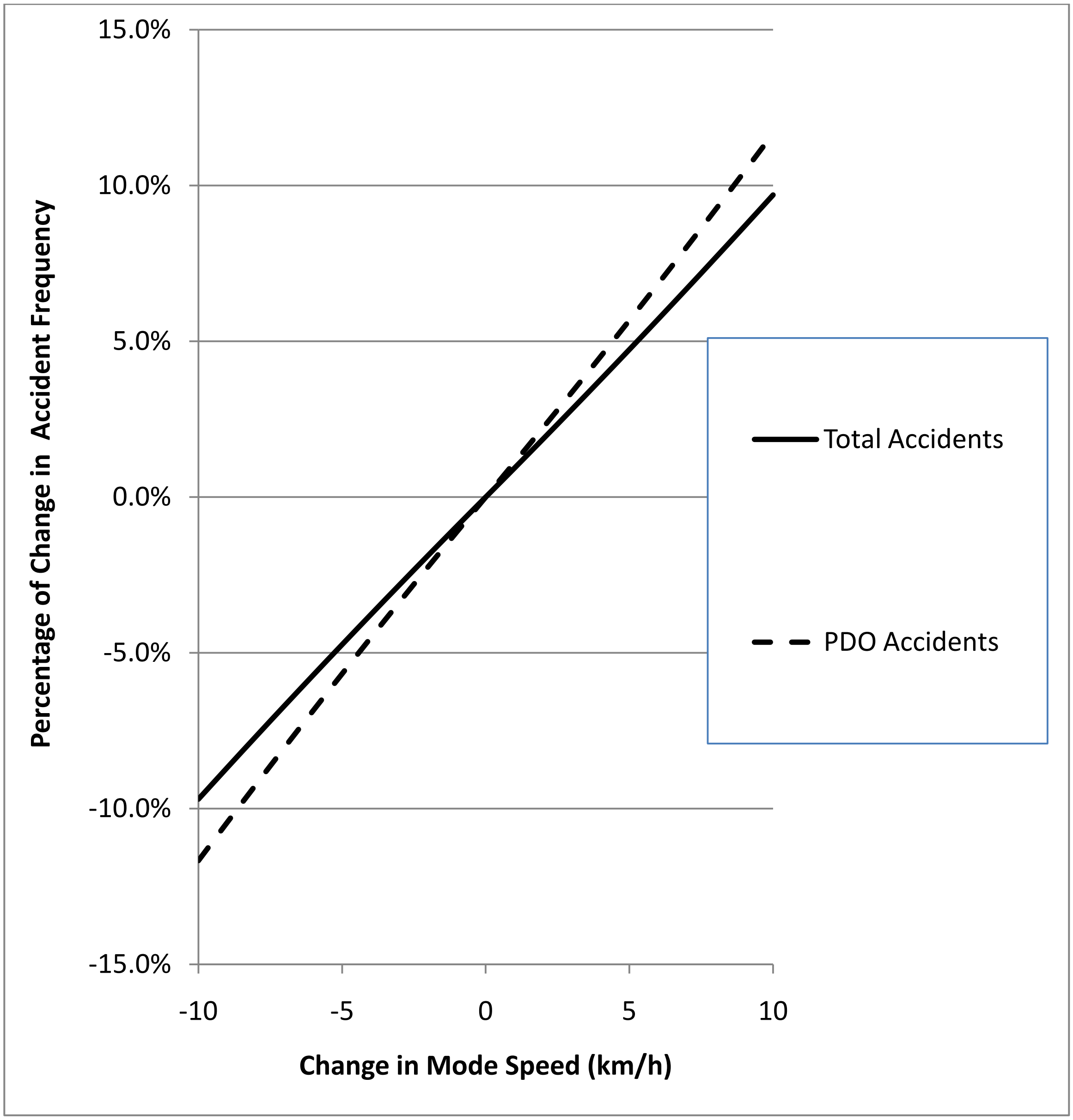
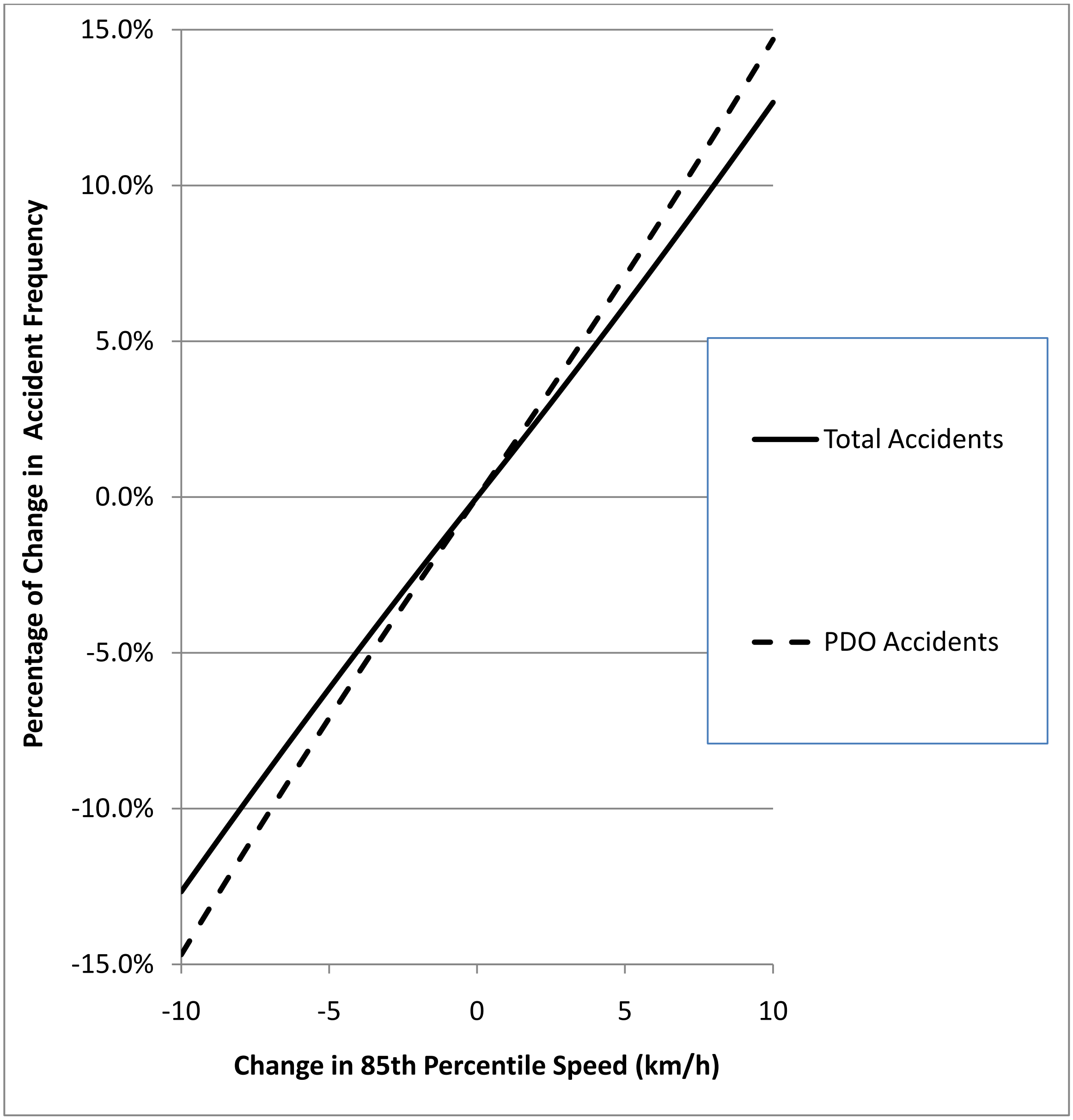


Figure 3.5: Relationship between Change in 85th Percentile Speed and Percentage of Change in Total and PDO Accident Frequency



Figures 3.1 and 3.2 show that the change in 85th percentile speed was associated with the largest percent change in both total and PDO accident frequencies. Alternatively, the change in mode speed was associated with the smallest percent change in both total and PDO accident frequencies. Figures 3.3 to 3.5 show that the change in average speed, mode speed, and 85th percentile speed was related to a larger percent change in PDO-related accidents than in total accident frequencies.

3.5 COMPARISON WITH OTHER STUDY RESULTS

The speed-accident relationship from this case-study was compared with that found by previous studies. The meta-analysis conducted by Finch et al. (1994) concluded that for every increase or reduction of 1 mile per hour in average traffic speed there is a 5% increase or decrease in the accident frequency. This is equivalent to 3% change in accident frequency with every change in 1 kilometer per hour. Taylor et al. (2000) showed that a reduction of 1 mile per hour in average speed corresponds to a 2% to 7% reduction in accident frequency which varies with the type of road section. Specifically, the percent reduction in accident frequency is about 6% (equivalent to 3.7% with every 1km/h reduction) on urban roads with low average speed. On urban roads with higher speed and rural main roads, the percent reduction was 3% (equivalent to 1.9% with 1km/h reduction). Taylor et al. (2000) also stated that a 5% reduction in accidents for every 1mph reduction remains as a general figure, which is a similar finding to that by Finch et al. (1994).

The results of this case-study showed that when the average speed of the traffic approaching a signalized intersection decreases by 1km/h, the number of total accidents at an intersection will be reduced by approximately 1%. This figure is significantly lower than the 3% change in accident frequency found in the above two studies.

Recall that the approach applied in this study is similar to that by Baruya (1998) which investigated the speed-accident relationship by using accident prediction models that relate the accident frequency to speed and other road and traffic characteristics. Baruya (1998) investigated the relationship between speed and accident frequency on European rural roads based on the speed, accident, traffic flow and other geometric data obtained from European countries. The Generalized Linear Modelling (GLM) method was applied to develop an accident prediction model, called EURO model, to describe the speed-accident relationship which can be applied in the European Union. The form of the EURO model is:

$$E(Y) = 5.663V^{0.748}L^{0.847}M^{-2.492}P^{0.114}\exp(0.038NI - 0.056W + 0.023S) \quad (3.22)$$

The symbols used in the model are: *E(Y)*, the predicted accident frequency; *V*, traffic flow; *L*, road section length; *M*, mean speed; *P*, proportion of speeders; *NI*, number of minor intersections; *W*, road width; *S*, posted speed limit.

The EURO model uses three speed-related variables namely; mean speed, proportion of speeders and posted speed limit. By contrast, there is only one speed-related variable (i.e., average speed, mode speed or 85th percentile speed) in the accident prediction models developed in this case-study. A likely problem with the EURO model is that the mean speed, proportion of speeders and posted speed limit are highly correlated. For example, the increase in the proportion of speeders or posted limit can consequently lead to the increase in mean speed. In fact, Baruya (1998) also developed models showing the correlation among the three variables. A multicollinearity problem may arise from the inclusion of correlated variables in one model. Although the reliability of the model as a whole cannot be affected by the presence of multicollinearity, the impact of an individual variable on the response variable may be less precisely estimated than if variables in one model are uncorrelated. Alternatively, the accident prediction models developed in this case-study are more suitable to examine the effect of individual speed variables on the frequency of accidents.

Another difference between the EURO model and the models developed in this case-study is that the coefficient estimate for the mean speed (M) is negative in the EURO model while the coefficient estimates for all the speed-related variables are positive in this case-study. Under the EURO model, higher mean speeds are associated with fewer accidents while the proportion of vehicles travelling above the speed limit (P) and speed limit (S) have a positive effect on accident occurrence. Based on the impact of proportion of speeders (P) on mean speed (M), Baruya (1998) obtained a relationship between the mean speed and accident frequency. Basically, a reduction of 1km/h in the mean speed (M) as a result of reducing the proportion of speeders (P) would reduce accident frequency by ($153.6/M$) percent. For instance, if the mean speed is 60, 70 and 80km/h, the reduction of accident frequency will be 2.56%, 2.19% and 1.92% respectively. All three percentages are higher than the 1% reduction that was found in this case-study. It should be emphasized that the developed models are suitable for signalized intersections in urban areas whereas the EURO model was developed for rural road sections. The difference in the traffic characteristics and road environment between urban and rural road areas could be the reason for the different speed-accident relationships.

3.6 APPLICATION OF ACCIDENT PREDICTION MODELS

The preceding sections mainly describe the development of accident prediction models for the purpose of investigating the relationship between traffic speed and accident frequency. This section will introduce two applications of the developed models: identification of the accident prone locations (APLs) and the ranking of these APLs.

3.6.1 IDENTIFICATION OF ACCIDENT-PRONE LOCATIONS

The identification of accident-prone locations is based on the empirical Bayes' technique described by Sayed and Abdelwahab (1997). Briefly, the empirical Bayes' technique combines the traffic and road characteristics of a specific site with the accident history of that site to obtain a refined estimate of the number of accidents at the specific site. This approach is adopted to combine the predicted number of accidents at an intersection from the accident prediction model with the intersection's historical accident data to obtain more accurate estimates. The Accident Prediction Model (APM) 5 as shown in Table 3.7 is used to identify the APLs for two reasons. First, the identification of APLs should take into account the total number of accidents occurring at a site not just the PDO accidents. Therefore, only the models developed for total accident counts are eligible to be used in the identification of APLs. The second reason lies in the fact that among the three models developed for total accident frequency, APM5 is the only one with all the coefficient estimates significant at 95% confidence level. Therefore, APM5 is considered to be more reliable when compared to the other two models and is applied to identify accident prone locations.

A similar procedure to that of Sayed and Rodriguez (1999) is used to identify the accident-prone locations. A brief description of the process is given below.

The first step is to calculate the parameters of the prior distribution of the predicted accident frequency, which is a gamma distribution with parameters α and β:

$$\beta = \frac{E(\Lambda)}{Var(\Lambda)} = \frac{\kappa}{E(\Lambda)} \tag{3.23}$$

$$\alpha = \beta \times E(\Lambda) = \kappa \tag{3.24}$$

where,

E(Λ) – predicted number of accidents as estimated from the accident prediction model (APM);

Var(Λ) – variance of the APM estimate.

The next step is to determine a reference point in order to identify a location as an APL. The location is identified as an APL if there is a significant probability that the estimated accident frequency exceeds the reference point. Usually the median (P_{50}) is selected as a possible reference point and is calculated so that:

$$\int_0^{P_{50}} \frac{(\kappa/E(\Lambda))^{\kappa} \times \lambda^{\kappa-1} \times e^{-(\kappa/E(\Lambda))\lambda}}{\Gamma(\kappa)} d\lambda = 0.5 \tag{3.25}$$

The third step is to calculate the parameters of the posterior distribution of the predicted accident frequency based on the empirical Bayes' technique. The posterior distribution also follows a gamma distribution with parameters α_1 and β_1:

$$\beta_1 = \frac{EB}{Var(\mathrm{EB})} = \frac{\kappa}{E(\Lambda)} + 1 \tag{3.26}$$

$$\alpha_1 = \beta_1 \times EB = \kappa + count \tag{3.27}$$

where,

count – observed number of accidents for a study site;

EB – empirical Bayes (EB) estimated expected number of accidents for a study site;

Var (EB) – variance of the EB estimate.

Therefore, the probability density function of the posterior distribution is:

$$f_{EB}(\lambda) = \frac{([\kappa/E(\Lambda)+1])^{(\kappa+count)} \times \lambda^{\kappa+count-1} \times e^{-([\kappa/E(\Lambda)+1])\lambda}}{\Gamma(\kappa+count)} \tag{3.28}$$

Finally, a location is identified as accident-prone if the probability of its predicted accident frequency under the posterior distribution exceeding P_{50} is significant:

$$\left\{1 - \int_0^{P_{50}} f_{EB}(\lambda) d\lambda\right\} \geq \delta \tag{3.29}$$

where,

$f_{EB}(\lambda)$ – probability density function of the posterior distribution of predicted accident frequency λ;

δ – desired confidence level, usually selected as 0.95.

Based on the APM5 and the process described above, 24 signalized intersections were identified as accident-prone. The list of these intersections is shown in Table 3.9. The symbol P in the table is used to indicate the probability of predicted accident frequency exceeding P_{50}.

Table 3.9: Accident-Prone Signalized Intersections

Intersection No.	Location	P
1	170 Street at 95 Avenue	1
2	23 Avenue at Gateway Boulevard	1
3	91 Street at 23 Avenue	1
4	97 Street at 137 Avenue	1
5	170 Street at 99 Avenue	1
6	170 Street at 90 Avenue	0.99998
7	91 Street at Millwoods Road	0.99998
8	97 Street at 167 Avenue	0.99998
9	167 Avenue at 66 Street	0.99998

Intersection No.	**Location**	**P**
10	170 Street at 87 Avenue	0.99996
11	23 Avenue at 111 Street	0.99994
12	Millwoods Road at 34 Avenue	0.99975
13	172 Street at 69 Avenue	0.99925
14	23 Avenue at Rabbit Hill Road	0.99793
15	97 Street at 135 Avenue	0.9977
16	97 Street at 153 Avenue	0.99724
17	Rabbit Hill Road at Terwillegar Drive	0.99673
18	137 Avenue at 40 Street	0.9953
19	23 Avenue at 66 Street	0.99032
20	137 Avenue at 170 Street	0.98285
21	50 Street at 23 Avenue	0.97334
22	167 Avenue at 82 Street	0.95683
23	91 Street at 63 Avenue	0.95262
24	97 Street at 176 Avenue	0.95132

3.6.2 RANKING OF ACCIDENT-PRONE LOCATIONS

It is important to rank accident-prone locations to assist the road authorities in deciding which APLs are likely to achieve the highest cost-effectiveness after receiving a specific safety treatment. A potential ranking criterion can be the difference between the empirical Bayes' estimate of accident frequency and the predicted accident frequency obtained from the accident prediction model. A large difference between these two values is associated with expected safety benefits and higher cost-effectiveness.

The ratio of the empirical Bayes' estimate to the predicted accident frequency is another ranking criterion. The value of this ratio reflects the risk of accident involvement in a location. Alternatively, the abovementioned criteria could be combined in a single ranking criterion. Table 3.10 ranks the accident-prone locations identified in the previous section based on the two ranking criteria separately and a combined criterion with equal weight given to the two criteria.

Table 3.10: Ranking of Accident-Prone Signalized Intersections

Intersection	**EB-Pred**	**EB/Pred**	**Rank EB-Pred**	**Rank EB/Pred**	**Rank Comb.**
170 Street at 95 Avenue	130.266	1.77453	1	2	1
23 Avenue at Gateway Boulevard	106.013	1.31961	2	8	3
91 Street at 23 Avenue	81.8172	1.53349	3	4	2

Intersection	**EB-Pred**	**EB/Pred**	**Rank EB-Pred**	**Rank EB/Pred**	**Rank Comb.**
97 Street at 137 Avenue	65.4681	1.28654	4	12	5
170 Street at 87 Avenue	47.7946	1.22697	5	17	9
91 Street at Millwoods Road	42.8009	1.3102	6	10	5
97 Street at 167 Avenue	41.1829	1.31544	7	19	13
23 Avenue at 111 Street	40.5197	1.27281	8	15	10
170 Street at 90 Avenue	39.7036	1.35206	9	7	5
170 Street at 99 Avenue	33.5662	1.62183	10	3	4
97 Street at 153 Avenue	30.452	1.14535	11	22	18
Rabbit Hill Road at Terwillegar Drive	27.1839	1.16613	12	20	17
Millwoods Road at 34 Avenue	24.9525	1.38827	13	6	8
97 Street at 135 Avenue	21.893	1.26307	14	16	15
23 Avenue at 66 Street	21.058	1.15056	15	21	19
23 Avenue at Rabbit Hill Road	20.9748	1.28746	16	11	14
137 Avenue at 40 Street	17.1763	1.2825	17	13	15
50 Street at 23 Avenue	16.6773	1.10861	18	24	23
137 Avenue at 170 Street	16.1394	1.16696	19	19	20
172 Street at 69 Avenue	15.413	1.51559	20	5	12
91 Street at 63 Avenue	11.7043	1.12266	21	23	24

Intersection	EB-Pred	EB/Pred	Rank EB-Pred	Rank EB/Pred	Rank Comb.
167 Avenue at 66 Street	9.50088	2.15455	22	1	10
97 Street at 176 Avenue	8.35211	1.20274	23	18	22
167 Avenue at 82 Street	6.74949	1.27824	24	14	20

4 SPEED-ACCIDENT MODELS FOR VANCOUVER

In Chapter 3, six accident prediction models have been developed for the purpose of investigating the relationship between speed and accident frequency at urban signalized intersections in the city of Edmonton. Three speed-related variables were considered: average speed, mode speed and 85th percentile speed. However, due to data availability issues, variables that reflect the dispersion of the traffic speed were not included in the model, i.e., speed standard deviation and speed variance data were missing. Note that previous studies showed that the absolute traffic speed as well as the speed dispersion can influence the occurrence of accidents (Lave, 1985; Garder and Gadirau, 1988; Taylor et al., 2000).

This chapter describes the results of developing accident prediction models for urban signalized intersections in Vancouver to investigate the relationship between speed and accident frequency. The main difference between the Edmonton- and Vancouver-based models is the inclusion of a speed dispersion variable which has been established to influence accident occurrence.

This chapter consists of five sections. The data sources for model development are described in Section 4.1. The second section describes the model form and structure. The third section summarizes the results. The fourth section evaluates the effect of speed on accident frequency. Finally, Section 4.5 compares the Vancouver- and Edmonton-based speed-accident models.

4.1 DATA DESCRIPTION

The speed, accident, and volume data were collected for a group of signalized intersections located in the Greater Vancouver area. Spot speeds were collected at each of the four approaches of the study intersection and only the data for working weekdays were used in this case-study. Based on these original spot speed data, the values of three speed variables were estimated: average speed, speed standard deviation and percent of speeding vehicles at each study intersection. The average speed and speed standard deviation were estimated during the off-peak period. The range of average speed was 35km/h to 64km/h while the speed standard deviation ranged from 0.58km/h to 13.5km/h. Speeding vehicles were defined as the percentage of vehicles travelling over the posted speed limit and the percent of speeding vehicles ranged from 10% to 100%.

Road accident data for signalized intersections were collected based on auto insurance claims record from Insurance Corporation of British Columbia (ICBC). Auto insurance claim records have been proven to be a reliable surrogate for collision data which can be used in road safety evaluation (deLeur and Sayed, 2001). In this case-study, accident data based on ICBC claim records were gathered for a three-year period from 2000 to 2002. The accident data were classified into two categories according to accident severity: fatal and injury accident and property damage only (PDO) accident.

A total of 84 signalized intersections were investigated to develop accident prediction models relating the accident frequency at signalized intersections to their traffic volume and speed characteristics. The response variable of the model was the number of accidents occurring at the study intersection over a three-year period from 2000 to 2002. The following explanatory variables were used: a) average value of three years' (2000~2002) annual average daily traffic (AADT) for major and minor intersecting road of the study intersection, and b) average speed, speed standard deviation, and percent of speeding vehicles on all four approaches of the study intersection.

4.2 MODEL DEVELOPMENT

The model form, error structure, goodness of fit, and assessment follow the same methodology discussed earlier in Section 3.2.

Since the basic model form has been previously discussed, this section will only list the exact model forms for each of the proposed models. Similar to the models for Edmonton, speed-related variables are introduced into the models in addition to the major and minor road AADT to investigate the relationship between speed and accident frequency. There are three speed-related variables (i.e., average speed, speed standard deviation and percent of speeding vehicles) and each of them was used to develop separate accident prediction models. Furthermore, separate models were developed for different levels of accident severity.

Model V1 (Fatal and Injury Accidents-Average Speed Model):

$$E(Y_1) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} Avg^{\beta_1} \tag{4.1}$$

Model V2 (PDO Accidents-Average Speed Model):

$$E(Y_2) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} Avg^{\beta_1} \tag{4.2}$$

Model V3 (Total Accidents-Average Speed Model):

$$E(Y) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} Avg^{\beta_1} \tag{4.3}$$

Model V4 (Fatal and Injury Accidents-Speed Standard Deviation Model):

$$E(Y_1) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp\,(\beta_1 D) \tag{4.4}$$

Model V5 (PDO Accidents-Speed Standard Deviation Model):

$$E(Y_2) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp\,(\beta_1 D) \tag{4.5}$$

Model V6 (Fatal and Injury Accidents-Percent Speeding Model):

$$E(Y_1) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp\,(\beta_1 SP) \tag{4.6}$$

Model V7 (PDO Accidents-Percent Speeding Model):

$$E(Y_2) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} \exp\,(\beta_1 SP) \tag{4.7}$$

where,

$E(Y_1)$ – number of fatal and injury accidents at intersection per 3 years (number of accidents/3 years);

$E(Y_2)$ – number of PDO accidents at intersection per 3 years (number of accidents/3 years);

$E(Y)$ – number of total accidents at intersection per 3 years (number of accidents/3 years);

V_1 – major road AADT (vehicles/day);

V_2 – minor road AADT (vehicles/day);

Avg – average traffic speed on four approaches of the study intersection (km/h);

D –speed standard deviation on four approaches of the study intersection (km/h);

SP –percent of speeding vehicles on four approaches of the study intersection;

α_0, α_1,α_2, β_j – model coefficients.

The above seven models are used to investigate the effect of speed characteristics on accident occurrence. In order to improve the prediction accuracy of the models, another group of models were developed that incorporate all statistically significant speed variables. It should be noted that speed variables that are highly correlated with each other cannot be combined in one model so as to prevent the multicollinearity problem. According to the correlation matrix in Table 4.1, the correlation coefficient between average speed (*Avg*) and percent of speeding (*SP*) was 0.938, which indicates a very strong correlation between the two variables. By contrast, the correlation coefficients between average speed and speed standard deviation (*D*), and percent of speeding were 0.385 and 0.406 respectively, which indicate a relatively weak correlation. Consequently, speed variables that can be combined in one model are: average speed and speed standard deviation, or speed standard deviation and percent of speeding vehicles.

Table 4.1: Correlation Matrix of Speed Variables

	Avg	***D***	***SP***
Avg	1.000	0.385	0.938
D	0.385	1.000	0.406
SP	0.938	0.406	1.000

The model forms for the second group of models are:

Model V8 (Fatal and Injury Accidents-Average Speed and Speed Standard Deviation Model):

$$E(Y_1) = \alpha_0 {V_1}^{\alpha_1} {V_2}^{\alpha_2} MS^{\beta_1} \exp\,(\beta_2 D) \tag{4.8}$$

Model V9 (Fatal and Injury Accidents-Percent Speeding and Speed Standard Deviation Model):

$$E(Y_1) = \alpha_0 V_1^{\alpha_1} V_2^{\alpha_2} \exp(\beta_1 SP + \beta_2 D) \tag{4.9}$$

4.3 RESULTS OF MODEL DEVELOPMENT

A total of seven models in the first group were developed and the modeling results for each model are shown in Tables 4.2 to 4.8. The results show that the Pearson χ^2 and the scaled deviance were significant at the 95% confidence level for all the seven models, indicating that all the models had a good fit to the data. The *t*-ratios of the parameter estimates for the intercept, major and minor traffic volume were significant at 95% confidence level for all the models. As for the speed-related variables, the *t*-ratios of the parameter estimates for speed standard deviation and percent speeding were significant at 95% confidence level in both fatal and injury accident and PDO accident models. However, the *t*-ratio of the parameter estimate for the average speed was significant for fatal and injury accident model but insignificant for PDO accident-based model. The average speed was used to develop a Total Accidents-Average Speed Model and it was found that the *t*-ratio of the parameter estimates for average speed was significant at 95% confidence level.

Table 4.2: Accident Prediction Model V1 (Fatal and Injury Accidents-Average Speed)

Model form: $E(Y_1) = 7 \times 10^{-10} V_1^{0.80} V_2^{0.41} Avg^{\,3.30}$				
SD=86.55 Pearson χ^2=83.10 Degree of freedom=80 $\chi^2_{(0.05,\,80)}$=101.9 $t_{(0.05,\,80)}$=1.96 $t_{(0.10,\,80)}$=1.64 κ =4.38				
Variable	*Constant*	V_1	V_2	*Avg*
Coefficient	7×10^{-10}	0.80	0.41	3.30
t-ratio	6.79^{**}	5.41^{**}	3.41^{**}	4.47^{**}
Note: ** – significant at 95% confidence level.				

Table 4.3: Accident Prediction Model V2 (PDO Accidents-Average Speed)

Model form: $E(Y_2) = 4.9 \times 10^{-8} V_1^{1.05} V_2^{0.66} Avg^{\,1.25}$				
SD=89.05 Pearson χ^2=94.37 Degree of freedom=80 $\chi^2_{(0.05,\,80)}$=101.9 $t_{(0.05,\,80)}$=1.96 $t_{(0.10,\,80)}$=1.64 κ =2.47				
Variable	*Constant*	V_1	V_2	*Avg*
Coefficient	4.9×10^{-8}	1.05	0.66	1.25
t-ratio	4.43^{**}	5.58^{**}	4.34^{**}	1.37
Note: ** – significant at 95% confidence level.				

Table 4.4: Accident Prediction Model V3 (Total Accidents-Average Speed)

<table>
<tr><td colspan="5">Model form: $E(Y) = 3.19 \times 10^{-8} {V_1}^{0.97} {V_2}^{0.59} Avg^{\,1.82}$</td></tr>
<tr><td colspan="5">SD=88.35 Pearson χ^2=91.60
Degree of freedom=80 $\chi^2_{(0.05,\ 80)}$=101.9 $t_{(0.05,\ 80)}$=1.96 $t_{(0.10,\ 80)}$=1.64
κ =2.97</td></tr>
<tr><td>Variable</td><td>Constant</td><td>V_1</td><td>V_2</td><td>Avg</td></tr>
<tr><td>Coefficient</td><td>3.19×10^{-8}</td><td>0.97</td><td>0.59</td><td>1.82</td></tr>
<tr><td>t-ratio</td><td>4.99**</td><td>5.72**</td><td>3.26**</td><td>2.18**</td></tr>
<tr><td colspan="5">Note:
** – significant at 95% confidence level.</td></tr>
</table>

Table 4.5: Accident Prediction Model V4 (Fatal and Injury Accidents-Speed Standard Deviation)

<table>
<tr><td colspan="5">Model form: $E(Y_1) = 3.71 \times 10^{-4} {V_1}^{0.62} {V_2}^{0.45}\ exp\ (0.22\ D)$</td></tr>
<tr><td colspan="5">SD=86.58 Pearson χ^2=81.07
Degree of freedom=80 $\chi^2_{(0.05,\ 80)}$=101.9 $t_{(0.05,\ 80)}$=1.96 $t_{(0.10,\ 80)}$=1.64
κ =4.53</td></tr>
<tr><td>Variable</td><td>Constant</td><td>V_1</td><td>V_2</td><td>D</td></tr>
<tr><td>Coefficient</td><td>3.71×10^{-4}</td><td>0.62</td><td>0.45</td><td>0.22</td></tr>
<tr><td>t-ratio</td><td>5.16**</td><td>4.01**</td><td>3.78**</td><td>4.71**</td></tr>
<tr><td colspan="5">Note:
** – significant at 95% confidence level.</td></tr>
</table>

Table 4.6: Accident Prediction Model V5 (PDO Accidents-Speed Standard Deviation)

Model form: $E(Y_2) = 2.75 \times 10^{-5} V_1^{0.79} V_2^{0.60}\ exp\ (0.28\ D)$				
SD=87.89 Pearson χ^2=84.74 Degree of freedom=80 $\chi^2_{(0.05,\ 80)}$=101.9 $t_{(0.05,\ 80)}$=1.96 $t_{(0.10,\ 80)}$=1.64 κ =3.20				
Variable	*Constant*	V_1	V_2	D
Coefficient	2.75×10^{-5}	0.79	0.60	0.28
t-ratio	6.07**	4.54**	4.47**	5.32**
Note: ** – significant at 95% confidence level.				

Table 4.7: Accident Prediction Model V6 (Fatal and Injury Accidents-Percent Speeding)

Model form: $E(Y_1) = 1.27 \times 10^{-4}\ V_1^{0.82}\ V_2^{0.42}\ exp\ (1.28\ SP)$				
SD=86.42 Pearson χ^2=83.40 Degree of freedom=80 $\chi^2_{(0.05,\ 80)}$=101.9 $t_{(0.05,\ 80)}$=1.96 $t_{(0.10,\ 80)}$=1.64 κ =4.41				
Variable	*Constant*	V_1	V_2	SP
Coefficient	1.27×10^{-4}	0.82	0.42	1.28
t-ratio	5.84**	5.52**	3.48**	4.68**
Note: ** – significant at 95% confidence level.				

Table 4.8: Accident Prediction Model V7 (PDO Accidents-Percent Speeding)

Model form: $E(Y_2) = 4.59 \times 10^{-6} V_1^{1.06} V_2^{0.66}\ exp\ (0.68\ SP)$				
SD=88.90 Pearson χ^2=96.41 Degree of freedom=80 $\chi^2_{(0.05,\ 80)}$=101.9 $t_{(0.05,\ 80)}$=1.96 $t_{(0.10,\ 80)}$=1.64 κ =2.52				
Variable	*Constant*	V_1	V_2	*SP*
Coefficient	4.59×10^{-6}	1.06	0.66	0.68
t-ratio	6.43**	5.67**	4.37**	1.97**
Note: ** – significant at 95% confidence level.				

Table 4.9: Accident Prediction Model V8 (Fatal and Injury Accidents-Average Speed and Percent Speeding)

Model form: $E(Y_1) = 4.67 \times 10^{-8} V_1^{0.65} V_2^{0.39} Avg^{\ 2.4}\ exp\ (0.16\ D)$					
SD=86.24 Pearson χ^2=81.04 Degree of freedom=79 $\chi^2_{(0.05,\ 79)}$=100.7 $t_{(0.05,\ 79)}$=1.96 $t_{(0.10,\ 79)}$=1.64 κ =5.18					
Variable	*Constant*	V_1	V_2	*Avg*	*D*
Coefficient	4.67×10^{-8}	0.65	0.39	2.4	0.16
t-ratio	5.44**	4.47**	3.49**	3.32**	3.51**
Note: ** – significant at 95% confidence level.					

Table 4.10: Accident Prediction Model V9 (Fatal and Injury Accidents-Speed Standard Deviation and Percent Speeding)

Model form: $E(Y_1) = 2.3 \times 10^{-4} {V_1}^{0.67} {V_2}^{0.40}\ exp\ (0.89\ SP + 0.16\ D)$					
SD=86.25 Pearson χ^2=81.54 Degree of freedom=79 $\chi^2_{(0.05, 79)}$=100.7 $t_{(0.05, 79)}$=1.96 $t_{(0.10, 79)}$=1.64 κ =5.11					
Variable	*Constant*	V_1	V_2	*SP*	*D*
Coefficient	2.3×10^{-4}	0.67	0.40	0.89	0.16
t-ratio	5.54**	4.55**	3.54**	3.21**	3.29**
Note: ** – significant at 95% confidence level.					

Table 4.9 and Table 4.10 show the results for the second group of models. The tables show that the Pearson χ^2 and the scaled deviance were significant at 95% confidence level for both models, indicating that the two models were a good fit to the data. The *t*-ratios of the parameter estimates for the intercept, major and minor traffic volume were significant at 95% confidence level for both models. The two speed-related variables were also significant at 95% confidence level.

4.4 EFFECT OF SPEED ON ACCIDENT FREQUENCY

Tables 4.2 to 4.8 show that for all the models developed, the regression coefficients for all the speed-related variables were positive, indicating that average speed, speed standard deviation, and percent of speeding vehicles were positively correlated to the number of accidents occurring at signalized intersections in Vancouver. The higher the average speed, speed standard deviation, and percent of speeding vehicles, the higher the expected accident frequency. It should be noted that the coefficient estimate for average speed in the PDO Accidents-Average Speed Model was not significant at the 95% confidence level. However, the coefficient estimates for average speed were significant in the Fatal and Injury Accidents-Average Speed Model and the Total Accidents-Average Speed Model. Furthermore, the high value of 3.3 of the coefficient estimate for average speed in the Fatal and Injury Accidents-Average Speed Model indicates that the average speed has a very strong impact on fatal and injury accident frequency.

The quantitative effect of speed on accident frequency can be investigated by changing the values of speed-related variables while holding all the other variables in the model constant. The percent of the increase (or decrease) in the number of accidents as a result of the increase (or decrease) of average speed, speed standard deviation or percent of speeding can be expressed as:

1) The change in average speed associated with the change in fatal and injury accident frequency:

$$P_1 = 3.3 \times \frac{\Delta Avg}{Avg} \tag{4.10}$$

2) The change in average speed associated with the change in total accident frequency:

$$P = 1.82 \times \frac{\Delta Avg}{Avg} \tag{4.11}$$

3) The change in speed standard deviation associated with the change in fatal and injury accident frequency:

$$P_1 = exp(0.22 \times \Delta D) - 1 = 1.246^{\Delta D} - 1 \quad (4.12)$$

4) The change in speed standard deviation associated with the change in PDO accident frequency:

$$P_2 = exp(0.28 \times \Delta D) - 1 = 1.323^{\Delta D} - 1 \quad (4.13)$$

5) The change in percent of speeding associated with the change in fatal and injury accident frequency:

$$P_1 = exp(1.28 \times \Delta SP) - 1 = 3.597^{\Delta SP} - 1 \quad (4.14)$$

6) The change in percent of speeding associated with the change in PDO accident frequency:

$$P_2 = exp(0.68 \times \Delta SP) - 1 = 1.974^{\Delta SP} - 1 \quad (4.15)$$

where,

P – percent of increase (or decrease) of total accident frequency at signalized intersection per 3 years;

P_1 – percent of the increase (or decrease) of fatal and injury accident frequency at signalized intersection per 3 years;

P_2 – percent of the increase (or decrease) of PDO accident frequency at signalized intersection per 3 years;

ΔAvg – increase (or decrease) of average traffic speed (km/h);

ΔD – increase (or decrease) of speed standard deviation (km/h);

ΔSP – increase (or decrease) of percent of speeding vehicles.

From the above equations, when the average speed increases (or decreases) by 1%, the fatal and injury accident frequency and total accident frequency will increase (or decrease) by 3.3% and 1.82%, respectively. Every 1km/h increase (or reduction) of speed standard deviation is associated with 24.6% of increase (or decrease) in the fatal and injury accident frequency and 32.3% of increase (or decrease) in the PDO accident frequency. The percent of increase (or decrease) of fatal and injury accident frequency associated with 10% increase (or decrease) of the percent of speeding vehicles is 13.6%. For the PDO accident frequency, it will increase (or decrease) by 7% with every 10% increase (or reduction) in the percent of speeding vehicles. Figure 4.1 compares the change in total accident with the change in PDO accident caused by the change in average speed, while Figures 4.2 and 4.3 compare the change in fatal and injury accident and PDO accident frequency associated with the change in speed standard deviation and percent speeding, respectively.

Figure 4.1 shows that the percent change in average speed can lead to greater percentage of change in fatal and injury accident frequency. Also, Figure 4.2 shows that the increase in speed standard deviation is associated with higher PDO accident frequency. By contrast, as shown in Figure 4.3, the number of fatal and injury accidents will increase more rapidly than PDO accidents when the percent of speeding vehicles increases.

Figure 4.1: Relationship between Percent of Change in Average Speed and Percent of Change in Fatal and Injury Accident and Total Accident Frequency

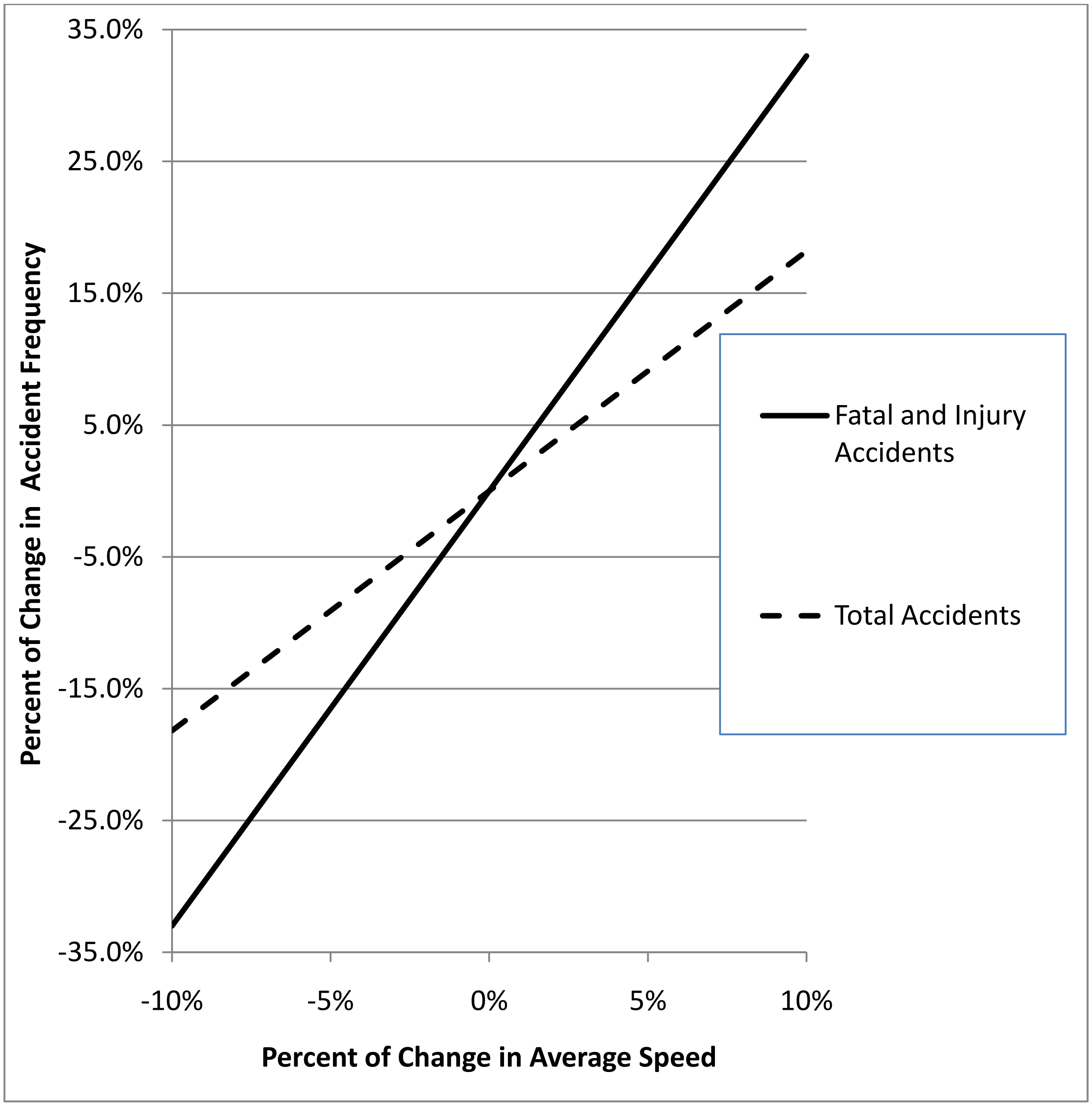


Figure 4.2: Relationship between Change in Speed Standard Deviation and Percent of Change in Fatal and Injury Accident and PDO Accident Frequency

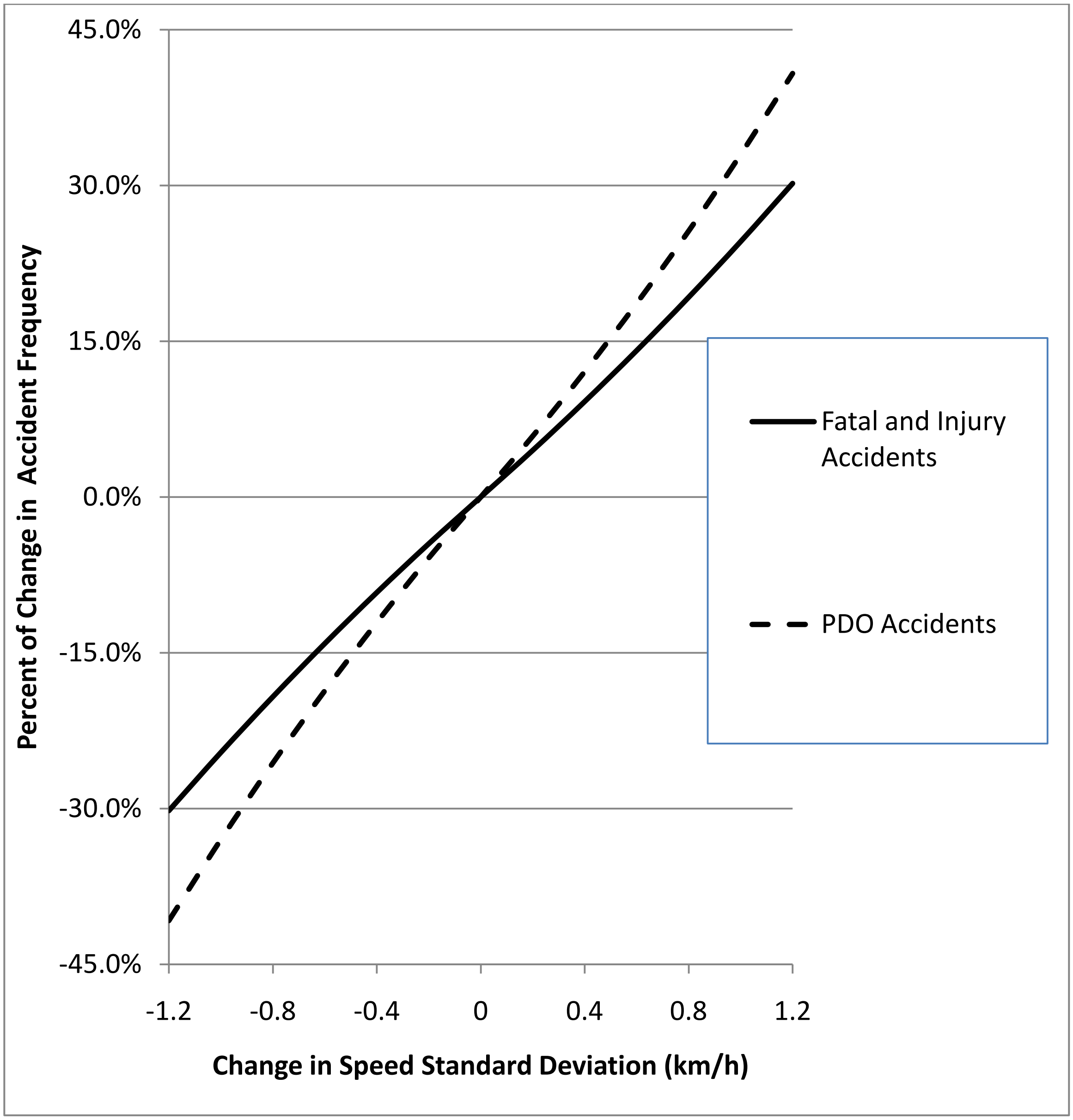
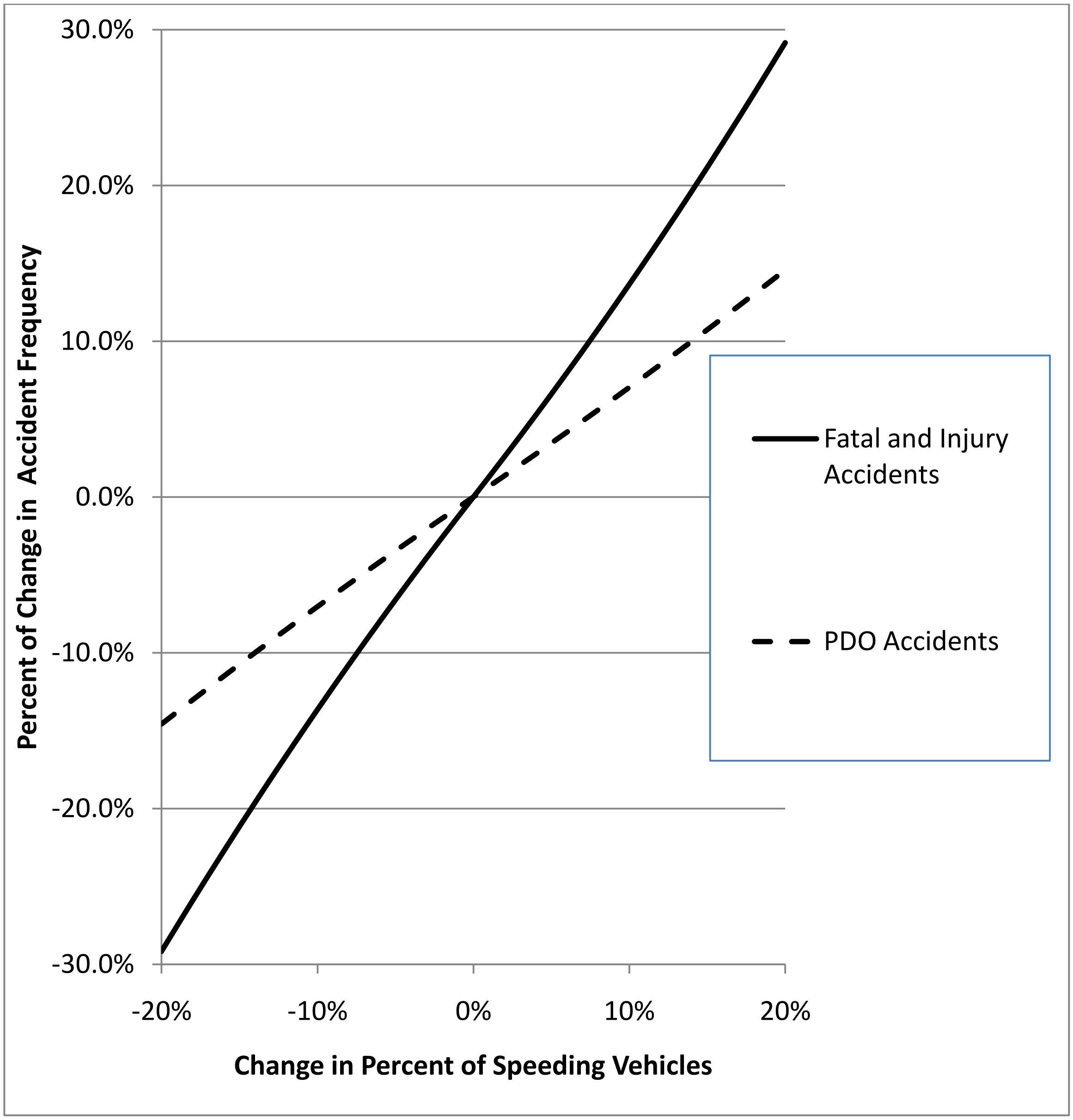


Figure 4.3: Relationship between Change in Percent of Speeding Vehicles and Percent of Change in Fatal and Injury Accident and PDO Accident Frequency



4.5 COMPARISON OF VANCOUVER MODEL WITH EDMONTON MODEL

Two case-studies from Edmonton and Vancouver were used to investigate the effect of speed on accident occurrence by developing accident prediction models which quantitatively relate the accident frequency to speed and other traffic and road factors. Both models were developed for signalized intersections in urban areas in the City of Edmonton and the Greater Vancouver area. The main difference between the two models is in the type of speed-related variables that were included in the model. The Edmonton model included three speed-related variables: average speed, mode speed, and 85th percentile speed. However, Vancouver model used average speed, speed standard deviation, and percent of speeding vehicles. Since the average speed is the only speed-related variable that is included in both Edmonton and Vancouver models, the comparison of two models is focused on the average speed-accident relationship.

The accident prediction model for Vancouver relating the average speed to total accident frequency is:

$$E(Y) = 3.19 \times 10^{-8} {V_1}^{0.97} {V_2}^{0.59} Avg^{\,1.82} \tag{4.16}$$

By contrast, the average speed-total accident model for Edmonton is:

$$E(Y) = 0.0001051\, {V_1}^{0.6090} {V_2}^{0.6952}\, exp\,(0.0099\, Avg + 0.2911\, FL) \tag{4.17}$$

It can be seen from the above two models that the coefficient estimate for average speed is positive for both models, indicating that the average speed is positively related with the total accident frequency. This relationship suggests that more accidents are expected to occur with higher average speeds. This positive correlation between average speed and accident frequency is similar to research findings from other previous studies (Finch et al., 1994; Taylor et al., 2000).

Figures 4.4 to 4.6 compare the Edmonton- and Vancouver-based models. From the Edmonton-based model, when the average speed of the traffic approaching the signalized intersection decreases by 1km/h, the number of total accidents occurring at an intersection will decrease by approximately 1.0%. The Vancouver-based model shows that every 1% change in the average speed is associated with 1.82% of change in total accident frequency. If the initial average speed is 50, 60 and 70km/h, the change in total accident frequency associated with 1km/h of change in average speed is 3.6%, 3.0% and 2.6%, respectively. These three values are higher than the 1.0% change in total accident frequency which is obtained from Edmonton-based model, but are close to what have been found in other previous studies. For instance, Finch et al. (1994) found that every increase or reduction of 1km/h in average traffic speed can result in 3% increase or reduction in the accident frequency. Taylor et al. (2000) found that a 1km/h reduction in average speed is associated with 1.2% to 4.4% decrease in accident frequency with 3% as a general figure.

Figure 4.4: Comparison of Edmonton- and Vancouver-Based Model (Relationship of Change in Average Speed and Percent of Change in Total Accident Frequency, Initial Speed: 50km/h)

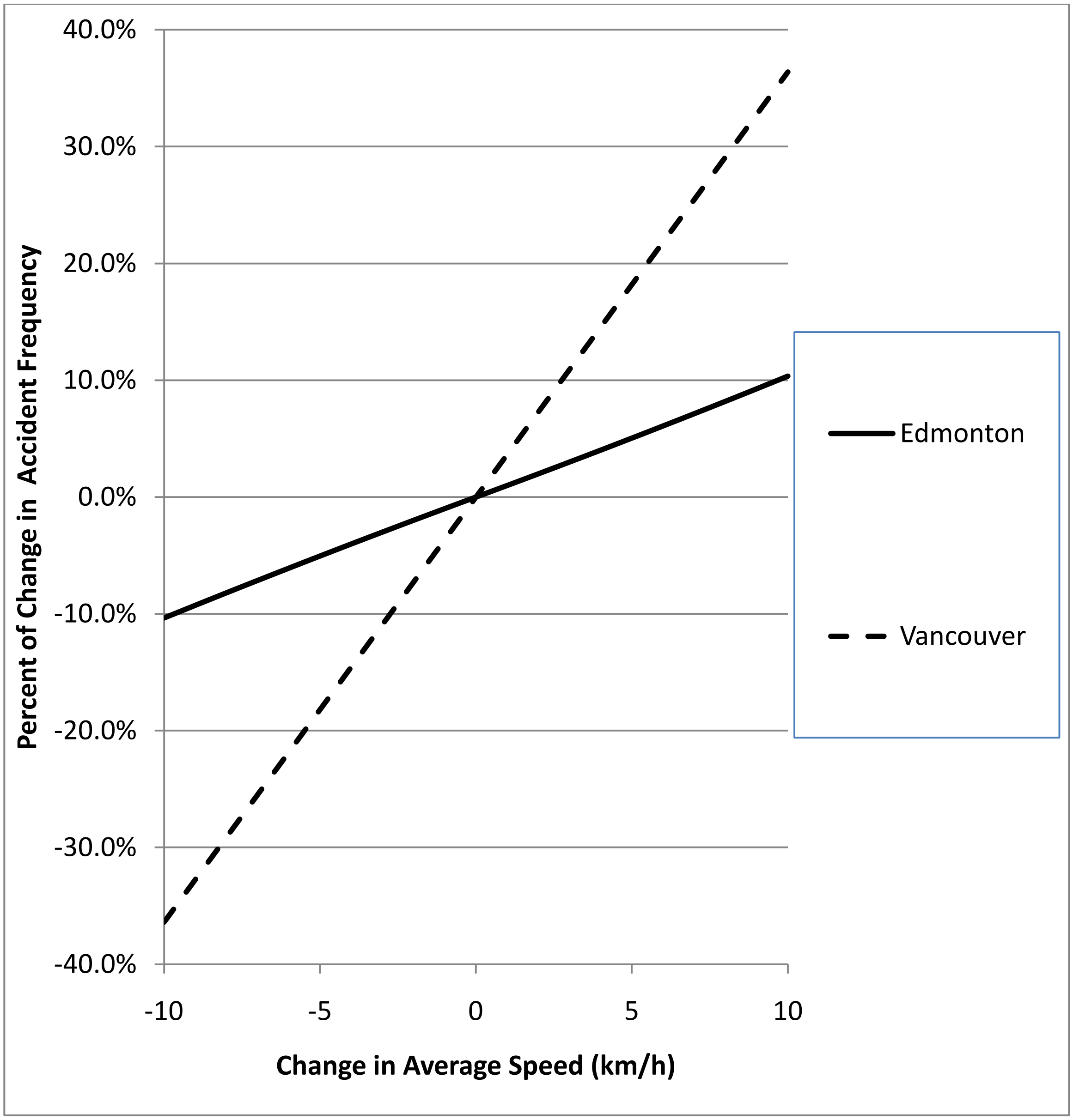


Figure 4.5: Comparison of Edmonton- and Vancouver-Based Model (Relationship of Change in Average Speed and Percent of Change in Total Accident Frequency, Initial Speed: 60km/h)

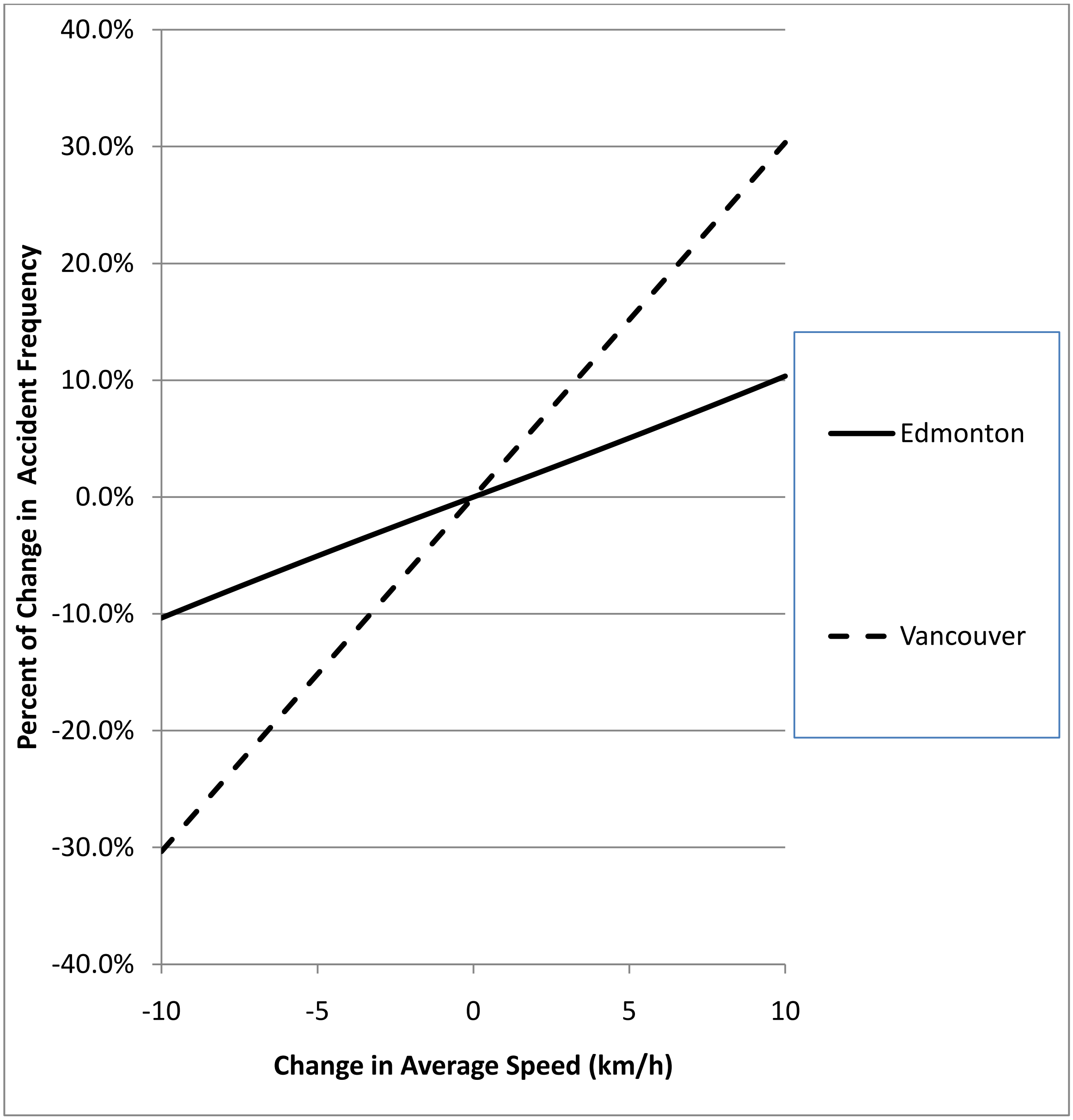
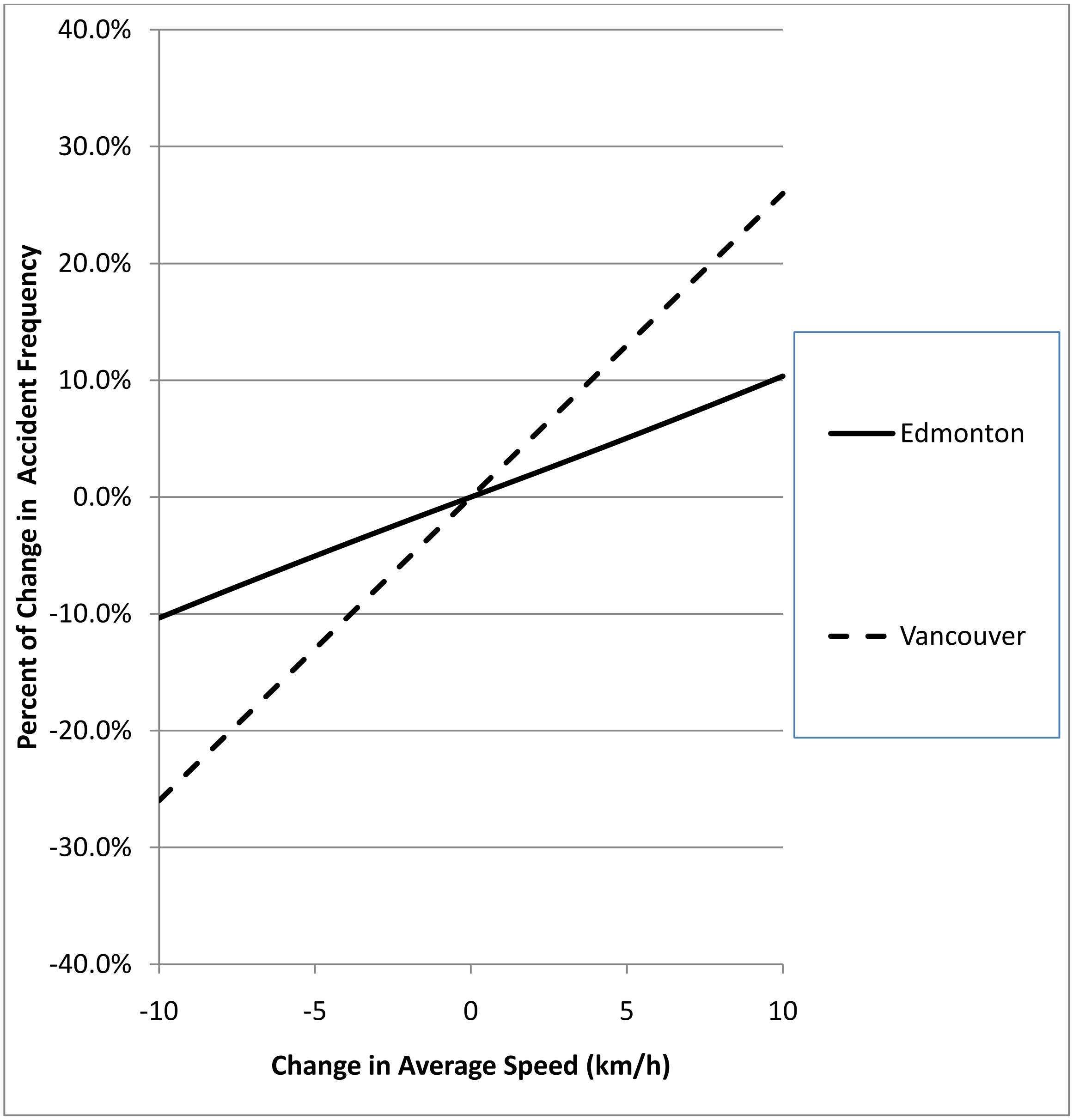


Figure 4.6: Comparison of Edmonton- and Vancouver-Based Model (Relationship of Change in Average Speed and Percent of Change in Total Accident Frequency, Initial Speed: 70km/h)



It should be emphasized that the relationship between speed dispersion and accident occurrence, which is an important aspect of speed-accident study, can be investigated using the Vancouver-based model. The speed dispersion is represented by the speed standard deviation in the model and it is positively correlated with both fatal and injury accident and PDO accident frequency. This finding confirms what has been found in other previous studies (Lave, 1985; Garber and Gadirau, 1988; Taylor et al., 2000) which suggest that both the speed and speed dispersion are important factors in road safety.

5 CONCLUSIONS

Speed is an important factor that influences road safety. A review of previous studies shows that the increase in speed leads to an increase in accident occurrence. This relationship has been established for the speed of individual vehicle and the speed of the traffic at road section. The review also shows that the accident frequency on road sections increases with the speed dispersion or speed variation in the traffic flow. Most studies investigated the speed-accident relationship in rural areas. There is a need to investigate the relationship between speed and accident in urban areas given the fact that the majority of road accidents occur on urban roads.

The objective of this study is to quantify the relationship between traffic speed and accident frequency at urban signalized intersections. This objective is achieved by developing accident prediction models which relate the accident frequency to speed variables and other intersection characteristics. Road accident, traffic speed, volume and road geometric data were obtained from the city of Edmonton and Vancouver in Canada for the purpose of developing accident prediction models. The generalized linear modelling technique was applied in the model development based on negative binomial error structure. The SAS 9.2 statistical analysis software was used to estimate the model coefficients through the method of maximum likelihood. A total of 15 accident prediction models were developed with 6 models for Edmonton and 9 models for Vancouver. These models were used to quantify the effect of traffic speed on accident frequency and the major findings are summarized below.

Major findings from the accident prediction models for Edmonton are:

- Average speed, mode speed and 85th percentile speed of the traffic are positively correlated with accident frequency at urban signalized intersections: the higher the traffic speed, the higher the expected number of accidents.
- Every 1 kilometre per hour increase (or decrease) in average traffic speed is associated with a 1.0% increase (or decrease) in the total accident frequency and a 1.2% increase (or decrease) in the property damage only accident frequency.
- Every 1 kilometre per hour increase (or decrease) in the mode speed of the traffic is associated with a 0.9% increase (or decrease) in the total accident frequency and a 1.1% increase (or decrease) in the property damage only accident frequency.
- Every 1 kilometre per hour increase (or decrease) in the 85th percentile speed of the traffic is associated with a 1.2% increase (or decrease) in the total accident frequency and a 1.4% increase (or decrease) in the property damage only accident frequency.

Major findings from the accident prediction models for Vancouver are:

- Average speed, speed standard deviation and percent of speeding vehicles are positively correlated with accident frequency at urban signalized intersections.
- Every 1% increase (or decrease) in average traffic speed is associated with a 3.3% increase (or decrease) in the fatal and injury accident frequency and a 1.82% increase (or decrease) in the total accident frequency. If the initial speed is 50, 60 and 70km/h, the change in the total accident frequency associated with every 1 kilometre per hour change in average speed is 3.6%, 3.0% and 2.6%, respectively.

- Every 1 kilometre per hour increase (or decrease) in speed standard deviation is associated with a 24.6% increase (or decrease) in the fatal and injury accident frequency and a 32.3% increase (or decrease) in the property damage only accident frequency.
- Every 10% of increase (or decrease) in the percent of speeding vehicles is associated with a 13.6% increase (or decrease) in the fatal and injury accident frequency and a 7.0% increase (or decrease) in the property damage only accident frequency.

Two speed variables in the models, namely the average speed and the speed standard deviation, were used to describe two characteristics of the speed in traffic flow. The average speed describes how fast the traffic is moving. The speed standard deviation represents the dispersion or spread of the traffic speed. Larger speed standard deviation indicates a larger spread of the traffic speed around the average speed or larger variation of speeds in traffic flow.

The aforementioned findings show that the average speed and speed standard deviation are positively correlated with accident frequency. Therefore, it can be concluded that both the average traffic speed and speed dispersion are important factors influencing road safety. The higher the average speed, the higher the expected accident frequency. Similarly, the larger the speed dispersion leads to higher number of accidents. This conclusion suggests that speed management programs, whose objectives are to manage and control the traffic speed and therefore minimize the accidents, should not only aim at slowing the traffic speed, but also aim at reducing the speed variation in the traffic flow. Setting both the maximum and minimum speed limits on freeways or motorways is a good example of speed management countermeasures which aim at reducing both the speed and speed dispersion.

The quantitative effect of speed on accident frequency found in this study can be used to estimate the reduction in accident frequency resulting from the reduction in speed, and therefore assess the effectiveness and cost-effectiveness of different speed management strategies or countermeasures. The estimation of the safety effectiveness and cost-effectiveness of speed management countermeasures is important in the selection of optimum measures by road agencies and authorities in order to achieve maximum safety benefits and highest rate of return on the investment.

6 FUTURE RESEARCH

The relationship between traffic speed and accident frequency that has been reported in this study is specific for signalized intersections in urban areas. It is suggested to conduct similar studies in the future for other types of intersections and different types of road sections in both urban and rural areas. In addition, a larger sample size is recommended in the future in the development of models so as to improve the model fit and parameter estimation.

The accident prediction models in this thesis have been developed based on the assumption that the error structure follows a negative binomial distribution. This type of model is also known as the Poisson-gamma model which accounts for the Poisson extra-variation or heterogeneity in the road accident data due to unknown or unobserved characteristics for the study sites such as road geometrics, traffic and road environment features. Although the Poisson-gamma model is commonly used in modelling accident occurrence, it does not account for one type of variation that can affect the distribution of accidents, namely the spatial effects. Neighbouring intersections or road segments can be considered as spatially correlated since they are likely to have similar roadway factors and environmental characteristics and therefore have similar accident occurrence. Incorporating the spatial effects in the development of accident prediction models has been getting increasing attention in recent years. Aguero-Valverde and Jovanis (2008) demonstrated that one of the most important reason to include spatial correlation in accident models is that spatial models pool information from neighbouring sites to improve parameter estimation.

Furthermore, the spatial correlation can be a surrogate for unknown, unobserved, and relevant covariates and thereby the model estimation can be improved. Congdon (2006) stated that ignoring spatial effects can lead to underestimation of variability. El-Basyouny and Sayed (2009) developed three spatial models for urban arterials and compared these models with the traditional model without the spatial effects. The results showed that spatial models provided significant improvement in goodness of fit.

The empirical Bayes (EB) and maximum likelihood approach were used in the model specification and estimation in this thesis. However, this approach ignores the uncertainty associated with parameter estimates and thus tends to overestimate the precision of the model parameters. The full Bayes (FB) approach, on the other hand, takes into account of this uncertainty and provides exact measures of uncertainty (Goldstein, 1999). FB approach has been recently used in roadway safety analysis such as ranking of accident-prone locations (e.g., Miaou and Song, 2005) and development of spatial models (e.g., Aguero-Valverde and Jovanis, 2008).

In the future work, the two advanced techniques as mentioned above, i.e., the spatial model and FB approach, can be introduced into the development of accident prediction models for the purpose of improvement in the model estimation. Therefore the speed-accident relationship can be investigated through the more reliable models.

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