Impact of Road Surface Temperature and Condition on the Risk of Winter Vehicle Collisions

by

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ABSTRACT

Pavement surface temperature and moisture condition are very important factors that influence road safety during the wintertime. Yet the literature lacks any serious research to determine their effects. Knowledge of pavement temperature is also necessary to prepare effective road winter maintenance operations.

This thesis examined the effect of pavement surface temperature and moisture condition on the risk of vehicle collisions during wintertime using 2001/2002 data from the City of Ottawa. Analysis included collisions involving fatalities, injury, PDO, single-vehicle, rear-end, and other impact types. During peak and off-peak periods, collision frequencies on wet pavement had their maximums at −1°C and remained relatively high around this temperature. The collision frequencies on dry surface had no specific pattern with changing temperature. A pavement moisture risk factor was calculated as the ratio between collision rate per hour of exposure on wet surface and that on dry surface at each pavement temperature. Results concluded that the risks of collision on wet surface were higher than those on dry surface for all categories and were higher during the off-peak period than during the peak period at all categories but the single-vehicle collisions. The increase in collision risk ranged from 12% for rear-end collisions during peak period to 106% for single-vehicle collisions, also during peak period.

Empirical Bayes probability method was developed as a powerful tool to determine the hazardous pavement surface temperature and moisture condition combinations. Results concluded that at 95% confidence level, driving on dry pavement surface during wintertime was not hazardous at any temperature and that moisture on

pavement surface increased the hazardous driving condition particularly when the surface temperature was at or below the freezing mark.

In addition, statistical models that can be used in the decision-making process for winter maintenance operations were developed to predict pavement surface temperature from weather variables. Advanced statistical tests were performed to detect multicollinearities and autocorrelation. The final version of the models included lag dependant variables.

A case study confirmed the model accuracy and applicability. The predicted values of the surface temperature were dependent on the accuracy of the air temperature and dew point forecasts.

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1. INTRODUCTION

The network of roads and highways represents the backbone of the transportation system in Canada. It has had a tremendous impact in shaping its society and economy. Since the turn of the century, this network has mushroomed with the evolution of the internal combustion engine and the automobile has become the most significant means of passenger travel in Canada.

In 2002, the Canadian road network had more than 1.4 million two-lane equivalent kilometres (Transport Canada 2004). The network consists of 110,000 kilometres of freeways and primary highways, 115,000 kilometres of secondary highways and other arterial roads, and more than 1.2 million kilometres of local streets and rural connector roads. In that year, personal spending on transportation was about CAN$103 billions in addition to CAN$2.6 billions on public transit. Government at their different levels spent over CAN$14 billion on roads. According to the 2002 Canadian Vehicle Survey, the number of light (gross weight less than 4,500 kilograms) vehicles was close to 17.3 million, including passenger cars and station wagons, vans, pickup trucks, and sport utility vehicles. In that year, there were 550 vehicles per 1000 people in Canada and Canadians relied on private motor vehicles to travel 289 billion-kilometres. An additional 857.1 million vehicle-kilometres were travelled on public transit with CAN$7.1 billion revenues reported by the bus industry, including government contributions.

During wintertime, Canadian roads and highways have to contend with very cold and severe weather conditions of falling snow, strong wind, freezing rain, and ice formation and accumulation on pavement surfaces. These conditions compromise the level of road safety by increasing the risk of vehicle collisions, damage to property, injury, and death. The frequency of collisions involving fatalities and injury in 2002 on Canadian roads was 159,498 resulting in 2,936 fatalities and 227,768 injuries (Transport Canada, 2004). The estimated social cost of the road collisions in this year to Canadians was about CAN$25 billions.

These harsh winter conditions can have adverse socioeconomic impacts on both individuals and businesses in terms of increasing travel times and costs. For example, some regions can be isolated causing their economic activities to decrease as a result of the inability of employees to reach their workplaces or the inability of consumers to reach the marketplaces. Furthermore, access to vital resources can come to a halt due to the inability of emergency and security services to operate efficiently. This regional economic slowdown can have a larger impact on the economy of a wider part of the country. Since main objectives of the municipal governments are to ensure the smooth flow of traffic on all roads at all times, provide road safety, and minimize harmful effects on the environment (Katko, 1993), winter maintenance operations to clear snow and ice from roads are undertaken. They include the application of salt chemicals for deicing and anti-icing purposes, which can have damaging effects on the surrounding wildlife and environment. The following section discusses the effects of winter conditions on the risk of vehicle collisions in Canada and the United States.

1.1. Weather Related Risk of Collisions

All regions in Canada and many regions across the United States experience a number of snow and freezing rain events during wintertime every year. These events create slippery road conditions leading to an increase in the frequency of traffic collisions. Considerable amounts of research and experimental field studies have been undertaken to establish relationships between the risk of collisions and specific weather conditions (Sherretz and Farhar, 1978; Brodsky and Hakkert, 1988; Andrey and Olley, 1990; Knapp, 2001). These studies provided empirically derived estimates of weather-related risk of collision, which varied from one study to another due to differences in methods of estimation and weather conditions. The studies also concluded that precipitation, in particular, represents a serious risk factor in road transportation. Collision frequency and risk level were found to increase during the freezing rain condition (Andrey *et al.*, 2003). Analysis of vehicle collisions during wintertime also revealed significant increases in injury and noninjury collision rates per million vehicle-kilometres during winter snow events when compared to injury and noninjury collision rates per million vehicle-kilometres during equivalent winter nonsnow events (Khattak and Knapp, 2001). For example, rear-end collisions occur due to skidding on wet pavement surface and were observed to correlate to the amount of snowfall in centimetres (Asano *et al.*, 2001).

1.2. Winter Maintenance

Winter maintenance is an operation undertaken to control the snow and ice formation on roads and sidewalks and to provide higher levels of traffic safety and traffic flow. The strategies used by transportation agencies to undertake these operations are generally mechanical (snow plowing, removal, and disposal), and chemical (application of salts as freezing- point depressants) (Blackburn *et al.*, 2004). The use of road salts as deicing and anti-icing chemicals has been the number one alternative, which has proven itself in dealing with slippery and icy roads (Katko, 1993). Sodium chloride, known as road salt, is the most commonly used chemical for snow and ice control. Other salts, such as, calcium chloride and magnesium chloride are also well-known deicers. Winter maintenance operations are associated with socioeconomic costs and benefits as well as environmental costs.

1.2.1. Socioeconomic Costs and Benefits

The cost of the winter events is very high. For example, to ensure the safe and efficient transportation of goods and people the, United States spends on average U.S. $2.1 billions annually on the maintenance operations to control snow and ice; over U.S. $700 millions of these expenditures are used to cover the cost of chemicals (Chollar and Nassif, 1998). Extra costs are added as a result of rust and corrosion to motor vehicle, roads, and bridges from the use of road salts. Although road salts have negative economic impacts on roads and vehicles, their use in winter maintenance operations has considerable socioeconomic benefits, which largely outweigh the high costs by reducing the number of deaths, injury, and damage to vehicles and properties. Some studies estimated these benefit/cost ratios in the range from 2.0:1 to 18.1:1 (TAC, 1999). Wikelius *et al.* (1996), quoted the benefit/cost ratios as about 2 for direct benefits and about 10 for indirect benefits. These estimates suggest that each dollar spent on winter maintenance produces at least two dollars in benefit.

1.2.2. Environmental Costs

Road salts pose a serious risk to the environment. They enter surface water, soil and ground water after snowmelt, and are dispersed through the air by splashing and spray from vehicles and as wind-borne powder (Environment Canada, 2002). They contain chloride ions, which are conservative, moving with water without being retarded or lost. Accordingly, almost all chloride ions that enter the soil and groundwater can ultimately be expected to reach surface water. It may, however, take from a few years to several decades or more for steady state groundwater concentrations to be reached. Therefore, although the benefits of using road salts in winter maintenance operations overweigh their costs, they are harmful to the environment and their use should be kept to a minimum.

1.2.3. Pavement Surface Temperature

The type and amount of deicers used in winter maintenance operations depend upon the pavement surface temperature and moisture on the road surface (Minsk, 1998). Pavement surface temperature determines whether falling snow will melt away and whether rain precipitations will freeze upon contacting the pavement surface. For example, ice will form on pavement surface when the dew point exceeds the pavement surface temperature (Karlsson, 2001). Therefore, knowledge of surface temperature ahead of time is an important element in preparing efficient and cost effective winter maintenance operations. However, according to Bernstein et al. (2004), "*Road temperature is, of course, one of the most important parameters to forecast correctly, yet it is also one of the most difficult to measure and forecast*".

Development of simple, reliable, and less expensive statistical models to predict pavement surface temperature to be used in planning winter maintenance operations is one of the key objectives of this research.

1.3. Road Weather Information Systems (RWIS)

Over the years, technologies and practices for winter maintenance operations have changed. In the past, visual inspection and primary statistical analysis were performed to identify and predict snow levels on the roads. Since the beginning of the 1980's, Road Weather Information Systems (RWIS) have been used in Europe and are becoming more widely used in several North American cities, provinces, and states. In addition, more RWIS installations are planned on U.S. and Canadian highways (Crevier and Delage, 2001). The RWIS consist of pavement and atmospheric sensors, located at Remote Processing Units (RPU), to provide continuous real-time information for winter road maintenance operations (Minsk 1998). Multiple sensors embedded within the pavement are used to measure pavement and bridge temperatures, often on multiple roads at an interchange (Bernstein *et al.*, 2004). These sensors also collect information on the surface condition and send them to adjacent towers. Through the proper software, this information can be available for maintenance staff and supervisors on a Local Area Network (Karlsson, 2001). The number of RPU's and area served by each RPU depend upon the availability of financial resources and the required accuracy of the information. Figure 1.1 shows the RPU at Hawthorne Road in the City of Ottawa, and Figures 1.2 – 1.4 show atmospheric and pavement sensors used to record the RWIS information.

The use of the RWIS, according to this research, would be more suitable for providing instant road and weather information to drivers on the roads but would not be suitable for planning winter maintenance operations. The following are some problems associated with the use of the RWIS as a tool for winter maintenance planning operations:

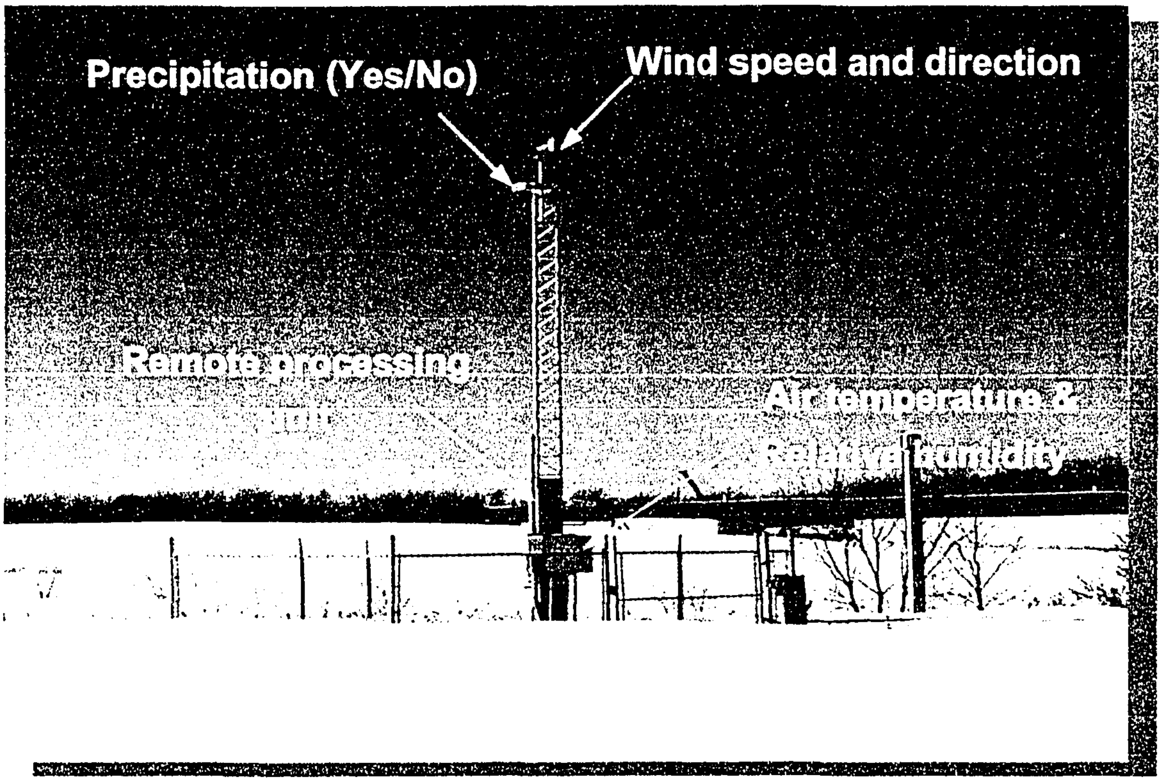
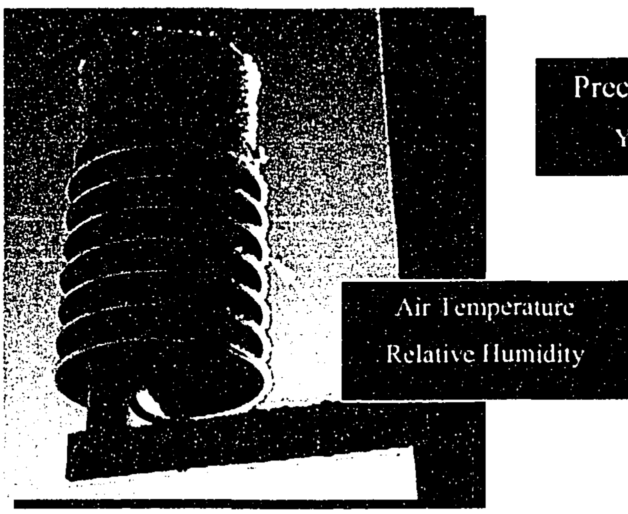
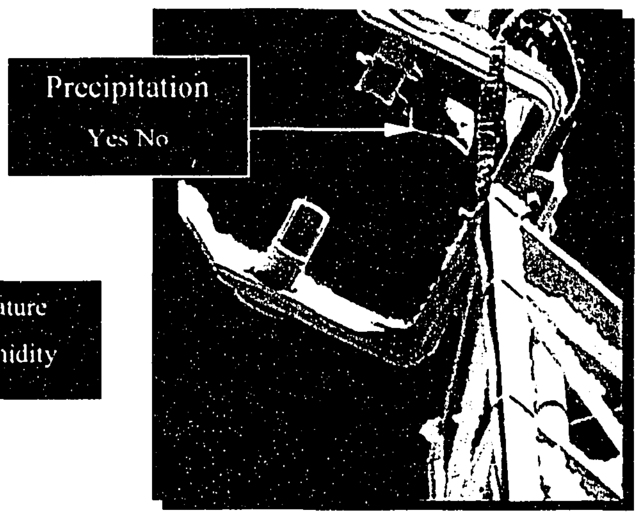


Figure 1.1: Atmospheric sensors and the remote processing unit at Hawthorne



(a)



(b)

Figure 1.2: Atmospheric sensors for (a) air temperature and relative humidity and (b) precipitation (Yes/No)

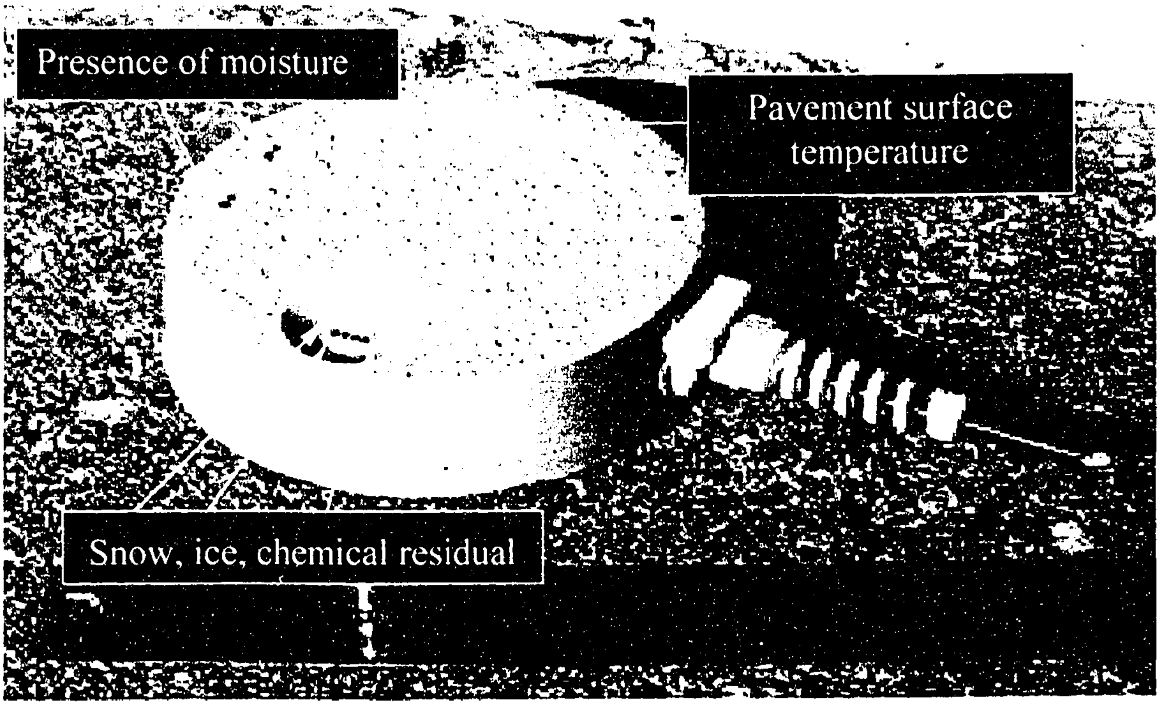


Figure 1.3: Pavement surface sensor

Figure 1.4: Pavement surface sensor embedded in the ground

1. The RWIS stations provide past and present-time information on pavement surface temperature and pavement moisture condition that have limited usefulness in planning future effective winter maintenance operations. The maintenance personnel need some leading time to prepare plans for their maintenance operations. Therefore, there will always be a time lag between receiving the information on pavement surface temperature and pavement moisture condition and the real-time of the maintenance operations.
2. The RWIS technology requires a large number of stations at very high costs in order to cover reasonably wide geographic areas. Many of the local governments do not have the financial resources needed to install and maintain these large number of RWIS stations.

According to Kwon and Fleege (2000). "*Although ice forecasting has significantly aided deicing operations, states recognize that statewide RWIS implementation is a large, expensive effort. A typical statewide RWIS costs tens of millions of dollars, and additional millions for system maintenance. States also recognized that much of the predicted and real-time weather information available from a RWIS, such as air temperature, humidity, precipitation, and wind speed and direction, is redundant - such data are freely available from the National Weather Service or from other private organizations.*"

During the analysis of data collected in the City of Ottawa in the winter of 2001/2002, all the RPU stations had suffered from dropout periods for almost all weather and pavement variables. Sensors and/or the weather recording instruments were unable to function as required due to unexpected technical difficulties. In some cases, it needed several days or weeks to fix the problem; in others it took over one month to get the stations back to work. Some of them were left idle for the whole winter due to lack of maintenance funds. Therefore, installation of more RWIS stations is not the answer for planning effective winter maintenance operations. Instead, providing a tool, such as a statistical model, which is able to predict the pavement surface temperature would be extremely beneficial to the local authorities. This model, however, should be as accurate as possible, reliable, cheap to operate and maintain, and user friendly.

1.4. Prediction of Pavement Surface Temperature

Road authorities have gone a long way in establishing systems, policies and procedures to develop efficient winter maintenance operations. Recent practices for snow and ice control on roadways are moving towards the use of pavement surface temperature as a guide to the application of a deicer. As a result, the knowledge of pavement surface temperature has become an important factor in planning more effective and efficient winter maintenance operations. One method of predicting pavement surface temperature is to identify those variables that affect the surface temperature such as the weather conditions (called the independent variable) and develop statistical models, which can quantify these interdependencies. The unknown parameters of these statistical models can be estimated from the historical observations of both pavement surface temperature and the independent variables using one of the available statistical techniques such as time series analysis or regression analysis. The estimated models can then be used to predict the pavement surface temperature for given values of the independent variables.

1.5. Problem Definition and Research Needs

Falling snow and the formation of ice on Canadian roads during the wintertime present significant potential impediments to safe travel. The weather conditions induce variations in the pavement surface condition (temperature and moisture), which in turn may create significant variations in surface traction, particularly when moisture is present on the surface. As a result, the risk of vehicle collision increases and can result in high socioeconomic costs to society in terms of death, injury, and property damage.

Most studies examined only the effect of weather related conditions on the risk of collision. Although many road collision investigations have suggested that there is a strong relationship between collision occurrences and surface condition (Brown and Baass, 1997), in-depth analysis of this relationship has not been undertaken. Examining the relationship between surface condition and the risk of collision will add to the efforts of enhancing the research of road safety. Moreover, the determination of the combinations of pavement surface temperature and pavement moisture condition at which road driving becomes hazardous will provide vital information to authorities and the public, which can lead to the reduction in the number of collisions and therefore substantial socioeconomic cost savings.

To control the effect of snow and ice formation on the pavement surface, authorities undertake winter maintenance operations. The application of road salts in these operations as deicers and anti-icers is associated with socioeconomic costs and negatively impact on the environment; therefore, their use should be kept to a minimum. The knowledge of surface temperature is one of the important elements in preparing an efficient and cost effective winter maintenance operations. Some North American cities, including the City of Ottawa, have installed Road Weather Information Systems to help planning their winter maintenance operations. The RWIS technology, however, suffers from many shortcomings, which limit its suitability for that purpose. In the mean time, data on different weather variables are already being collected by Environment Canada for various reasons, and are available for the local governments at marginal costs. Therefore, an attractive and more cost effective viable alternative for the use of a large number of RWIS is to use available data from the central government or the existing RWIS to develop statistical models capable of predicting pavement surface temperature at different locations that have similar pavement and weather conditions. These models, however, should be cheap to develop and maintain, accurate, reliable, and user friendly.

There are a number of reasonably simple models available to predict the pavement surface temperature. These models, however, were developed to predict the maximum and minimum surface temperatures from weather variables such as air temperature, dew point, precipitation, and wind speed. Other models were developed to predict the occurrence of frost and icy conditions on the roads. The models developed to predict the pavement surface temperature at all times were built on the basis of an equilibrium system of heat transfer equations. These models involved a very large number of variables interconnected through many equations, which are interdependent. The forecasts of many of these variables are required to predict the surface temperature and any small error, whether is stochastic or systematic, will find its way through all these interdependent equations and may result in considerable prediction errors in the surface temperature.

1.6. Research Objectives and Scope

The main objective of this thesis is to study the effect of pavement surface temperature and pavement moisture condition on the risk of vehicle collisions during the wintertime. This will allow for the identification of pavement surface temperatures and pavement moisture condition at which the risk of collision is higher than average. Such information can result in enormous savings to authorities and the public if used to decrease the risk of collision on city roads. The time period used for this study was from November 1, 2001 to March 31, 2002. Since the citywide traffic volume was not available for the City of Ottawa, the rates of collision per hour of exposure were used. These rates were calculated for collisions that occurred on wet and dry surfaces. For more data consistency, some adjustments were to the data were made. First, only collisions occurred on Monday to Friday was considered since the traffic pattern during the weekends is different from that during the working days. Secondly, only collisions occurred between 6:01 am to 9:00 pm were used since the traffic volumes during the late night and early morning hours are extremely light. Such a condition would logically produce very low numbers of collisions and would in turn bias the calculation of the collision rates. Finally, to minimize the need for the traffic volume, the study period was divided into peak and off-peak periods. The peak period included the hours from 6:00 am to 9:00 am and from 3:00 pm to 6:00 pm. The remaining hours constituted the off-peak period.

It is then assumed that the above adjustments would provide uniform and consistent traffic data within each period. There was no attempt to compare results from the peak period with the off-peak period since each has different characteristics such as speed and traffic volume, particularly since behaviour of the drivers, which was not taken into consideration in this study, is different in each period.

The existing types of pavement surface on the roads of the City of Ottawa are mainly asphalt concrete (about 94%) and gravel (about 6%). A total of less than 0.5 km (0.0045%) of the city roads is surfaced by Portland cement concrete. The majority of traffic occurs on the asphalt roads, and therefore this study did not attempt to break down vehicle collisions or surface temperature by the type of pavement.

To examine the effect of pavement surface temperature and pavement moisture condition on the risk of winter related collisions, the rates of collision were disaggregated into two classifications, severity and initial types of impact.

- Severity of collision included fatal collisions, collisions involving injury, and collisions involving property damage only (PDO).
- Initial types of impact included single-vehicle collisions, rear-end collisions, and other types of collisions.

Two different approaches were used to study the effect of pavement surface temperature and pavement moisture condition on the risk of collision. The first approach uses the pavement moisture risk factor, which is the ratio between the rate of collision on wet surface and the rate of collision on dry surface. The second approach applies the Empirical Bayes (EB) technique, analogous to that adopted by Higle and Witkowski (1998), to identify hazardous pavement surface temperature and pavement moisture condition combinations during the winter months. In that approach, the collision rate per hour of exposure associated with a particular pavement surface temperature and pavement moisture condition combination is assumed to be a random variable. Driving at a given pavement surface temperature and pavement moisture condition combination was considered in this research to be hazardous if the probability that the collision rate associated with this combination greater than the average collision rates of all combinations is greater than a predetermined tolerance level, usually 95% or 99%.

Another objective of this thesis is to develop simple statistical models capable of predicting pavement surface temperature at all times during the winter months from the knowledge of the weather variables forecast. These models may be used by the local authorities to develop more cost effective winter maintenance operations and to optimize the deicer application for snow and ice control. This will maximize their return on the cost of installing the RWIS stations while impacting positively on the environment. Three RPU's out of the nine RPU's in the City of Ottawa were excluded from the study due to the large amount of missing data during the dropout times. The remaining six were enough to develop the models.

A three-step modelling framework is used to achieve this objective: model formulation, model estimation, and diagnostic checking. Plotting data of surface temperature versus air temperature concluded that the linear model is adequate for the purpose of this study.

1.7. Thesis Organization

This thesis consists of eight chapters, which are organized as follows:

Chapter one presents an introduction to the nature and use of Canadian road and highway network, discusses the weather-related risk of collisions, and the importance of the winter maintenance operations. It discusses the socioeconomic benefits and costs, and the environmental costs of using the road salt deicers. Finally, it defines the problem under consideration as well as the objectives and scope of this research.

Chapter two presents a review of the literature on road safety and previous methods and modeling techniques used to predict pavement surface temperature from the knowledge of weather variables.

Chapter three discusses the manipulation of the collision data and explains the methodology used to compare collision rates on wet pavement surface to those on dry pavement surface at different surface temperatures during the peak and off-peak periods by using the pavement moisture risk factors.

Chapter four provides the theoretical framework of the EB statistical analysis and its application to determine the combinations of pavement surface temperature and pavement moisture condition (wet versus dry) at which road driving is hazardous (in other words, the probability that a collision rate higher than average is greater than a predetermined tolerance level).

Chapter five presents the models developed at different locations to predict pavement surface temperature from weather variables, using data from RWIS stations in the City of Ottawa during winter months of 2001/2002. Different statistical tests of multicollinearity and autocorrelation were also explained and performed.

Chapter six presents the introduction of the time-lag dependent variables in the surface temperature prediction models to improve their predictability. The modified autocorrelation tests were also discussed.

Chapter seven presents a case study for the prediction of surface temperature from the forecast of air temperature and dew point and identify the hazardous pavement surface temperature and pavement moisture condition combinations and compare the results to real collision data.

Finally, Chapter eight gives the conclusions of this research and some recommendations for future research.

2. LITERATURE REVIEW

Vehicle collisions on roads and highways represent an enormous problem in almost all countries. Although many safety measures, including stronger safety regulations and public awareness safety campaigns, have been taken in order to reduce road collisions, the total death resulting from worldwide traffic collisions each year still amounts to over 90% of the annual total transportation fatalities (Tighe *et al.*, 2000). An important factor contributing to vehicle collisions is the weather conditions (Edwards, 1998). During wintertime, weather conditions have significant impact on traffic, directly by causing poor visibility or indirectly by causing poor driving conditions (e.g. slipperiness due to snow, slush or ice on the road), therefore, multiplying the risk of collision (Toivonen and Kantonen, 2001). However, pavement surface temperature and pavement moisture condition have more direct relationship to the risk of vehicle collisions than the weather conditions, particularly during wintertime. Therefore, a major objective of this thesis is to try to examine and understand the extent of the effect of the pavement surface temperature and pavement moisture condition during the wintertime on the risk of collisions. The review of existing literature showed that although there is a large number of studies relating weather conditions during winter times to the risk of vehicle collisions, no serious in-depth attempt was made to study the effect of pavement surface temperature and pavement moisture condition on the risk of vehicle collisions.

In cases for which slippery roads are predicted, winter maintenance operations are undertaken to mitigate the danger of this condition and allow for smooth and safe traffic flow on the roads. Winter maintenance operations include the use of road salt deicers, which represents an environmental concern for both the public and governments.

This chapter presents a comprehensive literature review of previous research covering the following areas:

1. The risk of road vehicle collisions.
2. Impact of weather conditions on road vehicle collisions.
3. Road winter maintenance operations.
4. Modelling pavement surface temperature.

2.1. The Risk of Road Vehicle Collisions

There are various types of road collisions, which may raise particular concerns during the wintertime; each can results in different levels of injury. Road safety engineers need simple yet robust methods of comparing the relative risk of various types of collision to be able to plan and design safer roads and minimize injury. Several studies developed some of these methods and used them in identifying potential high-hazard locations, predicting the benefits expected from a collision countermeasure, and evaluating the impact of a countermeasure once it is in place (Davis, 2000).

Kim (2000) derived a simple and robust technique for estimating the relative risk of various types of collisions in terms of injury outcomes called "collision- and injury-outcome multipliers". In the multiplier concept, collisions are events that produce certain severity outcomes. He defined the injury-outcome multiplier, for example, as the ratio between total number of people injured during a specific time period and the total frequency of collisions during that period. Another example of the multiplier was the fatality multiplier, which was obtained by dividing the number of people killed in collisions over a ten-year period by the total frequency of collisions over the same period. The multiplier in this case represents the number of fatalities per single collision. Kim

(2000) examined the various types of collisions such as single-vehicle collisions (utility pole, run off the road, and overturn) and vehicle-to-vehicle collisions (head-on, rear-end, sideswipe same and opposite directions, angle same and opposite directions, and broadside) and found that single-vehicle collisions were much more serious in terms of severity outcomes than most of vehicle-to-vehicle collisions, with the exception of head-on collisions. He suggested that these collision multipliers could be used to establish baseline conditions before safety programs implementation and to establish targets or benchmarks for safety improvements. The multipliers could also be tied to budgetary process to ensure that the serious safety problems are being addressed adequately and to justify spending in a particular program area.

There are some limitations with the use of these multipliers. For example, they are data-driven and can be misleading or wrong if the data quality was poor or there were many missing observations. Another limitation is that they can be subject to misuse or abuse. The multipliers are much like the induced-exposure methods, whereby population involved in a collision is used as the base against which to compare the various rates or proportions associated with particular types of collisions. Therefore, they might not be transferable from one jurisdiction to another or even across time in the same jurisdiction.

A second method for comparing the relative risk of various types of collisions is the use of collision rates. Collision rate is habitually defined as the ratio of collisions to exposure (Hauer, 2001), and is usually expressed as collisions per millions of vehicle-km (or mile). Collision rates have traditionally been used to describe the safety of a road or the risk to people using it. In this thesis, an extensive use of the rates of collision will be made to study the effect of pavement surface temperature and pavement moisture condition on the risk of road collisions.

The next section discusses the methods and results reported by some of these research studies. The following two sections study the effect of pavement surface temperature and condition on the severity of road vehicle collisions and the initial types of collision impact.

2.1.1. Statistical Methods of Hazardous Locations Identification

Through the past years, significant progress has been made in developing statistical methods and applications for the road collision analysis, particularly in identifying and ranking potentially hazardous locations on the basis of historical data so that corrective measures can be implemented (Hauer, 1995). Some of these methods used the frequency of collisions and the others used the collision rates. The general concept used in these methods is that a location is considered hazardous if its rate (or frequency) of collisions during a specific period of time exceeds some specified level (Tarko *et al.*, 1996; Higle and Witkowski, 1988). Tarko *et al.* (1996) developed a methodology using the frequency of collisions to identify hazardous States, counties within individual States, townships, or even small units in the U.S.A. A statewide value of the frequency of collisions was used as reference level to identify counties where the expected frequency of collisions, fatalities, or injuries in a future year would be higher than those of other similar State counties. The methodology is based on the following six-point concept:

1. A given area is characterized by a normal frequency of collisions expected when the level of safety in this area conforms to the average safety level in the region.

2. Each safety problem is associated with a relevant collision category and existing or potential safety program.
3. A recorded frequency of collisions in a given collision category higher than the normal value (above-norm collisions) indicate the possibility of a related safety problem.
4. The safety problem for a given area can be stated only at a limited confidence level because of the randomness in collision occurrence.
5. Confidence level and above-norm collisions reflect the magnitude of the related safety problem.
6. The magnitude of the safety problem must be anticipated for the year when a relevant safety program is to be implemented.

Tarko *et al.* (1996) used a lognormal regression model, called the safety performance function, to estimate the normal frequency of collisions in counties with similar characteristics such as population, road mileage, vehicle-miles travelled, proportion of state road mileage, etc. The above-norm frequency of collisions in a given year for a county was calculated as the difference between the observed collisions in that county during the year and the normal frequency of collisions obtained from the regression model. Finally, a linear regression is applied using the historical above-norm frequency of collisions to estimate time trends for individual counties. The estimated equation can then be used to predict the above-norm value for future years. The counties are ranked based on a combined criterion that includes both the above-norm frequency of collisions and the confidence level. This ranking can then be used to determine the priority of allocating funds for various road safety programs.

Statistical methods were developed to identify hazardous locations using collision rates. These methods ranged from the simple comparison of collision rates under different conditions, to classical statistics, to the more complicated Empirical Bayes (EB) probability method. For example, in classical statistics, the specified level for determining the above-norm collision rates is taken as the mean collision rate over all locations in a region plus a multiple of the standard deviation of the location collision rates within that region over same period of time. The multiple used depends upon the required degree of confidence level. This is essentially the concept of confidence intervals (Higle and Witkowski, 1988).

A second statistical technique, which is used by many transportation researchers identify hazardous locations, is the rate-quality method introduced by Norden *et al.* (1956). This technique is based on statistical quality control techniques that were originally developed as a means to dynamically control the quality of industrial production. By setting upper and lower control limits on the amount of variability permitted in a particular process and by periodically sampling product quality, these techniques can provide a means of verifying that the process is in control. The control limits and the results of the periodic samples of product quality can be plotted on a control chart and any sample measures of product quality that fall outside the critical values established by the control limits are said to be out-of-control. The greater the difference between the observed sample values and the critical control limits, the less likely that the out-of-control situation is caused by randomness and the more likely that the process needs a correction of some kind (Stokes and Mutabazi, 1996).

Khisty (1996) used statistical tests to determine whether the traffic collision rate at a particular location (intersection or road segment) is abnormally high when compared with the rates of other locations with similar characteristics. The statistical tests are based on the assumption that traffic collisions are rare events and that the Poisson distribution can approximate the probability of their occurrence (Zegeer and Deen, 1977). The critical collision rate is determined statistically as a function of the average collision rate for the category of collision and vehicle exposure at the location under consideration. If the observed collision rate for a particular road is equal to or greater than its critical rate, the deviation is probably not due to chance and may be considered significantly greater than average.

This method differs from the classical statistics method in that a critical collision rate, depending on the required level of confidence, is calculated for each location rather than the whole region. If the observed collision rate at any location exceeds its critical rate, the location is considered hazardous.

The Bayesian approach is a third probabilistic method that has been applied to road safety problems by many researchers usually in the EB framework (Melcher *et al.*, 2001). This approach provides a coherent framework in which regional collision characteristics can be combined with a location specific collision history to mathematically identify hazardous locations. It combines the prior knowledge with the current knowledge to obtain a posterior knowledge. The prior knowledge represents the subjective part of the Bayes approach that describes particular beliefs or opinions about different values of a particular parameter. In the Bayesian method, hazardous locations can be identified on the basis of the probability that the collision rate exceeds some level (Harlow *et al.*, 1997).

The uncertainty concerning the location's collision rate (true unknown rate) before obtaining current knowledge can be specified by a prior probability density function (Davis, 2000). The Bayes theorem is then used to determine how the uncertainty should rationally change after current knowledge became available, and this updated uncertainty is expressed as a posterior probability density function.

Higle and Witkowski (1988) used the EB statistical method to identify hazardous locations on the basis of historical data. The data used were for five years collision (July 1981 to June 1986) at signalized intersections under the jurisdiction of the Pima County Department of Transportation in Tucson, Arizona, U.S.A. The actual frequency of collisions at a particular location was treated as a random variable (assumed to be a Poisson distribution), and a combination of the regional collision characteristics and the collision history at that location were used to determine the probability that the location was hazardous. The Bayesian analysis in that study applied two-step procedure. First, the collision histories across all sites within an appropriately defined region were aggregated. The collision rate (frequency of collisions per million vehicles entering the intersection) across the region was assumed to follow the gamma distribution, which was estimated in this first step. The second step was to combine this estimated regional distribution with the collision history at a particular site in the region to obtain a refined estimation of the probability distribution associated with the collision rate at that particular site (also a gamma distribution). The refined probability distribution was estimated for each site within the region. The method of moment estimates was used to calculate the parameters of the refined distributions. Finally a specific site was identified as hazardous at a specific confidence level if the probability that its true collision rate exceeds observed average rate across the region is greater than this confidence level. The empirical results from the Bayesian analysis were compared with the corresponding results from classical statistical analyses, and it was concluded that the use of collision rate data within the framework of the Bayesian analysis is a fundamentally sound procedure and that the EB may even be preferable to the use of the classical statistics method.

2.1.2. Severity of Road Vehicle Collisions

Severity of collisions is the loss resulting from collisions in terms of human death or injury and damage to properties. Krull *et al.* (2000) reported 37,280 fatal collisions during 1997 in the U.S. involving 54,000 vehicles out of which 10,000 (26.8%) collisions were due to vehicles rolled over. In collisions involving rollover, the proportion of fatal collisions was almost five times as high as the proportion of collisions involving injury and fourteen times as high as the proportion of collisions involving PDO.

Different approaches were used to examine the injury severity resulting from vehicle collisions. For example, Lui *et al.* (1988) used a logistic regression approach to model the probability of driver fatalities conditioned on the occurrence of a two-vehicle collision with at least one death. The probability was assumed a function of the driver's age, driver's gender, point of impact, vehicle deformation, seat belt use, and vehicle weight. However, other important factors such as inclement weather were not included. Data used were obtained from the Fatal Accidents Reporting System (FARS). These data are collected and administered by the National Highway Traffic Safety Administration in conjunction with all 50 state highway safety agencies in the U.S.A. The data contain information on motor vehicle collisions that occur on public roads and result in a death of a person within 30 days of the collision. Since collisions that involved more than two vehicles might involve a complex set of impacts from a number of directions, it was therefore much more difficult to designate a primary point of impact for each vehicle. Thus collisions involving more than two vehicles were excluded. Furthermore, because the data analysis was conditioned on each collision, single-vehicle collisions involving only one driver would have no information on the relative risk of being killed and therefore were excluded as well.

Lui *et al.* (1988) found that 97% of the collisions involved a front impact for at least one of the vehicles. In collisions with two unbelted drivers, a rear-end impact was only slightly and non-significantly more dangerous than a front-end impact but a driver hit on either the right or left side by the front of the other vehicle was at much higher risk than the other driver. Drivers of light vehicles, which usually deform severely in collisions, were at much higher risk than drivers of heavy vehicles that usually suffers minor or moderate deformation. Heavier vehicles were found to greatly reduce a driver's risk of being killed in a two-car collision. The seat belts were more effective for drivers in less severely damaged vehicles and their effectiveness varied by the direction and severity of impact. For the direction of impact, seat belts were found to be the most effective for rear-end impacts and the least effective for left impacts (driver side). Finally, a belted driver subjected to a left side impact was estimated to have a higher risk of being killed than an unbelted driver.

Shankar *et al.* (1996) derived a model to predict the probability of a collision having specific severity level, given that a collision has occurred. The severity of a collision was specified to be one of four discrete categories: disabling injury or fatality, evident injury, possible injury, and PDO. The result of the study concluded that the probability of possible injury is greater than the probability of the PDO, particularly in case of rear-end collisions occurring in rainy weather. The study also concluded that the probability of disabling injury or fatality was greater than the probability of no evident injury if at least one driver did not use the seat belt at the time of the collision.

Nassar *et al.* (1994) studied the factors affecting three types of collision severity: single-vehicle collisions, two-vehicle collisions, and multi-vehicle collisions. Factors found to be significant include seat belt use, alcohol, driver condition, and driver fault. Road surface condition was insignificant in this study.

Abdelwahab and Abdel-Aty (2001) applied Artificial Neural Network models to analyze the relationship between driver injury severity on one side, and driver, vehicle, road, and environment characteristics on the other side. The analysis focused on two-vehicle collisions that occurred at signalized intersections using collision data from the Central Florida area during 1997. Three levels of severities were considered: disabling or fatal injury, minor injury, and no injury (PDO). Driver characteristics considered were age, gender, alcohol usage (driver under the influence or not), fault (at fault or not), seat belt usage, and speed of vehicle. Vehicle characteristics were vehicle type and point of impact. Road and environment conditions considered were area type (rural versus urban), day (weekday versus weekend), time (peak versus off peak), light condition (daylight versus night), and weather condition (clear versus not clear).

The study examined 1,168 collisions involving 2,336 drivers. The number of drivers who suffered disabling or fatal injury was 140 (6%); the number of drivers who suffered minor injury was 1,108 (47.4%); and the number of drivers who suffered no injury was 1,088 (46.6%). The injury severity for several driver characteristics, road and environmental conditions, and vehicle factors were compared. The study found that drivers aged 25 to 34 have a higher proportion of traffic collisions causing no injury than do drivers of other ages and that female drivers tend to be involved in a higher proportion of collisions causing minor and disabling or fatal injury. The study also found that the use of seat belts at the time of collisions has a major effect on driver injury severity.

2.1.3. Initial Type of Collision Impact

Initial type of collision impact may be classified as single-vehicle collisions, rear-end collisions, and other types of collisions (including all types that are neither single-vehicle nor rear-end collisions). Single-vehicle collision occurs when a vehicle leaves or runs-off the road. The factors affecting the severity of single-vehicle collisions are different from those factors affecting the severity of collisions involving multiple-vehicles. In multiple-vehicle collisions, rear-end collisions constitute a substantial portion of the total vehicles damaged on the roads, and severity is highly related to factors such as the type of collision, size and weight of impacting vehicles, and points of contact (Krull *et al.*, 2000).

Krull *et al.* (2000) studied the severity of driver injury in single-vehicle collisions. The data used included 35,447 collisions from the 1994 – 1996 Michigan collision files and 24,296 collisions from the 1993- 1995 Illinois collision files. The data were chosen based on the quality of the available data in the states. The database was separated into individual files that can be linked together: the collision file, vehicle file, and road file. The collision and vehicle information were taken from police records. The three files were linked together for each state and analyzed. After the individual analysis, the two states were merged into one large file and reanalyzed. Logistic regression models of fatal and incapacitating injuries versus other injuries and non-injuries were then estimated separately and together using the SPSS (Statistical Package for the Social Sciences) software to examine the severity of single-vehicle collisions. The results of the study showed that 9% of single-vehicle collisions were either fatal or cause incapacitating driver injuries. In addition, driver-injury severity increases, among other things, with failure to use seat belts or alcohol use.

Khattak (2001) studied the effect of driver information and vehicle technology on injury severity in case of rear-end vehicle collisions. The study included only those collisions involving two and three vehicles on access-controlled divided roads in order to focus on information effects from vehicles ahead and remove confounding factors like driveways and intersections. The data used in the analysis were obtained from the 1994 – 1995 North Carolina Highway Safety Information System collision database. There were 3,912 collisions involving 8,311 vehicles, were made-up of 3,425 (87.5%) two-vehicle and 487 (12.5%) three-vehicle rear-end collisions. The analysis showed that the driver in the front vehicle is relatively more likely to get injured in a two vehicle-collision compared with a three-vehicle rear-end collision. Furthermore, in the three vehicle-collisions the driver in the middle vehicle is relatively more severely injured as compared with the rear driver in the two-vehicle rear-end collisions. The analysis of different passenger models and year of manufacturing concluded the technological improvements have a quantifiable beneficial effect on safety.

2.2. Impact of Weather Conditions on Vehicle Collisions

During wintertime, the falling snow and ice on roads and highways create hazardous driving conditions. Failure to act and deice roads effectively and as soon as possible can endanger the health and safety of the members of the community (Hanbali, 1994). The effects of adverse weather and road conditions on driver safety as well as the safety benefits of winter road maintenance have been the focus of a number of research studies (Brown and Baass, 1997). Hanbali (1994) examined the collision rates per million vehicle-kilometres for collisions involving injury and PDO before and after the application of salts. The study used data from a total of 1,600 lane-km of two-lane highways and one multilane divided freeway test sections in New York, Wisconsin, and Illinois. Collisions were recorded and collision rates were calculated for each hour before the deicing up to 12 hours and during the hour immediately after deicing. The results showed a significant decrease in collision rates after deicing maintenance activities when compared with those rates before deicing. For example, rate of collisions involving injury 4 hours before the deicing dropped from 4.99 collisions per million vehicle-kilometres to 0.58 collisions per million vehicle-kilometres during the hour immediately after deicing. The corresponding rates of collisions involving PDO dropped from 2.96 to 0.45 collisions per million vehicle-kilometres.

Brown and Baass (1997) examined the effect of harsh meteorological conditions on the safety record of Montérégie region of Quebec, Canada. They used data available from Quebec Automobile Insurance Board and the Quebec Ministry of Transportation on

2598 km of roads and highways between 1989 and 1992. A total of 44,021 collision reports were included in the study. Vehicle collision rates and frequencies during the four winter months (December to March, inclusive) were compared with those collisions during the summer months (April, May, July, and August). The study concluded that during winter months, the numbers and rates of death and serous injury were lowest while collisions involving PDO were most frequent and had their highest rates.

Past research provides evidence that risk of vehicle collision and injury increase during precipitation, particularly when freezing rain forms on the pavement surface as compared to dry driving conditions. The estimate of the risk, however, varies due to the differences in driving context and research methods. Andrey *et al.* (2003) adopted the matched pair approach to examine the temporal variations in weather-related risk of collision and injury using data for Ottawa, Canada over the period 1990-1998. In this approach, each time period during which precipitation occurred was paired with a control time period where precipitation (and other inclement weather conditions) did not occur. The event and control were spaced just one week apart, and matched in duration, time of the day and day of the week. For example, a rain event occurring from 8:00 a.m. to 11:00 a.m. on a Thursday was only matched to a Thursday, either one week prior to or one week afterward, when rain was not occurring from 8:00 a.m. to 11:00 a.m. Then the risk of collision and injury during precipitation relative to dry conditions were estimated. The estimated risks were used to compare weekdays versus weekends, nighttimes versus daytime, peak-period versus non-peak period, and early-winter season versus late-winter season. The study concluded that risk of collision increased significantly, by more than 100% for raining condition and approximately 50% for winter precipitation events as compared to the dry conditions, and it was especially high during the early winter season as compared to the late winter season. The study also showed that the risk of injury was also elevated during precipitation events, but to a lesser extent.

A conclusion of this study was that relative collision of risk ratios for winter precipitation events occurring in November and December were significantly higher than the events during the latter part of the winter season (January-April), whereas injury risks were significantly different. The basis of choosing the two periods was purely subjective and was never explained. For example, why the comparison was not between November-January and February-April, or any other combination. Would the conclusion be different? Another conclusion of the study was that weather-related collision and injury risks were marginally higher during weekends relative to weekdays, although differences were statistically significant only for winter-precipitation collision risks. This result is highly questionable since as it is well known fact that vehicle volumes in the City of Ottawa on Fridays are the highest among the seven days of the week, Andrey *et al.* (2003) for a reason, which again was never explained, have assumed the weekend to be from Friday to Sunday inclusive. This thesis uses the weekend as Saturday and Sunday as defined by the Federal Government, the largest employer in the City of Ottawa. In addition, combining information from Brown and Baass (1997) and Andrey *et al.* (2003), the winter month data in this thesis were from taken from November 1st to March 31st.

2.3. Road Winter Maintenance Operations

The term winter maintenance refers to the efforts undertaken by the governments of local municipalities during wintertime to keep the roads and streets safer and easier for citizens to perform their vital activities. When slippery road conditions are predicted, the winter road maintenance operations are undertaken, including snow removal, deicing and anti-icing, in particular:

1. Deicing is used to remove compacted snow or ice already bonded to the pavement surface by mechanical or chemical means or a combination of both.
2. Anti-icing is used to prevent the formation or development of bonded snow and ice to pavement surface by timely application of a chemical freezing-point depressant (Blackburn et al., 2004).

The road salt deicers are used to reduce the road hazardous conditions. The amount of road salts spread during wintertime has a negative impact on the environment and should be kept to a minimum. Environment Canada had concerns about the effects of the use of large quantities of road salts and their potential damage to the environment (Environment Canada, 2004). In 1995, salts used in Canada were put on the Priority Substances List under the Canadian Environmental Protection Act (CEPA) for environmental assessment. In 2001, Environment Canada published its recommendation that road salts containing inorganic chloride with or without Ferrocyanide be added to Schedule 1 (Toxic Substances List) under the CEPA. Environment Canada emphasized that the Government of Canada would not ban the use of road salts or propose any measures that would compromise or reduce road safety. In 2004, Environment Canada published a Code of practice for the environmental management of road salts (Environment Canada, 2004). The objective of the Code of Practice is to ensure environmental protection while maintaining road safety. There are two main recommendations in this code:

1. The development of salt management plans, based on a review of existing road maintenance operations, and identification of means and goal-setting to achieve reductions of the negative impacts of salt releases.
2. The implementation of best management practices in the areas of salt application, salt storage and snow disposal, as outlined in the Transportation Association of Canada's syntheses of Best Practice (TAC, 1990).

Other world institutions have developed several codes and regulations for the use of deicing salts on roads and highways to minimize their negative impact on the environment. For example, in 1993, the U.S. Federal Highway Administration (FHWA) sponsored the National Anti-icing Test and Evaluation Project No. 28, as a follow up to the Strategic Highway Research Program (SHRP) project No. 208, which introduced the use of anti-icing to the United States (Chollar and Nassif, 1998). In Project No. 28, fifteen state highway agencies tested and evaluated various anti-icing technologies and strategies to determine the topographical, climatological, meteorological, and traffic conditions under which anti-icing would be most effective. Extensive testing, evaluation, data collection, and analyses resulted in the development of the "*Manual of Practice for an Effective Anti-icing Program*", which provides information to winter maintenance managers and operators for successful development and implementation of an effective anti-icing program. It describes the significant factors that should be understood and must be addressed in an anti-icing program and includes recommendations and guidance for conducting anti-icing operations during specific precipitation and weather events. Similarly, the Finnish National Road Administration (Finnra) developed a salting table that recommends the proper application rates based on the road surface temperature and its forecast development in the next few hours, and the existing amount of moisture on the road and its changes (Raukola and Terhela, 2001). Accurate prediction of pavement surface temperature and pavement moisture condition is then critical in keeping the usage of salts to a minimum (Davis, 1996). Road surface temperatures, precipitation amount and form, wind conditions, and other environmental factors (sunlight exposure, surface conditions, etc.) affect the use and application of deicing salt. In recent years, significant advances have been made to improve the efficiency of winter maintenance operations. For example, modern spreaders and new sophisticated salting techniques can help in making the spread of salt on roads to be more accurate and consistent. Pavement conditions and weather information can be gathered and passed on to central locations using new advanced aerospace and information technologies (Davis, 1996). Improving the quantity and quality of information given to maintenance operators can help prepare more reliable winter maintenance programs for most eventualities and can prevent a great deal of waste through unnecessary spreading. In particular, further improvements to the accuracy of predicting the pavement surface temperature and condition can reduce the quantity of used salt and minimize the winter maintenance cost.

Over the years, winter maintenance technologies and practices have changed. In the past, visual inspection and primary statistical analysis were performed to respectively identify and predict snow levels on the roads. Pavement surface condition during the winter season can give a visual idea of what action may be undertaken, particularly, in determining the type and amount of necessary deicing salt to be used. Many countries have used information from the road weather information systems (RWIS) to predict ice and freezing conditions on road surface to minimize the risk of collision due to slippery roads (Pilli-Sihvola, 1993). The RWIS are being used together with pavement and atmospheric sensors, located at Remote Processing Units (RPU), to provide continuous real-time information for winter maintenance operation (Karlsson, 2001). The winter maintenance programs differ from one area to another, depending upon the national policies of snow removal and who are served. For example, many European countries have developed winter road maintenance standards and introduced new software techniques to help maintenance managers in assigning tasks. They initiated a Project called "VIKING" which attempts to coordinate traffic management schemes and implement Intelligent Transportation System (ITS) in Denmark, Sweden, Finland, Norway, and five regions from northern Germany (Leviäkangas, 1998). These countries and regions share common weather condition characteristics and thus many common problems. The project concentrates on predicting the conditions of the road surface, developing road weather monitoring equipment and systems, and disseminating road weather information to road users. It was executed in three phases; the first was in 1996 – 1997 during which the components of the project were defined, developed, and organized. The second phase, 1997 – 1999, aimed at consolidating national and Euro-regional plans. It included considerable technical and organizational development work. The third phase included the completion of traffic management centres within the Viking area, enabling cross-border weather, road and traffic information dissemination. One of the components of the VIKING is the mobile data probe vehicle, where a mobile unit is used to measure pavement friction levels and temperature readings. Infrared cameras are used to measure the pavement surface temperature. This information is sent to a main station for analysis, then decide on the appropriate course of action to launch maintenance operations and to control variable vehicle speed limit and message signs. The mobile data probe vehicle is also equipped with cameras capable of transmitting visual information about the road surface (Leviäkangas, 1998).

In North America, several cities have been using sophisticated RWIS to provide important data at certain locations to maintenance supervisors and road crews, which enable them to develop and implement operational winter maintenance strategies. Road-condition forecast, which is critical to the winter road maintenance, has been produced for different purposes (Crevier and Delage, 2001). For example, the 24-hour forecast is used differently from a 6 hour forecast by maintenance personnel. The longer-term forecast is used as an advance-planning tool, which is updated as more information made available. This forecast can allow for a more advance warning in cases where the hazardous road conditions may occur later in the forecasting period. The short-term forecast should be more trusted and used in issuing maintenance orders.

In addition, road winter maintenance personnel must be aware that these forecasts are produced for specific locations. Nevertheless, the forecasts can be extended to other areas having similar weather conditions and asphalt mix characteristics.

2.4. Pavement Surface Temperature Trend Analysis

Pavement surface temperature influences the snow and ice control operations. It has a major effect on how ice control chemicals perform and ultimately, on the treatment decision itself (Blackburn *et al.*, (2004). As pavement surface temperatures decline below about -11°C (12°F), most ice control chemicals become very inefficient in terms of the amount of ice melted per unit of chemical applied. Pavement surface temperature therefore derives the decision to plow only, plow and apply chemicals, or plow and apply abrasives.

Knowledge of trends of pavement surface temperature during daily cooling and warming cycles are very important in modelling and predicting surface temperature. Three studies were chosen from the literature examining these cycles using data from different locations representing different weather conditions. Kallas (1966) examined data from average climatic conditions, Straub (1968) examined data from a colder climate, and Rumney and Jimenez (1971) examined data from a warm desert climate.

Kallas (1966) examined the trend of pavement temperature data obtained from a yearlong study (June 1, 1964 to May 31, 1965) on pavement test sections located at College Park, Maryland. Pavement temperatures were measured at the surface and at depths 2, 4, and 6 inches in a 6-inch thick asphalt-concrete pavement, and at depths 2, 4, 6, 8, 10, and 12 inches in a 12-inch thick asphalt-concrete pavement. He also examined the trend of air temperature as compared to that of the pavement temperature. The study found that in a typical summer day, cycles of hourly pavement and air temperature had their lowest temperatures before sunrise at 6:00 am and increased rapidly until reached their highest temperatures in the afternoon at 3:00 pm. The highest pavement surface temperature during the study period was reported on June 30, 1964, where the surface temperature reached a maximum of 61°C (142°F) at 3:00 pm. The maximum air temperature at that day was 37.2°C (99°F), also at 3:00 pm.

Hourly pavement and air temperature changes for a typical winter day had almost same cycles as those of the summer days. The lowest pavement surface temperature of

−12.8°C (9°F) was recorded on January 19, 1965, at 7:00 am. The minimum air temperature at that day of −16.7°C (2°F) was recorded at 8:00 am.

In the second study, Straub *et al.* (1968) used a 6-inch and a 12-inch thick test pavement to measure for a full year (August 1, 1966 – July 31, 1967) at 5-minute intervals the temperature patterns resulting from the exposure to an actual northern climate. The test pavement was located at Potsdam, N.Y., on the campus of Clarkson College. Air temperature, percentage of cloud cover, and amount of solar radiation received during the day were also measured. The study has shown that during a typical winter day, both air and pavement surface temperatures varied according to a sine wave so that the minimum temperatures occur early in the morning and the maximums occur in the early afternoon. The study also concluded that pavement temperature was directly related to major climatic factors of air temperature and solar radiation, and that the problem of accurately measuring pavement surface temperature is important.

In the third study, Rumney and Jimenez (1971) developed empirical monographs, based on data from June 30, 1969 – May 30, 1970, collected in Tucson, Arizona to predict pavement temperature at the surface and at a 2-inch depth as a function of air temperature and hourly solar radiation. The study found pavement temperature cycles pattern similar to that stated by Kallas (1966), during which the surface temperature decreases slowly in the early morning hours and reaches its minimum around 6:00 am. After that, the surface temperature increases very rapidly as the heating effects of solar radiation win over the cooling effects of the air. The maximum surface temperature occurs between 12:00 and 3:00 pm. After 3:00 pm, the cooling effects of the air win over the radiation effects and the temperature falls rather rapidly until around 7:00 pm when it approaches the range of night air temperature, and continues to decrease until it reaches its minimum around 6:00 am. Furthermore, the study found that the surface temperature at night depends to a great extent on the atmospheric conditions and usually averages about 2.8°C (5°F) above the air temperature. The pavement surface temperature stays above the air temperature during summer months and can get below the air temperature during winter months.

All the three trend analyses of pavement surface temperature have used one-year data. The studies recognized that maximum and minimum temperature at specific date can change from one year to another, however, the cycles of pavement and air temperatures are changing continuously over same range of values. Therefore, the use multiple-years data was not necessary. In this thesis, data from one winter season are used to establish the relationship between pavement surface temperature, pavement moisture condition, and collision rates, as well as modelling pavement surface temperature as function of air temperature and dew point.

2.5. Modelling Pavement Surface Temperature

The literature is full of many research studies of modelling pavement temperatures for different purposes as functions of weather variables and meteorological parameters. Most of these studies were interested in predicting the minimum and maximum pavement temperatures, which is important in the selection of proper asphalt binder using performance-based specifications. Some studies applied linear regression analysis and other studies used physically based models based on Heat Transfer Theories (HTT) to develop pavement temperature prediction models. The HTT models are very complex, contain many equations to be estimated and calibrated, and many variables that will be very expensive to collect, maintain, and forecast for the use within these models. The next two sections discuss the different methods for predicting pavement temperature and their relationship to those models presented in Chapters 5 and 6 of this thesis.

2.5.1. Prediction of Pavement Temperature Using Linear Regression Models

Bosscher *et al.* (1998) used statistical regression to develop models relating pavement temperature to air temperature. The analysis was focused on the development of models estimating low and high surface temperatures from meteorological data to verify the assumption by the Superpave pavement temperature estimation procedure that minimum pavement surface temperature is equivalent to minimum air temperature. Data used were collected once every hour on pavement temperature, air temperature, relative humidity, wind speed, wind direction, and solar radiation in Wisconsin.

The pavement temperature profile was found to follow very closely the air temperature profile. The pavement temperature was generally higher than the air temperature for much of the time, particularly during night. However, on some occasions, the pavement temperatures were lower than the air temperatures, particularly during rapid increases of air temperature and during cloudy days. For a typical day, both the air and pavement surface experienced their coldest temperatures during the night; however, the minimum pavement temperature was constantly higher than the minimum air temperature. Conversely, during the day, the air and pavement surface experienced their maximum temperatures, and the maximum pavement temperature was, in general, higher than the maximum air temperature, because of the solar radiation.

Linear regression analysis was used to establish the model defining the minimum pavement temperature as a function of the minimum air temperature and other weather factors. Several mathematical forms were considered and the best low-temperature model was found to be a bilinear model, one for minimum air temperature below 0°C and the other for minimum air temperature above 0°C. The study was not clear which model is suitable for minimum air temperature equals 0°C. Although the R^2 value was high at 96.3%, the standard error was relatively high. The addition of average air temperature, calculated during the 24-hours preceding the time at which the minimum pavement temperature occurred as an independent variable has further improved the model. The same model showed further improvement when estimated for minimum air temperatures below –5°C.

Similar process was used to estimate a bilinear regression model relating maximum pavement temperature to maximum air temperature and daily total solar radiation intensity. The cut-off temperature between the two estimated equations was 10°C.

Another study of modelling minimum pavement temperature during wintertime was undertaken by Raad *et al.* (1998). The study established correlations between minimum air and pavement temperatures for different Alaskan climatic zones during wintertime. The four zones considered were:

1. *Maritime*; which is characterized by small temperature variations, high humidity, heavy precipitation, and high cloud and fog frequencies, little or no freezing weather, cool summers and warm winters, surface winds strong an persistent, and mean annual temperature 2°C to 6°C.

2. *Transition*; More pronounced temperature variations throughout the day and year, less cloudiness, lower precipitation and humidity, surface winds generally light, and mean annual temperature – 4°C to 2°C.
3. *Continental*; great annual temperature variations, low precipitation, low cloudiness, low humidity, surface winds generally light, and mean annual temperature – 9°C to – 4°C.
4. *Arctic*; Temperature variations lower than continental, precipitation extremely high, strong winds, and mean annual temperature – 12°C to – 7°C.

A linear regression equation between minimum air and pavement temperatures was fitted for each zone. The results indicated that for lower temperature range, minimum pavement temperature is always higher than minimum air temperature by 2°C to 7°C depending on the climate zone.

Neither Bosscher *et al.* (1998) or Raad *et al.* (1998) have attempted to examine any of the problems associated with the use of the linear regression models such as multicollinearity and autocorrelation. In addition, contrary to the findings of the first, the models considered in this thesis found no direct relationship between pavement surface temperature and the air temperature history. However, the result obtained by the second was also observed in data used to model pavement and air temperatures during wintertime for the Ottawa region.

2.5.2. Prediction of Pavement Temperature Using Heat Transfer Models

Barber (1957) was among the first researcher to propose a method of calculating maximum pavement temperature from weather reports, applying a thermal diffusion theory to a semi-infinite mass (pavement) in contact with air. He presented a relation between pavement temperature and wind speed, air temperature, and solar radiation, as controlled by the thermal properties of the pavement. The estimation of this relationship required 12 more equations and data on 17 variables. The variables used were pavement temperature, air temperature, average air temperature, daily range of air temperature, maximum variation of air temperature from mean, effective air temperature, mean effective air temperature, time from beginning of cycle, depth below the surface, pavement density, specific heat, solar radiation, absorptivity of surface to solar radiation, surface convection coefficient, conductivity, diffusivity, and wind speed.

The resulting equation can calculate maximum pavement temperature at locations having same temperature conditions and same total daily solar radiation. The study concluded that the "*calculations indicate the possibility of roughly correlating surface temperatures with the values reported by the Weather Bureau so that means are available to extrapolate field observed temperatures to other times and places. To calculate exact temperature for a given structure, exact values of its thermal properties and the ambient conditions must be known.*"

Dempsey and Thompson (1970) used the finite difference equations technique to develop a heat transfer model for evaluating frost action and temperature-related effects in multilayered pavement systems. The model was based on a one-dimensional Fourier second order partial differential equation of heat transfer equation for conductive heat transfer

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}, \quad x > 0, t > 0 \tag{2.1}$$

Where T = pavement temperature, x = depth, α = thermal diffusivity, and t = time. The estimation of the model required a considerable amount of data on 28 meteorological parameters, thermal properties of pavement materials, and weather conditions.

Shao *et al.* (1997) applied the one-dimensional Fourier second order partial differential equation of heat transfer equation to predict the pavement subsurface temperatures. Unlike Dempsey and Thompson (1970), the solution of the differential equation was given as an integral equation of Pavement temperature as a function of depth and time.

$$T(x,t) = \frac{1}{2\sqrt{\pi\alpha t}} \int_0^{\infty} G(\xi) \left[\exp\left\{ -\frac{(x-\xi)^2}{4\alpha t} \right\} - \exp\left\{ -\frac{(x+\xi)^2}{4\alpha t} \right\} \right] d\xi$$
$$+ \frac{2}{\sqrt{\pi}} \int_{\frac{x}{2\sqrt{\alpha t}}}^{\infty} F\left(t - \frac{x^2}{4\alpha\eta^2} \right) \exp\left(-\eta^2\right) d\eta \tag{2.2}$$

The above equation was then used to model the pavement surface temperature time history within a day using a sine curve with two different periods for the heating and cooling cycles that add to 24 hours. The surface temperature history for a day was determined using the previous day's cloud conditions and maximum air temperature, and the minimum air temperature for the day's morning. Similar to Dempsey and Thompson (1970), the estimation of the model required a considerable amount of data and the solution of mathematically complex differential and integral equations.

Solaimanian and Kennedy (1993) proposed a heat transfer model to calculate the maximum pavement temperature profile on the basis of maximum air temperature and hourly solar radiation. The model calculates 5 forms of energy affecting the pavement system and assumes that at maximum temperature, there is equilibrium and that the net energy (difference between absorbed and emitted) is equal to zero. The calculation of each of the five forms of energy is described below.

a. Direct Solar Radiation

The energy absorbed by the pavement from direct solar radiation, q_s (W/m^2), can be calculated as

$$q_s = \alpha R_i \tag{2.3}$$

where α = the surface absorptivity to the solar radiation and R_i is the incident solar radiation, which depends upon the angle i, between the direction of the normal to the surface receiving radiation and the direction of the solar radiation. Therefore, if R_n is the radiant energy incident on a surface placed normal to the direction of the rays of the sun, then

$$R_i = R_n \cos i = R_0 \, \tau_a^m \cos i \tag{2.4}$$

where R_o = solar constant, m = relative air mass, and τ_a = transmission coefficient for unit air mass. The relative air mass m is approximately equal to 1/(cos z) where z is the zenith angle (the angle between the zenith and direction of the sun's rays). The zenith angle depends upon the latitude φ, the time of the day, and the solar declination δ. The time is expressed in terms of the hour angle h (the angle through which the earth must turn to bring the meridian of a particular location directly under the sun). The zenith angle can be found from

$$\cos z = \sin\phi \ \sin\delta + \cos\phi \ \cos\delta \ \cos h \tag{2.5}$$

b. Atmospheric Radiation

The atmosphere absorbs radiation and emits it as longwave radiation to the earth. Atmospheric radiation absorbed by the pavement surface, q_a (W/m^2), is calculated from the following empirical formula:

$$q_a = \varepsilon_a \sigma T_{air}^4 \tag{2.6}$$

where, ε_a = constant, σ = Stefan-Boltzman constant, T_{air} = air temperature (°K).

c. Convection Energy

The rate of heat flow by convection to the surrounding air, q_c, is given by

$$q_c = h_c (T_s - T_{air}) \tag{2.7}$$

where T_s = surface temperature (°K) and h_c is the surface coefficient of heat transfer. For a pavement surface, h_c is given by

$$h_c = 698.24 \left[0.00144\, T_m^{0.3} U^{0.7} + 0.00007\, (T_s - T_{air})^{0.3} \right] \tag{2.8}$$

where T_m = average of air and surface temperatures (°K) and U = average daily wind velocity (m/s).

d. Conduction Energy

The conduction rate of heat flow from the pavement surface down, q_k, can be approximately calculated as

$$q_k = -k \frac{T_d - T_s}{d} \tag{2.9}$$

where k = thermal conductivity, d = depth (cm), and T_d = temperature at depth d (°K).

e. Radiation Energy Emitted from the Surface

The earth's surface is assumed to emit longwave radiation as a blackbody. The rate at which the surface emits radiation, q_r, is given by

$$q_r = \varepsilon \sigma T_s^4 \tag{2.10}$$

where ε = emission coefficient.

f. Equilibrium Temperature at the Pavement Surface

The equilibrium temperature at the pavement surface can be obtained by setting the net rate of heat flow at the pavement surface equal to zero. That is

$$q_s + q_a - q_c - q_k - q_r = 0 \tag{2.11}$$

Substituting from Equations (2.1) to (2.10) in (2.11), a fourth degree equation in Ts is obtained. One of the four solutions of this equation gives the pavement surface temperature.

Solaimanian and Kennedy (1993) concluded that the relationship between maximum pavement temperature and maximum air temperature is essentially linear. This supports the use of linear model used in Chapter 5 to estimate pavement surface temperature. The minimum pavement surface temperature was assumed to be equal to the minimum air temperature since minimum pavement surface temperature during wintertime is in most cases 1°C or 2°C higher than the minimum air temperature.

Similar to Dempsey and Thompson (1970), Solaimanian and Kennedy (1993) required a considerable amount of data on meteorological parameters, thermal properties of pavement materials, and weather conditions. The modelling process required the application of extensive heat transfer theories and thermodynamics as well as the estimation and calculations several equations. The potential of accumulating errors from any of the equations into the final form is high. In addition, the solution of the fourth degree equation is not unique and judgement has to be used at some point of time to choose the most relevant result.

Hermansson (2000) used formulas of convection and shortwave and longwave radiation derived by Solaimanian and Kennedy (1993) to develop a simulation model calculating the temperatures of asphalt concrete during summertime including maximum pavement temperature. Input data to the model are hourly values for solar radiation, air temperature, and wind velocity. The model did not consider the rainfall and is most suitable for fine weather. Calculated values of maximum pavement temperature from the model were compared with real measurements and showed good agreement. The maximum temperatures produced by the model were also compared to those results calculated from the formulas used within the Superpave and are based on the Solaimanian and Kennedy (1993) equilibrium equation. The Superpave formula implicitly assumes that there is equilibrium when a maximum temperature is reached, and that the net energy on the pavement surface is zero. Also according the Superpave, the equilibrium is reached when the sun is at its highest at 12:00 pm on midsummer day, the same time that the air is very warm. This assumption requires that pavement be subjected to a very long time of constant high air temperature and constant solar radiation. Hermansson (2000) found that the maximum pavement temperature obtained from the simulation model under this assumption was approximately 30°C higher than the measured temperature. This overestimation was probably due to the fact that the temperature of the pavement surface changes very rapidly on sunny days when high temperatures are reached and therefore the Superpave assumption is invalid. The Superpave formula also assumes for unknown reasons that the maximum pavement temperature is reached at wind velocity of 4.5 m/s. Under this assumption, the simulation model underestimated the maximum temperature by approximately 25°C when compared with that reached at calm conditions. Hermansson (2000) concluded that the errors resulting from both assumptions on the whole cancel each other and that these assumptions are strongly questioned.

Crevier and Delage (2001) developed a numerical Model of the Environment and Temperature of Roads (METRo), which was first implemented at the Ottawa Regional Centre in October of 1999 and is currently in operational use at other Canadian weather centres. It uses meteorological forecasts from the operational Global Environmental Multiscale (GEM) model of the Canadian Meteorological Centre, and roadside observations from the RWIS stations as input to provide 24-h road-condition forecasts two times per day, at 3:00 am and 3:00 pm local time. METRo is composed of three modules: the energy balance of the road surface (the central part), a heat-conduction module for the road material, and a module to handle water, snow, and ice accumulation on the road. It solves the energy balance equation at the road surface and the heat conduction in the road material for calculating the temperature evolution. Unlike Solaimanian and Kennedy (1993), the surface energy balance model in METRo consists of 7 forms of energy affecting the pavement system. These are the incoming flux, the absorbed incoming infrared radiation flux, the emitted flux, the sensible turbulent heat flux, the latent heat flux, the flux associated with phase changes of precipitation water, and an anthropogenic flux. The determination of each of these fluxes depends upon physical parameters whose values were chosen arbitrarily and the sensitivity of the model to changes in these parameter values was not examined. In general, METRo is very complicated model and its estimation and calibration require a considerable amount of data inputs. The development and maintenance of such large databases can be extremely expensive.

2.6. Conclusion: The Need

The literature review presented in this chapter examined research studies related to two main issues:

1. The effect of pavement surface temperature and pavement moisture condition on the risk of road vehicle collisions.
2. Different modelling techniques of predicting pavement surface temperature from weather and meteorological variables.

Different research studies suggested that pavement surface temperature is an extremely important factor affecting the risk of vehicle collisions, particularly during wintertime. Yet the literature review revealed a lack of serious in-depth research to quantify the effect of pavement temperature on the risk of vehicle collisions. Most research studies examined only the effect of weather related conditions on the risk of collisions.

Another important factor affecting the risk of vehicle collisions during wintertime is the pavement moisture condition. Many research studies have examined the effect of precipitation on the risk of vehicle collisions and concluded that precipitation increases the risk of collisions especially in freezing temperatures. Although the combined effect of both pavement moisture condition and pavement surface temperature was implicitly considered in these studies by classifying precipitation into rain, freezing rain, and snow, the explicit combined effect of both factors on the risk of collisions was not examined.

The combined effect of these two factors influence the severity of collisions such as fatality and injury, as well as the initial types of impact such as single-vehicle and rear-end collisions. The determination of this effect can help in designing safer roads, assigning proper speed limits, and manufacturing appropriate tires to decrease the risk of road collisions.

Predicting the pavement surface temperature is necessary to prepare effective road maintenance operations, which decrease the risk of vehicle collisions and impact positively on the environment by minimizing the used amount of road-salts. The RWIS technology has been widely utilized in Europe and North America to collect information that can be used to improve the design and implementation of winter maintenance operations. This technology however requires a large number of stations at very high costs in order to cover reasonably wide geographic areas in addition to many reliability and financial issues. Furthermore, the RWIS provide present-time or past information on pavement surface temperature that has limited usefulness in planning effective winter maintenance operations. Information provided by the RWIS can better be utilized when used as a tool to develop models that can predict pavement temperature.

The research undertaken in this thesis aims at filling these gaps by explicitly examining and quantifying the combined effect of pavement surface temperature and pavement moisture condition on vehicle collisions during wintertime. It is to the knowledge of the author of this thesis that establishing this kind of relationship was never done before and therefore, results presented in Chapters 3 and 4 are new and cannot be compared with any previous work.

Another result of the literature review is that most of the existing pavement temperature prediction models are designed to forecast mainly the maximum pavement temperature and few have tried to forecast the minimum temperature. In addition, those models using heat transfer theories are very complex and depending upon many parameters whose values are arbitrarily chosen. A problem with this kind of models is that any error in one parameter or more estimated by an equation can multiply when used by the other equations. The more variables and equation used, the less manageable will be the modelling error. In addition, the data required to estimate these models are very large and the cost of maintaining them can be enormous.

In all cases, the basic statistical tests associated with the regression analysis were not undertaken. These shortcomings clearly identify the need of building a simple and reliable regression model capable of predicting pavement surface temperature from observations provided by the existing RWIS. This can be achieved by applying as many rigorous statistical tests as possible to improve the prediction capability of such models. Results from these models can be extended to other areas having similar weather conditions and pavement characteristics, which can lead to enormous savings to those cities that do not have the financial resources to install these expensive RWIS systems.

3. RISK ANALYSIS OF VEHICLE COLLISIONS

Four major factors can affect the risk of road collision. These are the vehicle, the road, road users, and the environment. The effect of the vehicle is a function of its type and size, technology used, safety equipment, etc. The effect of the road is a function of the road geometric design, alignment, surface texture, signs and signals, etc. The effect of road user is a function of driver's age, gender, driving experience, physical abilities, health condition, etc. Finally, the effect of the environment is a function of weather related conditions such as air temperature, relative humidity, dew point, fog, high winds, precipitation, etc. Pavement moisture condition can result in a number of physical changes in the road surface friction. Pavement surface temperature in winter has a significant influence on highway maintenance and safety issues concerned with snow, and ice management (Adams *et al*, 2004). It ultimately determines the form of moisture on the pavement surface would take.

In this chapter and the next one, analysis will be conducted to examine quantitatively the effect of pavement surface temperature and pavement moisture condition on the risk of vehicle collision and establish some indices to measure this effect. This chapter examines relative risk of collision on the wet surface as compared to that on the dry surface at each temperature by using collision rates and moisture risk factors associated with each combination of pavement surface temperature and pavement moisture condition. The risk factor measures the relative risk of collision as a ratio between the collision rate per hour of exposure on wet surface and the collision rate per hour of exposure on dry surface.

The next chapter applies the Empirical Bayes (EB) technique, analogous to that adopted by Higle and Witkowski (1998), to identify the pavement surface temperature and pavement moisture condition combinations at which the road driving is more hazardous than others. In that approach, the collision rate per hour of exposure associated with a particular pavement surface temperature and pavement moisture condition on the pavement surface is assumed to be a random variable. The posterior probability of a collision rate at specific pavement surface temperature and pavement moisture condition, being greater than the average collision rate (above normal collision rate), is used to determine whether or not the road driving is more hazardous.

The next two sections describe the process undertaken to prepare and analyze the data and state the underlying assumptions used to measure and compare the risk of vehicle collision on wet and dry surfaces.

3.1. Description of Collision Data

A collision data file for a twelve-month period (November 1, 2001 – October 31, 2002) was obtained for the City of Ottawa. A sample of the original file is presented in Table 3.1. The file contained 24,150 records; each has different fields describing the events, collision characteristics, and circumstances for a vehicle that was involved in a collision. The fields of interest for this thesis from the data file were:

- A collision identification number (Accident ID) uniquely identifies each collision. All vehicles involved in a collision are assigned the same identification number of that collision but listed in a different record. The number of records per collision in this database ranged from one (single car collision) to a maximum of six (a collision involving six vehicles).

- Initial impact type of the collision (Impact Type): takes a value of 1 (approaching), 2 (at angle), 3 (rear-end), 4 (sideswipe), 5 (turning movement), 6 (single motor vehicle (SMV) unattended), 7 (other SMV), or 99 (non of the above).

Table 3.1: Sample of the original file of vehicle collisions obtained from the City of Ottawa (November 1, 2001 – October 31, 2002)

Accident ID	Impact type	Traffic control	Date	Time	Day	Dir.	Vehicle manv.	Weather	Class of acc.
010012841	6	10	2001/12/19	12:00 PM	4	0	0	0	3
010178852	7	10	2001/12/22	10:50 AM	7	4	2	1	3
010239097	7	1	2001/11/21	07:55 PM	4	2	4	2	3
010239384	7	1	2001/11/01	02:30 AM	5	3	4	1	2
010239428	7	10	2001/11/01	06:40 AM	5	4	1	7	3
010239448	3	1	2001/11/01	07:33 AM	5	4	5	7	3
010239448	3	1	2001/11/01	07:33 AM	5	4	5	7	3
010239464	3	2	2001/11/01	08:02 AM	5	4	1	1	2
010239464	3	2	2001/11/01	08:02 AM	5	4	2	1	2
010239464	3	2	2001/11/01	08:02 AM	5	4	2	1	2
010239488	3	1	2001/11/01	08:48 AM	5	2	2	2	3
010239488	3	1	2001/11/01	08:48 AM	5	2	10	2	3
010239490	3	10	2001/11/01	08:53 AM	5	2	2	2	3
010239490	3	10	2001/11/01	08:53 AM	5	2	1	2	3
010239490	3	10	2001/11/01	08:53 AM	5	2	1	2	3
010239511	7	1	2001/11/01	09:26 AM	5	2	4	1	3
010239514	3	1	2001/11/01	09:27 AM	5	3	1	1	3
010239514	3	1	2001/11/01	09:27 AM	5	3	10	1	3
010239516	5	10	2001/11/01	09:30 AM	5	3	6	1	2
010239516	5	10	2001/11/01	09:30 AM	5	4	1	1	2
010239526	7	2	2001/11/01	09:40 AM	5	4	2	7	2
010239548	2	10	2001/11/01	11:50 AM	5	2	9	1	2
010239548	2	10	2001/11/01	11:50 AM	5	4	1	1	2
010239601	7	10	2001/11/01	11:00 AM	5	2	1	1	3

- Date of collision (Date): the format of this field is YYYY/MM/DD (year/month/day).
- Time of collision (Time): the format of this field is HOUR: MINUTE AM or PM.
- Day of the week (Day): takes a value of 1 (Sunday) to 7 (Saturday).
- Severity of collision (Class of Acc): collisions involving fatalities were given a value of 1, injury a value of 2, and PDO a value of 3.

Several steps were undertaken to transform the collision data file into the required format. Since one of the objectives of this thesis was to study the effect of road surface temperature and pavement moisture condition during the winter months on vehicle collisions, the first step was to consider only collisions that occurred during the five winter months (November 1, 2001 to March 31, 2002). There were 6,183 collisions involving 10,802 vehicles during these five months. As mentioned earlier, detailed traffic volumes for the City of Ottawa were not available but the daily traffic patterns and volumes during the weekdays are normally different from those during the weekends. Therefore, the second step was to remove those collisions that occurred during the weekends to avoid potential inconsistencies in the data. The result of this step was a reduction in records to 8,333 vehicles involved in 4,697 collisions. The third step was to map the resulting file into a new file containing only one record for each collision with the number of vehicles involved in that collision appearing as a new variable. Then the HOUR format was changed from 1 - 12 am/pm to 1 – 24 and the collisions were aggregated into each hour of the day. For example, all collisions that occurred between 14:01 and 15:00 were added and assigned to the 15th hour together with the total number of vehicles involved in these collisions. Changes in pavement surface temperature within each hour are expected to be minimal with no significant effect on the results of this research. In addition, the traffic volume on a typical city road usually decrease substantially at the night hours and becomes almost negligible during the early morning hours. As the exact traffic volumes at different hours of the day were not available, only those collisions that occurred between the 7^{th} and the 21^{st} hours (i.e. from 6:01 am to 9:00 pm) were chosen for the analysis to maintain the consistency of traffic exposure as much as possible. *In addition, the hours of the day were divided into peak and off peak.* This break down of driving hour should add to the consistency of the traffic conditions since changes in traffic volume within each category is expected to be small.

The last step was to remove the records of the single motor vehicles unattended (IMPACTTYPE = 6) as they were mainly due to sabotage or other factors unrelated to driving conditions. The final collision data file contained 3,870 collisions involving 7,258 vehicles. These data provided reasonable and fairly consistent traffic volumes on the daily basis. As stated earlier, 94% of the roads in the City of Ottawa are made of asphalt concrete, and therefore the effect of the type of pavement surface should be negligible and was not considered in this thesis.

The next phase was to separate the frequency of collisions occurred on wet pavement surface from those occurred on dry pavement surface. These data were then merged with the data file containing the pavement surface temperature at each date and hour of the day (details on the pavement surface temperature database are explained in Chapter 6). Table 3.2 presents a part of this new merged file. The fields in this file are: date, hour, surface temperature (°C), number of collisions that occurred on wet and dry surfaces, and number of vehicles involved in these collisions.

Table 3.2: Numbers of collisions and vehicles in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Date	Hour	Surface temperature	Number of collisions			Number of vehicles		
			Dry	Wet	Total	Dry	Wet	Total
2001/11/02	7	12.67	0	1	1	0	1	1
	8	13.16	2	0	2	5	0	5
	9	14.37	0	4	4	0	8	8
	10	14.12	0	0	0	0	0	0
	11	13.40	0	2	2	0	4	4
	12	13.97	0	1	1	0	2	2
	13	13.97	0	4	4	0	9	9
	14	14.78	0	4	4	0	7	7
	15	15.03	0	4	4	0	7	7
	16	14.23	0	2	2	0	4	4
	17	13.99	0	6	6	0	13	13
	18	13.80	0	12	12	0	25	25
	19	13.61	0	6	6	0	12	12
	20	13.47	0	0	0	0	0	0
	21	12.93	0	1	1	0	1	1
2001/11/05	7	4.51	1	0	1	2	0	2
	8	4.65	0	0	0	0	0	0
	9	5.62	0	0	0	0	0	0
	10	9.41	1	0	1	2	0	2
	11	13.17	1	0	1	2	0	2
	12	13.77	2	0	2	2	0	3
	13	13.91	1	0	1	2	0	2
	14	14.49	1	0	1	2	0	2
	15	13.21	0	0	0	0	0	0
	16	11.03	0	0	0	0	0	0
	17	9.31	3	0	3	5	0	5
	18	8.34	0	0	0	0	0	0
	19	7.69	2	0	2	3	0	3
	20	7.10	0	2	2	0	4	4
	21	6.62	6	0	6	9	0	9

3.2. Preparation and Description of Data

In order to examine the effect of the pavement surface temperature and pavement moisture condition on the risk of vehicle collisions, the numbers of collisions occurred on wet surface was compared to those occurred on dry surface at each temperature. This comparison, as shown in Table 3.3, may not reveal the true nature of the relationship between the risk of collision and pavement surface temperature or pavement moisture condition since the number of hours of exposure is expected to affect the number of collisions. In general, the more hours of exposure at a given temperature, the more collisions expected to occur at this temperature. Therefore, in order to make the comparison more meaningful, the rates of collision per hour of exposure, rather than the number of collisions, were compared. This required the calculation of the numbers of hours of wet and dry pavement surface at each temperature during the study period. The results, given in Table 3.4, show that the total number of hours was 1,605 hours out of which 862 hours had wet pavement surface and 743 hours had dry surface.

The numbers of hours at the lower and higher ends of the temperature spectrum tend to decrease and the rates of collisions and vehicles per hour of exposure become sensitive to small stochastic changes in the numbers of collisions and vehicles. Therefore, collisions corresponding to less than 15 hours were excluded. As a result, the analysis included only those collisions that took place at temperatures larger than and including –8°C. To prevent any bias in the choice of the number of collisions and exposure hours at the higher end of the temperatures, same number of positive temperatures was used. The analysis included only those collisions that took place at temperatures up to and including +8°C.

Table 3.3: Numbers of collisions and vehicles at different temperatures in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Number of collisions			Number of vehicles		
		Dry	Wet	Total	Dry	Wet	Total
(-17.5, -16.5)	-17	0	0	0	0	0	0
(-16.5, -15.5)	-16	3	0	3	6	0	6
(-15.5, -14.5)	-15	6	0	6	12	0	12
(-14.5, -13.5)	-14	6	3	9	10	7	17
(-13.5, -12.5)	-13	4	7	11	7	15	22
(-12.5, -11.5)	-12	5	11	16	9	21	30
(-11.5, -10.5)	-11	13	19	32	24	41	65
(-10.5, -9.5)	-10	25	31	56	50	61	111
(-9.5, -8.5)	-9	15	26	41	31	47	78
(-8.5, -7.5)	-8	39	85	124	72	167	239
(-7.5, -6.5)	-7	45	64	109	90	121	211
(-6.5, -5.5)	-6	39	68	107	73	123	196
(-5.5, -4.5)	-5	40	92	132	85	166	251
(-4.5, -3.5)	-4	65	87	152	128	152	280
(-3.5, -2.5)	-3	72	162	234	147	282	429
(-2.5, -1.5)	-2	33	229	262	63	433	496
(-1.5, -0.5)	-1	72	347	419	138	592	730
(-0.5, 0.5)	0	66	221	287	125	393	518
(0.5, 1.5)	1	53	189	242	107	350	457
(1.5, 2.5)	2	63	164	227	121	310	431
(2.5, 3.5)	3	70	128	198	130	248	378
(3.5, 4.5)	4	68	77	145	126	138	264
(4.5, 5.5)	5	72	114	186	130	225	355
(5.5, 6.5)	6	61	64	125	118	117	235
(6.5, 7.5)	7	52	53	105	98	104	202
(7.5, 8.5)	8	94	45	139	172	86	258
(8.5, 9.5)	9	48	26	74	98	47	145
(9.5, 10.5)	10	33	63	96	65	129	194
(10.5, 11.5)	11	23	49	72	44	88	132
(11.5, 12.5)	12	28	3	31	57	5	62
(12.5, 13.5)	13	34	17	51	67	33	100
(13.5, 14.5)	14	31	35	66	60	73	133
(14.5, 15.5)	15	18	8	26	33	14	47
(15.5, 16.5)	16	18	0	18	36	0	36
(16.5, 17.5)	17	19	3	22	40	6	46
(17.5, 18.5)	18	10	0	10	18	0	18
(18.5, 19.5)	19	10	2	12	21	4	25
(19.5, 20.5)	20	10	0	10	20	0	20
(20.5, 21.5)	21	1	0	1	2	0	2
(21.5, 22.5)	22	0	0	0	0	0	0
(22.5, 23.5)	23	8	0	8	16	0	16
(23.5, 24.5)	24	6	0	6	11	0	11
Total		1,378	2,492	3,870	2,660	4,598	7,258

Table 3.4: Number of hours at different temperatures (November 1, 2001 – March 31, 2002)

Temperature Range	Temperature	Number of hours		
		Dry	Wet	Total
(-17.5, -16.5)	-17	1	0	1
(-16.5, -15.5)	-16	1	0	1
(-15.5, -14.5)	-15	1	0	1
(-14.5, -13.5)	-14	3	1	4
(-13.5, -12.5)	-13	4	4	8
(-12.5, -11.5)	-12	5	6	11
(-11.5, -10.5)	-11	9	7	16
(-10.5, -9.5)	-10	10	9	19
(-9.5, -8.5)	-9	12	11	23
(-8.5, -7.5)	-8	16	18	34
(-7.5, -6.5)	-7	20	17	37
(-6.5, -5.5)	-6	23	22	45
(-5.5, -4.5)	-5	21	23	44
(-4.5, -3.5)	-4	25	34	59
(-3.5, -2.5)	-3	39	56	95
(-2.5, -1.5)	-2	19	69	88
(-1.5, -0.5)	-1	40	72	112
(-0.5, 0.5)	0	35	76	111
(0.5, 1.5)	1	37	89	126
(1.5, 2.5)	2	35	67	102
(2.5, 3.5)	3	32	56	88
(3.5, 4.5)	4	34	37	71
(4.5, 5.5)	5	45	43	88
(5.5, 6.5)	6	32	28	60
(6.5, 7.5)	7	25	21	46
(7.5, 8.5)	8	42	16	58
(8.5, 9.5)	9	38	14	52
(9.5, 10.5)	10	23	25	48
(10.5, 11.5)	11	21	16	37
(11.5, 12.5)	12	19	4	23
(12.5, 13.5)	13	23	9	32
(13.5, 14.5)	14	18	8	26
(14.5, 15.5)	15	10	2	12
(15.5, 16.5)	16	7	0	7
(16.5, 17.5)	17	5	1	6
(17.5, 18.5)	18	5	0	5
(18.5, 19.5)	19	2	1	3
(19.5, 20.5)	20	2	0	2
(20.5, 21.5)	21	1	0	1
(21.5, 22.5)	22	0	0	0
(22.5, 23.5)	23	2	0	2
(23.5, 24.5)	24	1	0	1
Total		743	862	1.605

The final set of data included a total of 3,193 collisions involving 5,930 vehicles at temperatures between –8°C and +8°C. The numbers of hours in this range for dry and wet conditions were 520 and 744 respectively, a total of 1,264 hours. Figure 3.1 presents the distribution of these hours along the temperature range. It shows that the distribution of hours for wet condition has a peak at +1°C and the distribution for the dry condition has no clear trend. Figures 3.2 and 3.3 present the distributions of the number of collisions and vehicles at each pavement surface temperature. Both distributions are almost identical since the number of vehicle is highly correlated to the number of collisions. Therefore, the analyses in the rest of this thesis will include only the numbers and rates of collisions.

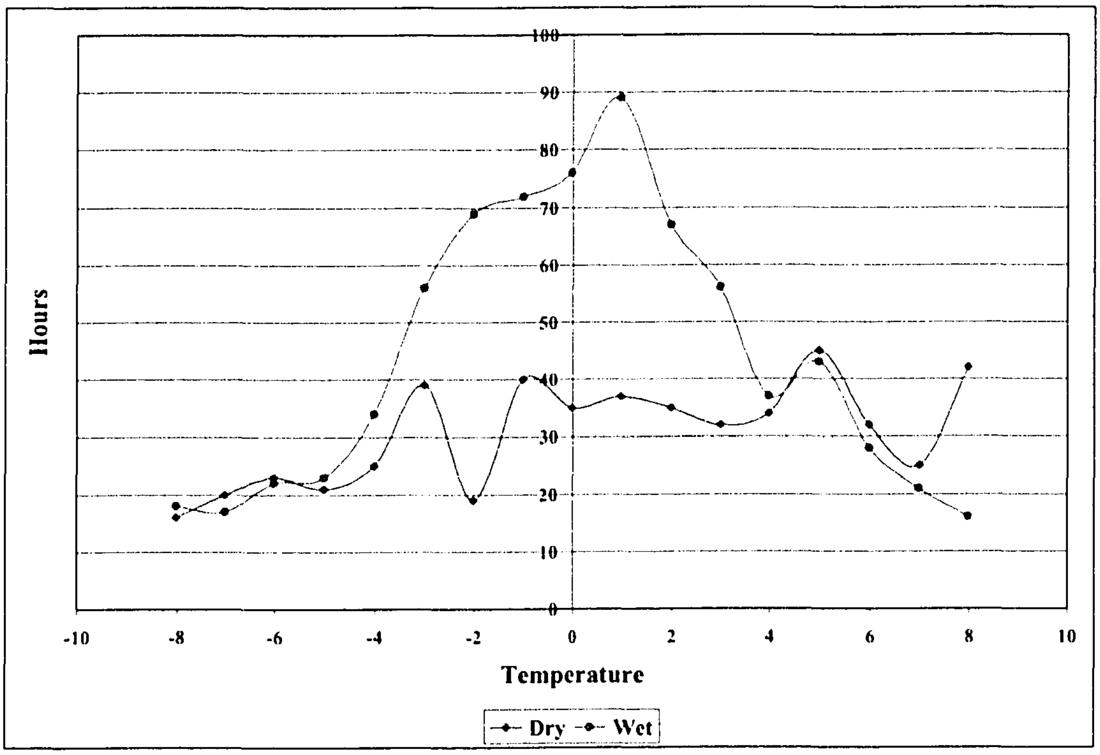


Figure 3.1: Distributions of hours at different temperatures for dry and wet pavement surfaces

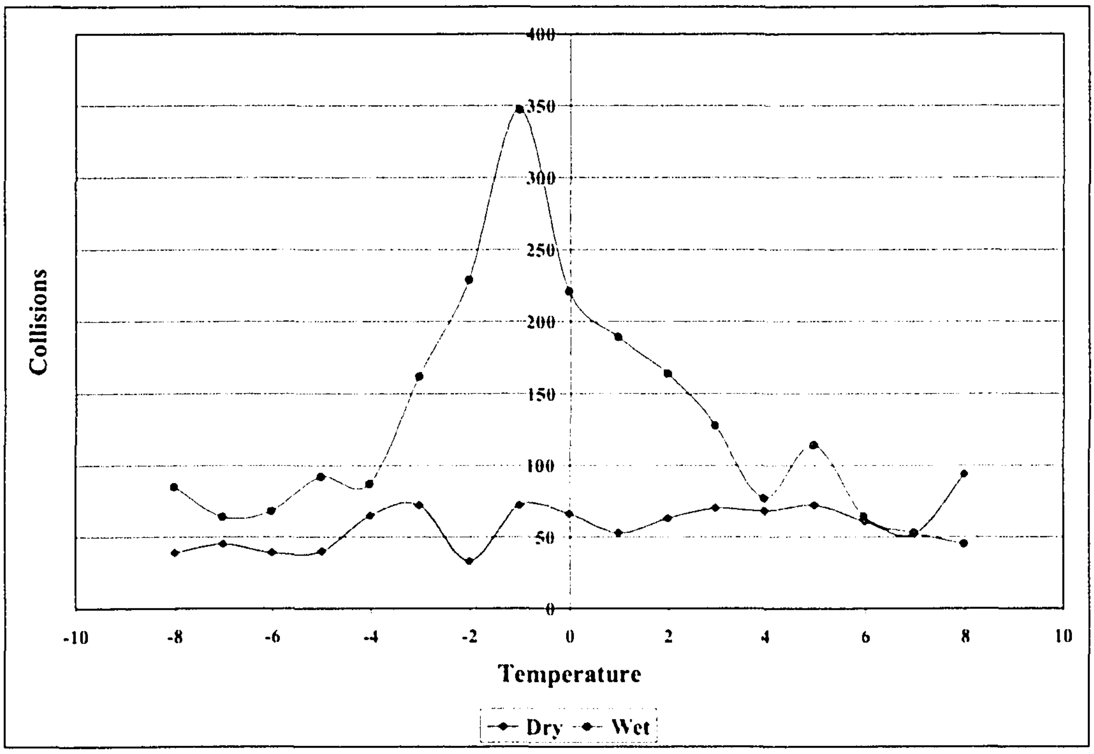


Figure 3.2: Distributions of total collisions at different temperatures on wet and dry surfaces

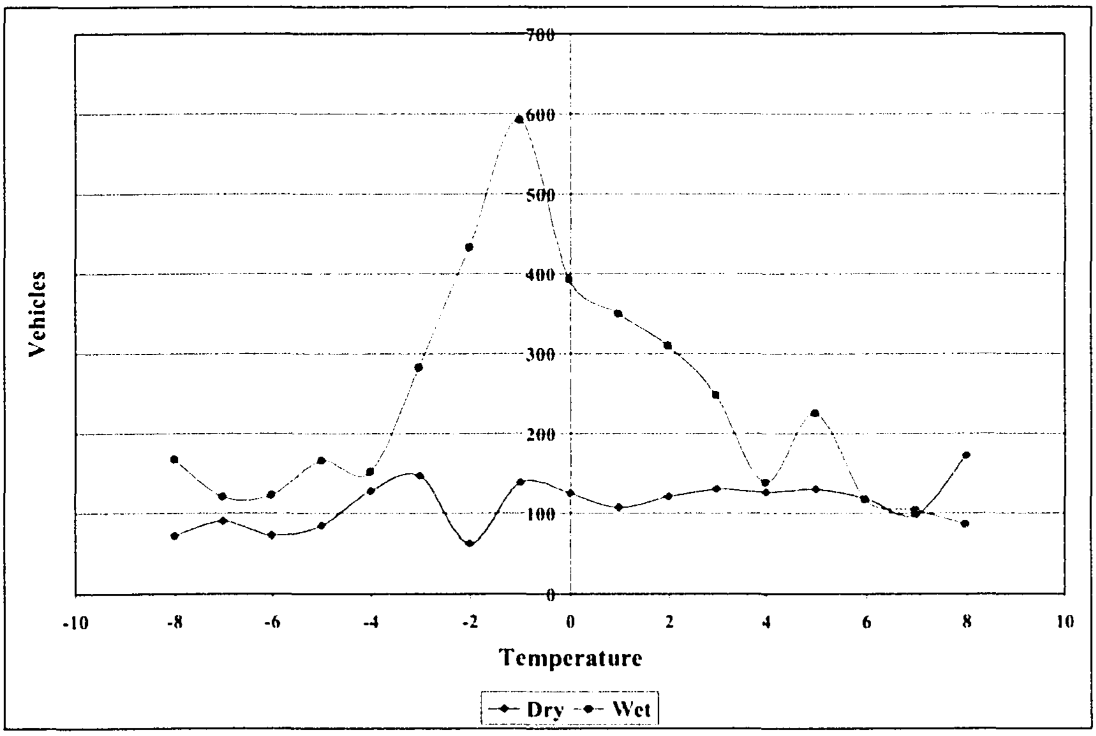


Figure 3.3: Distributions of total vehicles involved in collisions at different temperatures on wet and dry surfaces

This research also examines the effect of surface temperature and pavement moisture condition on the severity of collisions and the types of initial impact. The number of collisions was therefore disaggregated into these two classifications as follows:

- Severity of collision includes fatal collisions, collisions involving injury, and collisions involving PDO.
- Types of initial impact includes single-vehicle collisions, rear-end collisions, and other types of collisions.

The number of hours and collisions in each of the six categories was further disaggregated into dry and wet pavement conditions. Finally, the data was divided in two time periods, the peak hours and off-peak hours. The peak hours in the City of Ottawa are from 6:00 to 9:00 am and from 3:00 to 6:00 pm. This break up of the analysis adds to the consistency of the data and assumes that traffic volumes are fairly constant within each period for the 5 months duration.

Table 3.5 presents the numbers and percentages of collisions for all categories during peak and off-peak periods. It shows that during the study period, there were a total of 3,193 collisions out of which 1,566 (49.04%) occurred during peak period and 1,627 (50.96%) during off-peak period. During the peak period, there were 2 fatal collisions, 330 collisions involving injury, 1,234 collisions involving PDO, 353 single vehicle collisions, 517 rear-end collisions, and 696 collisions involving other types of initial impact. On the other hand, during the off-peak period there were 7 fatal collisions, 385 collisions involving injury, 1,235 collisions involving PDO, 419 single-vehicle collisions, 427 rear-end collisions, and 781 collisions involving other types of initial impact. The numbers of collisions during the peak and off-peak periods were then disaggregated into wet versus dry pavement surface. The number of the exposure hours during the peak and off-peak periods are given in Table 3.6.

3.3. Methodology of Road Risk Analysis

A number of road safety analysis methods have been developed to identify hazardous locations and intersections. Different risk indices were developed to compare factors that affect road safety. For example, Tarko *et al.* (1996) calculated the above norm collisions as the difference between the number of observed collisions and normal number of collisions obtained from a performance function. Another risk factor used by Andrey *et al.* (2003) in which the total number of collisions in a winter event period was divided by the total number of collisions in a control period. Other researchers used the collision rates per million vehicle-kilometers instead of the number of collisions to identify hazardous locations.

Table 3.5: Numbers of collisions by category

Class	Peak		Off-Peak		Total	
	Number	Percentage	Number	Percentage	Number	Percentage
Total	1,566	100.00	1,627	100.00	3193	100.00
Fatal	2	0.13	7	0.43	9	0.28
Injury	330	21.07	385	23.66	715	22.39
PDO	1,234	78.80	1,235	75.91	2,469	77.33
Single	353	22.54	419	25.75	772	24.18
Rear-end	517	33.01	427	26.25	944	29.56
Other	696	44.45	781	48.00	1,477	46.26

The rate of collision at an intersection per million vehicles entering the intersection was also used to identify hazardous intersections (Higle and Witkowski, 1988).

Although this thesis examines a topic, which is different from the identification the hazardous locations, similar methodologies were adopted to identify those pavement surface temperature and pavement moisture condition that make road-driving condition more hazardous than others during the winter season. A pavement moisture risk factor was calculated as the ratio between the collision rate per hour of exposure on the wet surface and the collision rate per hour of exposure on the dry surface. If the pavement moisture risk factor is larger than 1, the driving on wet surface is considered to involve a higher risk of collision than driving on dry surface. Otherwise, the driving on wet surface is considered to involve a lower risk of collision than driving on dry surface. Finally, if the pavement moisture risk factor equals 1, the risk of driving on either wet or dry surface would be the same.

3.4. Results of Road Risk Analysis

As explained earlier, all the analyses presented in this thesis are undertaken using collision data collected in the City of Ottawa during the five months' study period (November 1, 2001 – March 31, 2002) on weekdays (Monday – Friday) between 6:01 am to 9:00 pm. Only those collisions occurred at temperature range from –8°C and +8°C are considered in the analysis. The following sections present the risk of collision analysis within each category.

Table 3.6: Hours of exposure at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	10	13	23	6	5	11	16	18	34
(-7.5, -6.5)	-7	6	9	15	14	8	22	20	17	37
(-6.5, -5.5)	-6	6	10	16	17	12	29	23	22	45
(-5.5, -4.5)	-5	13	12	25	8	11	19	21	23	44
(-4.5, -3.5)	-4	10	20	30	15	14	29	25	34	59
(-3.5, -2.5)	-3	14	22	36	25	34	59	39	56	95
(-2.5, -1.5)	-2	11	36	47	8	33	41	19	69	88
(-1.5, -0.5)	-1	16	39	55	24	33	57	40	72	112
(-0.5, 0.5)	0	12	25	37	23	51	74	35	76	111
(0.5, 1.5)	1	15	32	47	22	57	79	37	89	126
(1.5, 2.5)	2	19	28	47	16	39	55	35	67	102
(2.5, 3.5)	3	11	17	28	21	39	60	32	56	88
(3.5, 4.5)	4	14	10	24	20	27	47	34	37	71
(4.5, 5.5)	5	18	11	29	27	32	59	45	43	88
(5.5, 6.5)	6	14	10	24	18	18	36	32	28	60
(6.5, 7.5)	7	9	10	19	16	11	27	25	21	46
(7.5, 8.5)	8	15	8	23	27	8	35	42	16	58
Total		213	312	525	307	432	739	520	744	1264

3.4.1. Total Collisions

Table 3.7 gives the total numbers of collision on wet and dry pavement surfaces during the peak and off-peak periods at each temperature between –8°C and +8°C. There were 1,038 collisions occurred on wet surface and 528 collisions occurred on dry surface during the peak period. During the off-peak period, there were 1,151 collisions occurred on wet surface and 476 collisions occurred on dry surface. Figures 3.4 and 3.5 present the distributions of total collision at different temperatures on the wet and dry surfaces during the peak and off-peak periods. As shown in Figure 3.4, collisions on the wet surface during the peak period had a maximum of 203 at −1°C and remained relatively high around this temperature where roads were mainly icy or slushy. Figure 3.5 showed a similar maximum of 150 collisions on wet surface during the off-peak period at 0°C. Unlike the wet surface, the number of collisions on dry surface during both peak and off-peak periods showed no specific pattern with changing temperature.

The total collision rates per hour of exposure were calculated by dividing the numbers of total collisions during the peak and off-peak periods in Table 3.7 by the corresponding number of hours of exposure in Table 3.6. Table 3.8 gives these total collision rates on the dry and wet pavement surfaces. During the peak period, the average rate of collision per hour of exposure on wet surface was 3.26 as compared to 2.61, the average rate of collision per hour of exposure on dry surface. During the off-peak period, the average rate of collision per hour of exposure on wet surface was 2.97 as compared to 1.56, the average rate of collision per hour of exposure on dry surface.

A pavement moisture risk factor was calculated at each temperature as the ratio between the rate of collision per hour of exposure on the wet surface and the rate of collision per hour of exposure on the dry surfaces. For example, during peak period at −1°C in Table 3.8, the risk factor was 2.60 (by dividing 5.21 by 2.00), which indicates that the risk of collision when driving on wet pavement surface during the peak period at -1°C was 160% higher than the risk of collision when driving on dry surface under the same conditions. Similarly, the risk factor during off-peak period at −1°C was 2.62 (by dividing 4.36 by 1.67), which indicates that the risk of collision when driven on wet pavement surface during the off-peak period at −1°C was 162% higher than the risk of collision when driven on dry surface under the same conditions. The average pavement moisture risk factors during the peak and off-peak periods were 1.34 and 1.72 respectively, but a particular risk, however, depends upon the pavement surface temperature.

Table 3.7: Total collisions at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	29	48	77	10	37	47	39	85	124
(-7.5, -6.5)	-7	25	41	66	20	23	43	45	64	109
(-6.5, -5.5)	-6	18	34	52	21	34	55	39	68	107
(-5.5, -4.5)	-5	26	47	73	14	45	59	40	92	132
(-4.5, -3.5)	-4	40	49	89	25	38	63	65	87	152
(-3.5, -2.5)	-3	34	73	107	38	89	127	72	162	234
(-2.5, -1.5)	-2	22	128	150	11	101	112	33	229	262
(-1.5, -0.5)	-1	32	203	235	40	144	184	72	347	419
(-0.5, 0.5)	0	24	71	95	42	150	192	66	221	287
(0.5, 1.5)	1	26	66	92	27	123	150	53	189	242
(1.5, 2.5)	2	33	88	121	30	76	106	63	164	227
(2.5, 3.5)	3	26	46	72	44	82	126	70	128	198
(3.5, 4.5)	4	34	28	62	34	49	83	68	77	145
(4.5, 5.5)	5	43	40	83	29	74	103	72	114	186
(5.5, 6.5)	6	39	26	65	22	38	60	61	64	125
(6.5, 7.5)	7	29	28	57	23	25	48	52	53	105
(7.5, 8.5)	8	48	22	70	46	23	69	94	45	139
Total		528	1,038	1,566	476	1,151	1,627	1,004	2,189	3,193

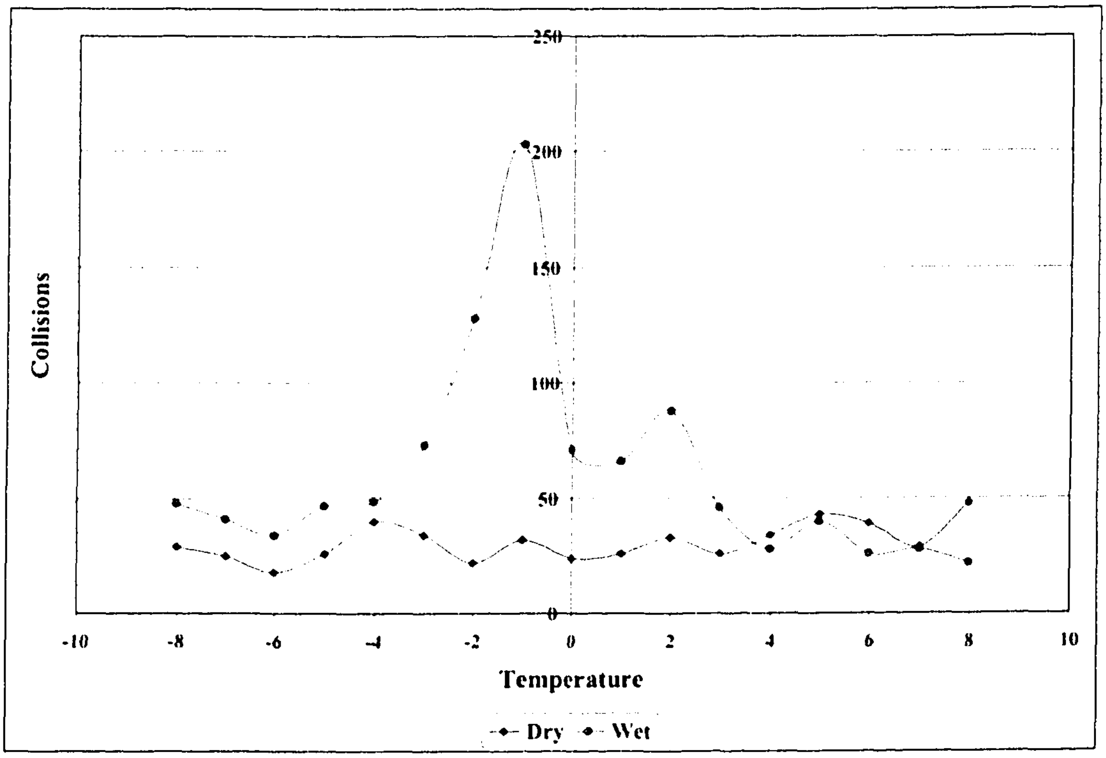


Figure 3.4: Distributions of total collisions at different temperatures on wet and dry surfaces during the peak period

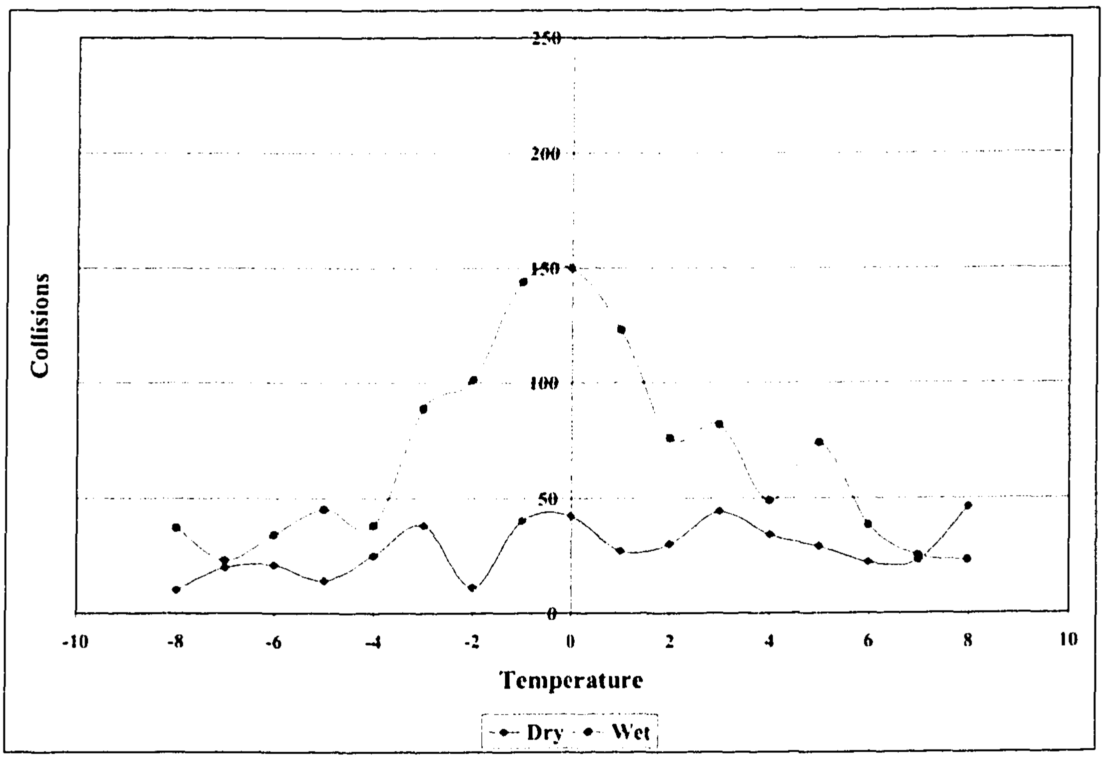


Figure 3.5: Distributions of total collisions at different temperatures on wet and dry surfaces during the off-peak period

Table 3.8: Rates of total collisions per hour of exposure at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period				Off-peak period			
		Dry	Wet	Total	Risk	Dry	Wet	Total	Risk
(-8.5, -7.5)	-8	2.90	3.69	3.35	1.27	1.67	7.40	4.27	4.44
(-7.5, -6.5)	-7	4.17	4.56	4.40	1.09	1.43	2.88	1.95	2.01
(-6.5, -5.5)	-6	3.00	3.40	3.25	1.13	1.24	2.83	1.90	2.29
(-5.5, -4.5)	-5	2.00	3.92	2.92	1.96	1.75	4.09	3.11	2.34
(-4.5, -3.5)	-4	4.00	2.45	2.97	0.61	1.67	2.71	2.17	1.63
(-3.5, -2.5)	-3	2.43	3.32	2.97	1.37	1.52	2.62	2.15	1.72
(-2.5, -1.5)	-2	2.00	3.56	3.19	1.78	1.38	3.06	2.73	2.23
(-1.5, -0.5)	-1	2.00	5.21	4.27	2.60	1.67	4.36	3.23	2.62
(-0.5, 0.5)	0	2.00	2.84	2.57	1.42	1.83	2.94	2.59	1.61
(0.5, 1.5)	1	1.73	2.06	1.96	1.19	1.23	2.16	1.90	1.76
(1.5, 2.5)	2	1.74	3.14	2.57	1.81	1.88	1.95	1.93	1.04
(2.5, 3.5)	3	2.36	2.71	2.57	1.14	2.10	2.10	2.10	1.00
(3.5, 4.5)	4	2.43	2.80	2.58	1.15	1.70	1.81	1.77	1.07
(4.5, 5.5)	5	2.39	3.64	2.86	1.52	1.07	2.31	1.75	2.15
(5.5, 6.5)	6	2.79	2.60	2.71	0.93	1.22	2.11	1.67	1.73
(6.5, 7.5)	7	3.22	2.80	3.00	0.87	1.44	2.27	1.78	1.58
(7.5, 8.5)	8	3.20	2.75	3.04	0.86	1.70	2.88	1.97	1.69
Mean		2.61	3.26	2.93†	1.34	1.56	2.97	2.26†	1.72
Variance		0.53	0.63	0.67†	…	0.08	1.78	1.41†	…

† Mean and variance of the rates of total collisions are calculated from the 34 observations of dry and wet surfaces.

These results show that during peak period, the risk of collision when driving on wet pavement surface was, on average, 34% higher than the risk of collision when driving on dry surfaces. Similarly, during off-peak period, the risk of collision when driving on wet pavement surface was, on average, 72% higher than the risk of collision when driving on dry surface. The overall average and variance of the rates of total collisions per hour of exposure were calculated from the 34 observations of both wet and dry surfaces combined during each of the peak and off-peak period for the determination of the Bayes Posterior parameter in the next Chapter. Table 3.8 gives these values as (2.93, 0.67) for peak period and (2.26, 1.41) for off-peak period.

Figures 3.6 and 3.7 present the distributions of the collision rates at different temperatures on wet and dry surfaces during the peak and off-peak periods respectively. Figures 3.6 shows that the rate of collision per hour of exposure on wet surface during the peak period was higher than on dry surface at all temperatures between –8°C and +8°C, except at – 4°C, +6°C, +7°C and +8°C.

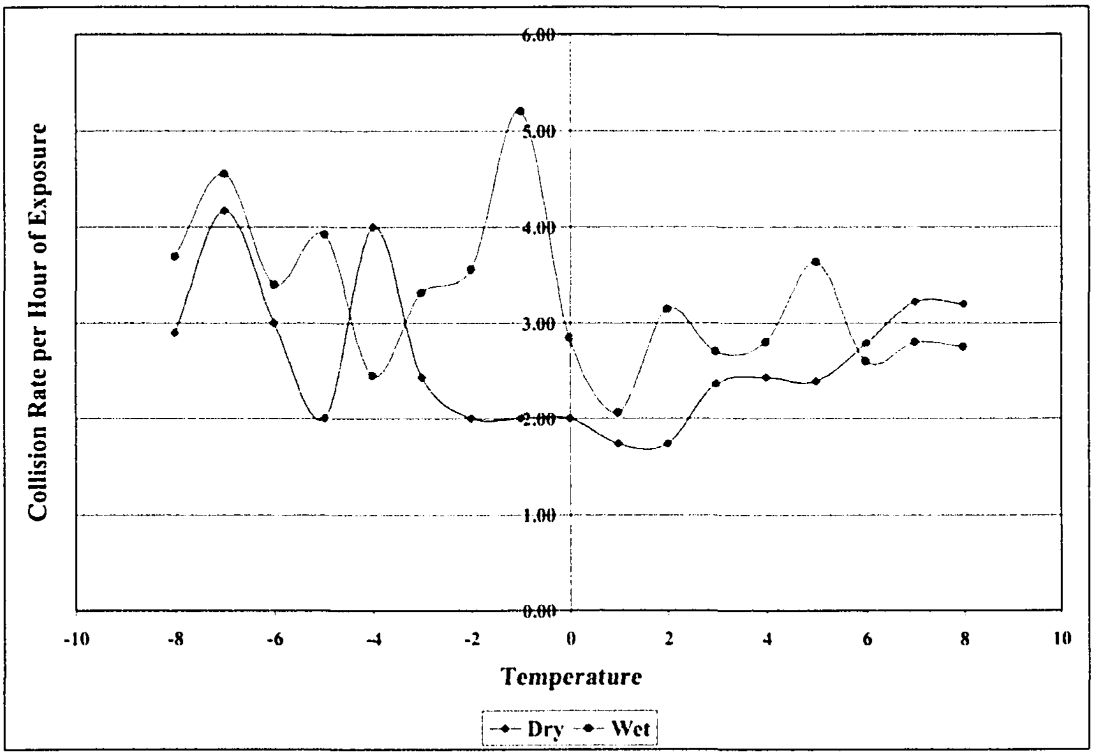


Figure 3.6: Distributions of collision rates per hour of exposure at different temperatures on wet and dry surfaces during the peak period

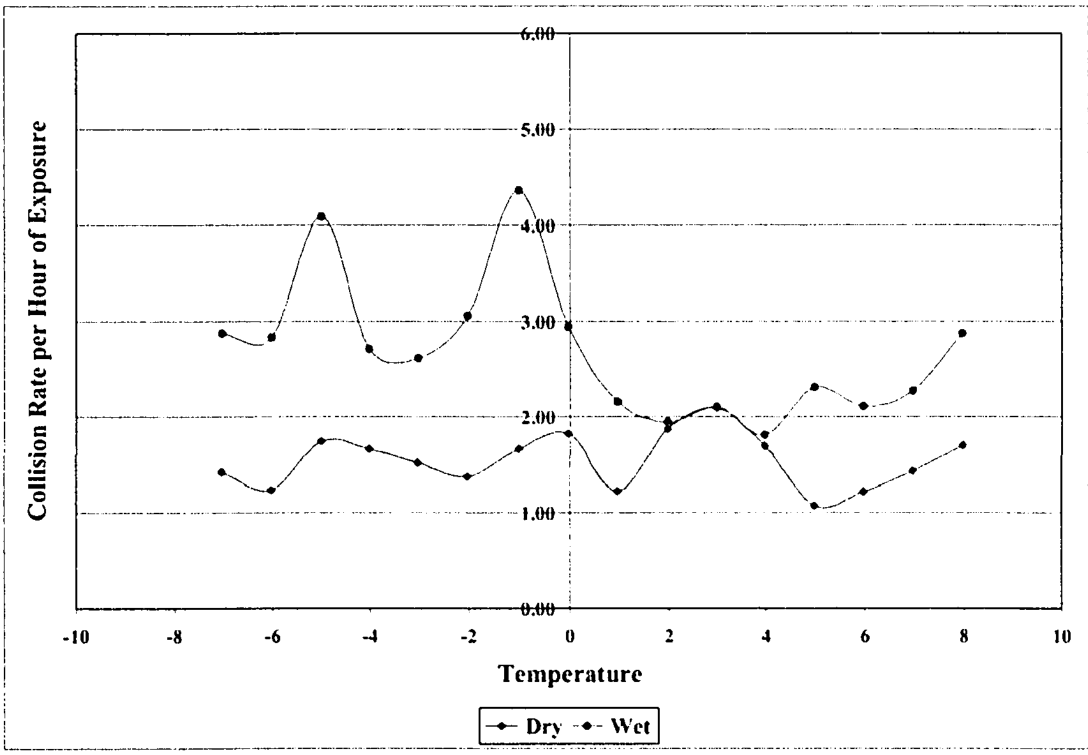


Figure 3.7: Distributions of collision rates per hour of exposure at different temperatures on wet and dry surfaces during off-peak period

Similarly, Figure 3.7 shows that the collision rate per hour of exposure on wet surface was higher than the collision rate per hour of exposure on dry surface during the off-peak period at all temperatures between –8°C and +8°C. Finally, Figure 3.8 presents the distributions of the pavement moisture risk factors for total collisions during peak and off-peak periods. It should be noted that a higher risk factor might result from either a large numerator (collision rate on wet surface) or a small denominator (collision rate on dry surface). Therefore, one needs to be careful in interpreting the significance of high risk factors.

The analysis in this section suggests that moisture on pavement surface increases the risk of collision during the off-peak period at all temperatures. The results showed also that the rate of collision per hour of exposure on wet surface during the peak period was higher than the rate of collision per hour of exposure on dry surface during the peak period at sub-zero temperatures and above zero temperatures up to +5°C. Therefore, wet pavement condition increases the risk of collision at temperatures between –8°C and +5°C irrespective to the traffic volume. Beyond +5°C, the rate of collision per hour of exposure on dry surface was higher than the rate of collision per hour of exposure on wet surface. The cause of this difference can be due to higher vehicle speeds during the off-peak period and other human factors, which are beyond the scope of this analysis. This thesis only examines the effect of pavement moisture condition on the risk of collision by comparing collision rates on wet surface to collision rates on dry surface at different temperatures during peak and off-peak periods separately. No attempt was made to compare collisions between peak and off-peak periods.

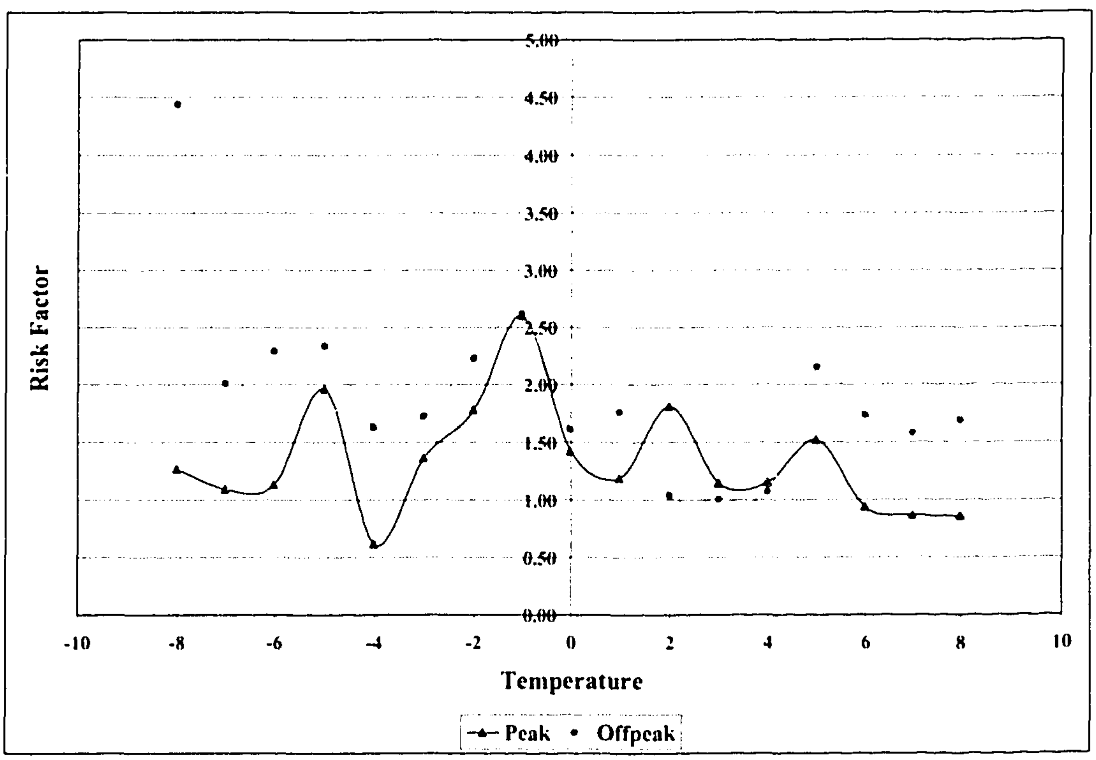


Figure 3.8: Pavement moisture risk factors using collision rates per hour of exposure at different temperatures during the peak and off-peak periods

3.4.2. Severity of Collision

One of the most important aspects of road safety is to be able to assess the consequences of road vehicle collisions. For example, a collision may result in minor or major damage to vehicles and property and may include minor or severe injury, or even fatality. The socioeconomic impact of these losses can be very high to society. Therefore, this section is devoted to examine the effect of the pavement surface temperature and pavement moisture condition on the severity of collisions, and identify the hazardous pavement surface temperature and pavement moisture condition combinations within each class of collision severity.

Unfortunately, the police records collected by the City of Ottawa did not classify whether injury or property damage are of minor or major nature. They only specify the existence of collisions with fatal injury, injury, or PDO. Therefore, the classification of collision severity in this research will be limited to the three main categories available in the data. This limitation, however, does not affect the generality of application of this methodology. The analysis can easily be extended to any set of data with available sub-classifications. In addition, the analysis of the socioeconomic impacts of road collisions is beyond the scope of this research and will not be dealt with in this thesis.

3.4.2.a. Fatal Collisions

The first category in the severity of collisions includes fatal collisions. Table 3.9 lists all fatal collisions during the peak and off-peak hours in the study period. There were 2 fatal collisions on the wet surface and nothing on the dry surface during the peak period. On the other hand, there were 7 fatal collisions during the off-peak period out of which 5 collisions occurred on the wet surface and 2 collisions occurred on the dry surface. Because of the small number of fatal collisions, the rates of collision and risk factors were not calculated. However, it may be seen from Table 3.9 that the risk of fatal collision increases between – 1°C and +1°C on wet pavement surface during both the peak and off-peak periods.

Table 3.9: Fatal collisions at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	0	0	0	0	1	1	0	1	1
(-7.5, -6.5)	-7	0	0	0	0	0	0	0	0	0
(-6.5, -5.5)	-6	0	0	0	0	0	0	0	0	0
(-5.5, -4.5)	-5	0	0	0	0	0	0	0	0	0
(-4.5, -3.5)	-4	0	0	0	1	0	1	1	0	1
(-3.5, -2.5)	-3	0	0	0	0	0	0	0	0	0
(-2.5, -1.5)	-2	0	0	0	0	0	0	0	0	0
(-1.5, -0.5)	-1	0	1	1	0	1	1	0	2	2
(-0.5, 0.5)	0	0	1	1	0	1	1	0	2	2
(0.5, 1.5)	1	0	0	0	0	1	1	0	2	2
(1.5, 2.5)	2	0	0	0	0	0	0	0	0	0
(2.5, 3.5)	3	0	0	0	1	0	1	1	0	1
(3.5, 4.5)	4	0	0	0	0	0	0	0	0	0
(4.5, 5.5)	5	0	0	0	0	1	0	0	0	0
(5.5, 6.5)	6	0	0	0	0	0	0	0	0	0
(6.5, 7.5)	7	0	0	0	0	0	0	0	0	0
(7.5, 8.5)	8	0	0	0	0	0	0	0	0	0
Total		0	2	2	2	5	7	2	7	9

3.4.2.b. *Collisions Involving Injury*

The second category in the severity of collisions includes those collisions involving injury. Table 3.10 gives the number of collisions with injury during the peak and off-peak periods at each temperature between –8°C and + 8°C on the dry and wet pavement surfaces.

Table 3.10: Collisions involving injury at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	8	9	17	2	9	11	10	18	28
(-7.5, -6.5)	-7	4	10	14	4	6	10	8	16	24
(-6.5, -5.5)	-6	3	10	13	11	10	21	14	20	34
(-5.5, -4.5)	-5	5	8	13	2	9	11	7	17	24
(-4.5, -3.5)	-4	9	12	21	6	7	13	15	19	34
(-3.5, -2.5)	-3	4	18	22	8	17	25	12	35	47
(-2.5, -1.5)	-2	7	21	28	3	21	24	10	42	52
(-1.5, -0.5)	-1	10	35	45	14	32	46	24	67	91
(-0.5, 0.5)	0	3	21	24	13	32	45	16	53	69
(0.5, 1.5)	1	7	7	14	7	29	36	14	36	50
(1.5, 2.5)	2	8	20	28	9	15	24	17	35	52
(2.5, 3.5)	3	2	14	16	9	19	28	11	33	44
(3.5, 4.5)	4	12	5	17	7	8	15	19	13	32
(4.5, 5.5)	5	6	7	13	3	27	30	9	34	43
(5.5, 6.5)	6	12	6	18	6	6	12	18	12	30
(6.5, 7.5)	7	4	5	9	7	9	16	11	14	25
(7.5, 8.5)	8	13	5	18	15	3	18	28	8	36
Total		117	213	330	126	259	385	243	472	715

During the peak period, there were 330 collisions with injury out of which 117 (35.45%) occurred on dry surface and 213 (64.55%) on wet surface. During the off- period, there were 385 collisions with injury out of which 126 (32.73%) occurred on dry surface and 259 (67.27%) on wet surface. Figures 3.9 and 3.10 present the distributions of collisions involving injury at each temperature on wet and dry surfaces during the peak and off-peak periods respectively. The figures show that the number of collisions involving injury on the wet surface during the peak period had a maximum of 35 collisions at –1 °C. Similarly, the number of collisions involving injury had a maximum of 32 at –1°C and 0°C on wet surface during the off-peak periods. The numbers of collisions involving injury on dry surface during both the peak and off-peak periods showed no specific pattern with changing temperature.

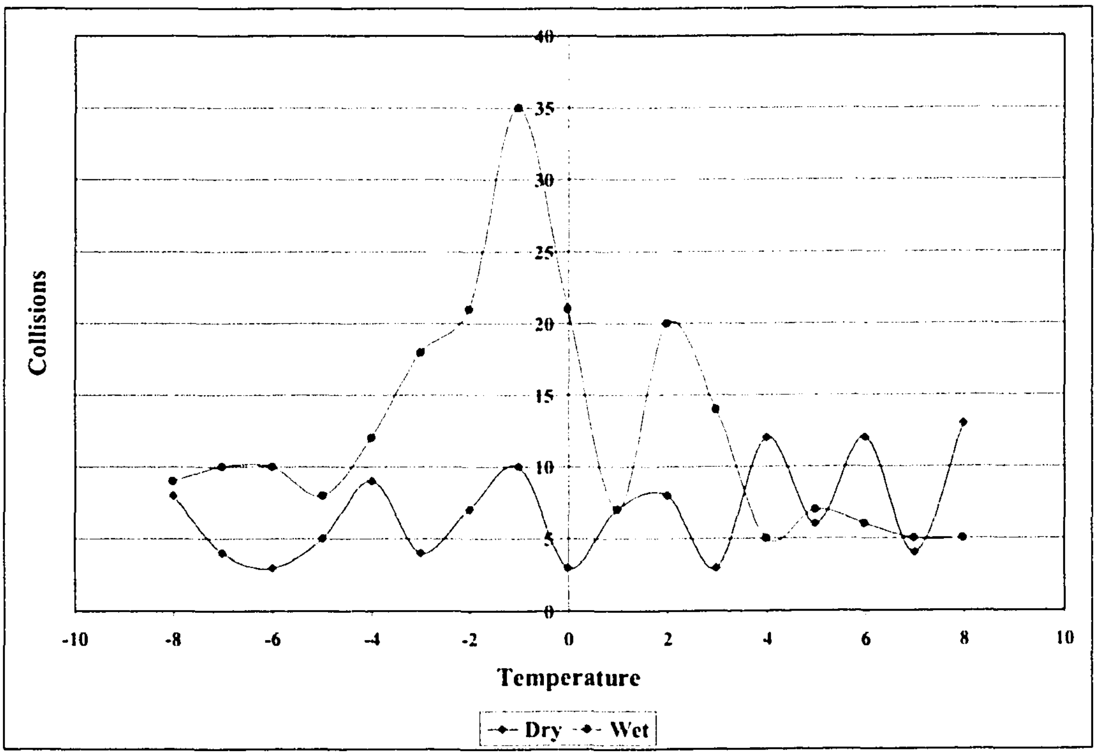


Figure 3.9: Distributions of collisions involving injury at different temperatures on wet and dry surfaces during peak period

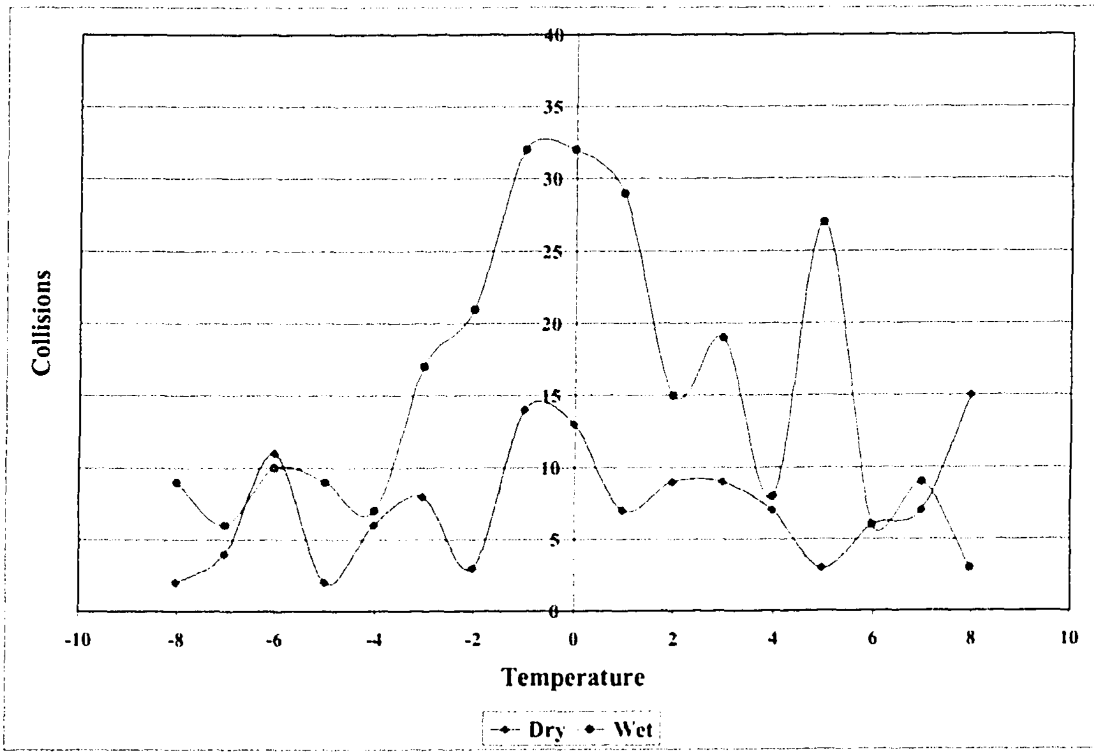


Figure 3.10: Distributions of collisions involving injury at different temperatures on wet and dry surfaces during the off-peak period

The rates of collisions involving injury per hour of exposure were calculated by dividing the numbers of collisions involving injury during the peak and off-peak periods in Table 3.10 by the corresponding number of hours of exposure in Table 3.6. Table 3.11 gives the rates of collisions involving injury per hour of exposure on dry and wet pavement surfaces during the peak and off-peak periods. The average collision rate on wet surface during the peak period was 0.70 as compared to 0.56 on dry surface, and during the off-peak period, it was 0.68 on wet surface as compared to 0.40 on dry surface. The average pavement moisture risk factors during the peak and off-peak periods were 1.24 and 1.46 respectively. The table shows localized peaks of the pavement moisture risk factor at +3°C during the peak period and –8°C and +5°C during the off-peak period.

As explained earlier, these are mainly due to the low collision rates on dry surface and should not be interpreted as more risky condition.

Table 3.11: Rates of collisions involving injury per hour of exposure at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period				Off-peak period			
		Dry	Wet	Total	Risk	Dry	Wet	Total	Risk
(-8.5, -7.5)	-8	0.80	0.69	0.74	0.87	0.33	1.80	1.00	5.40
(-7.5, -6.5)	-7	0.67	1.11	0.93	1.67	0.29	0.75	0.45	2.63
(-6.5, -5.5)	-6	0.50	1.00	0.81	2.00	0.65	0.83	0.72	1.29
(-5.5, -4.5)	-5	0.38	0.67	0.52	1.73	0.25	0.82	0.58	3.27
(-4.5, -3.5)	-4	0.90	0.60	0.70	0.67	0.40	0.50	0.45	1.25
(-3.5, -2.5)	-3	0.29	0.82	0.61	2.86	0.32	0.50	0.42	1.56
(-2.5, -1.5)	-2	0.64	0.58	0.60	0.92	0.38	0.64	0.59	1.70
(-1.5, -0.5)	-1	0.63	0.90	0.82	1.44	0.58	0.97	0.81	1.66
(-0.5, 0.5)	0	0.25	0.84	0.65	3.36	0.57	0.63	0.61	1.11
(0.5, 1.5)	1	0.47	0.22	0.30	0.47	0.32	0.51	0.46	1.60
(1.5, 2.5)	2	0.42	0.71	0.60	1.70	0.56	0.38	0.44	0.68
(2.5, 3.5)	3	0.18	0.82	0.57	4.53	0.43	0.49	0.47	1.14
(3.5, 4.5)	4	0.86	0.50	0.71	0.58	0.35	0.30	0.32	0.85
(4.5, 5.5)	5	0.33	0.64	0.45	1.91	0.11	0.84	0.51	7.59
(5.5, 6.5)	6	0.86	0.60	0.75	0.70	0.33	0.33	0.33	1.00
(6.5, 7.5)	7	0.44	0.50	0.47	1.13	0.44	0.82	0.59	1.87
(7.5, 8.5)	8	0.87	0.63	0.78	0.72	0.56	0.38	0.51	0.68
Average		0.56	0.70	0.63†	1.24	0.40	0.68	0.54†	1.46
Variance		0.05	0.04	0.05†	…	0.02	0.13	0.09†	…

† Average and variance of the rates of collisions and vehicles involving injury are calculated from the 34 observations of dry and wet surfaces.

These results suggest that during the peak period, the risk of collision involving injury when driving on wet pavement surface was, on average, 24% higher than the risk of collision involving injury when driving on dry surface. Similarly, during the off-peak period, the risk of collision involving injury when driving on wet pavement surface was, on average, 46% higher than the risk of collision involving injury when driving on dry surface. The overall average and variance of the rates of collision involving injury per hour of exposure on both wet and dry surfaces combined were (0.63, 0.05) during the peak period and (0.54, 0.09) during the off-peak period.

Figures 3.11 and 3.12 present the distributions of the rates of collision involving injury per hour of exposure at different temperatures on wet and dry surfaces during the peak and off-peak periods.

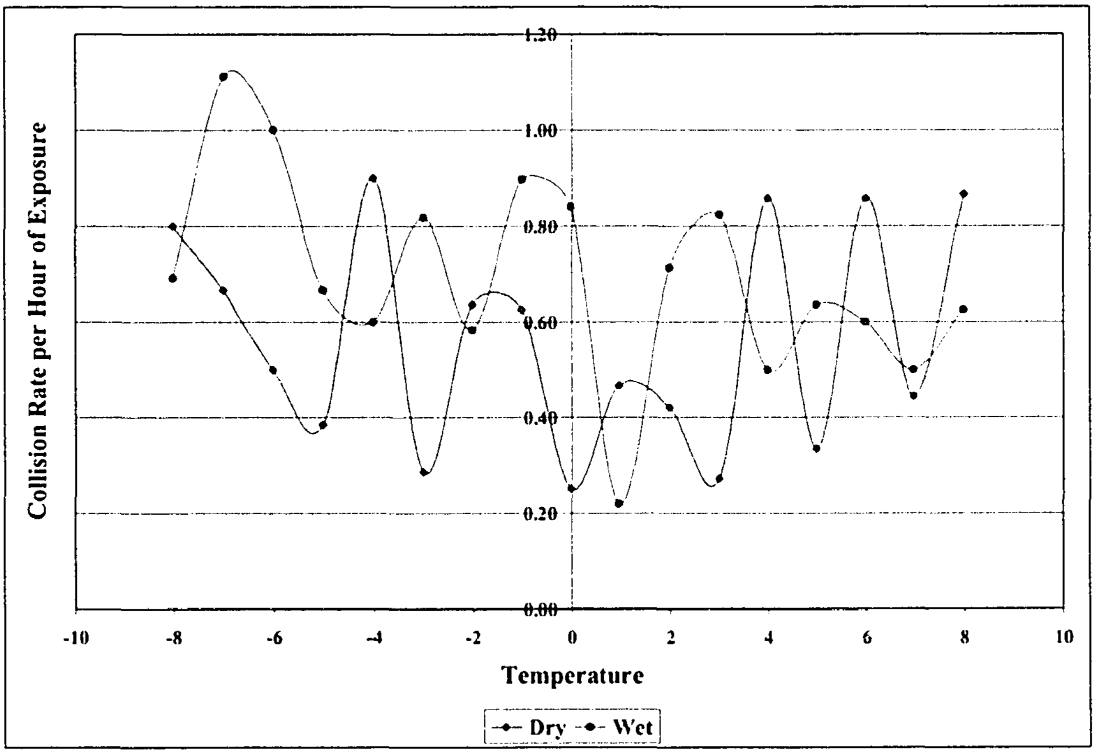


Figure 3.11: Distributions of rates of collision involving injury per hour of exposure at different temperatures on wet and dry surfaces during the peak period

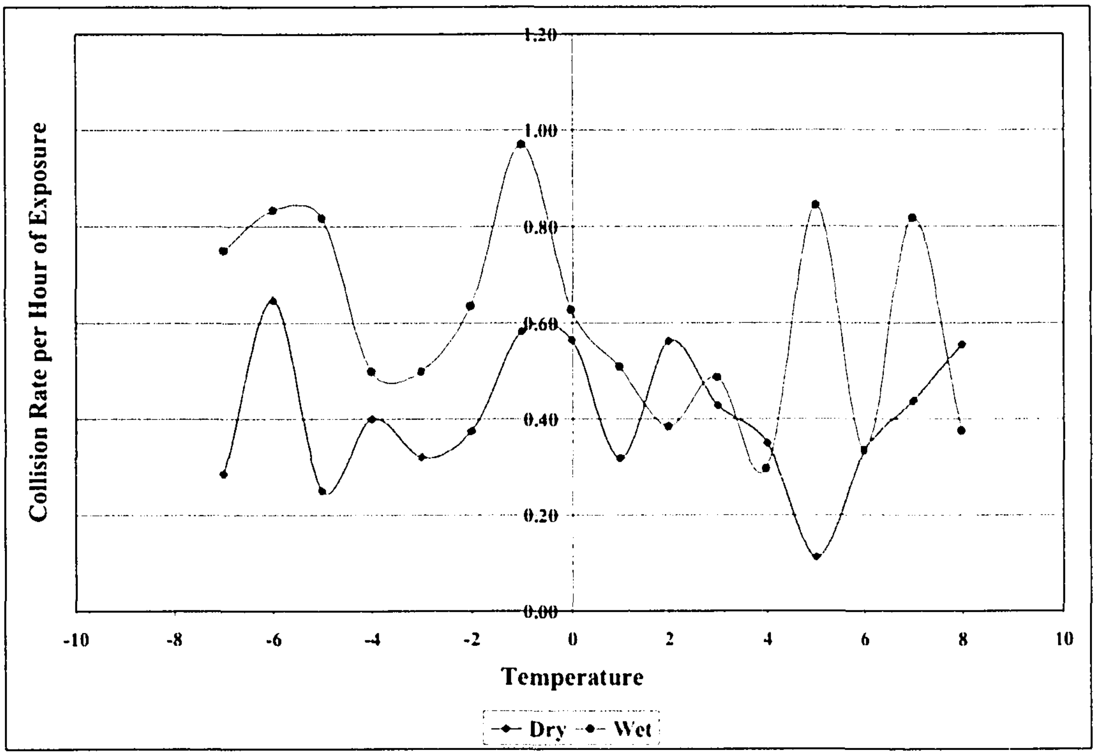


Figure 3.12: Distribution of rates of collision involving injury per hour of exposure at different temperatures on wet and dry surfaces during the off-peak period

Figure 3.11 shows that during the peak period, there was no pattern in the relationship between the rates of collisions involving injury per hour of exposure on wet or dry surfaces and the surface temperature. However, the risk of collision involving injury on wet surface was particularly higher than the dry surface at − 1°C and 0°C.

On the other hand, Figure 3.12 shows that during the off-peak period, the rates of collision involving injury per hour of exposure on wet surface were higher than on the dry surface at all temperatures except at +2°C, +4°C, and +8°C. Figure 3.13 presents the pavement moisture risk factors for collisions involving injury at different temperatures during the peak and off-peak periods.

The results of this section indicate that the moisture on pavement surface increases the risk of collision involving injury during the off-peak periods at sub-zero temperatures and had no clear effect on the risk of collision involving injury during the peak period except at – 1°C and 0°C where the risk on wet surface was higher than the risk of collision on dry surface.

3.4.2.c. Collisions Involving Property Damage Only (PDO)

The third category of the severity of collisions includes the collisions involving PDO. As seen in Table 3.12, there were 1,234 collisions involving PDO between –8°C and + 8°C during the peak period out of which 411 (33.31%) occurred on dry surface and 823 (66.69%) occurred on wet surface. During the off-peak period, there were 1,235 collisions involving PDO out of which 348 (28.18%) occurred on dry surface and 887 (71.82%) occurred on wet surface.

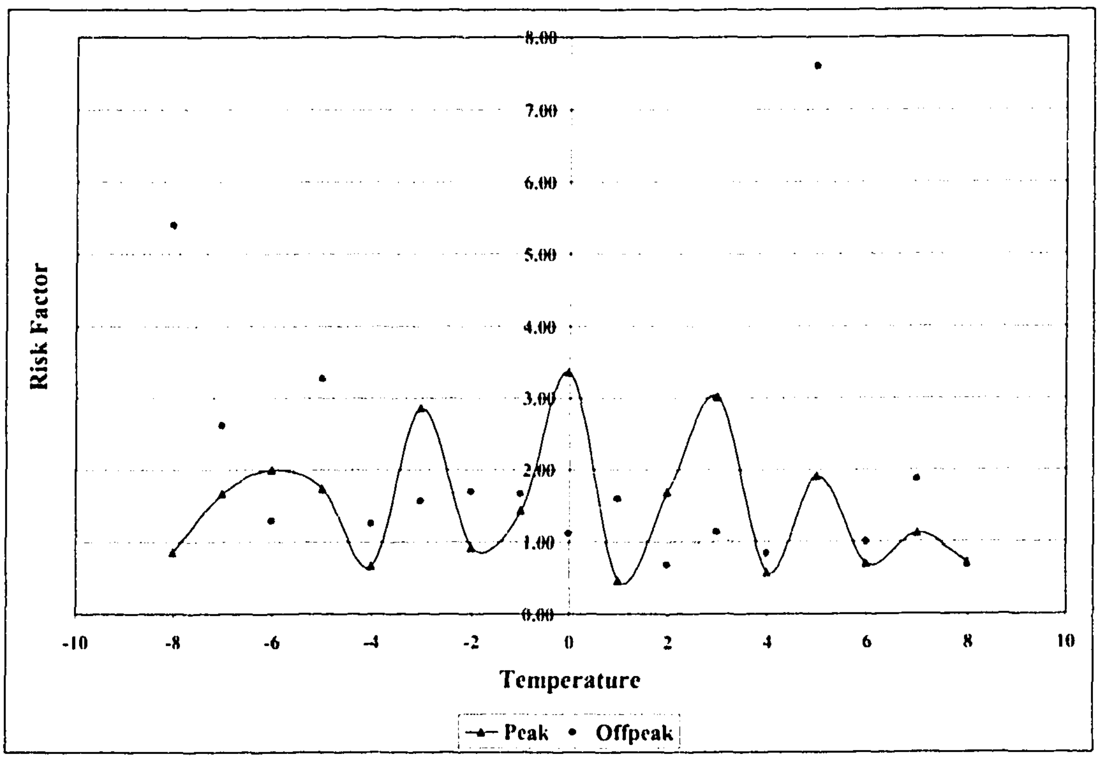


Figure 3.13: Pavement moisture risk factors using rates of collision involving injury per hour of exposure at different temperatures during the peak and off-peak periods

Figures 3.14 and 3.15 present the distributions of the numbers of collisions involving PDO at each temperature on wet and dry surface during the peak and off-peak periods respectively. The number of collisions on wet pavement during the peak period had a maximum of 167 collisions at –1°C and during the off-peak period had a maximum of 117 at 0°C.

Table 3.12: Collisions involving PDO at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	21	39	60	8	27	35	29	66	95
(-7.5, -6.5)	-7	21	31	52	16	17	33	37	48	85
(-6.5, -5.5)	-6	15	24	39	10	24	34	25	48	73
(-5.5, -4.5)	-5	21	39	60	12	36	48	33	75	108
(-4.5, -3.5)	-4	31	37	68	18	31	49	49	68	117
(-3.5, -2.5)	-3	30	55	85	30	72	102	60	127	187
(-2.5, -1.5)	-2	15	107	122	8	80	88	23	187	210
(-1.5, -0.5)	-1	22	167	189	26	111	137	48	278	326
(-0.5, 0.5)	0	21	49	70	29	117	146	50	166	216
(0.5, 1.5)	1	19	59	78	20	93	113	39	152	191
(1.5, 2.5)	2	25	68	93	21	61	82	46	129	175
(2.5, 3.5)	3	24	32	56	34	63	97	58	95	153
(3.5, 4.5)	4	22	23	45	27	41	68	49	64	113
(4.5, 5.5)	5	37	33	70	26	46	72	63	79	142
(5.5, 6.5)	6	27	20	47	16	32	48	43	52	95
(6.5, 7.5)	7	25	23	48	16	16	32	41	39	80
(7.5, 8.5)	8	35	17	52	31	20	51	66	37	103
Total		411	823	1234	348	887	1235	759	1710	2469

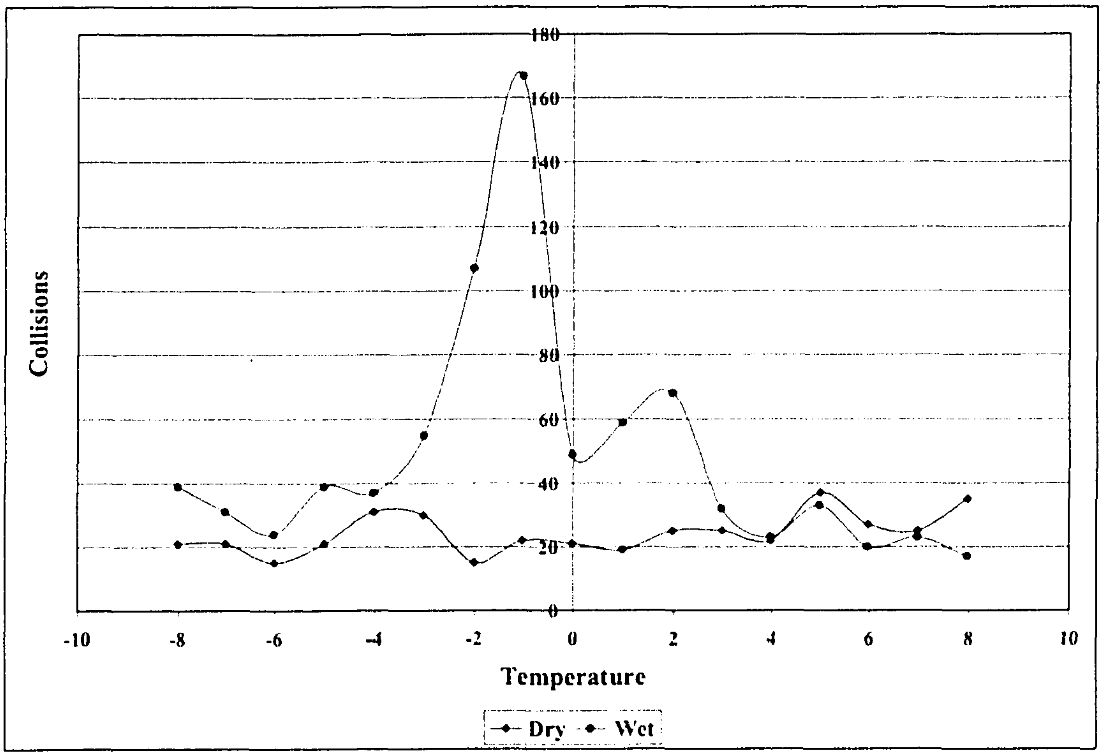


Figure 3.14: Distributions of collisions involving PDO on wet and dry surfaces at different temperatures during the peak period

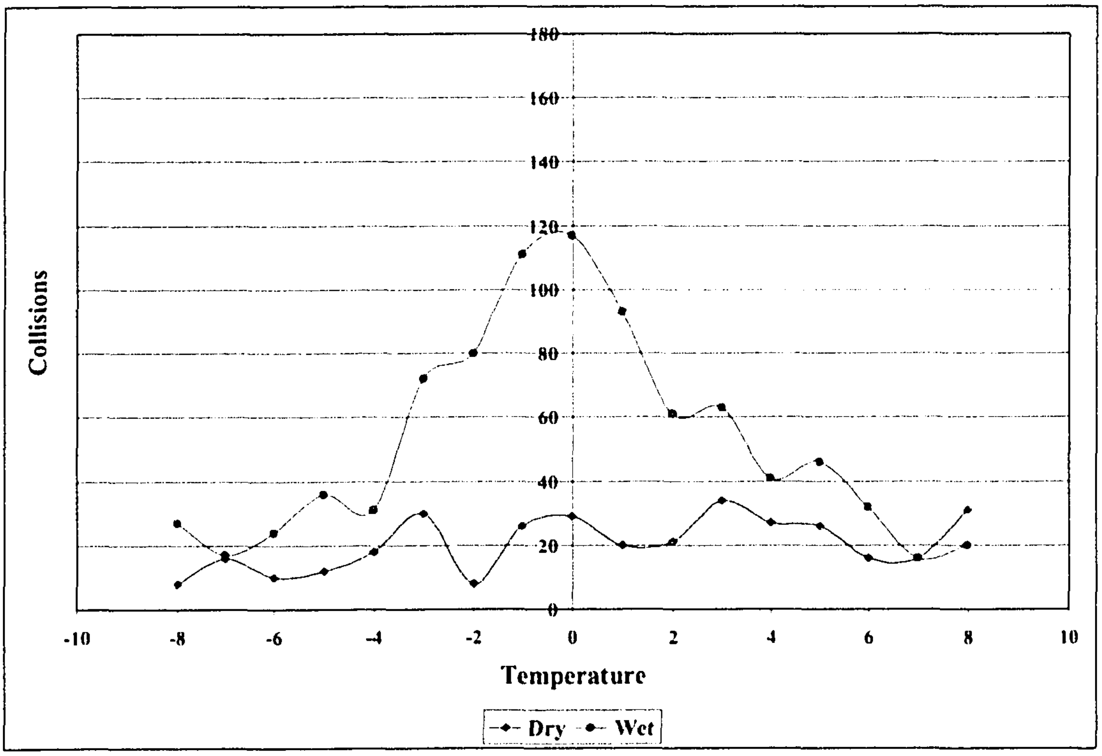


Figure 3.15: Distributions of collisions involving PDO on wet and dry surfaces at different temperatures during the off-peak period

The numbers of collisions involving PDO remained high around these maximums. Similar to collisions involving injury, the numbers of collisions involving PDO on dry surface during both the peak and off-peak periods showed no specific pattern with changing temperature.

The collision rates involving PDO per hour of exposure were calculated by dividing the numbers of collisions involving PDO during the peak and off-peak periods in Table 3.12 by the corresponding number of hours of exposure in Table 3.6. Table 3.13 gives these collision rates per hour of exposure on dry and wet pavement surfaces. The average rate of collision involving PDO per hour of exposure on wet surface during the peak period was 2.56 as compared to 2.05 on dry surface, and during the off-peak period, it was 2.28 on wet surface as compared to 1.15 on dry surface. The average pavement moisture risk factors during the peak and off-peak periods were 1.37 and 1.81 respectively. These results suggest that during peak period, the risk of collision involving PDO when driving on wet pavement surface was, on average, 37% higher than the risk of collision involving PDO when driving on dry surfaces. Similarly, during the off-peak period, the risk of collision involving PDO when driving on wet pavement surface was, on average, 81% higher than the risk of collision involving PDO when driving on dry surface. The overall average and variance of the rates of collision involving PDO per hour of exposure of both wet and dry surfaces combined were (2.31, 0.49) and (1.71, 0.83) during peak and off-peak periods respectively.

Figures 3.16 and 3.17 present the distributions of the rates of collision involving PDO per hour of exposure at different temperatures on wet and dry surfaces during the peak and off-peak periods. Figure 3.16 shows that during the peak period, there was no pattern in the relationship between the rates of collision involving PDO per hour of exposure on wet or dry surfaces and the surface temperature; however, the risk of collision on wet surface was higher than the dry surface between – 3°C and + 2°C.

Table 3.13: Rates of collisions involving PDO per hour of exposure during the peak and off-peak periods in the City of Ottawa at different temperatures during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period				Off-peak period			
		Dry	Wet	Total	Risk	Dry	Wet	Total	Risk
(-8.5, -7.5)	-8	2.10	3.00	2.61	1.43	1.33	5.40	3.18	4.05
(-7.5, -6.5)	-7	3.50	3.44	3.47	0.98	1.14	2.13	1.50	1.86
(-6.5, -5.5)	-6	2.50	2.40	2.44	0.96	0.59	2.00	1.17	3.40
(-5.5, -4.5)	-5	1.62	3.25	2.40	2.01	1.50	3.27	2.53	2.18
(-4.5, -3.5)	-4	3.10	1.85	2.27	0.60	1.20	2.21	1.69	1.85
(-3.5, -2.5)	-3	2.14	2.50	2.36	1.17	1.20	2.12	1.73	1.76
(-2.5, -1.5)	-2	1.36	2.97	2.60	2.18	1.00	2.42	2.15	2.42
(-1.5, -0.5)	-1	1.38	4.28	3.44	3.11	1.08	3.36	2.40	3.10
(-0.5, 0.5)	0	1.75	1.96	1.89	1.12	1.26	2.29	1.97	1.82
(0.5, 1.5)	1	1.27	1.84	1.66	1.46	0.91	1.63	1.43	1.79
(1.5, 2.5)	2	1.32	2.43	1.98	1.85	1.31	1.56	1.49	1.19
(2.5, 3.5)	3	2.18	1.88	2.00	0.86	1.62	1.62	1.62	1.00
(3.5, 4.5)	4	1.57	2.30	1.88	1.46	1.35	1.52	1.45	1.12
(4.5, 5.5)	5	2.06	3.00	2.41	1.46	0.96	1.44	1.22	1.49
(5.5, 6.5)	6	1.93	2.00	1.96	1.04	0.89	1.78	1.33	2.00
(6.5, 7.5)	7	2.78	2.30	2.53	0.83	1.00	1.45	1.19	1.45
(7.5, 8.5)	8	2.33	2.13	2.26	0.91	1.15	2.50	1.46	2.18
Average		2.05	2.56	2.31†	1.37	1.15	2.28	1.71†	1.81
Variance		0.42	0.46	0.49†	…	0.06	0.98	0.83†	…

† Average and variance of the rates of collisions and vehicles involving PDO are calculated from the 34 observations of dry and wet surfaces.

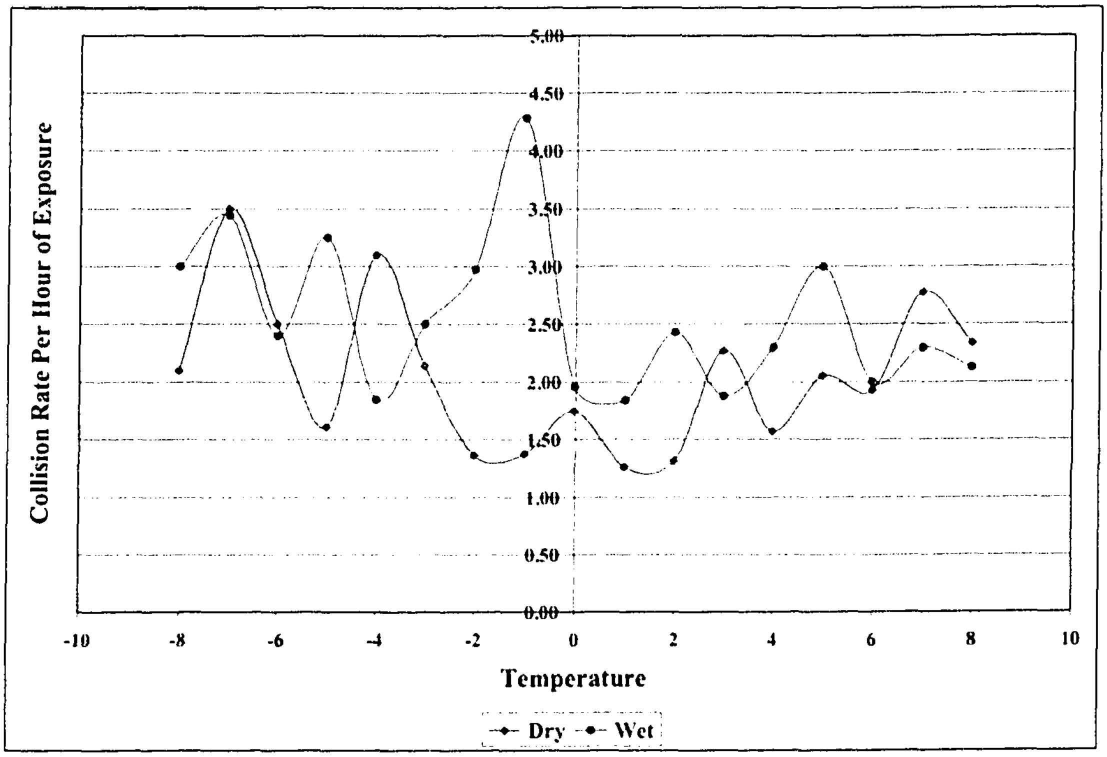


Figure 3.16: Distributions of rates of collision involving PDO per hour of exposure at different temperatures on wet and dry surfaces during the peak period

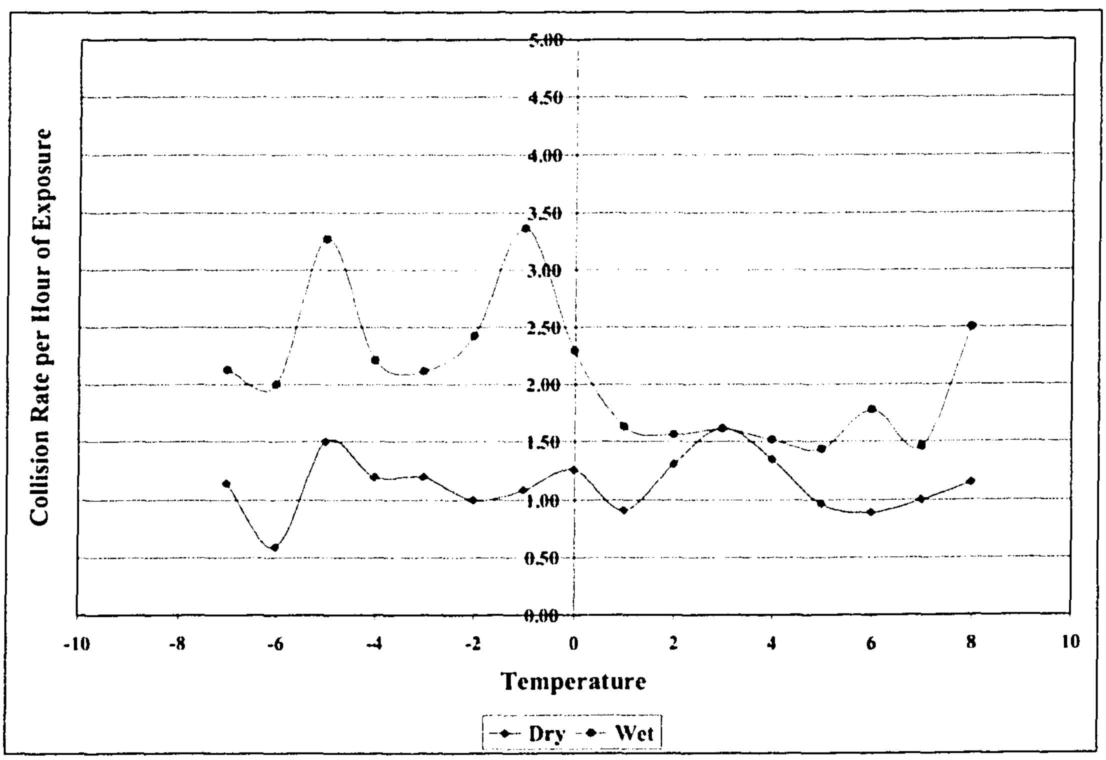


Figure 3.17: Distributions of rates of collision involving PDO per hour of exposure on wet and dry surfaces at different temperatures during the off-peak period

On the other hand, Figure 3.17 shows that during off-peak period, the rates of collisions involving PDO on wet surface were higher than on dry surface at all temperatures. Figure 3.18 presents the pavement moisture risk factors for collisions involving PDO at different temperatures during the peak and off-peak periods.

The results of this section suggest that, on average, moisture on pavement surface increases the risk of collision involving PDO at all temperatures during the off-peak period and between – 3°C and + 2°C during the peak period. In other words, wet pavement condition increases the risk of collision involving PDO between – 3°C and + 2°C irrespective of the traffic volume.

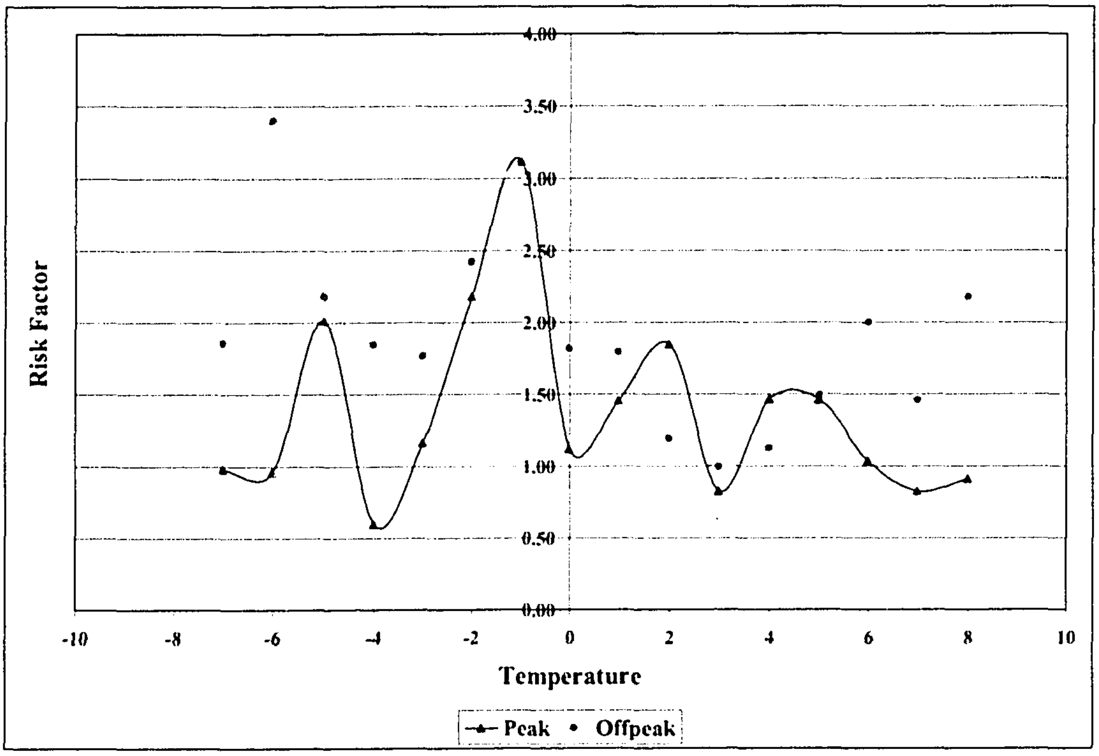


Figure 3.18: Pavement moisture risk factors using rates of collision involving PDO per hour of exposure at different temperatures during the peak and off-peak periods

3.4.3. Types of Initial Impact

Another important aspect of road safety is the type of initial impact of vehicle collision. Two types of initial impact are of a particular interest during the wintertime. The first type is the single vehicle collision, which may be taken as an indication of a vehicle gone out of control as a result of slippery conditions in case of wet pavement surface. The second type is the rear-end collision, which may also be due to the failure of drivers to stop on time as a result of slippery surface conditions. Therefore, the types of initial collision impact were classified in this thesis into three categories; single-vehicle collisions rear-end collisions, and the remaining (other) types of initial impact. There were 772 single-vehicle collisions (24.18% of total collisions), 944 rear-end collisions (29.56% of total collisions), and 1,477 other types initial collision impact (46.26% of total collisions).

The next three sections discuss the effect of pavement surface temperature and pavement moisture condition on the different types of initial impact during the peak and off-peak periods by comparing the rates of collision per hour of exposure on wet surface with the rates of collision per hour of exposure on dry surface at each temperature. A pavement moisture risk factor will also be calculated at each temperature to measure the relative risk between wet and dry surfaces.

3.4.3.a. Single-Vehicle Collisions

The numbers of single-vehicle collisions at each temperature on wet and dry pavement surfaces are given in Table 3.14. There were 572 single-vehicle collisions occurred on wet surface as compared to 200 occurred on dry surface between –8˚C and +8˚C. During the peak period, there were 353 single-vehicle collisions out of which 265

(75.07%) occurred on wet surface and 88 (24.93%) occurred on dry surface. During the off-peak period, there were 419 single-vehicle collisions with injury out of which 307 (73.27%) occurred on wet surface and 112 (26.73%) occurred on dry surface. The distributions of single-vehicle collisions at each temperature on wet and dry surfaces during peak and off-peak periods are given in Figures 3.19 and 3.20 respectively.

Table 3.14: Single-vehicles collisions at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	6	11	17	3	6	9	9	17	26
(-7.5, -6.5)	-7	2	6	8	6	7	13	8	13	21
(-6.5, -5.5)	-6	2	9	11	6	9	15	8	18	26
(-5.5, -4.5)	-5	3	10	13	3	11	14	6	21	27
(-4.5, -3.5)	-4	8	16	24	4	12	16	12	28	40
(-3.5, -2.5)	-3	4	27	31	4	29	33	8	56	64
(-2.5, -1.5)	-2	3	25	28	2	33	35	5	58	63
(-1.5, -0.5)	-1	1	72	73	9	52	61	10	124	134
(-0.5, 0.5)	0	4	18	22	10	47	57	14	65	79
(0.5, 1.5)	1	5	13	18	2	35	37	7	48	55
(1.5, 2.5)	2	7	18	25	6	16	22	13	34	47
(2.5, 3.5)	3	6	7	13	10	12	22	16	19	35
(3.5, 4.5)	4	8	6	14	10	13	23	18	19	37
(4.5, 5.5)	5	9	10	19	13	11	24	22	21	43
(5.5, 6.5)	6	5	8	13	6	7	13	11	15	26
(6.5, 7.5)	7	3	3	6	7	4	11	10	7	17
(7.5, 8.5)	8	12	6	18	11	3	14	23	9	32
Total		88	265	353	112	307	419	200	572	772

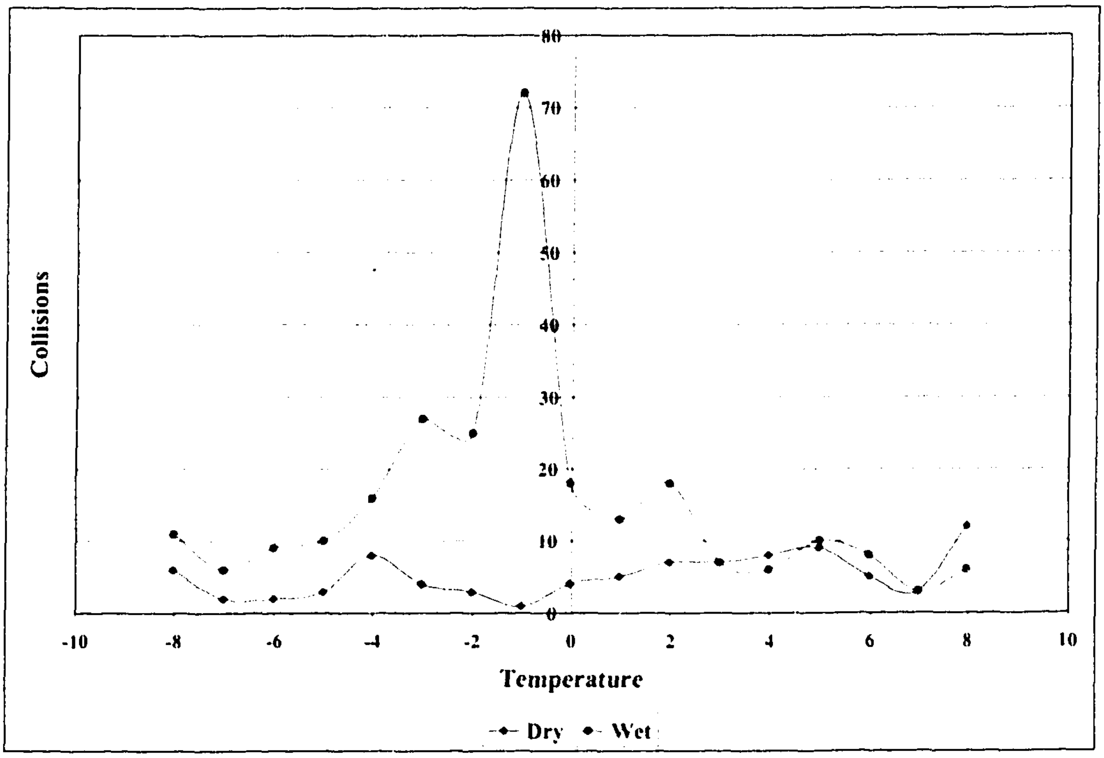


Figure 3.19: Distributions of single-vehicle collisions on wet and dry surfaces at different temperatures during the peak period

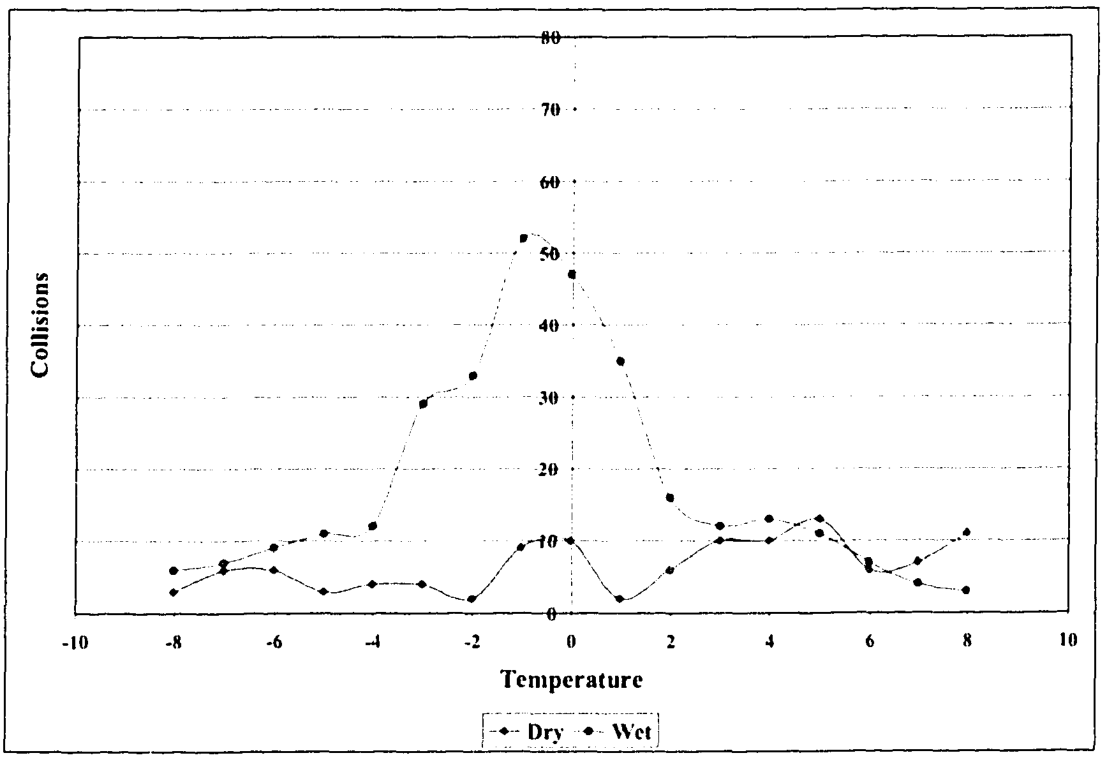


Figure 3.20: Distributions of single-vehicle collisions on wet and dry surfaces at different temperatures during the off-peak period

The number of single-vehicle collisions on wet pavement had a maximum of 72 during the peak period and a maximum of 52 during the off-peak period at −1°C. The numbers of single-vehicle collisions on dry surface during both the peak and off-peak periods, however, showed no specific pattern with changing temperature.

The rates of single-vehicle collision per hour of exposure were calculated by dividing the numbers of collisions during the peak and off-peak periods in Table 3.14 by the corresponding numbers of hours of exposure in Table 3.6.

The single-vehicle collision rates per hour of exposure on dry and wet pavement surfaces during the peak and off-peak periods were given in Table 3.15. The average of single-vehicle collision rates per hour of exposure on wet surface was 0.79 during the peak period as compared to 0.42 on dry surface, and during the off-peak period, it was 0.72 on wet surface as compared to 0.37 on dry surface. The average pavement moisture risk factors during peak and off-peak periods were 2.06 and 1.95 respectively. These results suggest that during the peak period, the risk of single-vehicle collision when driving on wet pavement surface was, on average, 106% higher than when driving on dry surface. Similarly, during off-peak period, the risk of single-vehicle collision when driving on wet pavement surface was, on average, 95% higher than when driving on dry surface. The overall average and variance of rates of single-vehicle collisions per hour of exposure of both wet and dry surfaces combined were (0.60, 0.11) and (0.55, 0.10) during the peak and off-peak periods respectively.

Figures 3.21 and 3.22 present the distributions of the rates of single-vehicle collisions per hour of exposure at different temperatures on wet and dry surfaces during the peak and off-peak periods. Figure 3.21 shows that the rate of single-vehicle collision per hour of exposure on wet surface during the peak period was higher than on the dry surface at all temperatures except at +3°C, +7°C and +8°C.

Table 3.15: Rates of single-vehicle collisions per hour of exposure during the peak and off-peak periods in the City of Ottawa at different temperatures during weekdays between 6:01 am and 9:00 (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period				Off-peak period			
		Dry	Wet	Total	Risk	Dry	Wet	Total	Risk
(-8.5, -7.5)	-8	0.60	0.85	0.74	1.41	0.50	1.20	0.82	2.40
(-7.5, -6.5)	-7	0.33	0.67	0.53	2.00	0.43	0.88	0.59	2.04
(-6.5, -5.5)	-6	0.33	0.90	0.69	2.70	0.35	0.75	0.52	2.13
(-5.5, -4.5)	-5	0.23	0.83	0.52	3.61	0.38	1.00	0.74	2.67
(-4.5, -3.5)	-4	0.80	0.80	0.80	1.00	0.27	0.86	0.55	3.21
(-3.5, -2.5)	-3	0.29	1.23	0.86	4.30	0.16	0.85	0.56	5.33
(-2.5, -1.5)	-2	0.27	0.69	0.60	2.55	0.25	1.00	0.85	4.00
(-1.5, -0.5)	-1	0.06	1.85	1.33	29.54	0.38	1.58	1.07	4.20
(-0.5, 0.5)	0	0.33	0.72	0.59	2.16	0.43	0.92	0.77	2.12
(0.5, 1.5)	1	0.33	0.41	0.38	1.22	0.09	0.61	0.47	6.75
(1.5, 2.5)	2	0.37	0.64	0.53	1.74	0.38	0.41	0.40	1.09
(2.5, 3.5)	3	0.55	0.41	0.46	0.75	0.48	0.31	0.37	0.65
(3.5, 4.5)	4	0.57	0.60	0.58	1.05	0.50	0.48	0.49	0.96
(4.5, 5.5)	5	0.50	0.91	0.66	1.82	0.48	0.34	0.41	0.71
(5.5, 6.5)	6	0.36	0.80	0.54	2.24	0.33	0.39	0.36	1.17
(6.5, 7.5)	7	0.33	0.30	0.32	0.90	0.44	0.36	0.41	0.83
(7.5, 8.5)	8	0.80	0.75	0.78	0.94	0.41	0.38	0.40	0.92
Average		0.42	0.79	0.60†	2.06	0.37	0.72	0.55†	1.95
Variance		0.04	0.12	0.11†	···	0.01	0.13	0.10†	···

† Average and variance of the rates of single-vehicle collisions and vehicles are calculated from the 34 observations of dry and wet surfaces.

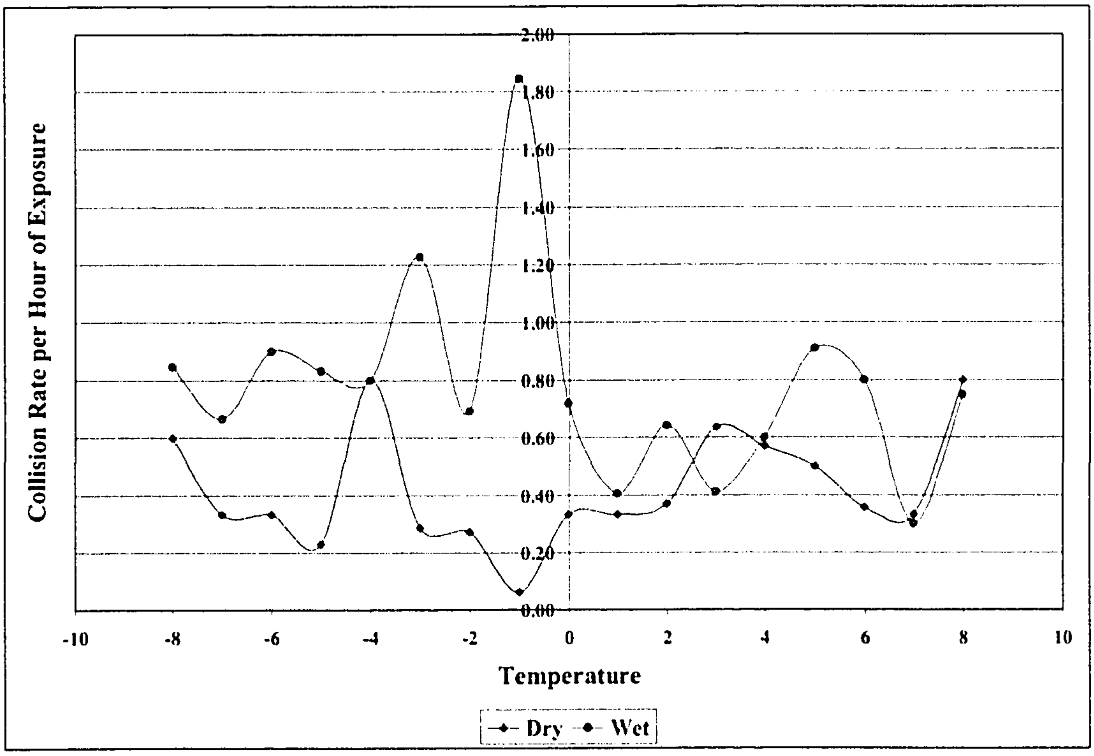


Figure 3.21: Distributions of single-vehicles collision rates per hours of exposure at different temperatures on wet and dry surfaces during the peak period

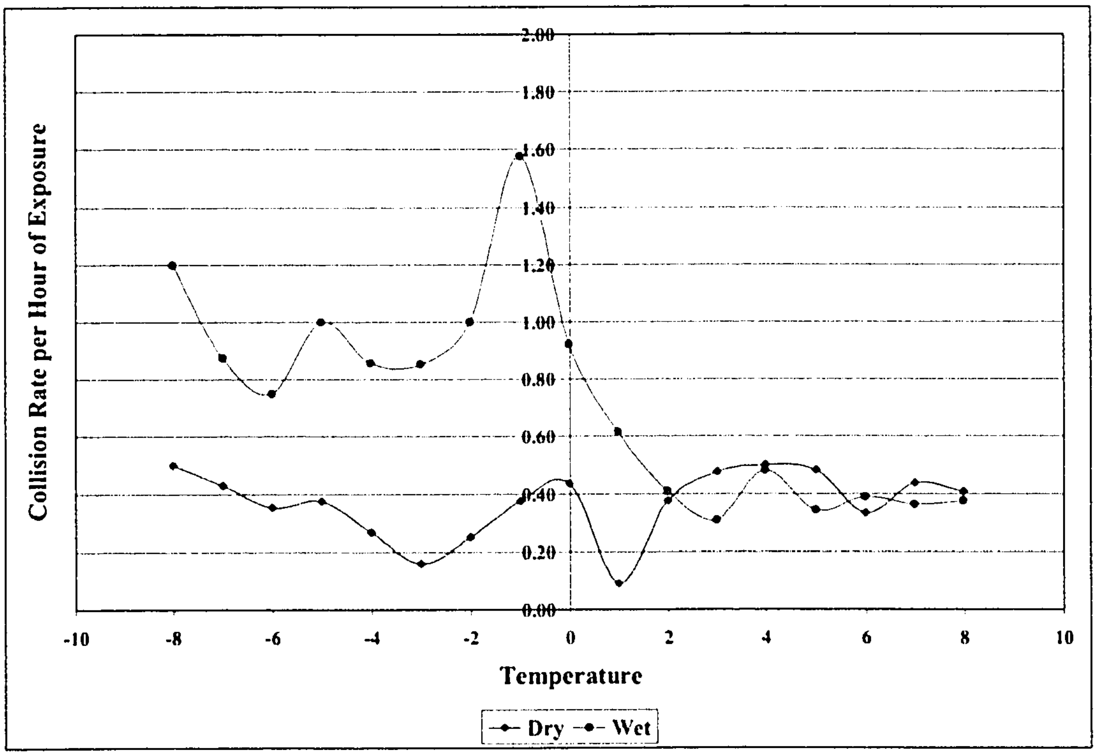


Figure 3.22: Distributions of single-vehicles collision rates per hours of exposure on wet and dry surfaces at different temperatures during off-peak period

On the other hand, Figure 3.22 shows that during the off-peak period, the rates on wet surface were higher than on the dry surface at all temperatures between –8°C and +2°C, then reverse the trend between +3°C and +8°C. Figure 3.23 presents the pavement moisture risk factors for single-vehicle collisions at different temperatures during the peak and off-peak periods.

The results from the analysis in this section suggest that moisture on pavement surface increases the risk of single-vehicle collision during the peak and off-peak periods at temperatures between – 8°C and +2°C. In other words, wet pavement condition increases the risk of single-vehicle collisions at all sub-zero temperatures irrespective of the volume of traffic.

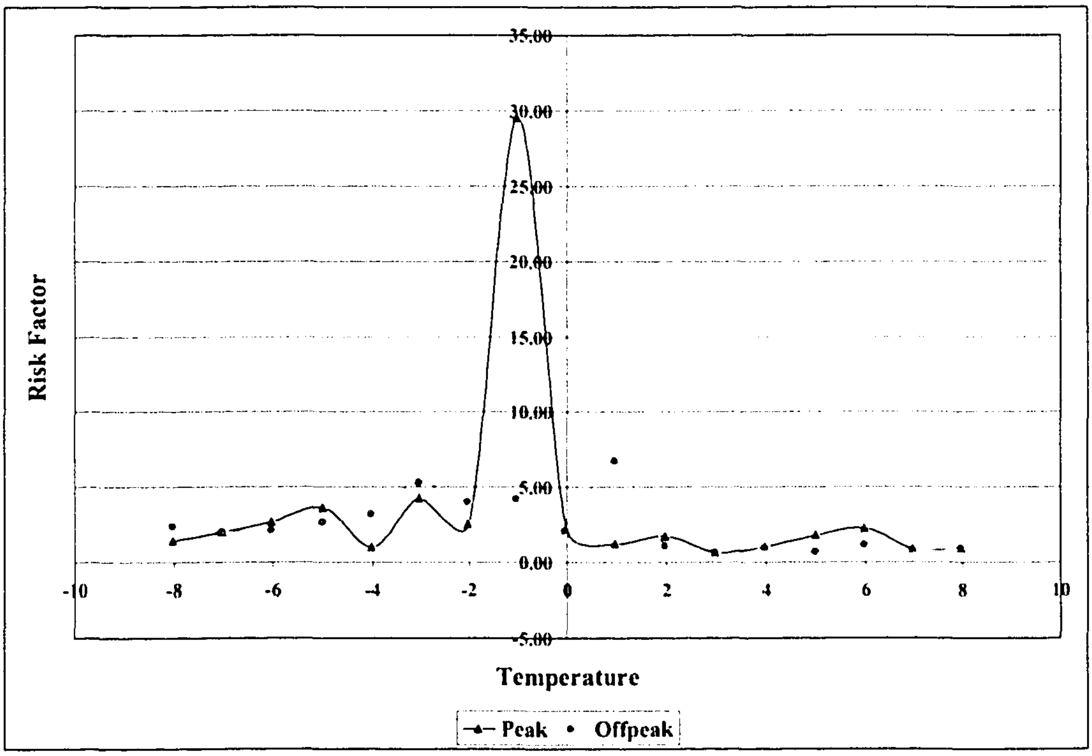


Figure 3.23: Pavement moisture risk factors using single-vehicle collision rates per hours of exposures at different temperatures during the peak and off-peak periods

3.4.3.b. *Rear-end Vehicle Collisions*

Rear-end vehicle collisions is the second category in the initial type of collision impact considered in this research. Table 3.16 gives the numbers of rear-end collisions at each temperature on wet and dry pavement surfaces during the peak and off-peak periods. There were 613 rear-end collisions occurred on wet surface as compared to 331 on dry surface between −8°C and +8°C. During the peak period, there were 517 rear-end collisions out of which 321 (62.09%) occurred on wet surface and 196 (37.91%) on dry surface. During the off- period, there were 427 rear-end collisions out of which 292 (68.38%) occurred on wet surface and 135 (31.62%) on dry surface.

Figures 3.24 and 3.25 present the distributions of the rear-end collisions at different temperatures on wet and dry surfaces during the peak and off-peak periods respectively. The number of rear-end collisions on wet surface had maximums of 51 at −1°C during the peak period and 40 at 0°C during the off-peak period. The numbers of rear-end collisions on dry surface during the peak and off-peak periods showed no specific pattern with changing temperature.

The rear-end collision rates per hour of exposure were calculated by dividing the numbers of collisions during peak and off-peak periods in Table 3.16 by the corresponding number of hours of exposure in Table 3.6. Table 3.17 gives these collision rates on dry and wet pavement surfaces during the peak and off-peak periods. The average of the rates of rear-end collision per hour of exposure on wet surface during the peak period was 1.03 as compared to 0.98 on dry surface, and during the off-peak period, it was 0.79 on wet surface as compared to 0.46 on dry surface. The average pavement moisture risk factors during the peak and off-peak periods were 1.12 and 1.54

respectively. These results suggest that during the peak period, the risk of rear-end collision when driving on wet pavement surface was, on average, 12% higher than when driving on dry surface. Similarly, during off-peak period, the risk of rear-end collision when driving on wet pavement surface was, on average, 54% higher than when driving on dry surface.

Table 3.16: Rear-end collisions at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	11	17	28	6	12	18	17	29	46
(-7.5, -6.5)	-7	10	17	27	5	5	10	15	22	37
(-6.5, -5.5)	-6	9	10	19	6	9	15	15	19	34
(-5.5, -4.5)	-5	12	10	22	3	12	15	15	22	37
(-4.5, -3.5)	-4	14	12	26	11	5	16	25	17	42
(-3.5, -2.5)	-3	13	20	33	10	27	37	23	47	70
(-2.5, -1.5)	-2	5	35	40	2	28	30	7	63	70
(-1.5, -0.5)	-1	14	51	65	12	28	40	26	79	105
(-0.5, 0.5)	0	9	24	33	11	40	51	20	64	84
(0.5, 1.5)	1	6	25	31	9	25	34	15	50	65
(1.5, 2.5)	2	11	33	44	8	19	27	19	52	71
(2.5, 3.5)	3	7	20	27	14	23	37	21	43	64
(3.5, 4.5)	4	10	9	19	9	9	18	19	18	37
(4.5, 5.5)	5	18	15	33	5	23	28	23	38	61
(5.5, 6.5)	6	18	8	26	4	11	15	22	19	41
(6.5, 7.5)	7	13	11	24	7	9	16	20	20	40
(7.5, 8.5)	8	16	4	20	13	7	20	29	11	40
Total		196	321	517	135	292	427	331	613	944

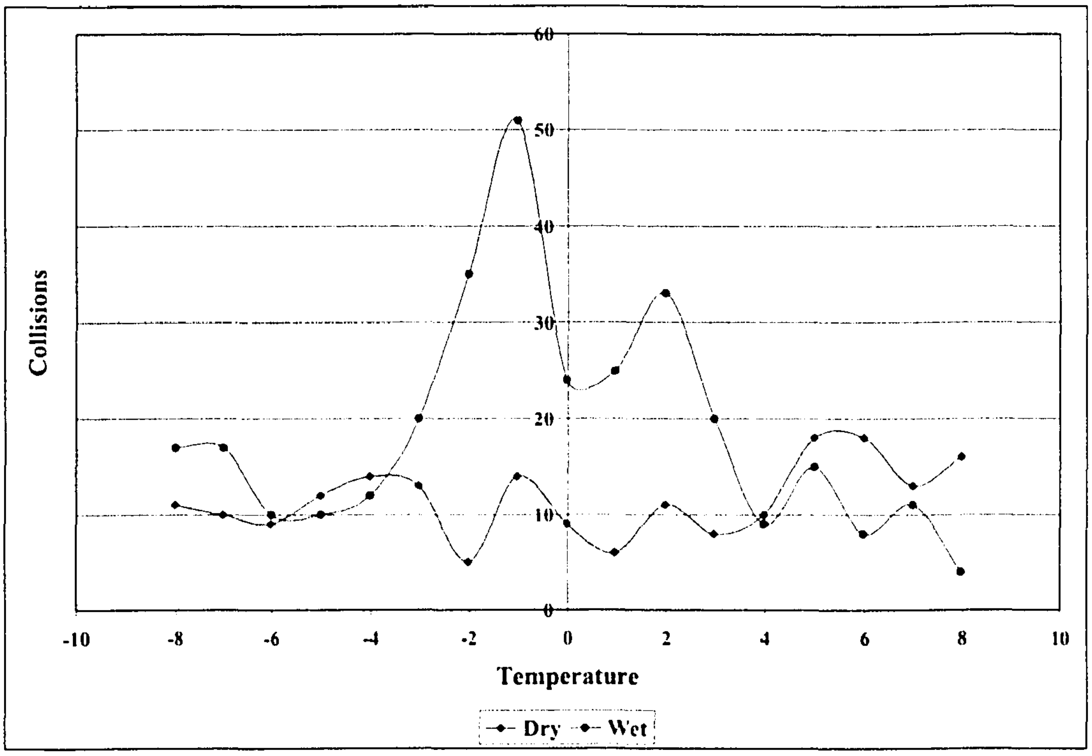


Figure 3.24: Distributions of rear-end collisions at different temperatures on wet and dry surfaces during the peak period

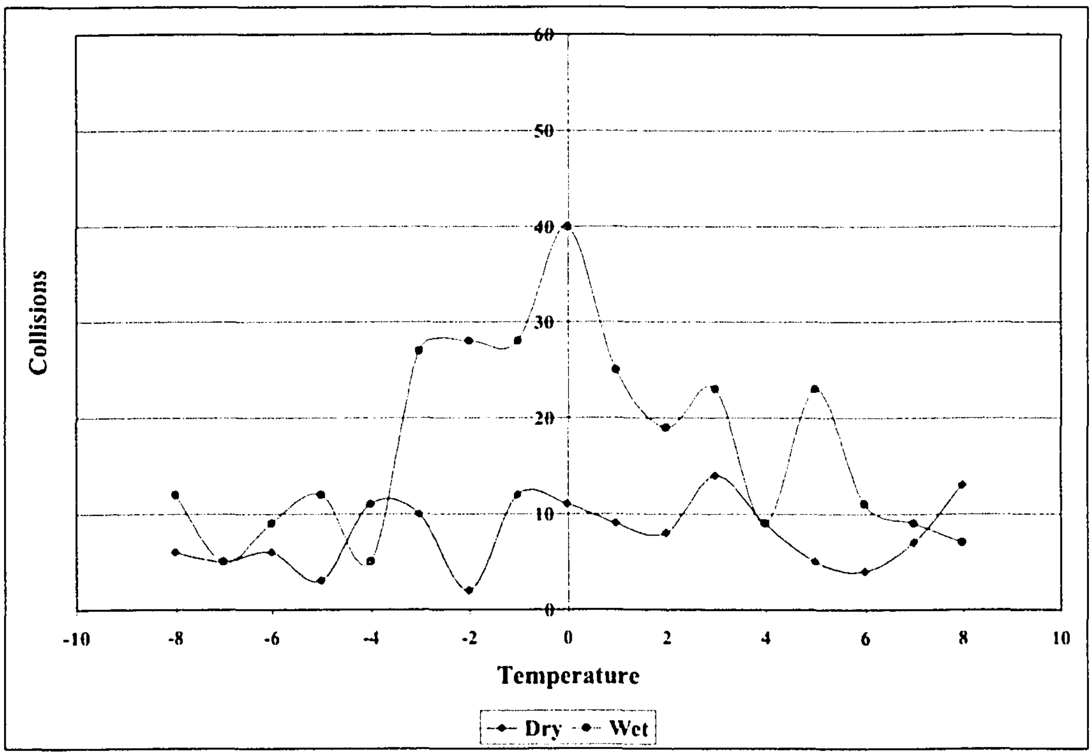


Figure 3.25: Distributions of rear-end collisions at different temperatures on wet and dry surfaces during the off-peak period

Table 3.17: Rates of rear-end collisions per hour of exposure during the peak and off-peak periods in the City of Ottawa at different temperatures during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period				Off-peak period			
		Dry	Wet	Total	Risk	Dry	Wet	Total	Risk
(-8.5, -7.5)	-8	1.10	1.31	1.22	1.19	1.00	2.40	1.64	2.40
(-7.5, -6.5)	-7	1.67	1.89	1.80	1.13	0.36	0.63	0.45	1.75
(-6.5, -5.5)	-6	1.50	1.00	1.19	0.67	0.35	0.75	0.52	2.13
(-5.5, -4.5)	-5	0.92	0.83	0.88	0.90	0.38	1.09	0.79	2.91
(-4.5, -3.5)	-4	1.40	0.60	0.87	0.43	0.73	0.36	0.55	0.49
(-3.5, -2.5)	-3	0.93	0.91	0.92	0.98	0.40	0.79	0.63	1.99
(-2.5, -1.5)	-2	0.45	0.97	0.85	2.14	0.25	0.85	0.73	3.39
(-1.5, -0.5)	-1	0.88	1.31	1.18	1.49	0.50	0.85	0.70	1.70
(-0.5, 0.5)	0	0.75	0.96	0.89	1.28	0.48	0.78	0.69	1.64
(0.5, 1.5)	1	0.40	0.78	0.66	1.95	0.41	0.44	0.43	1.07
(1.5, 2.5)	2	0.58	1.18	0.94	2.04	0.50	0.49	0.49	0.97
(2.5, 3.5)	3	0.64	1.18	0.96	1.85	0.67	0.59	0.62	0.88
(3.5, 4.5)	4	0.71	0.90	0.79	1.26	0.45	0.33	0.38	0.74
(4.5, 5.5)	5	1.00	1.36	1.14	1.36	0.19	0.72	0.47	3.88
(5.5, 6.5)	6	1.29	0.80	1.08	0.62	0.22	0.61	0.42	2.75
(6.5, 7.5)	7	1.44	1.10	1.26	0.76	0.44	0.82	0.59	1.87
(7.5, 8.5)	8	1.07	0.50	0.87	0.47	0.48	0.88	0.57	1.82
Average		0.98	1.03	1.01†	1.12	0.46	0.79	0.62†	1.54
Variance		0.14	0.11	0.12†	...	0.04	0.21	0.15†	...

† Average and variance of the rates of rear-end collisions and vehicles are calculated from the 34 observations of dry and wet surfaces.

The overall average and variance of rates of rear-end collision per hour of exposure on both wet and dry surfaces combined were (1.01, 0.12) and (0.62, 0.15) during the peak and off-peak periods respectively.

Figures 3.26 and 3.27 present the distributions of the rear-end collision rates per hour of exposure at different temperatures on wet and dry surfaces during the peak and off-peak periods respectively. During the peak period, Figure 3.26 shows that the rate of rear-end collision per hour of exposure on wet surface was higher than on dry surface at –8°C, –7°C and between –2°C and +5°C. The rates on wet surface were lower than on dry surface at temperatures between –6°C and –3°C and between +6°C and +8. Figure 3.27 shows that during the off-peak period, the rates of rear-end collision on wet surface were higher than on dry surface at all temperatures except – 4°C, +2°C, +3°C and +4°C. Figure 3.28 shows the distributions of the risk factors for rear-end collisions during peak and off-peak periods.

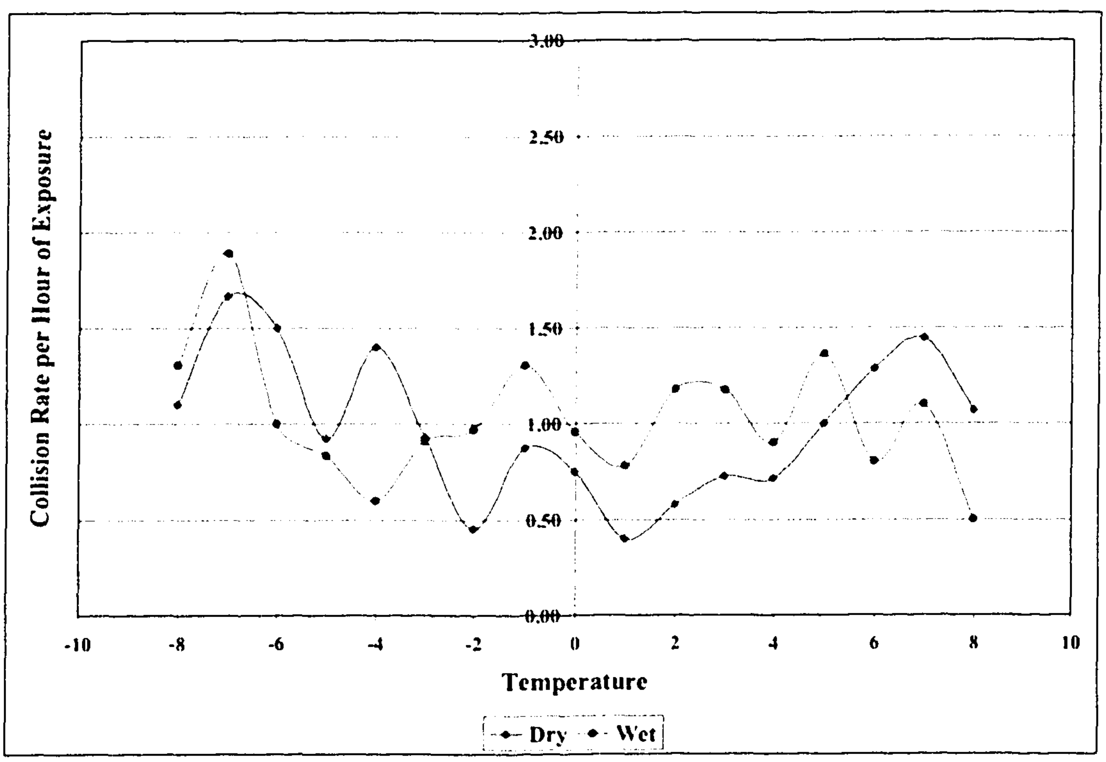


Figure 3.26: Distributions of rear-end collision rates per hour of exposure on wet and dry surfaces at different temperatures during the peak period

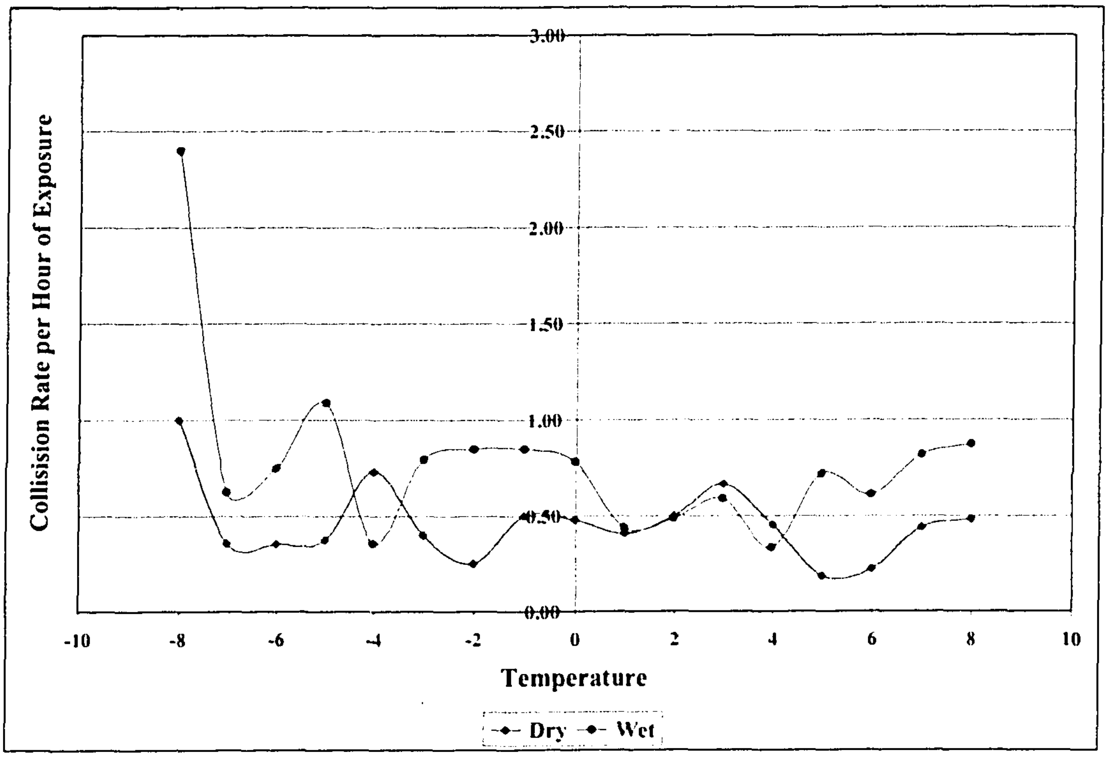


Figure 3.27: Distributions of rear-end collision rates per hour of exposure on wet and dry surfaces at different temperatures during the off-peak period

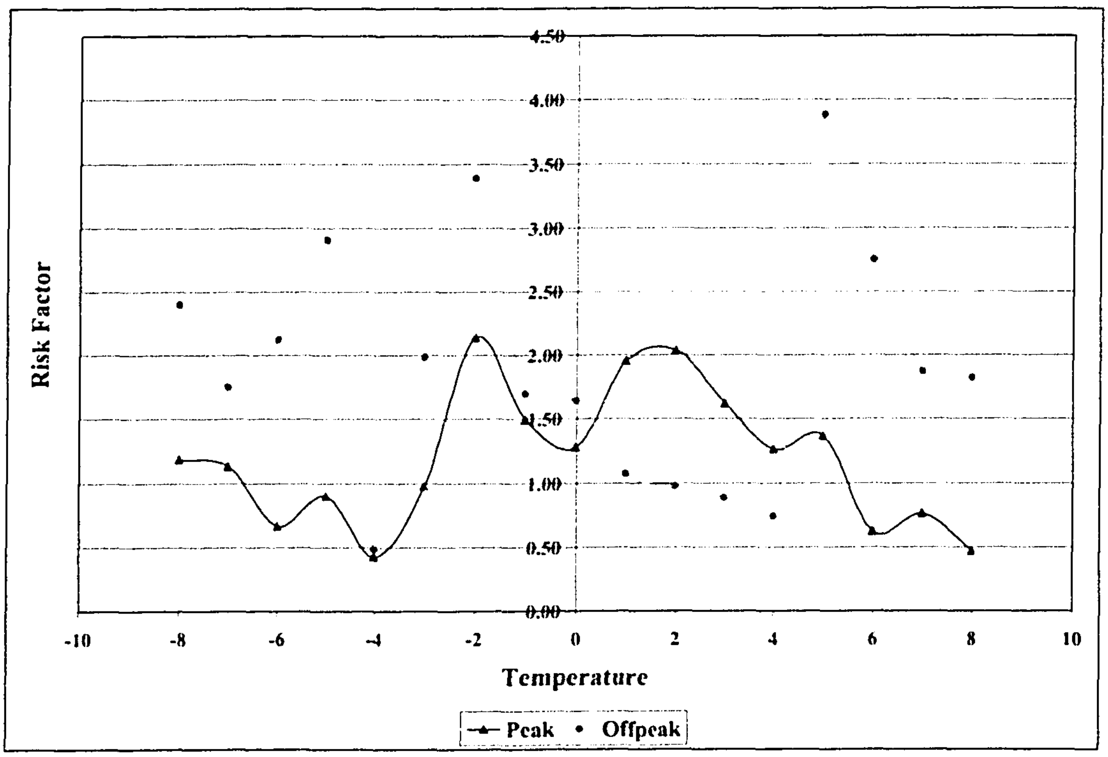


Figure 3.28: Pavement moisture risk factors using rear-end collision rates per hours of exposure at different temperatures during the peak and off-peak periods

This section suggests that moisture on pavement surface increases the risk of rear-end collision during the peak and off-peak periods at temperatures between –2°C and +1°C irrespective of the traffic volume.

3.4.3.c. Other Types of Initial Impact of Vehicle Collision

The final classification of initial impact is the other types of initial impact (all those that are neither single nor rear-end vehicle collisions). Table 3.18 gives the numbers of other types of collisions at each temperature on wet and dry pavement surfaces during the peak and off-peak periods. There were 1,004 collisions involving other types of initial impact occurred on wet surface as compared to 473 occurred on dry surface between –8°C and +8°C. During the peak period, there were 696 other types of collisions out of which 452 (64.94%) occurred on wet surface and 244 (35.06%) occurred on dry surface. During the off- period, there were 781 other types of collisions out of which 552 (70.68%) occurred on wet surface and 229 (29.32%) occurred on dry surface.

Figures 3.24 and 3.25 present the distributions of the other types of collisions at different temperatures on wet and dry surfaces during peak and off-peak periods respectively. The number of the other types of collisions on wet surface had a maximum of 80 during the peak period and 64 during the off-peak period at –1°C. The numbers of the other types of collisions on dry surface during the peak and off-peak periods showed no specific pattern with changing temperature.

Table 3.19 gives the other-types of collision rates per hour of exposure, which were calculated by dividing the numbers of collisions during the peak and off-peak periods in Table 3.18 by the corresponding number of hours of exposure in Table 3.6. The average of the other types of collision rates during the peak period was 1.44 on wet surface as compared to 1.21 on dry surface, and during the off-peak period, it was 1.46 on wet surface as compared to 0.73 on dry surface. The average pavement moisture risk factors during peak and off-peak periods were 1.26 and 1.71 respectively.

Table 3.18: Collisions involving other types of initial impact during the peak and off-peak periods in the City of Ottawa at different temperatures during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period			Off-peak period			Total		
		Dry	Wet	Total	Dry	Wet	Total	Dry	Wet	Total
(-8.5, -7.5)	-8	12	20	32	1	19	20	13	39	52
(-7.5, -6.5)	-7	13	18	31	9	11	20	22	29	51
(-6.5, -5.5)	-6	7	15	22	9	16	25	16	31	47
(-5.5, -4.5)	-5	11	27	38	8	22	30	19	49	68
(-4.5, -3.5)	-4	18	21	39	10	21	31	28	42	70
(-3.5, -2.5)	-3	17	26	43	24	33	57	41	59	100
(-2.5, -1.5)	-2	14	68	82	7	40	47	21	108	129
(-1.5, -0.5)	-1	17	80	97	19	64	83	36	144	180
(-0.5, 0.5)	0	11	29	40	21	63	84	32	92	124
(0.5, 1.5)	1	15	28	43	16	63	79	31	91	122
(1.5, 2.5)	2	15	37	52	16	41	57	31	78	109
(2.5, 3.5)	3	13	19	32	20	47	67	33	66	99
(3.5, 4.5)	4	16	13	29	15	27	42	31	40	71
(4.5, 5.5)	5	16	15	31	11	40	51	27	55	82
(5.5, 6.5)	6	16	10	26	12	20	32	28	30	58
(6.5, 7.5)	7	13	14	27	9	12	21	22	26	48
(7.5, 8.5)	8	20	12	32	22	13	35	42	25	67
Total		244	452	696	229	552	781	473	1004	1477

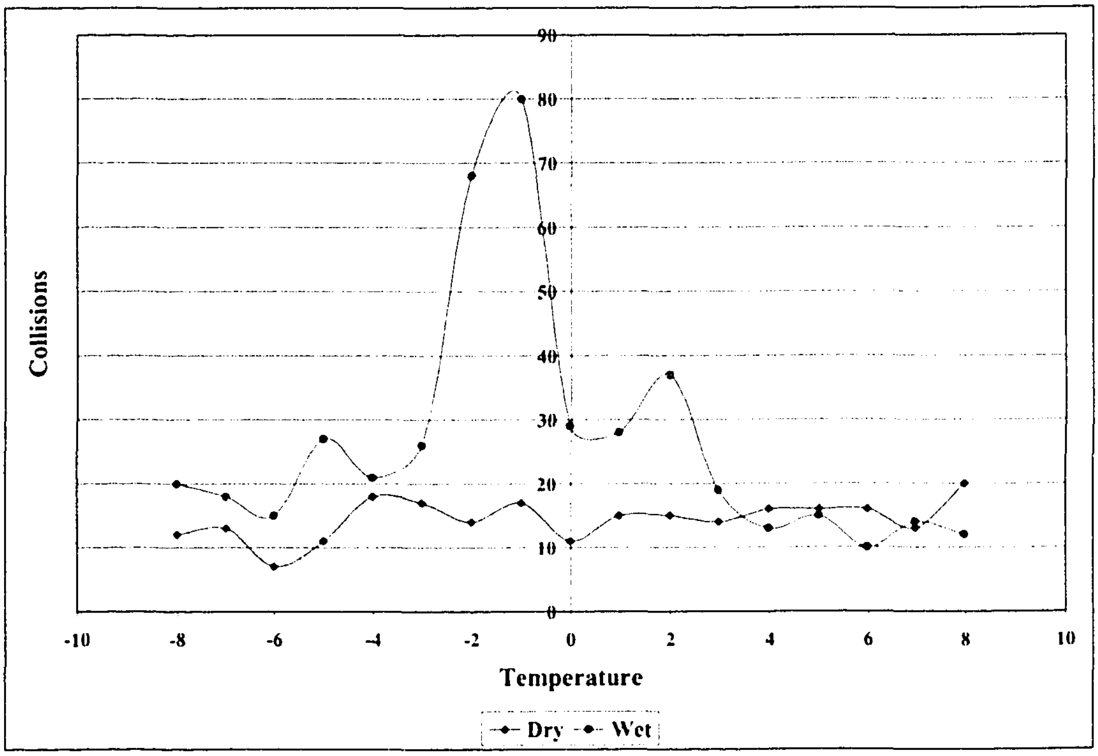


Figure 3.29: Distributions of collisions involving other types of initial impact on wet and dry surfaces at different temperatures during the peak period

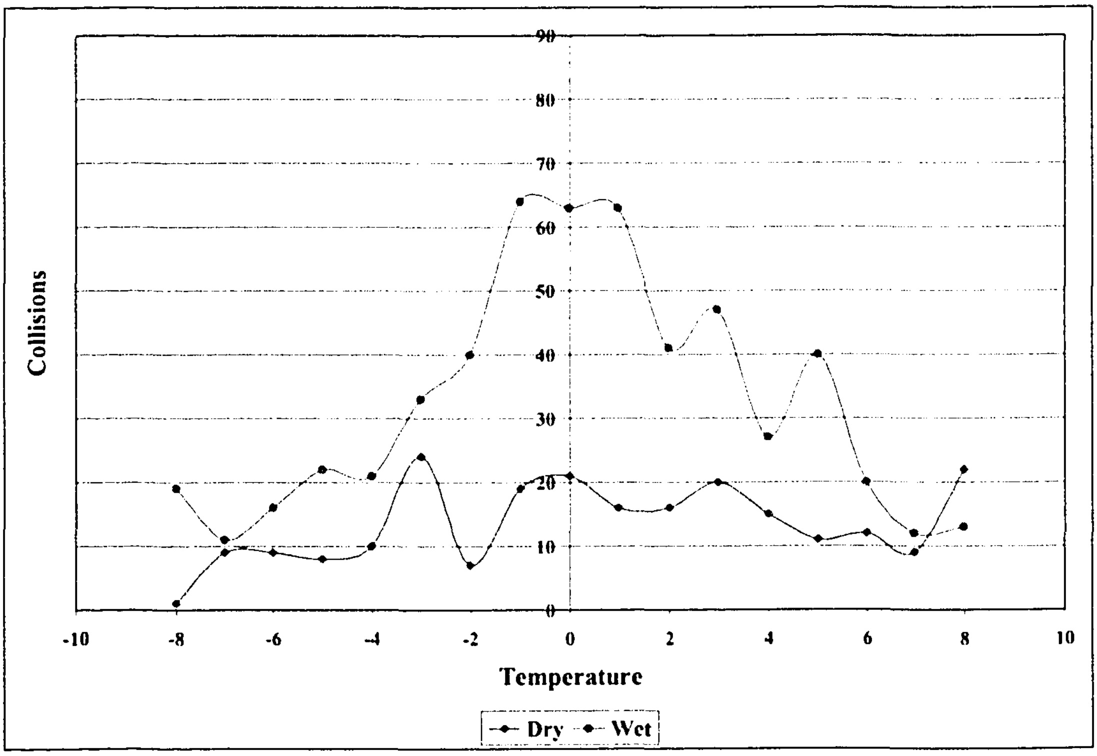


Figure 3.30: Distributions of collisions involving other types of initial impact on wet and dry surfaces at different temperatures during the off-peak period

Table 3.19: Rates of collisions involving other types of initial impact per hour of exposure at different temperatures during the peak and off-peak periods in the City of Ottawa during weekdays between 6:01 am and 9:00 pm (November 1, 2001 – March 31, 2002)

Temperature Range	Temp.	Peak period				Off-peak period			
		Dry	Wet	Total	Risk	Dry	Wet	Total	Risk
(-8.5, -7.5)	-8	1.20	1.54	1.39	1.28	0.17	3.80	1.82	22.80
(-7.5, -6.5)	-7	2.17	2.00	2.07	0.92	0.64	1.38	0.91	2.14
(-6.5, -5.5)	-6	1.17	1.50	1.38	1.29	0.53	1.33	0.86	2.52
(-5.5, -4.5)	-5	0.85	2.25	1.52	2.66	1.00	2.00	1.58	2.00
(-4.5, -3.5)	-4	1.80	1.05	1.30	0.58	0.67	1.50	1.07	2.25
(-3.5, -2.5)	-3	1.21	1.18	1.19	0.97	0.96	0.97	0.97	1.01
(-2.5, -1.5)	-2	1.27	1.89	1.74	1.48	0.88	1.21	1.15	1.39
(-1.5, -0.5)	-1	1.06	2.05	1.76	1.93	0.79	1.94	1.46	2.45
(-0.5, 0.5)	0	0.92	1.16	1.08	1.27	0.91	1.24	1.14	1.35
(0.5, 1.5)	1	1.00	0.88	0.91	0.88	0.73	1.11	1.00	1.52
(1.5, 2.5)	2	0.79	1.32	1.11	1.67	1.00	1.05	1.04	1.05
(2.5, 3.5)	3	1.18	1.12	1.14	0.95	0.95	1.21	1.12	1.27
(3.5, 4.5)	4	1.14	1.30	1.21	1.14	0.75	1.00	0.89	1.33
(4.5, 5.5)	5	0.89	1.36	1.07	1.53	0.41	1.25	0.86	3.07
(5.5, 6.5)	6	1.14	1.00	1.08	0.88	0.67	1.11	0.89	1.67
(6.5, 7.5)	7	1.44	1.40	1.42	0.97	0.56	1.09	0.78	1.94
(7.5, 8.5)	8	1.33	1.50	1.39	1.13	0.81	1.63	1.00	1.99
Average		1.21	1.44	1.33†	1.26	0.73	1.46	1.10†	1.71
Variance		0.12	0.16	0.15†	···	0.05	0.45	0.38†	···

† Average and variance of total rates of other types of impact are calculated from the 34 observations of dry and wet surfaces.

These results suggest that during peak period, the risk of collision in the other types of initial impact when driving on wet pavement surface was, on average, 26% higher than when driving on dry surface, and during off-peak period, the risk of collision in the other types of initial impact when driving on wet pavement surface was, on average, 71% higher than when driving on dry surface. The overall average and variance of the collision rates per hour of exposure of other types of initial impact on wet and dry surfaces combined were (1.33, 0.15) and (1.10, 0.38) during peak and off-peak periods respectively.

The distributions of collision rates per hour of exposure at different temperatures on wet and dry surfaces in the other types of initial impact during the peak and off-peak periods were given in Figures 3.31 and 3.32 respectively. Figure 3.31 shows that during the peak period, there was no pattern between the rates on wet and dry surfaces, however, that rate on wet surface was higher than the dry surface at temperatures – 2°C, – 1°C, 0°C, + 2°C, + 4°C and + 5°C.

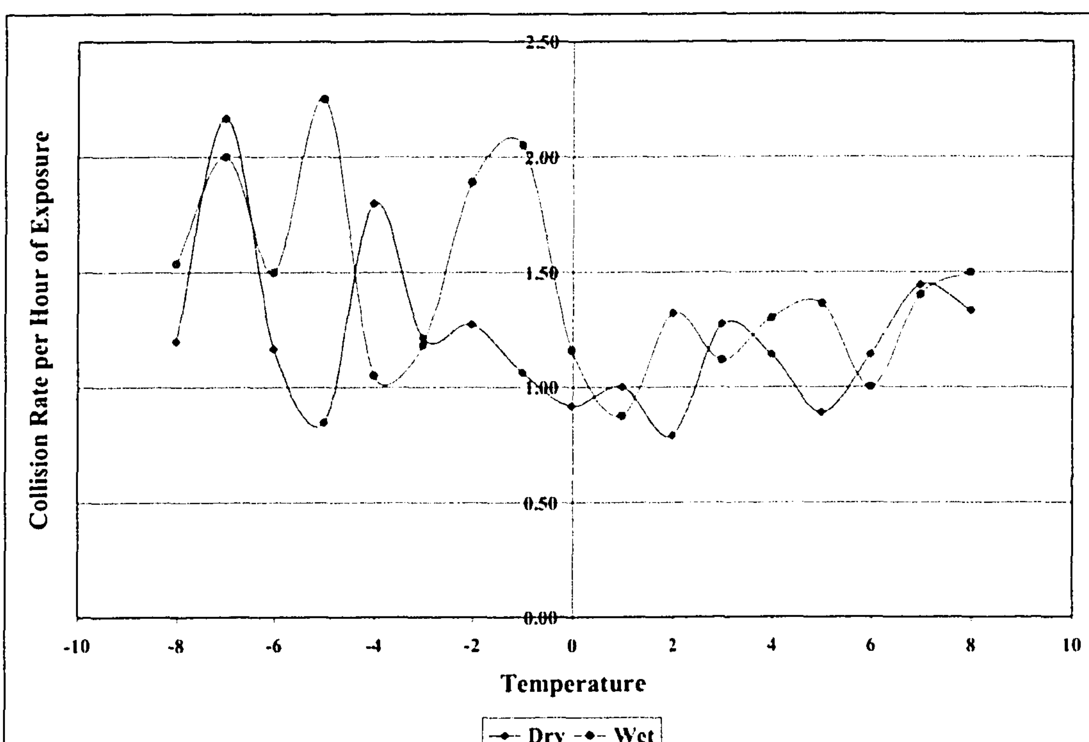


Figure 3.31: Distributions of rates of other collisions per hour of exposure at different temperatures on wet and dry surfaces during the peak period

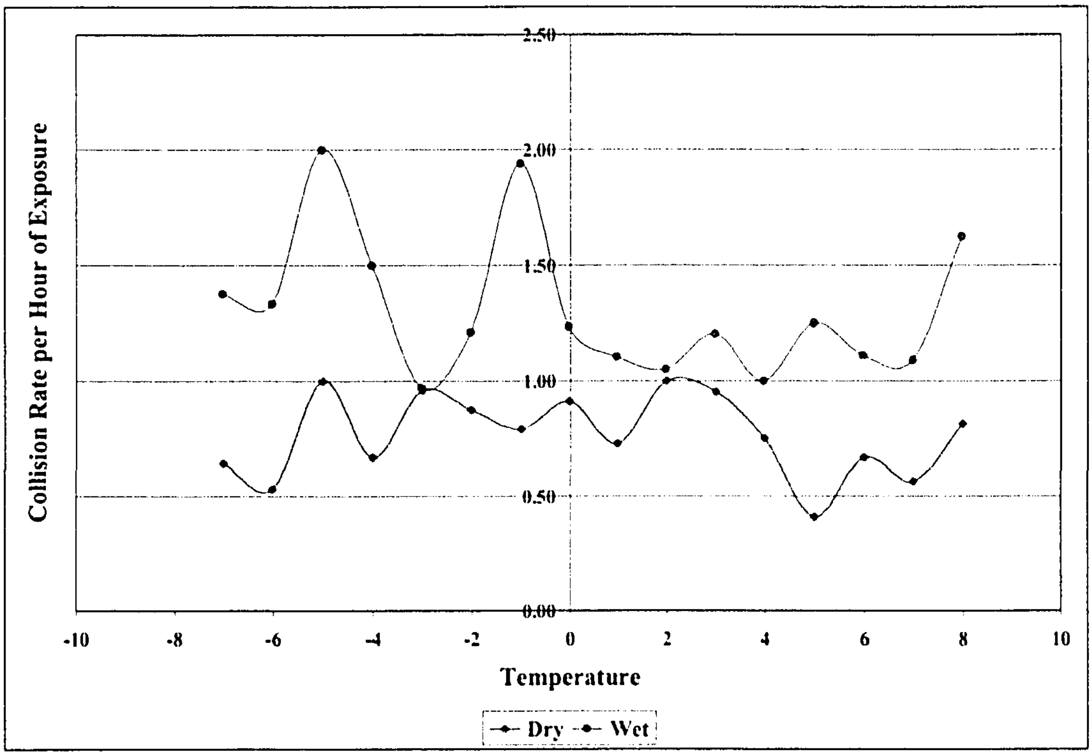


Figure 3.32: Distributions of rates of other collisions per hour of exposure at different temperatures on wet and dry surfaces during the off-peak period

Figure 3.32 shows that during the off-peak period, the rates of other types of collision on wet surface were higher than on dry surface at all temperatures. Figure 3.33 shows the distributions of the pavement moisture risk factors for other types of initial impact during peak and off-peak periods.

This section concludes that on average, the moisture on pavement surface increases the risk of collision in the other types of initial impact around the freezing temperature irrespective of the traffic volume.

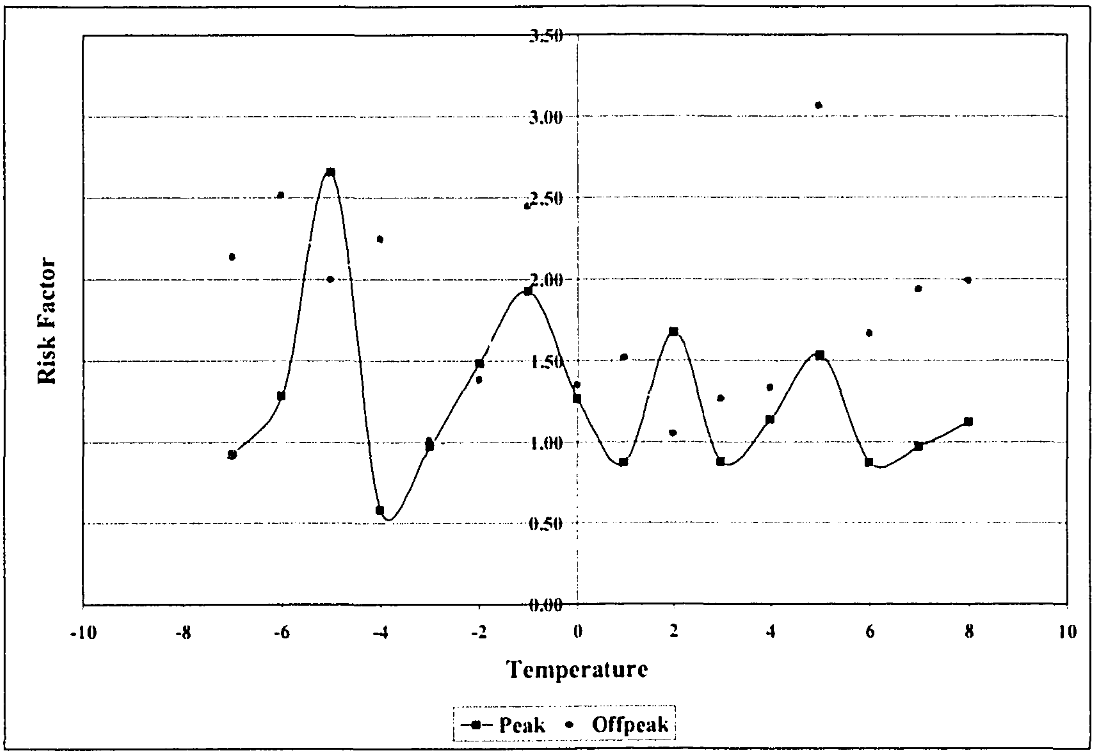


Figure 3.33: Pavement moisture risk factors using collision rates involving other types of initial impact per hour of exposure at different temperatures during the peak and off-peak periods

3.5. Summary

This chapter examined quantitatively the effect of surface temperature and pavement moisture condition during the winter months on the risk of vehicle collisions. The study used collision and weather data from the City of Ottawa from November 1, 2001 to March 31, 2002.

The traffic volumes on the roads of the City of Ottawa were not available to calculate the collision rates per million vehicle-kilometres. Therefore, the data were disaggregated into peak and off-peak periods, which eliminated the need for the traffic volumes. Alternative collision rates per hour of exposure, which are more suitable for this research, were developed. To further maintain the consistency of the data, only observations on weekdays from 6:01 am to 9:00 pm were used. Analyses of the effects of pavement moisture condition and surface temperature on the risk of collisions were conducted. The analyses included the total collisions, severity of collisions, and initial type of impact. The severity of collisions was divided into fatal injury, injury, and PDO. The initial type of impact was divided into single-vehicle collisions, rear-end collisions, other types of initial impact.

The numbers of collisions had their maximums at –1°C on wet pavement for all categories and remained relatively high around this temperature, but they did not show any specific pattern on the dry surface. During the peak period, the pavement moisture risk factor was greater than 1 for total collisions between –3°C and +5°C, for collisions involving injury at –1°C and 0°C, for collisions involving PDO between –3°C and +2°C, for single vehicle collisions between –8°C and +2°C, for rear-end collisions between –2°C and +5°C, and for collisions involving other types of initial impact between –2°C and 0°C. Only singles vehicle collisions had a pavement moisture risk factor greater than 1 at all sub-zero temperatures.

During the off-peak period, the pavement moisture risk factor was greater than 1 at all temperatures, between –8°C and +8°C for the total collisions, collisions involving PDO, and collisions involving other types of initial impact. The pavement moisture risk factor was also greater than 1 at temperatures between –8°C and +1°C for collisions involving injury, between –8°C and +2°C for single vehicle collisions, and between –8°C and +1°C (except at –4°C) for rear-end collisions. The pavement moisture risk factor was grater than 1 at all sub-zero temperatures for all categories, except for rear-end collisions at –4°C.

Wet pavement moisture condition increased the risk of collision at all categories at $-1^{\circ}C$ and $0^{\circ}C$ in both the peak and off peak periods, i.e. irrespective of the traffic volume.

The number and rates of total collisions discussed in section 3.4.1 should give a better insight into the effect of surface temperature and pavement moisture condition on the risk of collision because of the larger numbers of collisions and hours of exposure, which would minimize the randomness effect of the collision occurrence. Based on this, wet pavement condition has increased the risk of collision at all temperatures between $-8^{\circ}C$ and $+8^{\circ}C$ during the off-peak period and at temperatures between $-8^{\circ}C$ and $+5^{\circ}C$, except at $-4^{\circ}C$, and the risks for both periods are very high at $-1^{\circ}C$.

4. BAYESIAN ANALYSIS OF ROAD SAFETY

The methodology used in the previous chapter only to compare the risk of collision on wet surface with the risk of collision on dry surface at a given temperature during the peak and off-peak periods. This chapter develops a methodology to identify the surface temperature and pavement moisture condition combinations at which driving will be hazardous using the Empirical Bayes (EB) probability method. Numbers of hours and collision rates developed in Chapter 3 during the peak and off-peak periods for total collisions, fatal collisions, collisions involving injury, collisions involving PDO, single-vehicle collisions, rear-end collisions, and other types of initial impact will be used in the analysis.

4.1. Background

The Bayesian technique has been applied to road safety problems by numerous researchers, usually in the EB framework (Melcher *et al.* 2001). This technique combines prior knowledge with current knowledge to obtain posterior knowledge. The prior knowledge represents the subjective part of the Bayes approach that describes particular beliefs or opinions about different values of a particular parameter (Harlow *et al.* 1997). The strength of the EB method comes from the fact that it is a dynamic and continuous process. In that, whenever new information become available, the model can always be updated to reflect these new information.

Higle and Witkowski (1988) applied the Bayesian analysis to collision data from the jurisdiction of the Pima County Department of Transportation in Tucson, Arizona, United States, to identify hazardous locations on the basis of historical data. Because of the random variations that are inherent in the collision phenomena, the collision rate associated with a particular location is considered to be a random variable, a quantity that cannot be predicted with absolute certainty. Moreover, the vast differences in collision histories usually noticed among various locations suggest that the random variables used to describe the collision rates should differ from one location to another. Bayesian analysis provides a framework wherein regional collision characteristics can be combined with location-specific collision histories, which results in a coherent method by which the random variables representing the collision rates at the various locations can be mathematically defined. In addition, by using a Bayesian identification technique, the hazardous locations can be identified on the basis of the probability that the collision rate would exceed some level.

The topic of interest in this research is to identify the pavement surface temperature and pavement moisture condition combinations at which the road driving is hazardous. Even though this is different from identifying hazardous locations, an adaptation of the two-step procedure of EB identification method of hazardous location suggested by Higle and Witkowski (1988) can be applied to identify such combinations. The first step is to estimate the aggregate probability (prior) distribution of all rates of collisions at all pavement surface temperatures and pavement moisture conditions. This prior distribution can then be combined with the distribution of a collision rate at a particular surface temperature and pavement moisture condition to obtain the refined estimation of the probability (posterior) distribution associated with the collision rate at this particular temperature and pavement moisture condition. This process will be repeated at all temperatures and pavement moisture conditions during the peak and off-peak periods. With these refined posterior distributions, the probability that the road is hazardous at a specific surface temperature and pavement moisture condition can be determined.

4.2. Bayesian Methodology

The following notations are used to describe the Bayesian identification process. Let for $i = 1, \ldots, m$:

m = Number of subgroups (each subgroup consists of a specific temperature and pavement moisture condition),

N_i = a random variable representing the number of collisions in subgroup i,

n_i = a given number of collisions in subgroup i,

H_i = a random variable representing the number of exposure hours for subgroup i, i.e. the number of hours during which a certain temperature was reached,

h_i = a given number of exposure hours for subgroup i,

$\Theta_i = N_i / H_i$ = the collision rate per hour of exposure for subgroup i (assumed to be a random variable), and

$\theta_i = n_i / h_i$ = a given value of the collision rate per hour of exposure for subgroup i

The following two assumptions are similar to those used by Morin (1967), Hauer and Persaud (1983); (1984), Glauz *et al.* (1985), and Higle and Witkowski (1988). In analogy with the methodology used by Higle and Witkowski (1988), the first assumption is that for any subgroup i of temperature level and pavement moisture condition, when the collision rate is θ_i, the actual number of collisions n_i follows the Poisson distribution with mean value $\theta_i h_i$, that is

$$f\left(n_i \middle| \theta_i, h_i\right) = P_r\{N_i = n_i \mid \Theta_i = \theta_i, h_i\} = \frac{(\theta_i h_i)^{n_i}}{n_i!} e^{-\theta_i h_i} \tag{4.1}$$

The second assumption is that the probability density function associated with the collision rate θ of all subgroups combined is a Gamma distribution with parameters α and β, such that

$$f_R(\theta \mid \alpha, \beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} \theta^{\alpha - 1} e^{-\beta\theta} \tag{4.2}$$

The first step in the Bayesian analysis is the determination of the prior distribution $f_R(\theta|\alpha,\beta)$ by estimating the values of α and β. The most two commonly used methods of estimation are the Method of Moment Estimates (MME) and the Maximum Likelihood Estimation (MLE) method. In the first method, the parameters α and β are chosen such that the mean and variance of the Gamma distribution are equal to the sample mean and variance respectively. Since the mean and variance of the Gamma distribution in Equation 4.2 are α/β and α/β^2 respectively, therefore

$$\frac{\alpha}{\beta} = \bar{\theta} = \frac{1}{m} \sum_{i=1}^{m} \frac{N_i}{H_i} \tag{4.3}$$

$$\frac{\alpha}{\beta^2} = s_\theta^2 = \frac{1}{m-1} \sum_{i=1}^{m} \left(\frac{N_i}{H_i} - \bar{\theta} \right)^2 \tag{4.4}$$

The estimated values of α and β can be determined by solving Equations 4.3 and 4.4. In the second method (MLE), the parameters α and β are chosen such that the likelihood function is the most likely to have generated the observed data. That is if $x_1, x_2, \ldots, x_m$, are the observed values of the collision rates, then α and β are chosen to maximize the likelihood function.

$$L(\alpha,\beta|\theta_1,\theta_2,...,\theta_m) = \prod_{i=1}^{m}\frac{\beta^{\alpha}}{\Gamma(\alpha)}\theta_i^{\alpha-1}e^{-\beta\theta_i} = \left\{\frac{\beta^{\alpha}}{\Gamma(\alpha)}\right\}^{m}\left\{\prod_{i=1}^{m}\theta_i\right\}^{\alpha-1}e^{-\beta\sum_{i=1}^{m}\theta_i} \quad (4.5)$$

The MLE values of α and β can be calculated by solving the two equations

$$\frac{\partial L(\alpha,\beta|\ \theta_1,\theta_2,...,\theta_m)}{\partial\alpha} = 0 \quad (4.6)$$

and

$$\frac{\partial L(\alpha,\beta|\theta_1,\theta_2,...,\theta_m)}{\partial\beta} = 0 \quad (4.7)$$

The estimation of the values of α and β, and thus the determination of the prior distribution in Equation 4.2, concludes the first step of the Bayesian Analysis.

In the second step of the Bayesian analysis, the estimated prior distribution is combined with the conditional probability of collision occurrences within subgroup i to generate posterior distribution $f_i(\theta|\ n_i,\ h_i,\ \alpha,\ \beta)$, or the i^{th} subgroup-specific probability density function of the collision rate θ for a given number of collisions n_i and number of hours of exposures h_i, and pavement moisture condition. That is

$$f_i(\theta|\,n_i,h_i,\alpha,\beta) = \frac{f_R(\theta|\,\alpha,\beta)\,f(n_i,h_i|\,\theta)}{\int f_R(\theta|\,\alpha,\beta)\,f(n_i,h_i|\,\theta)\,d\theta} \quad (4.8)$$

Here $f(n_i,\ h_i\ |\theta)$ denotes the data likelihood, which gives the probability of observing the data as a function of θ. If we can assume that the temperature at collision specific rate does not influence its hours of exposure, then Equation 4.8 simplifies to:

$$f_i(\theta|\,n_i,h_i,\alpha,\beta) = \frac{f_R(\theta|\,\alpha,\beta)\,f(n_i|\,\theta,h_i)}{\int f_R(\theta|\,\alpha,\beta)\,f(n_i|\,\theta,h_i)\,d\theta} \quad (4.9)$$

It is well known that the probability density function $f_i(\theta \mid n_i, h_i, \alpha, \beta)$ is a gamma distribution with parameters α_i, β_i (Berger, 1985), where

$$\alpha_i = \alpha + n_i \tag{4.10}$$

$$\beta_i = \beta + h_i \tag{4.11}$$

Therefore, the posterior distribution associated with the subgroup i is given by

$$f_i(\theta \mid n_i, h_i, \alpha_i, \beta_i) = \frac{\beta_i^{\alpha_i}}{\Gamma(\alpha_i)} \theta^{\alpha_i - 1} e^{-\beta_i \theta} \tag{4.12}$$

It is noted from Equations 4.10 and 4.11 that as n_i and h_i increase, values of the subgroup-specific parameters α_i and β_i will depend more on the observed data and be insensitive to the initial values α and β. For that reason, it would be preferable to use the MME estimates rather than the MLE estimates since they are substantially easier to calculate. In this thesis, the MME method is used to estimate all the parameters α and β.

Finally, a criterion similar to that used by Higle and Witkowski (1988), is used to identify whether or not a road surface at a particular temperature and pavement moisture condition is hazardous. A road surface at a particular temperature and pavement moisture condition is hazardous if the probability that its true collision rate per hour of exposure, Θ_i, exceeds the observed average collision rate per hour of exposure for all subgroups, is greater than a pre-specified confidence level δ. That is if

$$P_r\left\{\Theta_i \rangle\ \bar{\theta} \mid n_i, h_i, \alpha_i, \beta_i\right\} > \delta \tag{4.13}$$

Alternatively, a road surface at a particular temperature and pavement moisture condition is hazardous if

$$1 - F_i(\bar{\theta}|n_i, h_i, \alpha_i, \beta_i) = 1 - \int_0^{\bar{\theta}} f_i(\theta|n_i, h_i, \alpha_i, \beta_i)\, d\theta$$

$$= 1 - \int_0^{\bar{\theta}} \frac{\beta_i^{\alpha_i}}{\Gamma(\alpha_i)} \theta^{\alpha_i - 1} e^{-\beta_i \theta}\, d\theta \rangle \delta \tag{4.14}$$

Typically, δ is a reasonably high number, such as. 0.99 or 0.95. Following Tarko *et al.* (1996), the method presented here is founded on the following six premises:

1. A given pavement surface temperature and pavement moisture condition combination is characterized by a *normal* collision rate per hour of exposure, which is expected to materialize when the level of safety for this combination conforms with the average safety level of all surface temperatures and pavement moisture condition combinations.
2. Each safety problem is associated with a relevant collision category (e.g. fatal, injury, single-vehicle or rear-end collisions) and existing or potential road safety program such as road winter maintenance program.
3. A recorded collision rate in a given collision category higher than normal value (above-norm collision rate) indicates the possibility of a related road safety problem.
4. The safety problem for a given combination of pavement surface temperature and pavement moisture condition can be stated only at a limited confidence level because of the randomness in collision rates.
5. Confidence level and above-norm collision rates reflect the magnitude of the related safety problem.
6. The magnitude of the road safety problem at a pavement surface temperature and pavement moisture condition combination must be anticipated in case of the

above norm collision rate when a relevant road safety program is to be implemented

4.3. Empirical Results

In order to identify the pavement surface temperature and pavement moisture condition at which driving becomes hazardous, the mean and variance, $\bar{\theta}$ and s^2, of the rates of collisions per hour of exposure at different temperatures are calculated. Then using Equations 4.3 and 4.4, the prior parameters α and β can be determined. From Equations 4.10 and 4.11, the posterior parameters α_i and β_i can be calculated for the i^{th} subgroup-specific probability density function $f_i(\theta | n_i, h_i, \alpha_i, \beta_i)$.

This process was applied to identify the hazardous surface temperature and pavement moisture condition for the numbers and rates of total collisions during the peak and off-peak periods given in Tables 3.7 and 3.8. Then it was repeated for two cases of collision severity (Tables 3.10 to 3.13), and the three cases of initial type of impact (Tables 3.14 to 3.19). The results are presented in the following sections.

4.3.1. Total Collisions

The average and variance of the rates of total collisions per hour of exposure on dry and wet surface combined during the peak period were given in Table 3.8 as $\bar{\theta}$ = 2.93 and s^2 = 0.67. Solving Equations 4.3 and 4.4, the estimated values of the parameters α and β of the prior distribution are 12.81 and 4.37, respectively. Table 4.1 presents the estimated values of the Bayes posterior parameters α_i and β_i of the i^{th} distribution-specific model (specific surface temperature and pavement moisture condition). The values in Table 4.1 were obtained by substituting in Equations 4.10 and 4.11 by the estimated parameters of the prior distribution, the numbers of collision on dry and wet surfaces from the third and fourth columns of Table 3.7, and the corresponding numbers of hours in the 3rd and 4th columns of Table 3.6. Finally, the posterior probabilities of hazardous road driving (when the rate of collisions per hour of exposure is higher than the average rate of collisions for all surface temperatures and pavement moisture condition) on dry and wet surfaces were given in the 4th and 7th columns of Table 4.1 respectively. They were calculated from the Bayes posterior gamma distribution in Equation 4.14 using the MS Excel.

It is worth noting that the calculation of the probabilities in Table 4.1 depends on the values of the parameters α_i and β_i, and the average of the collision rates $\bar{\theta}$. For a fixed $\bar{\theta}$ and β_i, an increase of α_i (which depends on the number of collisions) would increase the posterior probability (probability defined in Equation 4.14). On the other hand, for a fixed $\bar{\theta}$ and α_i, an increase of β_i (depends on the number of hours of exposure) will decrease the posterior probability. If both parameters α_i and β_i simultaneously increased or decreased, the result could be an increase, decrease or no change in the posterior probability, depending on the amount of change in each parameter. The parameter β_i is a scale parameter and its change produces relatively larger change in the posterior probability defined by Equation 4.14 than the change produced by changing the location parameter α_i.

Table 4.1: Posterior parameters and probabilities of total collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	41.81	14.37	0.46	60.81	17.37	0.90
-7	37.81	10.37	0.89	53.81	13.37	0.98
-6	30.81	10.37	0.50	46.81	14.37	0.74
-5	38.81	17.37	0.03	59.81	16.37	0.94
-4	52.81	14.37	0.94	61.81	24.37	0.11
-3	46.81	18.37	0.15	85.81	26.37	0.82
-2	34.81	15.37	0.05	140.81	40.37	0.98
-1	44.81	20.37	0.02	215.81	43.37	1.00
0	36.81	16.37	0.04	83.81	29.37	0.39
1	38.81	19.37	0.01	78.81	36.37	0.00
2	45.81	23.37	0.00	100.81	32.37	0.71
3	38.81	15.37	0.16	58.81	21.37	0.29
4	46.81	18.37	0.10	40.81	14.37	0.40
5	55.81	22.37	0.10	52.81	15.37	0.86
6	51.81	18.37	0.37	38.81	14.37	0.28
7	41.81	13.37	0.64	40.81	14.37	0.40
8	60.81	19.37	0.68	34.81	12.37	0.38

The results in Table 4.1 show that for total collisions at confidence level $\delta = 0.95$, driving on dry pavement surface were not hazardous at any temperature, while on wet pavement surface, the hazardous driving condition occurred on wet pavement at temperatures of –7°C, –2°C, and –1°C.

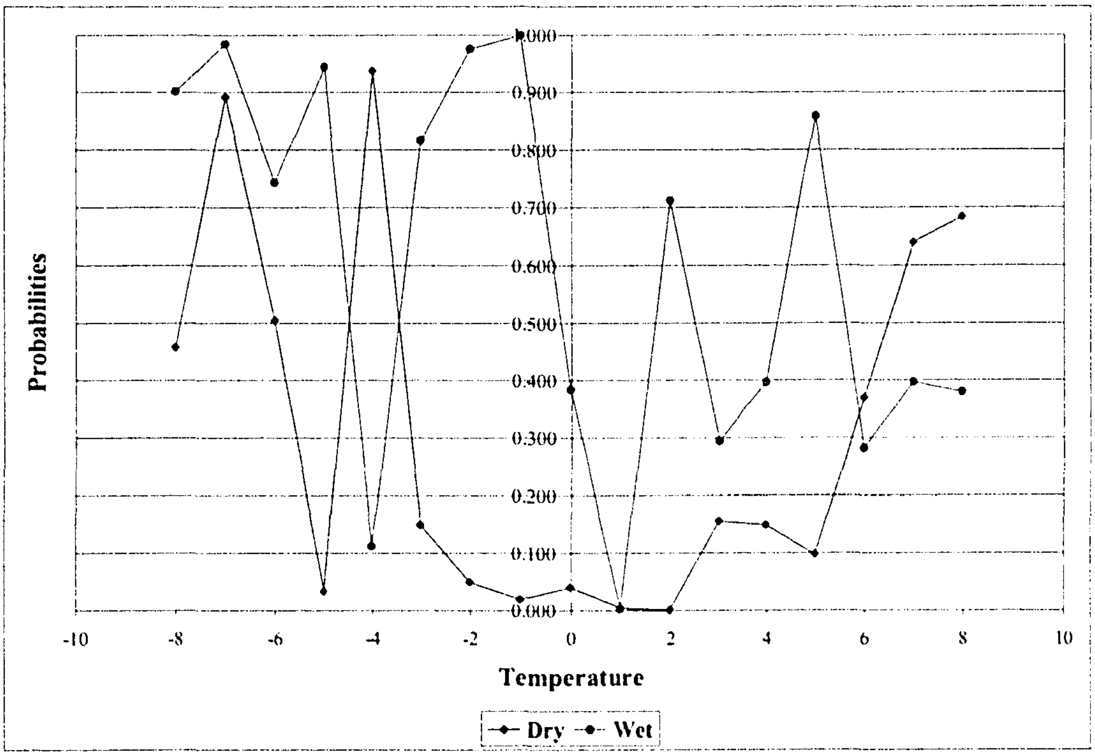


Figure 4.1: Posterior probabilities for total collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

The posterior probabilities for total collisions on dry and wet surfaces combined during the peak period are presented in Figures 4.1. The figure shows that the posterior probabilities of higher than average rate of collision per hour of exposure were greater on wet surface than on dry surface during the peak period at all temperatures between – 8°C and +5°C, except at – 4°C. This variation could be due to the stochastic nature of the collision rates.

The distributions of the posterior probabilities of total collisions on wet and dry surfaces during the peak period in Figure 4.1 are similar to the distributions of total collision rates per hour of exposure on wet and dry surfaces during the peak period in Figure 3.6. Both methods are in agreement about the relationship between the risks of collision on wet surface and dry surface. The posterior probability, however, is capable of identifying the hazardous surface temperature and pavement moisture condition combinations.

Similarly, the average and variance of the rates of total collisions per hour of exposure on wet and dry surface combined during the off-peak period were given in Table 3.8 as $\bar{\theta}$ = 2.26 and s^2 = 1.41. The estimated values of the parameters α and β of the prior distribution from solving Equations 4.3 and 4.4 were 3.62 and 1.60 respectively. Table 4.2 presents the estimated values of the Bayes posterior parameters α_i and β_i of the i^{th} distribution-specific model. The results show that similar to the peak period, driving on dry pavement surface during the off-peak period was not hazardous at any temperature with 95% confidence level. However, driving on wet pavement surface was hazardous at – 8°C, – 5°C, – 2°C, –1°C and 0°C.

The posterior probabilities for total collisions on dry and wet surfaces combined, during the off-peak periods, are presented in Figure 4.2. The figure shows that during the off-peak period, the posterior probabilities on wet surface were higher than on dry surface at all temperatures between – 8°C and +8°C, except at +2°C and +3°C. In Figure 3.7, the risk factors were greater than 1 at all temperatures and equal to 1 at +3°C. At +2°C, the risk factor was almost equal to 1. The variation between Figures 3.7 and 4.2 was due to the stochastic nature of the collision rates in the Bayes posterior probability distribution. All other values in both figures were in agreement.

In the above analysis, total collision rates per hour of exposure on dry and wet pavement surfaces were compared to their overall combined average and variance to calculate the posterior probabilities.

Table 4.2: Posterior parameters and probabilities of total collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	13.62	7.60	0.16	40.62	6.60	1.00
-7	23.62	15.60	0.02	26.62	9.60	0.83
-6	24.62	18.60	0.00	37.62	13.60	0.87
-5	17.62	9.60	0.16	48.62	12.60	1.00
-4	28.62	16.60	0.06	41.62	15.60	0.84
-3	41.62	26.60	0.01	92.62	35.60	0.90
-2	14.62	9.600	0.04	104.62	34.60	1.00
-1	43.62	25.60	0.02	147.62	34.60	1.00
0	45.62	24.60	0.08	153.62	52.60	1.00
1	30.62	23.60	0.00	126.62	58.60	0.29
2	33.62	17.60	0.14	79.62	40.60	0.09
3	47.62	22.60	0.29	85.62	40.60	0.24
4	37.62	21.60	0.04	52.62	28.60	0.05
5	32.62	28.60	0.00	77.62	33.60	0.56
6	25.62	19.60	0.00	41.62	19.60	0.32
7	26.62	17.60	0.01	28.62	12.60	0.48
8	49.62	28.60	0.02	26.62	9.60	0.83

The analysis suggests that, with 95% confidence level, driving on dry surface was not hazardous at any surface temperature and was hazardous at the (–2°C, wet) and (–1°C, wet) combinations irrespective of the traffic volume. There were also hazardous driving conditions at (–7°C, wet) during the peak period and at (–8°C, wet), (–5°C, wet), and (0°C, wet) during the off-peak period. The risk of collision was, in general, higher on wet surface than on dry surface at or below the freezing mark irrespective of the traffic volume.

Another interesting problem is to examine the effect of the surface temperature separately on the risk of collision. That is to determine at which surface temperature the road driving would be hazardous on dry pavement surface by comparing the rates of collision on dry surface to their average. The same can be repeated for wet pavement surface. During the peak period, the average and variance, $\bar{\theta}$ and s^2, of the rates of total collisions on dry surface were given in the 3rd column of Table 3.8 as 2.61 and 0.53 respectively. Solving Equations 4.3 and 4.4, the estimated values of the parameters α and β of the prior distribution for collisions on dry surface were 12.75 and 4.89.

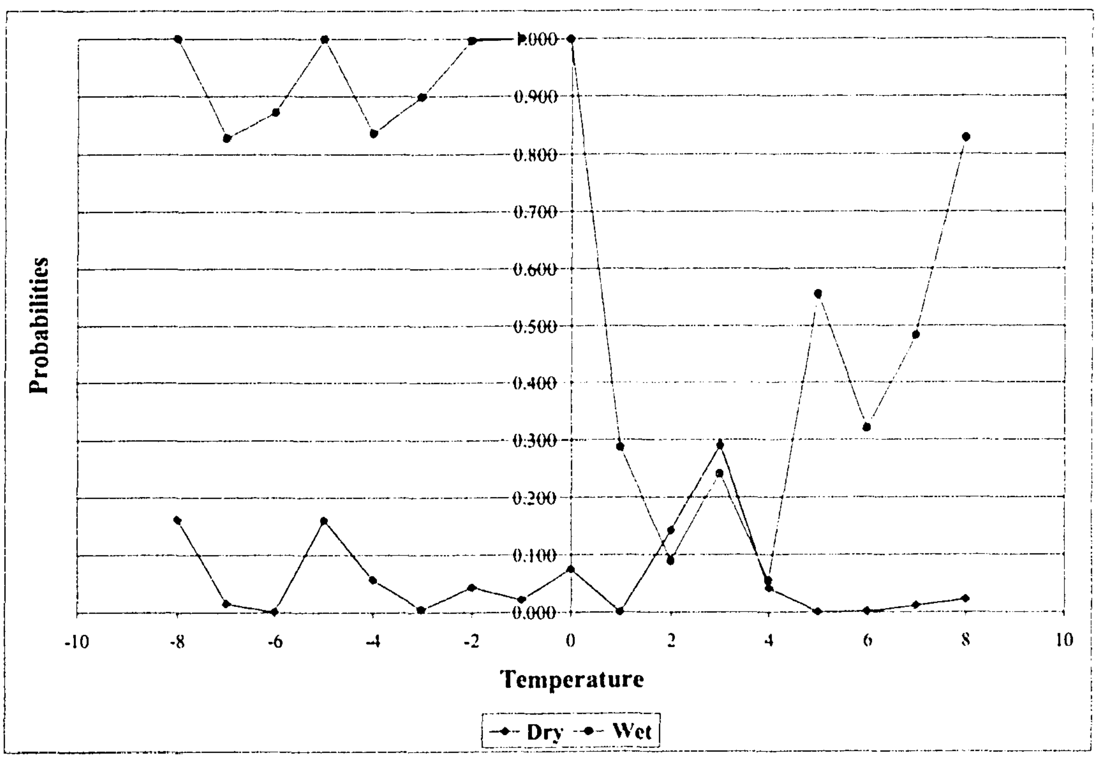


Figure 4.2: Posterior probabilities of total collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Similarly, the average and variance of the rates of total collision on wet surface were given in the 4th column of Table 3.8 as 3.26 and 0.63 respectively. The estimated values of the parameters α and β of the prior distribution were 16.95 and 5.20. The estimated parameters α_i and β_i and the posterior probabilities for dry and wet surfaces during the peak period were given in Tables 4.3.

Table 4.3: Posterior parameters and probabilities of total collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

Temperature	Dry			Wet		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	41.75	14.89	0.66	64.95	18.20	0.75
-7	37.75	10.89	0.95	57.95	14.20	0.95
-6	30.75	10.89	0.65	50.95	15.20	0.56
-5	38.75	17.89	0.11	63.95	17.20	0.84
-4	52.75	14.89	0.98	65.95	25.20	0.03
-3	46.75	18.89	0.34	89.95	27.20	0.54
-2	34.75	15.89	0.13	144.95	41.20	0.81
-1	44.75	20.89	0.08	219.95	44.20	1.00
0	36.75	16.89	0.12	87.945	30.20	0.13
1	38.75	19.89	0.03	82.945	37.20	0.00
2	45.75	23.89	0.01	104.95	33.20	0.36
3	38.75	15.89	0.32	62.95	22.20	0.12
4	46.75	18.89	0.34	44.95	15.20	0.24
5	55.75	22.89	0.29	56.95	16.20	0.70
6	51.75	18.89	0.62	42.95	15.20	0.16
7	41.75	13.89	0.80	44.95	15.20	0.24
8	60.75	19.89	0.88	38.95	13.20	0.25

At 95% confidence level, the calculated posterior probabilities indicate that road driving was hazardous on dry surface at – 7°C and – 4°C relative to all temperatures within the dry surface condition. On wet surface, the collision rates were above average at –7°C and –1°C relative to all temperatures within the wet surface condition. The posterior probabilities for total collisions on dry and wet surfaces separately during the peak period are presented in Figure 4.3. The figure shows that there was no relationship between posterior probabilities on wet and dry surfaces.

During the off-peak period, the average and variance of the rates of total collisions on dry surface were given in the 7th column of Table 3.8 as 1.56 and 0.08 respectively.

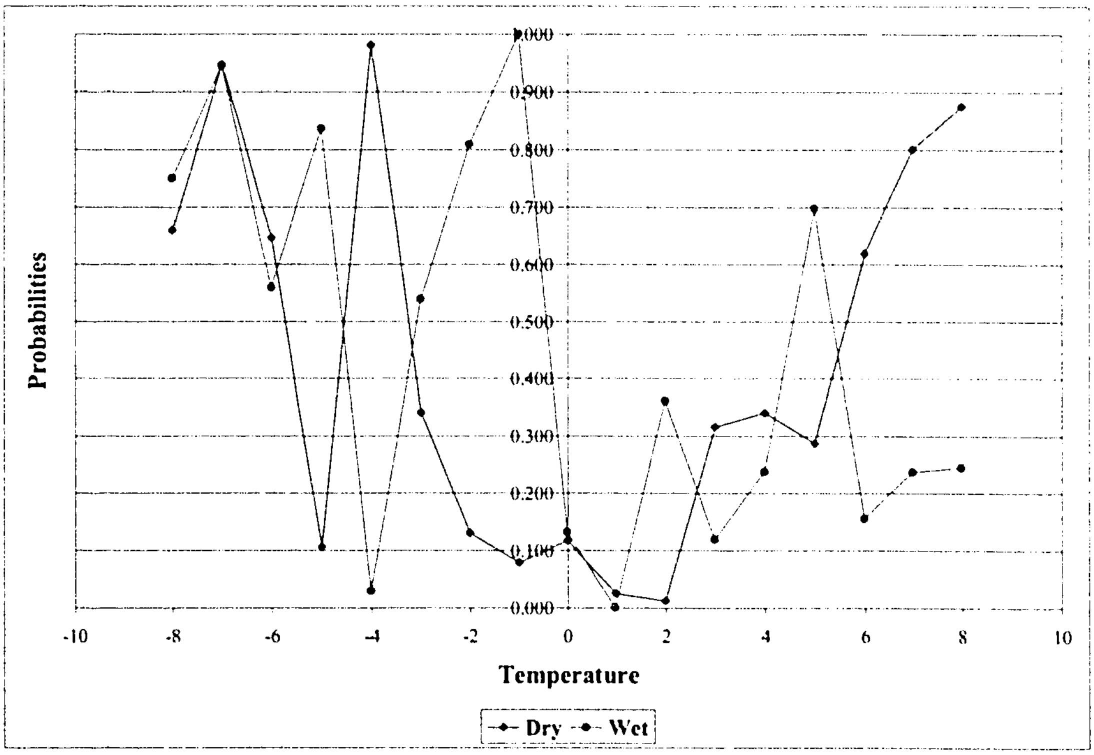


Figure 4.3: Posterior probabilities of total collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

The estimated values of the parameters α and β of the prior distribution for collisions on dry surface were 32.29 and 20.74. Similarly, the average and variance of the rates of total collisions on wet surface were given in the 8^{th} column of Table 3.8 as 2.97 and 1.78 respectively. The estimated values of the parameters α and β of the prior distribution were 4.95 and 1.67. The estimated parameters α_i and β_i and the posterior probabilities for dry and wet surfaces during the off-peak period were given in Tables 4.4. The posterior probabilities for total collisions indicate that driving condition was not hazardous at any temperature with 95% confidence level on dry surface relative to all temperatures within the dry pavement condition. The collision rates, however, were above average at –8°C, –5°C, and –1°C on wet surface relative to all temperatures within the wet surface condition.

The probabilities on dry and wet surfaces separately during the off-peak periods are presented in Figure 4.4. The posterior probabilities on dry surface was higher than on wet at all temperatures between 0°C and +8°C. There was no specific trend of changes in the posterior probabilities below the freezing temperature.

The posterior probabilities on dry pavement surface during the peak period in Table 4.1 were smaller than the posterior probabilities during the peak period in Tables 4.3 at all temperatures. This was due to the use of a relatively larger average of collision rates on dry and wet surfaces combined in the first case as compared to the smaller average of collision rates on the dry surfaces only. Same relationship is true during the off-peak period. Conversely, the posterior probabilities on wet pavement surface during the peak period in Table 4.1 were larger than the posterior probabilities during the peak period in Tables 4.3 at all temperatures. This was due to the use of a relatively larger average of collision rates on dry and wet surfaces combined in the first cases as compared to the smaller average of collision rates on the dry surfaces only. Same relationship is true during the off-peak period. Figures 4.5 and 4.6 present the posterior probabilities during the peak period calculated from the average of rates of total collisions on dry and wet surfaces combined versus those calculated only from the average of collision rates on dry and wet surfaces separately.

Table 4.4: Posterior parameters and probabilities of total collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Temperature	Dry			Wet		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	42.29	26.74	0.52	41.95	6.67	1.00
-7	52.29	34.74	0.39	27.95	9.67	0.42
-6	53.29	37.74	0.22	38.95	13.67	0.38
-5	46.29	28.74	0.57	49.95	12.67	0.97
-4	57.29	35.74	0.57	42.95	15.67	0.28
-3	70.29	45.74	0.44	93.95	35.67	0.11
-2	43.29	28.74	0.39	105.95	34.67	0.60
-1	72.29	44.74	0.61	148.95	34.67	1.00
0	74.29	43.74	0.76	154.95	52.67	0.44
1	59.29	42.74	0.17	127.95	58.67	0.00
2	62.29	36.74	0.73	80.95	40.67	0.00
3	76.29	41.74	0.91	86.95	40.67	0.00
4	66.29	40.74	0.62	53.95	28.67	0.00
5	61.29	47.74	0.06	78.95	33.67	0.01
6	54.29	38.74	0.20	42.95	19.67	0.02
7	55.29	36.74	0.38	29.95	12.67	0.09
8	78.29	47.74	0.66	27.95	9.66	0.42

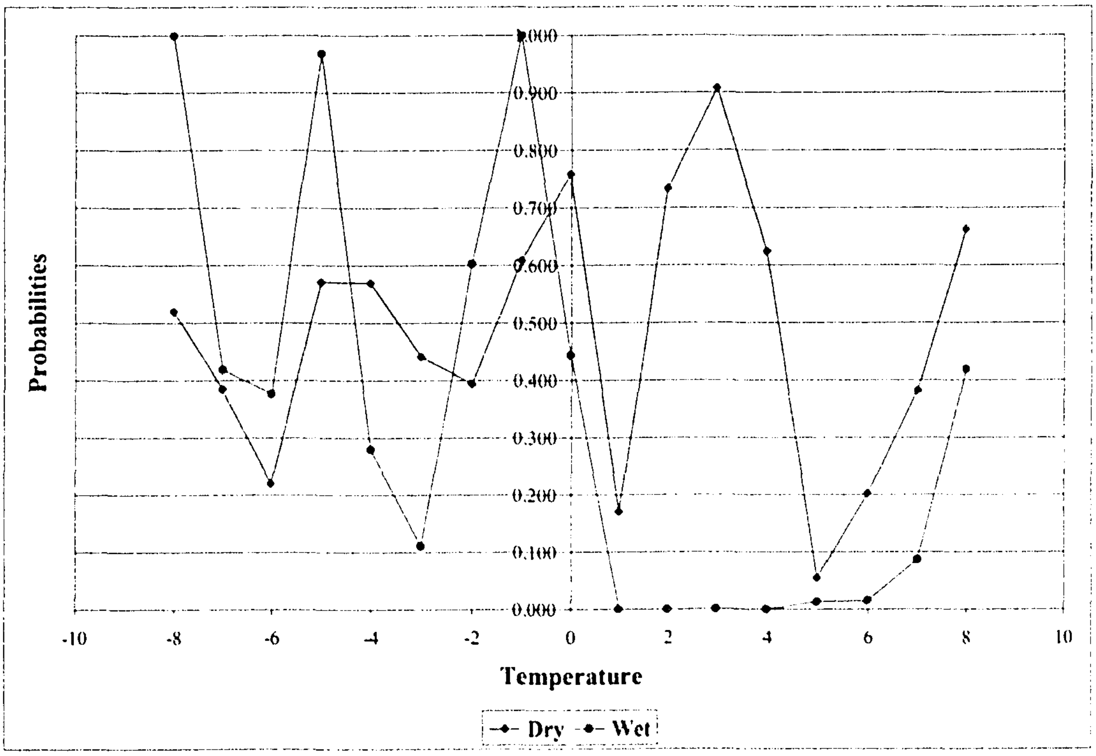


Figure 4.4: Posterior probabilities for total collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

4.3.2. Severity of Collision

The previous section examined the effect of pavement surface temperature and pavement moisture condition on the risk of collision using the rates of total collisions per hour of exposure on dry and wet surfaces combined and separately during the peak and off-peak periods. The following three sections will repeat same analyses to examine these effects on the risk of fatal collisions, collisions involving injury, and collisions involving PDO.

4.3.2.a. Fatal Collisions

As mentioned in section 3.4.1.a, there were nine fatal collisions during the five months study, seven occurred on wet surface out of which five occurred between – 1°C and +1 °C, and the other two occurred at – 8°C and 5°C. The remaining two occurred at – 4°C and 3°C on dry surface.

The number of collisions in this case is very small and therefore, it would not be appropriate to construct a Bayes posterior distribution for the rates of fatal collisions. Analysis undertaken in Section 3.4.1.a would be sufficient to explain the effect pavement surface temperature and pavement moisture condition on the risk of fatal collisions during the peak and off-peak periods on wet and dry surfaces.

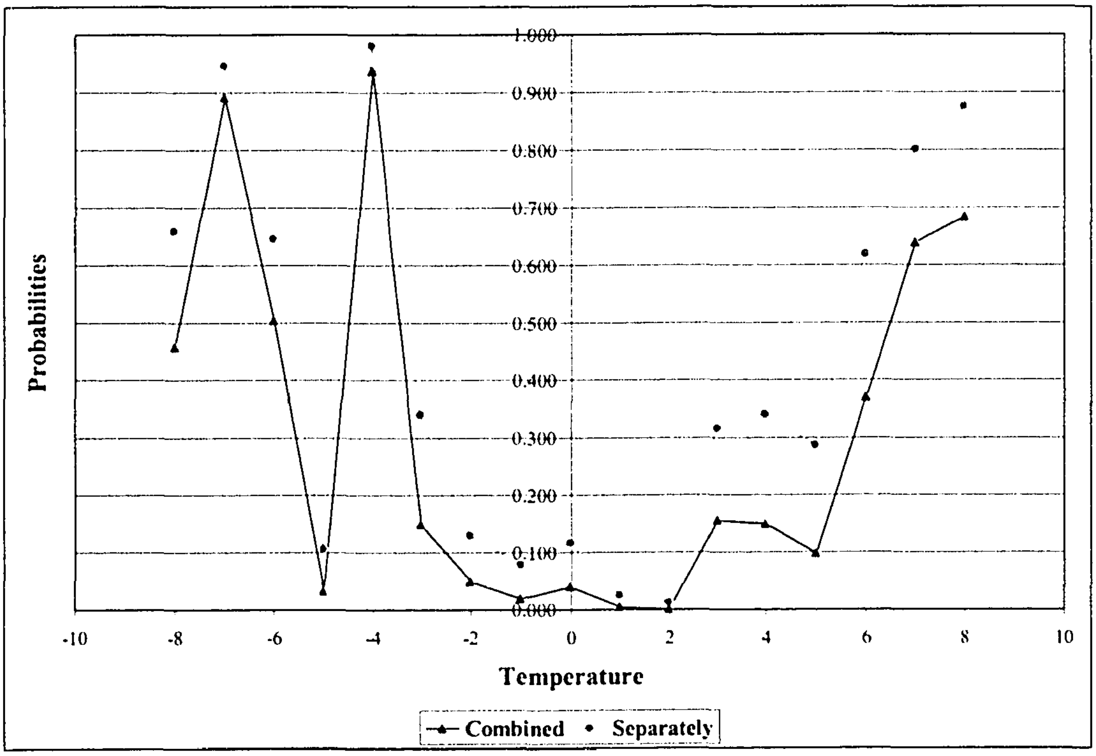


Figure 4.5: Posterior probabilities of total collisions on dry surface in the City of Ottawa during the peak period

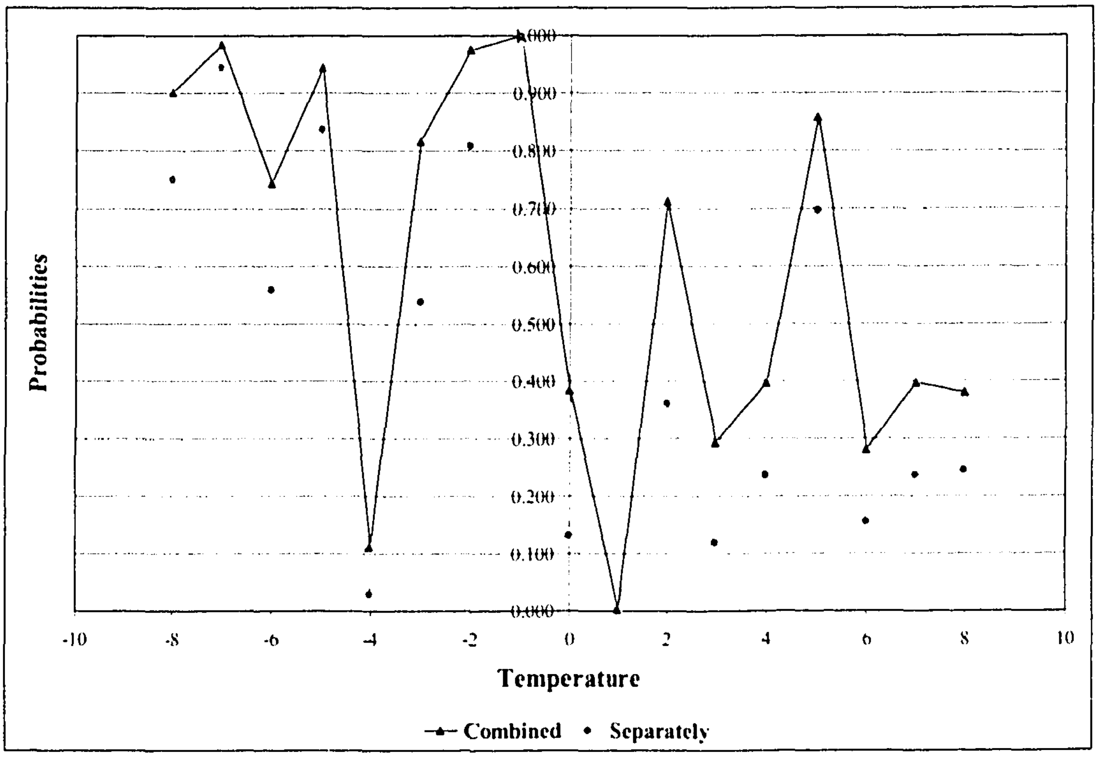


Figure 4.6: Posterior probabilities of total collisions on wet surface in the City of Ottawa during the peak period

4.3.2.b. *Collisions Involving Injury*

The average and variance of the rates of collisions involving injury per hour of exposure on dry and wet surfaces combined during the peak period were given in Table 3.11 as 0.63 and 0.05 respectively. Solving Equations 4.3 and 4.4, the estimated values of the prior parameters α and β were 7.69 and 12.22. The estimated posterior parameters α_i and β_i for collisions involving injury were obtained by substituting the estimated prior parameters and corresponding values from Tables 3.6 and 3.10 in Equations 4.10 and 4.11. Table 4.5 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14 during the peak period. These probabilities show that at 95% confidence level, there were no above average rates of collisions involving injury on dry surface at any temperature, while on wet surface, the rate of collision was higher than average only at – 1°C. Figure 4.7 shows no specific trend exists between the posterior probabilities of collisions involving injury on dry and wet surfaces during the peak period. However, the posterior probability on wet surface was clearly higher than the posterior probability on dry surface at – 1°C and 0°C. It is worth noting that the distributions of the posterior probabilities on wet and dry surfaces during the peak period in Figure 4.7 are similar to the distributions of collision rates per hour of exposure on wet and dry surfaces during the peak period in Figure 3.11.

Table 4.5: Posterior parameters and probabilities of collisions involving injury on dry and wet surfaces combined in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	15.69	22.22	0.64	16.69	25.22	0.55
-7	11.69	18.22	0.49	17.69	21.22	0.85
-6	10.69	18.22	0.37	17.69	22.22	0.81
-5	12.69	25.22	0.18	15.69	24.22	0.51
-4	16.69	22.22	0.73	19.69	32.22	0.42
-3	11.69	26.22	0.09	25.69	34.22	0.79
-2	14.69	23.22	0.47	28.69	48.22	0.36
-1	17.69	28.22	0.46	42.69	51.22	0.96
0	10.69	24.22	0.09	28.69	37.22	0.84
1	14.69	27.22	0.25	14.69	44.22	0.00
2	15.69	31.22	0.16	27.69	40.22	0.66
3	10.69	23.22	0.12	21.69	29.22	0.75
4	19.69	26.22	0.75	12.69	22.22	0.33
5	13.69	30.22	0.09	14.69	23.22	0.47
6	19.69	26.22	0.75	13.69	22.22	0.43
7	11.69	21.22	0.29	12.69	22.22	0.33
8	20.69	27.22	0.78	12.69	20.22	0.46

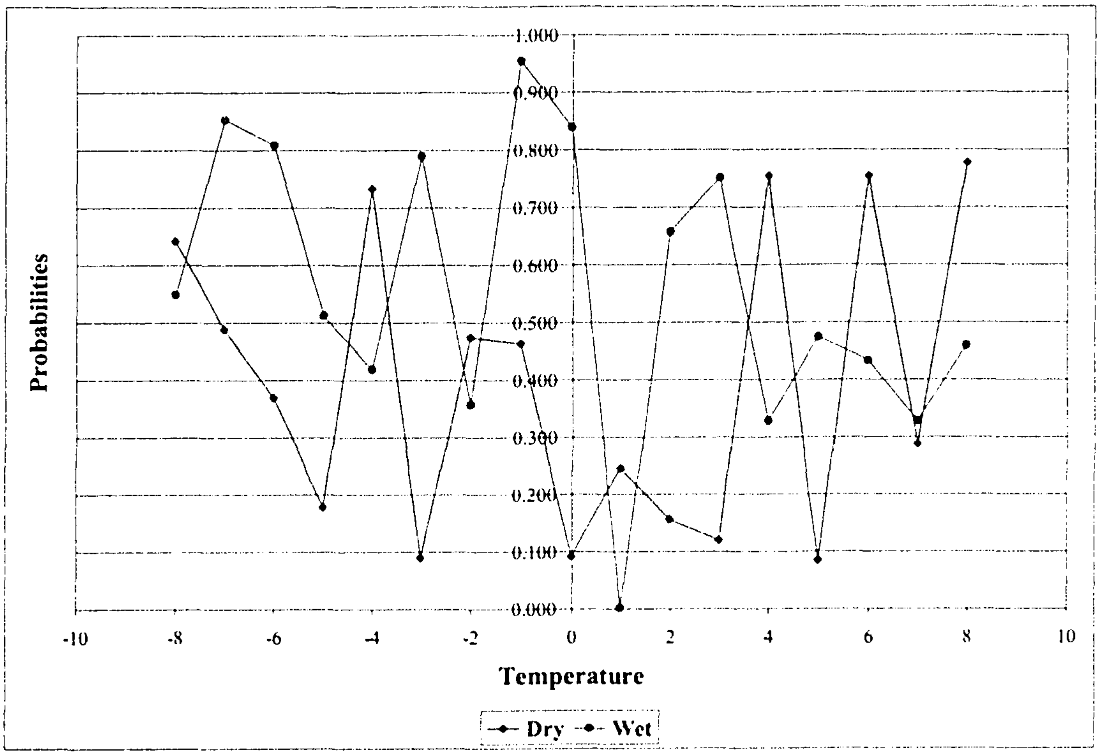


Figure 4.7: Posterior probabilities of collisions involving injury on dry and wet surfaces combined in the City of Ottawa during the peak period

Table 3.11 also gives the average and variance of the rates of collisions involving injury per hour of exposure on dry and wet surface combined during the off-peak period as 0.54 and 0.09 respectively. Solving Equations 4.3 and 4.4, the estimated values of the prior parameters α and β are 3.24 and 6.01. The estimated posterior parameters α_i and β_i and probabilities for collisions involving injury were obtained by substituting the estimated prior parameters and corresponding values from Tables 3.6 and 3.10 in Equations 4.10, 4.11, and 4.14. The probabilities in Table 4.6 show that at 95% confidence level during the off-peak period, there were no above average rates of collisions involving injury per hour of exposure on dry surface at any temperature, while on wet surface, the rate of collision involving injury per hour of exposure was higher than average at – 8°C, – 1°C, and +5°C.

Table 4.6: Posterior parameters and probabilities of collisions involving injury on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	5.24	12.01	0.26	12.24	11.01	0.99
-7	7.24	20.01	0.10	9.24	14.01	0.69
-6	14.24	23.01	0.66	13.24	18.01	0.84
-5	5.24	14.01	0.15	12.24	17.01	0.81
-4	9.24	21.01	0.23	10.24	20.01	0.39
-3	11.24	31.01	0.06	20.24	40.01	0.36
-2	6.24	14.01	0.27	24.24	39.01	0.73
-1	17.24	30.01	0.57	35.24	39.01	1.00
0	16.24	29.01	0.53	35.24	57.01	0.77
1	10.24	28.01	0.08	32.24	63.01	0.36
2	12.24	22.01	0.51	18.24	45.01	0.09
3	12.24	27.01	0.24	22.24	45.01	0.31
4	10.24	26.01	0.12	11.24	33.01	0.04
5	6.24	33.01	0.00	30.24	38.01	0.97
6	9.24	24.01	0.12	9.24	24.01	0.12
7	10.24	22.01	0.28	12.24	17.01	0.81
8	18.24	33.01	0.51	6.24	14.01	0.27

Figure 4.8 shows the posterior probabilities for risk of collisions involving injury on wet surface during the off-peak period was larger than on dry surface at all temperatures between at − 8°C and +1°C. There was no clear trend between the two posterior distributions above +1°C. Again, the distributions of the posterior probabilities on wet and dry surfaces during the off-peak period in Figure 4.8 are similar to the

distributions of the collision rates per hour of exposure on wet and dry surfaces during the off-peak period in Figure 3.12.

In the above analysis, rates of collision involving injury per hour of exposure on dry and wet pavement surfaces were compared to their overall combined average and variance to calculate the posterior probabilities. This analysis suggests that, with 95% confidence level, driving on dry surface was not hazardous at any surface temperature and was hazardous at the (−1°C, wet) combination irrespective of the traffic volume. There were also hazardous driving conditions at the (−8°C, wet) and (+5°C, wet) combinations during the off-peak period. The risk of collision was, in general, higher on wet surface than on dry surface at or below the freezing mark irrespective of the traffic volume.

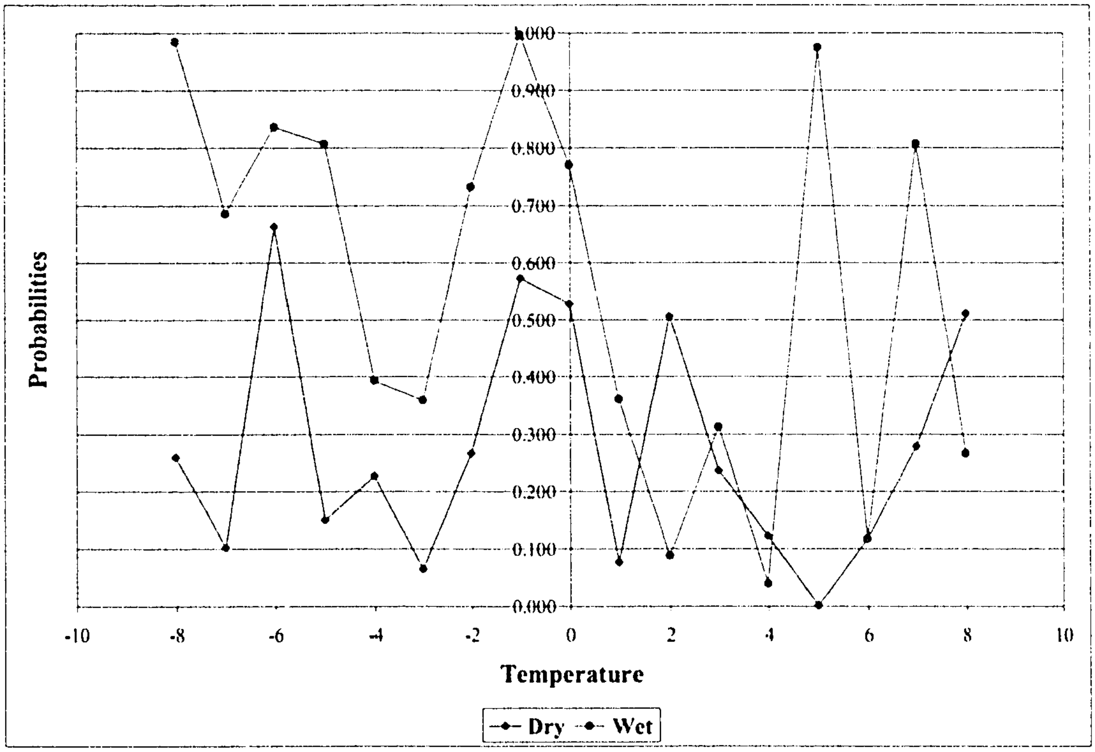


Figure 4.8: Posterior probabilities of collisions involving injury on dry and wet surfaces combined in the City of Ottawa during the off-peak period

To examine the effect of surface temperature on the risk of collisions involving injury on dry and wet surfaces separately during the peak period, the average and variance of the rates of collisions involving injury on dry and wet surfaces during the peak period were calculated separately in the 3rd and 4th columns of Table 3.11. The average and variance of the rates of collisions involving injury on dry surface were 0.56 and 0.05 respectively. Solving Equations 4.3 and 4.4, the estimated prior parameters α and β for collisions involving injury on dry surface were 5.99 and 10.64 respectively. Similarly, the average and variance of the rates of collisions involving injury on wet surface were 0.70 and 0.04 respectively. The estimated values of the parameters α and β of the prior distribution are 11.02 and 15.84. Table 4.7 gives the estimated values of the posterior parameters α_i and β_i and the posterior probabilities on dry and wet surfaces separately during the peak period. At 95% confidence level, the calculated posterior probabilities indicate that there were no rates of collisions involving injury higher than average on dry or wet surface during the peak period. Figure 4.9 shows that during the peak period, there was no specific relationship between the posterior probabilities on wet or dry surface and the surface temperature.

During the off-peak period, the average and variance of the rates of collision involving injury on dry surface were given in the 7th column of Table 3.11 as 0.40 and 0.02 respectively. The estimated values of the parameters α and β of the prior distribution for collisions on dry surface were 8.17 and 20.25.

The average and variance of the rates of collisions involving injury on wet surface were given in the 8th column of Table 3.11 as 0.68 and 0.13 respectively. The estimated values of the parameters α and β of the prior distribution were 3.62 and 5.36. Table 4.8

gives the estimated parameters α_i and β_i and the posterior probabilities on dry and wet surfaces separately during the off-peak period. The posterior probabilities indicate that there was no above average rates of collisions per hour of exposure involving injury on dry surface at any temperature with 95% confidence level relative to all temperatures within the dry pavement condition.

Table 4.7: Posterior parameters and probabilities of collisions involving injury on dry and wet surfaces separately in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	13.99	20.64	0.72	20.02	28.84	0.47
-7	9.99	16.64	0.54	21.02	24.84	0.79
-6	8.99	16.64	0.41	21.02	25.84	0.73
-5	10.99	23.64	0.23	19.02	27.84	0.44
-4	14.99	20.64	0.80	23.02	35.84	0.32
-3	9.99	24.64	0.12	29.02	37.84	0.67
-2	12.99	21.64	0.55	32.02	51.84	0.23
-1	15.99	26.64	0.57	46.02	54.84	0.88
0	8.99	22.64	0.11	32.02	40.84	0.73
1	12.99	25.64	0.32	18.02	47.84	0.00
2	13.99	29.64	0.22	31.02	43.84	0.51
3	8.99	21.64	0.14	25.02	32.84	0.65
4	17.99	24.64	0.84	16.02	25.84	0.29
5	11.99	28.64	0.12	18.02	26.84	0.41
6	17.99	24.64	0.84	17.02	25.84	0.38
7	9.99	19.64	0.33	16.02	25.84	0.29
8	18.99	25.64	0.86	16.02	23.84	0.41

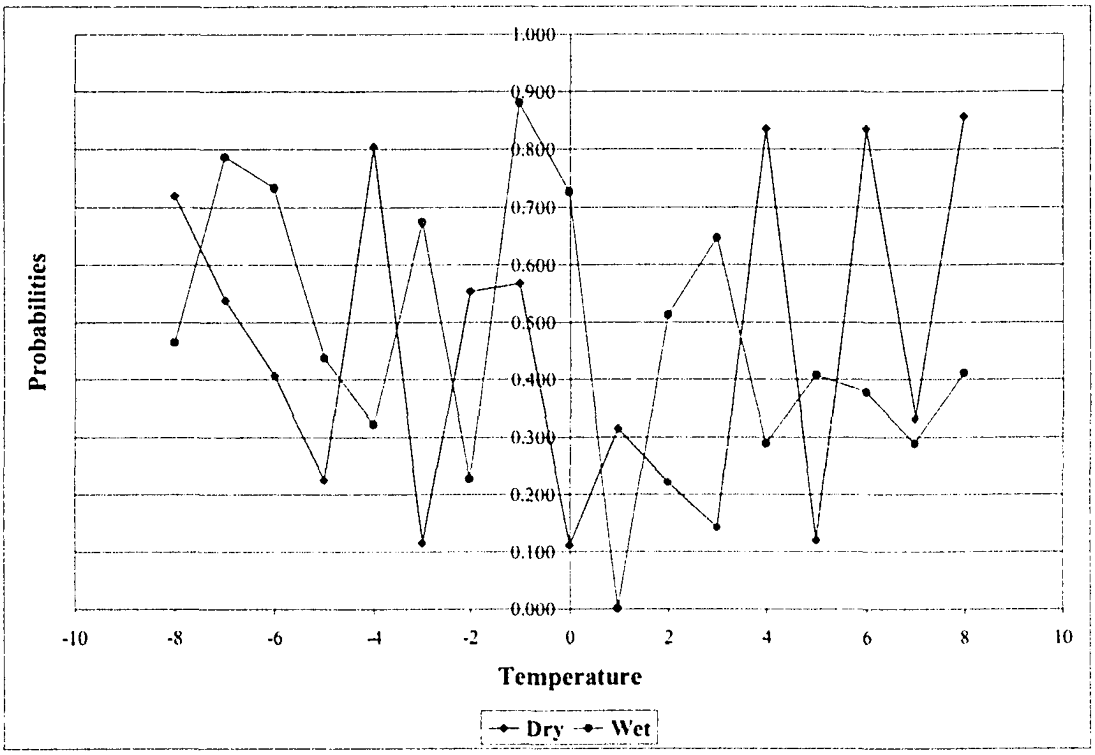


Figure 4.9: Posterior probabilities of collisions involving injury on dry and wet surfaces separately in the City of Ottawa during the peak period

The collision rates were above average, however, on wet surface at –8°C and –1°C relative to all temperatures within the wet surface condition. The posterior probabilities for collisions involving injury on dry and wet surfaces separately during the off-peak period are presented in Figures 4.10. The probabilities show no specific trend between the risk of collisions on wet or dry surface and changes in temperature.

4.3.2.c. Collisions Involving Property Damage Only

From Table 3.13, the average and variance of the rates of collisions involving PDO per hour of exposure on dry and wet surface combined during the peak period were 2.31 and 0.49. Solving Equations 4.3 and 4.4, the estimated values of the prior parameters α and β were 10.90 and 4.72 respectively. The estimated posterior parameters α_i and β_i for collisions involving PDO were obtained by substituting the prior parameters and from Tables 3.6 and 3.12 in Equations 4.10 and 4.11. Table 4.9 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14.

Table 4.8: Posterior parameters and probabilities of collisions involving injury on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	10.166	26.247	0.408	12.622	10.363	0.965
-7	12.166	34.247	0.293	9.622	13.363	0.536
-6	19.166	37.247	0.829	13.622	17.363	0.674
-5	10.166	28.247	0.319	12.622	16.363	0.644
-4	14.166	35.247	0.461	10.622	19.363	0.212
-3	16.166	45.247	0.282	20.622	39.363	0.101
-2	11.166	28.247	0.435	24.622	38.363	0.375
-1	22.166	44.247	0.820	35.622	38.363	0.960
0	21.166	43.247	0.786	35.622	56.363	0.325
1	15.166	42.247	0.293	32.622	62.363	0.057
2	17.166	36.247	0.716	18.622	44.363	0.011
3	17.166	41.247	0.521	22.622	44.363	0.071
4	15.166	40.247	0.363	11.622	32.363	0.006
5	11.166	47.247	0.020	30.622	37.363	0.836
6	14.166	38.247	0.341	9.622	23.363	0.038
7	15.166	36.247	0.524	12.622	16.363	0.644
8	23.166	47.247	0.801	6.622	13.363	0.167

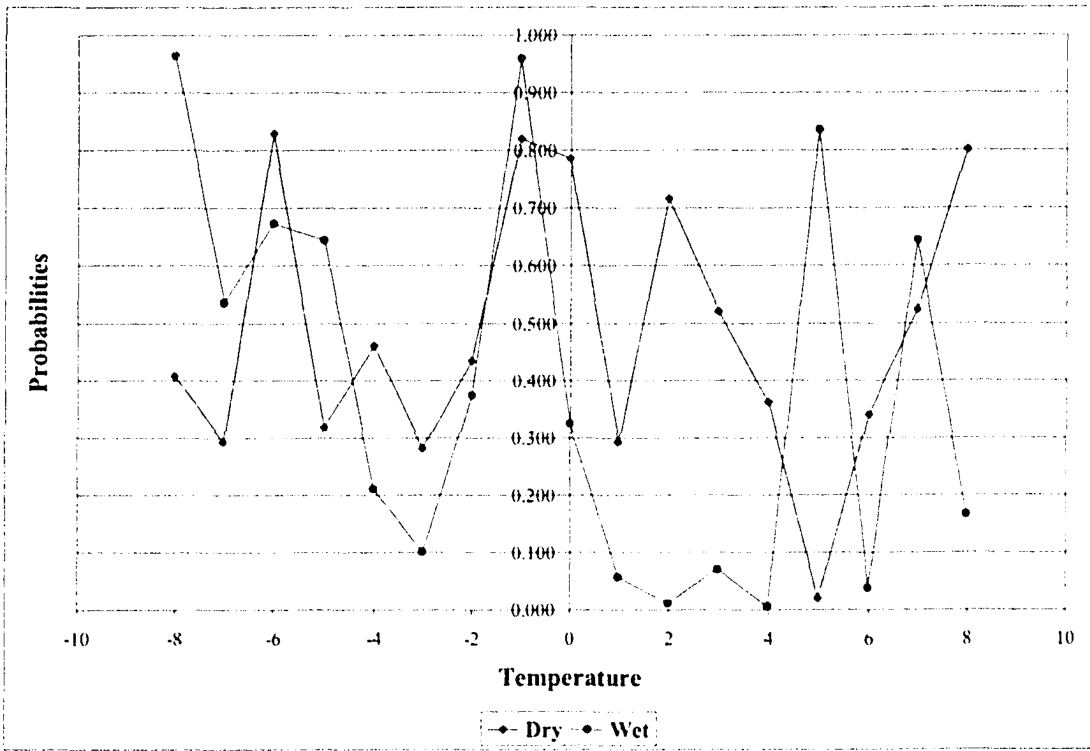


Figure 4.10: Posterior probabilities of collisions involving injury on dry and wet surfaces separately in the City of Ottawa during the off-peak period

These probabilities show that at 95% confidence level during the peak period, there were no above average rates of collisions involving PDO on dry surface at any temperature, while on wet pavement surface, the rate of collision was higher than average at –7°C, –5°C, –2°C and –1°C. Figure 4.11 shows no specific trend between the posterior probabilities for risk of collisions involving PDO on dry and wet surfaces during the peak period except that the risk of collision involving PDO was higher on wet surface than on dry surface between –3°C and +2°C.

The distributions of the posterior probabilities of collisions involving PDO on wet and dry surface during the peak period in Figure 4.11 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the peak and off-peak periods in Figure 3.16. Similarly, Table 3.13 gives the average and variance of the rates of collision involving PDO per hour of exposure on dry and wet surface combined during the off-peak period as 1.71 and 0.83 respectively. Solving Equations 4.3 and 4.4, the estimated values of the prior parameters α and β were 3.51 and 2.05. The estimated posterior parameters α_i and β_i for collisions involving PDO were obtained by substituting the estimated prior parameters and corresponding values from Tables 3.6 and 3.12 in Equations 4.10 and 4.11.

Table 4.9: Posterior parameters and probabilities of collisions involving PDO on dry and wet surfaces combined in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	31.90	14.72	0.34	49.90	17.72	0.91
-7	31.90	10.72	0.91	41.90	13.72	0.95
-6	25.90	10.72	0.57	34.90	14.72	0.54
-5	31.90	17.72	0.06	49.90	16.72	0.95
-4	41.90	14.72	0.90	47.90	24.72	0.10
-3	40.90	18.72	0.34	65.90	26.72	0.69
-2	25.90	15.72	0.03	117.90	40.72	0.99
-1	32.90	20.72	0.01	177.90	43.72	1.00
0	31.90	16.72	0.12	59.90	29.72	0.13
1	29.90	19.72	0.01	69.90	36.72	0.04
2	35.90	23.72	0.00	78.90	32.72	0.64
3	35.90	15.72	0.45	42.90	21.72	0.14
4	32.90	18.72	0.045	33.90	14.72	0.47
5	47.90	22.72	0.25	43.90	15.72	0.88
6	37.90	18.72	0.19	30.90	14.72	0.27
7	35.90	13.72	0.75	33.90	14.72	0.47
8	45.90	19.72	0.50	27.90	12.72	0.37

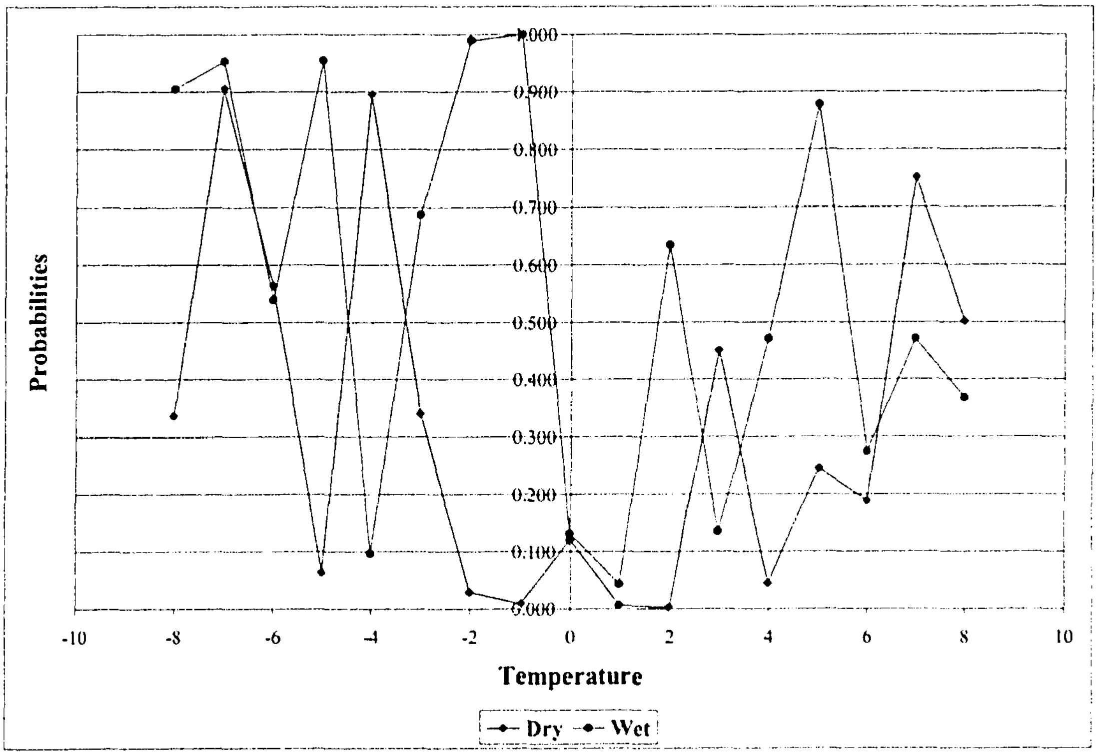


Figure 4.11: Posterior probabilities of collisions involving PDO on dry and wet surfaces combined in the City of Ottawa during the peak period

Table 4.10 presents the posterior parameters and probabilities of hazardous road driving calculated from the Bayes posterior gamma distribution in Equation 4.14. The probabilities show that at 95% confidence level during the peak period, there were no above average rates of collisions involving PDO on dry surface at any temperature, while on wet surface, the rate of collision was higher than average at – 8°C, – 5°C, – 2°C, –1°C and 0°C.

Figure 4.12 shows that the posterior probabilities for risk of collisions involving PDO on wet surface during the off-peak period were larger than on dry surface at all temperatures between – 8°C and +8°C except at +3°C.

The distributions of the posterior probabilities of collisions involving PDO on wet and dry surfaces during the off-peak periods in Figure 4.12 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the off-peak period in Figure 3.17.

In the above analysis, rates of collision involving PDO per hour of exposure on dry and wet pavement surfaces were compared to their overall combined average and variance to calculate the posterior probabilities.

Table 4.10: Posterior parameters and probabilities of collisions involving PDO on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	11.51	8.05	0.23	30.51	7.05	1.00
-7	19.51	16.05	0.05	20.51	10.05	0.76
-6	13.51	19.05	0.00	27.51	14.05	0.73
-5	15.51	10.05	0.31	39.51	13.05	1.00
-4	21.51	17.05	0.06	34.51	16.05	0.89
-3	33.51	27.05	0.02	75.51	36.05	0.95
-2	11.51	10.05	0.06	83.51	35.05	1.00
-1	29.51	26.05	0.01	114.51	35.05	1.00
0	32.51	25.05	0.04	120.51	53.05	1.00
1	23.51	24.05	0.00	96.51	59.05	0.31
2	24.51	18.05	0.10	64.51	41.05	0.23
3	37.51	23.05	0.36	66.51	41.05	0.31
4	30.51	22.05	0.10	44.51	29.05	0.21
5	29.51	29.05	0.00	49.51	34.05	0.11
6	19.51	20.05	0.00	35.51	20.05	0.56
7	19.51	18.05	0.01	19.51	13.05	0.25
8	34.51	29.05	0.01	23.51	10.05	0.91

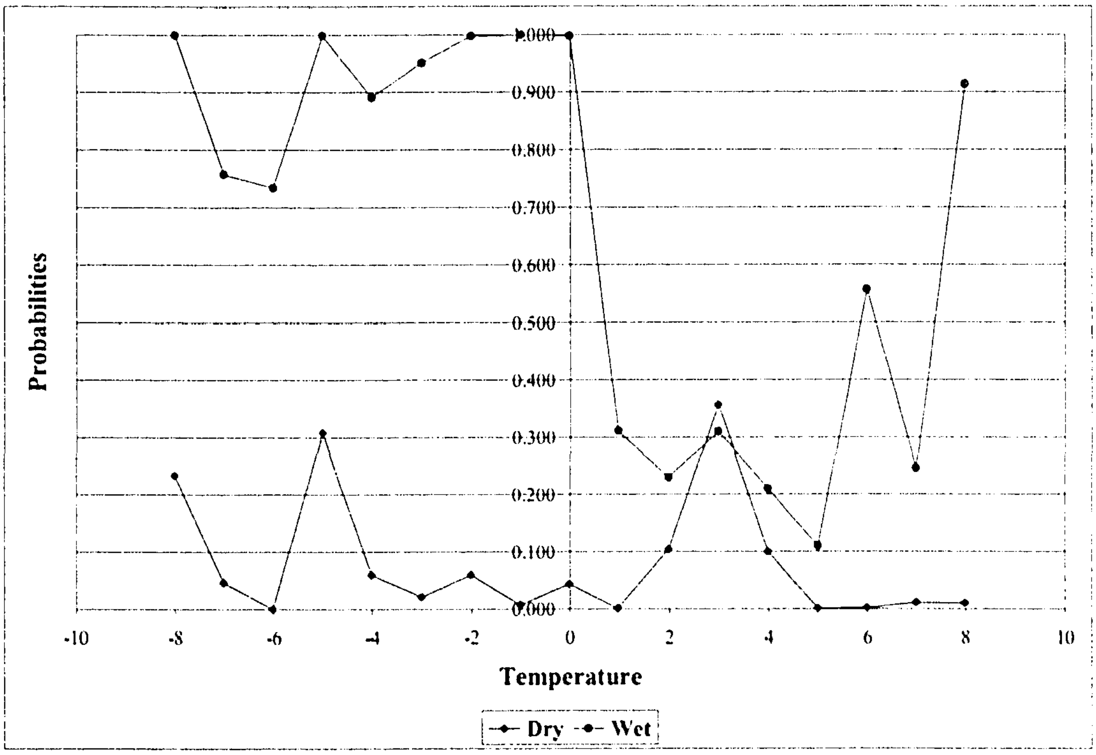


Figure 4.12: Posterior probabilities of collisions involving PDO on dry and wet surfaces combined in the City of Ottawa during the off-peak period

This analysis suggests that, with 95% confidence level, driving on dry surface was not hazardous at any surface temperature and was hazardous at the (–5°C, wet), (-2°C, wet), and (–1°C, wet) combinations irrespective of the traffic volume. There were also hazardous driving conditions during the peak period at the (–7°C, wet), and during the off-peak period at (–8°C, wet) and (0°C, wet) combinations. The risk of collision was, in general, higher on wet surface than on dry surface between –3°C and +2°C irrespective of the traffic volume.

The average and variance of the rates of collisions involving PDO on dry surface separately, during the peak period were given in the 3rd column of Table 3.13 as 2.06 and 0.42. Solving Equations 4.3 and 4.4, the estimated prior parameters α and β for collisions involving PDO on dry surface were 10.14 and 4.93. Similarly, the average and variance of the rates of collisions involving PDO on wet surface only were given in the 4th column of Table 3.13 as 2.56 and 0.46. The estimated values of the parameters α and β of the prior distribution were 14.37 and 5.61. Table 4.11 gives the estimated values of the posterior parameters α_i and β_i, and the posterior probabilities on dry and wet surfaces separately during the peak period, which were calculated by substituting the prior parameters and values in Tables 3.6 and 3.12 in Equations 4.10, 4.11 and 4.14. The posterior probabilities of collisions involving PDO indicate that at 95% confidence level, road driving on dry surface was hazardous when compared to all other temperatures with dry pavement condition only at – 7°C and – 4°C. On wet pavement surface, the road driving was hazardous when compared to the other temperatures with wet pavement condition only at – 1°C. Figure 4.13 shows no specific trend between the posterior probabilities on dry or wet surface and the surface temperature during the peak period.

During the off-peak period, the average and variance of the rates of collisions involving PDO on dry surface were given in the 7th column of Table 3.13 as 1.15 and 0.06. The estimated values of the parameters α and β of the prior distribution for collisions on dry surface were 21.35 and 18.61. Similarly, the average and variance of the rates of collisions involving PDO on wet surface were given in the 8th column of Table 3.13 as 2.28 and 0.98 respectively.

The estimated values of the parameters α and β of the prior distribution were 5.29 and 2.32. Table 4.12 gives the estimated parameters α_i and β_i and the posterior probabilities of collisions involving PDO on dry and wet surfaces separately during the off-peak period. The posterior probabilities indicate that there was no above average rates of collisions involving PDO on dry surface at any temperature with 95% confidence level relative to all temperatures within the dry pavement condition. The collision rates were above average, however, on wet surface at –8°C, –5°C, and –1°C relative to all temperatures within the wet surface condition. The posterior probabilities for collisions involving PDO on dry and wet surfaces separately during the off-peak period were presented in Figures 4.14. The figure shows that the posterior probabilities on dry surface are higher than on wet between 0°C and +7°C.

Table 4.11: Posterior parameters and probabilities of collisions involving PDO on dry and wet surfaces separately in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	31.14	14.93	0.51	53.37	18.61	0.78
-7	31.14	10.93	0.95	45.37	14.61	0.89
-6	25.14	10.93	0.69	38.37	15.61	0.38
-5	31.14	17.93	0.15	53.37	17.61	0.88
-4	41.14	14.93	0.96	51.37	25.61	0.03
-3	40.14	18.93	0.56	69.37	27.61	0.42
-2	25.14	15.93	0.07	121.37	41.61	0.92
-1	32.14	20.93	0.04	181.37	44.61	1.00
0	31.14	16.93	0.24	63.37	30.61	0.04
1	29.14	19.93	0.02	73.37	37.61	0.01
2	35.14	23.93	0.02	82.37	33.61	0.33
3	35.14	15.93	0.64	46.37	22.61	0.05
4	32.14	18.93	0.12	37.37	15.61	0.32
5	47.14	22.93	0.48	47.37	16.61	0.75
6	37.14	18.93	0.37	34.37	15.61	0.17
7	35.14	13.93	0.87	37.37	15.61	0.32
8	45.14	19.93	0.72	31.37	13.61	0.26

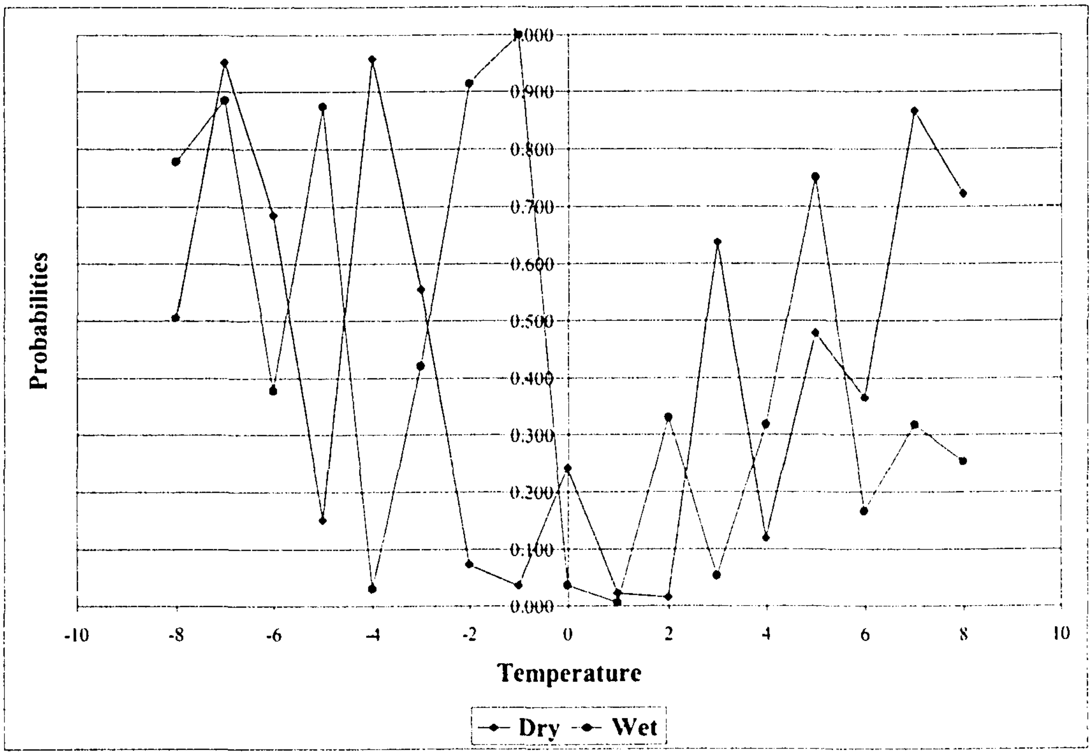


Figure 4.13: Posterior probabilities of collisions involving PDO on dry and wet pavement separately in the City of Ottawa during the peak period

4.3.3. Initial Type of Impact

Another micro level classification of interest in this research is the effect of pavement surface temperature and pavement moisture condition on the initial type of collision impact. The following three sections discuss these effects on three types of initial impact; single-vehicle collision, rear-end collisions, and all other types of collisions.

4.3.3.a. Single-Vehicle Collisions

From Table 3.15, the average and variance of the rates of single-vehicle collisions per hour of exposure on dry and wet surfaces combined during the peak period were 0.60 and 0.11. The estimated values of the prior parameters α and β were 3.22 and 5.33

respectively. The estimated posterior parameters α_i and β_i for single-vehicle collisions were obtained by substituting the prior parameters and from Tables 3.6 and 3.14 in Equations 4.10 and 4.11. Table 4.13 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14. These probabilities show that at 95% confidence level during the peak period, there were no above average rates of single-vehicle collisions on dry surface at any temperature, while on wet pavement surface, the rate of collision was higher than average at –3°C and –1°C.

Table 4.12: Posterior parameters and probabilities of collisions involving PDO on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	29.35	24.61	0.56	32.29	7.32	1.00
-7	37.35	32.61	0.47	22.29	10.32	0.37
-6	31.35	35.61	0.05	29.29	14.32	0.26
-5	33.35	26.61	0.67	41.29	13.32	0.97
-4	39.35	33.61	0.53	36.29	16.32	0.42
-3	51.35	43.61	0.56	77.29	36.32	0.26
-2	29.35	26.61	0.39	85.29	35.32	0.69
-1	47.35	42.61	0.39	116.29	35.32	1.00
0	50.35	41.61	0.63	122.29	53.32	0.52
1	41.35	40.61	0.20	98.29	59.32	0.00
2	42.35	34.61	0.64	66.29	41.32	0.00
3	55.35	39.61	0.92	68.29	41.32	0.00
4	48.35	38.61	0.71	46.29	29.32	0.00
5	47.35	45.61	0.23	51.29	34.32	0.00
6	37.35	36.61	0.22	37.29	20.32	0.08
7	37.35	34.61	0.33	21.29	13.32	0.04
8	52.35	45.61	0.48	25.29	10.32	0.62

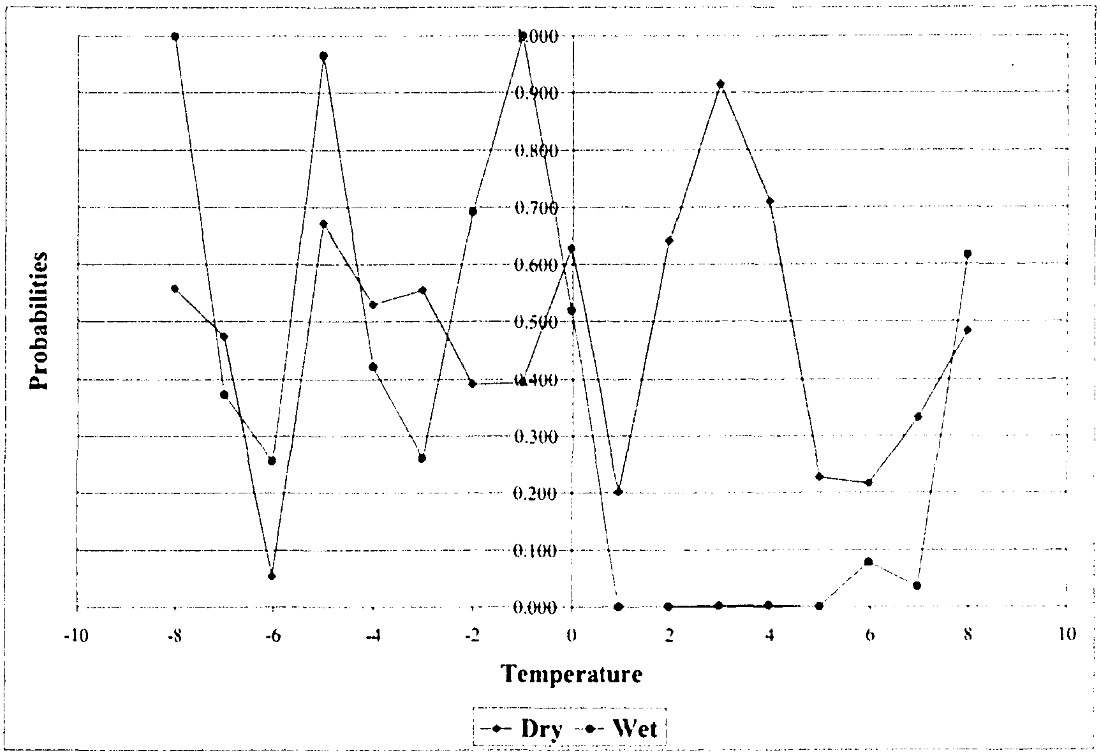


Figure 4.14: Posterior probabilities of collisions involving PDO on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Figure 4.15 shows that the posterior probabilities for risk of single-vehicle collisions during the peak period on wet surface was higher than on dry surface at all temperatures between –8°C and 0°C.

The distributions of the posterior probabilities of single-vehicle collisions on wet and dry surfaces during the peak periods in Figure 4.15 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the peak period in Figure 3.21. Similarly, Table 3.15 gives the average and variance of the rates of single-vehicle collisions per hour of exposure on dry and wet surface combined during the off-peak period as 0.55 and 0.10 respectively. Solving Equations 4.3 and 4.4, the estimated values of the prior parameters α and β were 2.93 and 5.37.

The estimated posterior parameters α_i and β_i for single-vehicle collisions were obtained by substituting the estimated prior parameters and corresponding values from Tables 3.6 and 3.14 in Equations 4.10 and 4.11. Table 4.14 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14 during the off-peak period.

Table 4.13: Posterior parameters and probabilities of single-vehicle collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	9.22	15.33	0.45	14.22	18.33	0.79
-7	5.22	11.33	0.21	9.22	14.33	0.53
-6	5.22	11.33	0.21	12.22	15.33	0.80
-5	6.22	18.33	0.04	13.22	17.33	0.77
-4	11.22	15.33	0.70	19.22	25.33	0.81
-3	7.22	19.33	0.06	30.22	27.33	1.00
-2	6.22	16.33	0.09	28.22	41.33	0.72
-1	4.22	21.33	0.00	75.22	44.33	1.00
0	7.22	17.33	0.12	21.22	30.33	0.72
1	8.22	20.33	0.09	16.22	37.33	0.07
2	10.22	24.33	0.09	21.22	33.33	0.57
3	10.22	16.33	0.50	10.22	22.33	0.15
4	11.22	19.33	0.41	9.22	15.33	0.45
5	12.22	23.33	0.27	13.22	16.33	0.82
6	8.22	19.33	0.12	11.22	15.33	0.70
7	6.22	14.33	0.16	6.22	15.33	0.12
8	15.22	20.33	0.77	9.22	13.33	0.62

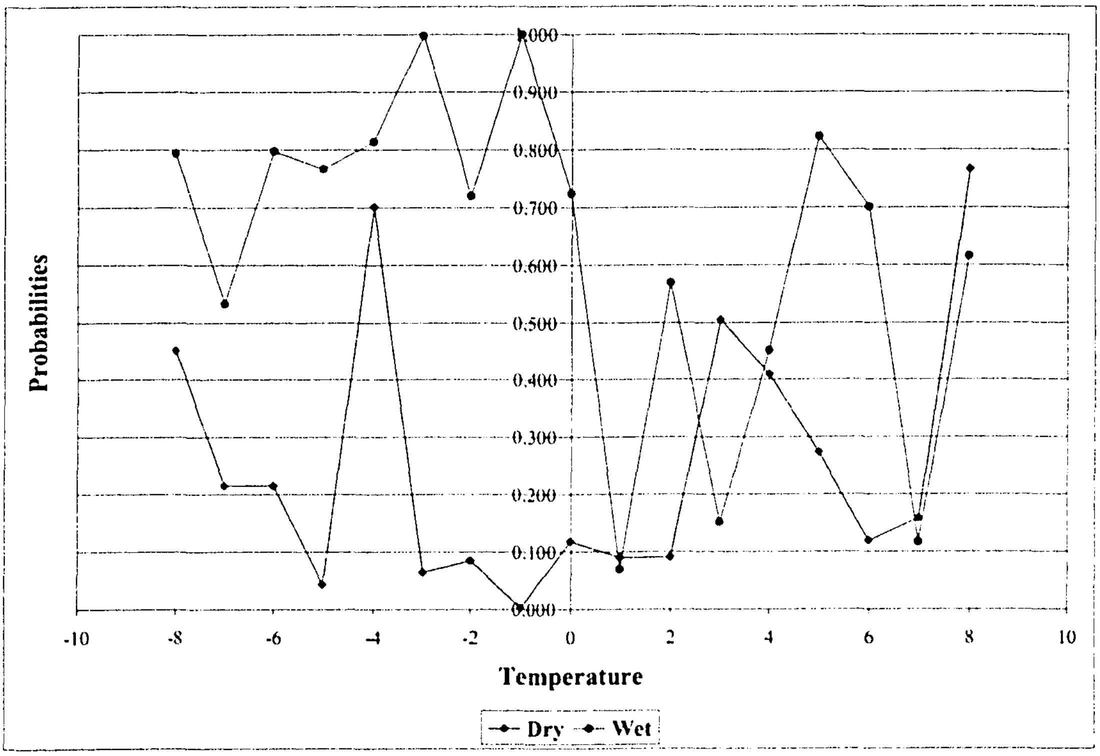


Figure 4.15: Posterior probabilities of single-vehicle collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

The probabilities show that during the off-peak period at 95% confidence level there were no above average rates of single-vehicle collisions on dry surface at any temperature, while on wet surface, the rate of single-vehicle collision was higher than average at – 2°C, –1°C, and 0°C.

Figure 4.16 shows that the posterior probabilities for risk of single-vehicle collisions on wet surface during the off-peak period were larger than on dry surface at all temperatures between – 8°C and +1°C. The results of this analysis suggest that wet pavement condition increases the risk of single-vehicle collisions during the peak and off-peak periods at sub-zero temperatures and that there were above average single-vehicle collision rates on wet surface at –3°C and –1°C during the peak period and at –2°C, –1°C, and 0°C during the off-peak period. The distributions of the posterior probabilities of single-vehicle collisions on wet and dry surfaces during the off-peak periods in Figure 4.16 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the off-peak period in Figure 3.22.

Table 4.14: Posterior parameters and probabilities of single-vehicle collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	5.93	11.37	0.40	8.93	10.37	0.88
-7	8.93	19.37	0.26	9.93	13.37	0.79
-6	8.93	22.37	0.14	11.93	17.37	0.75
-5	5.93	13.37	0.26	13.93	16.37	0.93
-4	6.93	20.37	0.07	14.93	19.37	0.88
-3	6.93	30.37	0.00	31.93	39.37	0.98
-2	4.93	13.37	0.14	35.93	38.37	1.00
-1	11.93	29.37	0.12	54.93	38.37	1.00
0	12.93	28.37	0.22	49.93	56.37	1.00
1	4.93	27.37	0.00	37.93	62.37	0.73
2	8.93	21.37	0.17	18.93	44.37	0.12
3	12.93	26.37	0.31	14.93	44.37	0.02
4	12.93	25.37	0.37	15.93	32.37	0.31
5	15.93	32.37	0.31	13.93	37.37	0.05
6	8.93	23.37	0.11	9.93	23.37	0.18
7	9.93	21.37	0.27	6.93	16.37	0.21
8	13.93	32.37	0.16	5.93	13.37	0.26

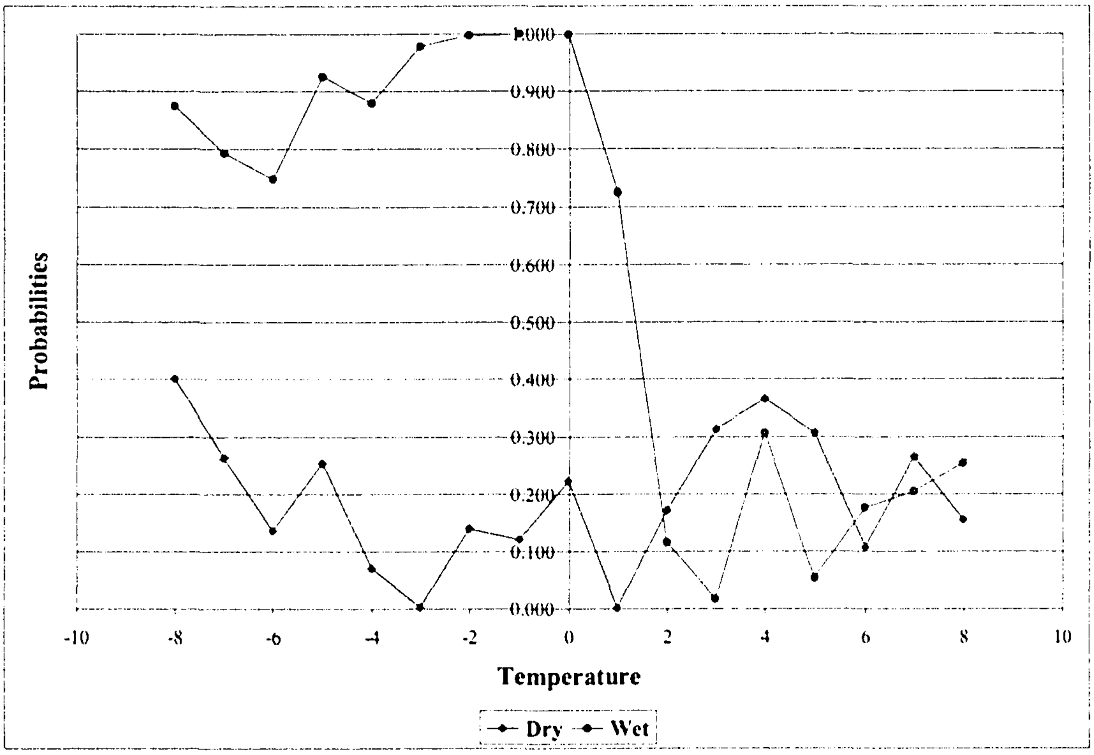


Figure 4.16: Posterior probabilities of single-vehicle collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

In the above analysis, rates of single-vehicle collisions per hour of exposure on dry and wet pavement surfaces were compared to their overall combined average and variance to calculate the posterior probabilities. This analysis suggests that, with 95% confidence level, driving on dry surface was not hazardous at any surface temperature and was hazardous at the (–1°C, wet) combination irrespective of the traffic volume. There were also hazardous driving conditions during the peak period at (–3°C, wet), and during the off-peak period at (–3°C, wet) and (0°C, wet). The risk of collision was, in general, higher on wet surface than on dry surface between –3°C and +2°C irrespective of the traffic volume.

To study the effect of surface temperature only on the risk of collisions during the peak period, the average and variance of the rates of single-vehicle collision on dry surface during the peak period were given in the 3rd column of Table 3.15 as 0.42 and 0.04 respectively. Solving Equations 4.3 and 4.4, the estimated prior parameters α and β for single-vehicle collisions on dry surface are 4.39 and 10.44 respectively. Similarly, the average and variance of the rates of single-vehicle collisions on wet surface were given in the 4th column of Table 3.15 as 0.79 and 0.12 respectively. The estimated values of the parameters α and β of the prior distribution were 5.05 and 6.42. Table 4.15 gives the estimated values of the posterior parameters α_i and β_i, and probabilities of single-vehicle collisions on dry and wet surfaces separately during the peak period. The posterior probabilities indicate that at 95% confidence level, road driving on dry surface was not hazardous at any temperature when compared to all other temperatures with dry surface condition. On wet pavement surface, the road driving was hazardous when compared to all other temperatures with wet surface condition at – 3°C and – 1°C. Figure 4.17 shows that the posterior probabilities on wet surface were higher than on dry surface between – 3°C and 0°C, and that the posterior probabilities on dry surface were higher on wet surface than on dry surface between +1°C and +5°C.

During the off-peak period, the average and variance of the rates of single-vehicle collisions on dry surface were given in the 7th column of Table 3.15 as 0.37 and 0.01 respectively. The estimated values of the parameters α and β of the prior distribution for collisions on dry surface are 9.83 and 26.75. Similarly, the average and variance of the rates of single-vehicle collisions during the off-peak period on wet surface were given in the 8th column of Table 3.15 as 0.72 and 0.13 respectively. The estimated values of the parameters α and β of the prior distribution were 4.09 and 5.65. Table 4.16 gives the estimated parameters α_i and β_i and the posterior probabilities on dry and wet surfaces during the off-peak period. The posterior probabilities indicate that with 95% confidence level, there was no above average rate of single-vehicle collisions on the dry surface at any temperature relative to all temperatures within the dry surface condition. The collision rates were above average, however, on wet surface at only −1 °C when compared to all temperatures within the wet surface condition.

Table 4.15: Posterior parameters and probabilities of single-vehicle collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	10.39	20.44	0.69	16.05	19.42	0.55
-7	6.39	16.44	0.37	11.05	15.42	0.34
-6	6.39	16.44	0.37	14.05	16.42	0.59
-5	7.39	23.44	0.17	15.05	18.42	0.52
-4	12.39	20.44	0.87	21.05	26.42	0.50
-3	8.39	24.44	0.23	32.05	28.42	0.97
-2	7.39	21.44	0.25	30.05	42.42	0.26
-1	5.39	26.44	0.02	77.05	45.42	1.00
0	8.39	22.44	0.32	23.05	31.42	0.34
1	9.39	25.44	0.30	18.05	38.42	0.01
2	11.39	29.44	0.35	23.05	34.42	0.19
3	11.39	21.44	0.74	12.05	23.42	0.05
4	12.39	24.44	0.70	11.05	16.42	0.26
5	13.39	28.44	0.62	15.05	17.42	0.61
6	9.39	24.44	0.35	13.05	16.42	0.48
7	7.39	19.44	0.34	8.05	16.42	0.06
8	16.39	25.44	0.94	11.05	14.42	0.43

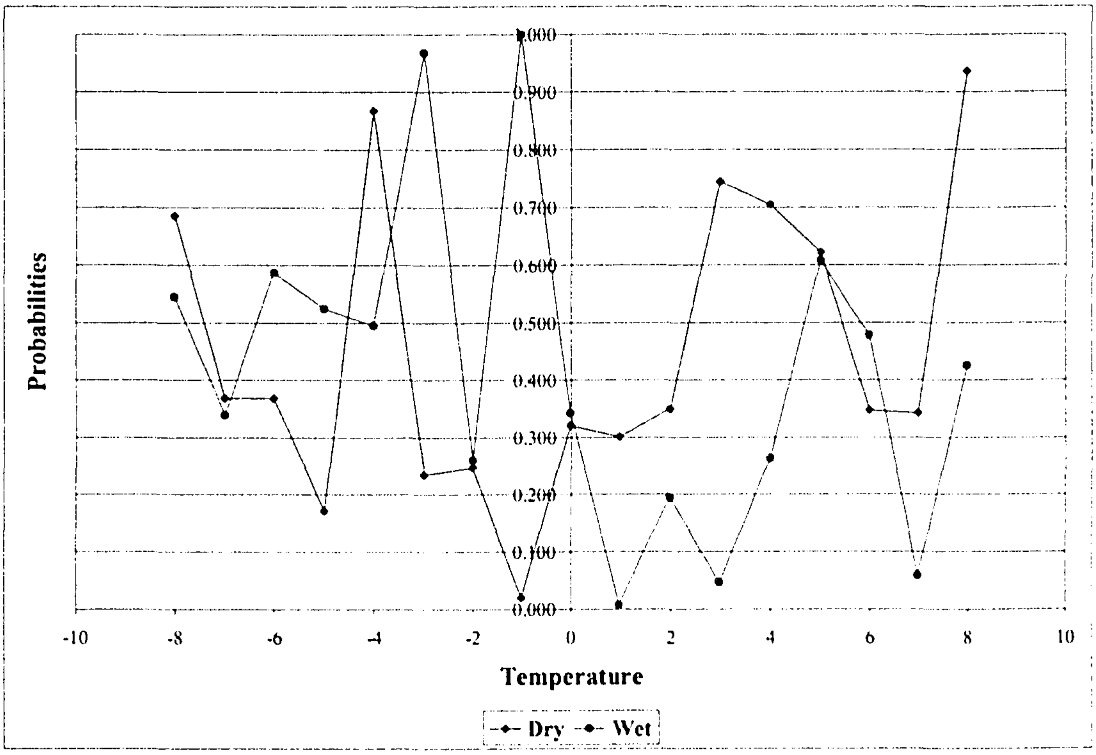


Figure 4.17: Posterior probabilities of single-vehicle collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

The posterior probabilities for single-vehicle collisions on dry and wet surfaces separately during the off-peak period were presented in Figures 4.18. Figure 4.18 shows that the posterior probabilities on wet surface were higher than on dry surface between –8°C and +1°C, and that the posterior probabilities on dry surface were higher on wet surface than on dry surface between +2°C and +8°C.

4.3.3.b. Rear-end Vehicle Collisions

The average and variance of the rates of rear-end vehicle collisions per hour of exposure on dry and wet surfaces combined during the peak period were given in Table 3.17 as 1.01 and 0.12. The estimated values of the prior parameters α and β are 8.54 and 8.44 respectively. The estimated posterior parameters α_i and β_i for rear-end collisions are obtained by substituting the prior parameters and from Tables 3.6 and 3.16 in Equations 4.10 and 4.11. Table 4.17 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14. These probabilities show that at 95% confidence level during the peak period, there were no above average rates of rear-end collisions on dry surface at any temperature, while on wet pavement surface, the rate of collision was higher than the average only at –7°C.

Table 4.16: Posterior parameters and probabilities of single-vehicle collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	12.83	32.75	0.55	10.09	10.65	0.76
-7	15.83	40.75	0.56	11.09	13.65	0.61
-6	15.83	43.75	0.44	13.09	17.65	0.50
-5	12.83	34.75	0.47	15.09	16.65	0.77
-4	13.83	41.75	0.32	16.09	19.65	0.65
-3	13.83	51.75	0.09	33.09	39.65	0.77
-2	11.83	34.75	0.36	37.09	38.65	0.94
-1	18.83	50.75	0.49	56.09	38.65	1.00
0	19.83	49.75	0.61	51.09	56.65	0.93
1	11.83	48.75	0.05	39.09	62.65	0.16
2	15.83	42.75	0.48	20.09	44.65	0.01
3	19.83	47.75	0.68	16.09	44.65	0.00
4	19.83	46.75	0.71	17.09	32.65	0.07
5	22.83	53.75	0.73	15.09	37.65	0.00
6	15.83	44.75	0.41	11.09	23.65	0.05
7	16.83	42.75	0.58	8.09	16.65	0.09
8	20.83	53.75	0.57	7.09	13.65	0.14

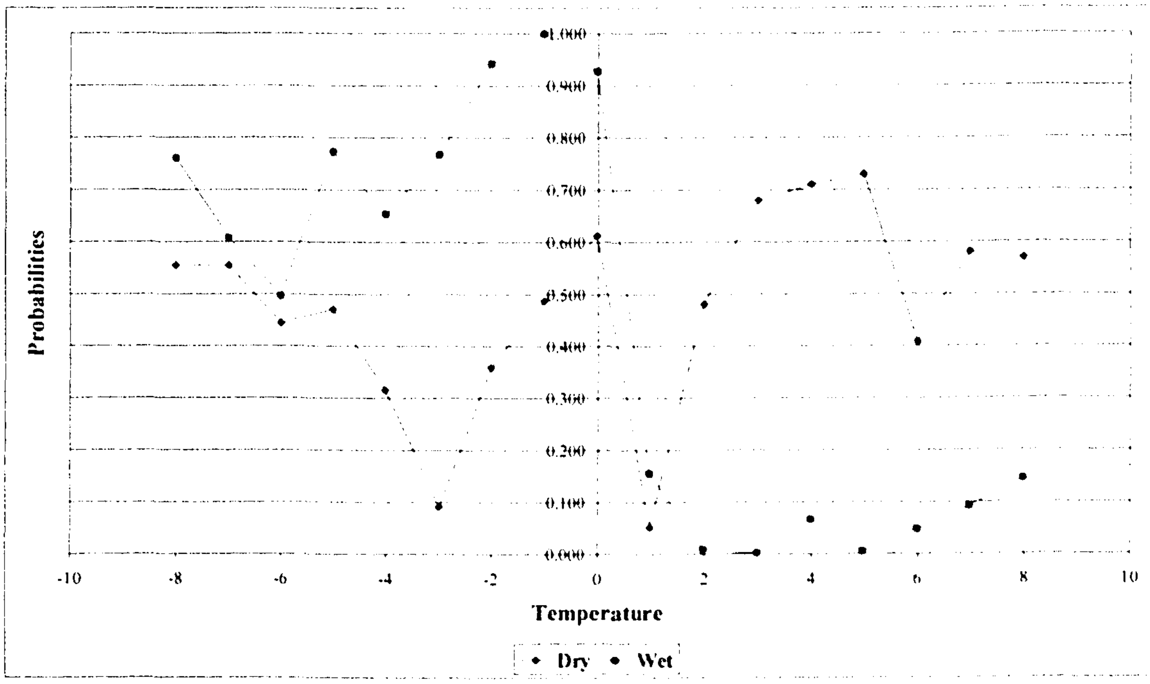


Figure 4.18: Posterior probabilities of single-vehicle collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Figure 4.19 shows that posterior probabilities on wet surface were higher than on dry surface between –2°C and +5°C. The distributions of the posterior probabilities of rear-end collisions on wet and dry surfaces during the peak period in Figure 4.19 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the off-peak period in Figure 3.26.

Similarly, Table 3.18 gives the average and variance of the rates of rear-end collisions per hour of exposure on dry and wet surfaces combined during the off-peak period as 0.62 and 0.15 respectively. Solving Equations 4.3 and 4.4, the estimated values of the prior parameters α and β were 2.58 and 4.15. The estimated posterior parameters α_i and β_i for rear-end collisions were obtained by substituting the estimated prior parameters and corresponding values from Tables 3.6 and 3.16 in Equations 4.10 and

4.11. Table 4.18 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14. The probabilities show that at 95% confidence level during the off-peak period, there were no above average rates of rear-end collisions on dry surface at any temperature, while on wet surface, the rate of collision was higher than the average only at – 8°C.

Table 4.17: Posterior parameters and probabilities of rear-end collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	19.54	18.44	0.55	25.54	21.44	0.77
-7	18.54	14.44	0.82	25.54	17.44	0.95
-6	17.54	14.44	0.75	18.54	18.44	0.46
-5	20.54	21.44	0.37	18.54	20.44	0.29
-4	22.54	18.44	0.79	20.54	28.44	0.05
-3	21.54	22.44	0.37	28.54	30.44	0.32
-2	13.54	19.44	0.06	43.54	44.44	0.40
-1	22.54	24.44	0.30	59.54	47.44	0.94
0	17.54	20.44	0.21	32.54	33.44	0.39
1	14.54	23.44	0.02	33.54	40.44	0.11
2	19.54	27.44	0.04	41.54	36.44	0.76
3	16.54	19.44	0.21	28.54	25.44	0.68
4	18.54	22.44	0.16	17.54	18.44	0.37
5	26.54	26.44	0.46	23.54	19.44	0.78
6	26.54	22.44	0.76	16.54	18.44	0.28
7	21.54	17.44	0.79	19.54	18.44	0.55
8	24.54	23.44	0.54	12.54	16.44	0.13

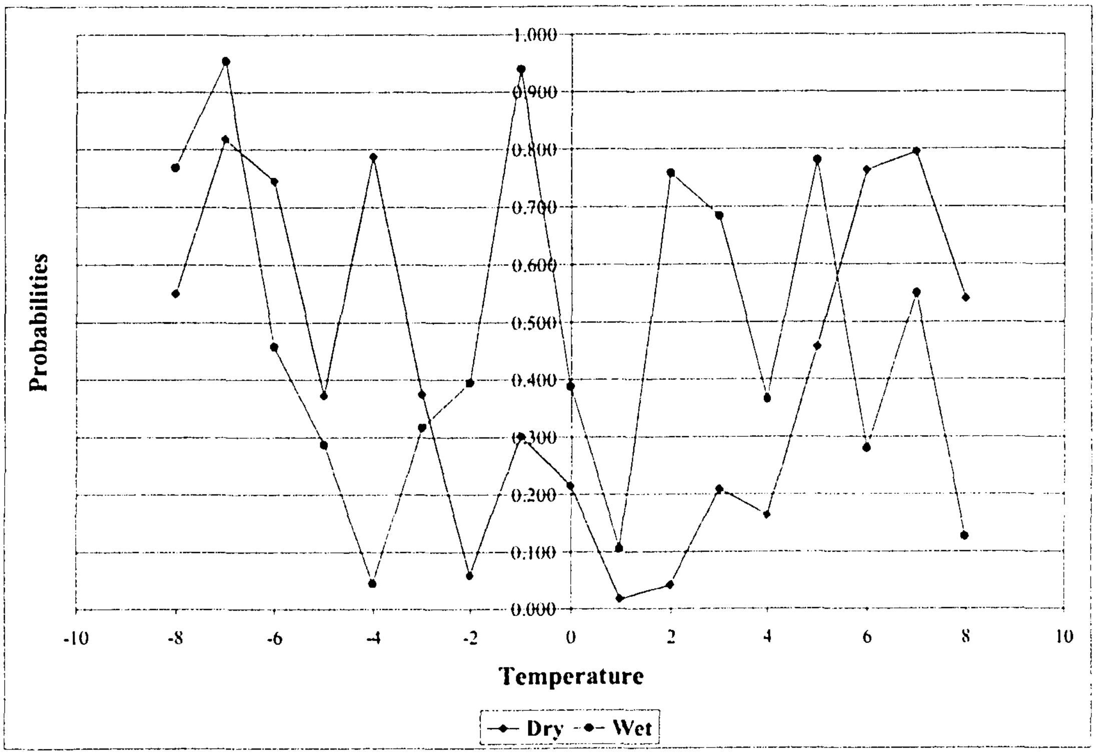


Figure 4.19: Posterior probabilities of rear-end collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

Figure 4.20 shows the posterior probabilities for risk of rear-end collisions on wet surface during the off-peak period was higher than on dry surface at all temperatures between – 8°C and 0°C except at – 4°C. There was no clear trend above 0°C. The distributions of the posterior probabilities of rear-end collisions on wet and dry surfaces during the off-peak period in Figure 4.20 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the off-peak period in Figure 3.27.

In the above analysis, rates of rear-end collisions per hour of exposure on dry and wet pavement surfaces were compared to their overall combined average and variance to calculate the posterior probabilities.

Table 4.18: Posterior parameters and probabilities of rear-end collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	8.58	10.15	0.77	14.58	9.15	1.00
-7	7.58	18.15	0.10	7.58	12.15	0.45
-6	8.58	21.15	0.07	11.58	16.15	0.64
-5	5.58	12.15	0.19	14.58	15.15	0.93
-4	13.58	19.15	0.65	7.58	18.15	0.10
-3	12.58	29.15	0.07	29.58	38.15	0.86
-2	4.58	12.15	0.09	30.58	37.15	0.92
-1	14.58	28.15	0.21	30.58	37.15	0.92
0	13.58	27.15	0.18	42.58	55.15	0.90
1	11.58	26.15	0.09	27.58	61.15	0.03
2	10.58	20.15	0.25	21.58	43.15	0.13
3	16.58	25.15	0.56	25.58	43.15	0.38
4	11.58	24.15	0.15	11.58	31.15	0.02
5	7.58	31.15	0.00	25.58	36.15	0.71
6	6.58	22.15	0.01	13.58	22.15	0.44
7	9.58	20.15	0.16	11.58	15.15	0.72
8	15.58	31.15	0.16	9.58	12.15	0.72

This analysis suggests that, with 95% confidence level, driving on dry surface was not hazardous at any surface temperature. There were hazardous driving conditions during the peak period at (–7°C, wet), and during the off-peak period at (–8°C, wet). The risk of collision was, in general, higher on wet surface than on dry surface between –2°C and 0°C irrespective of the traffic volume.

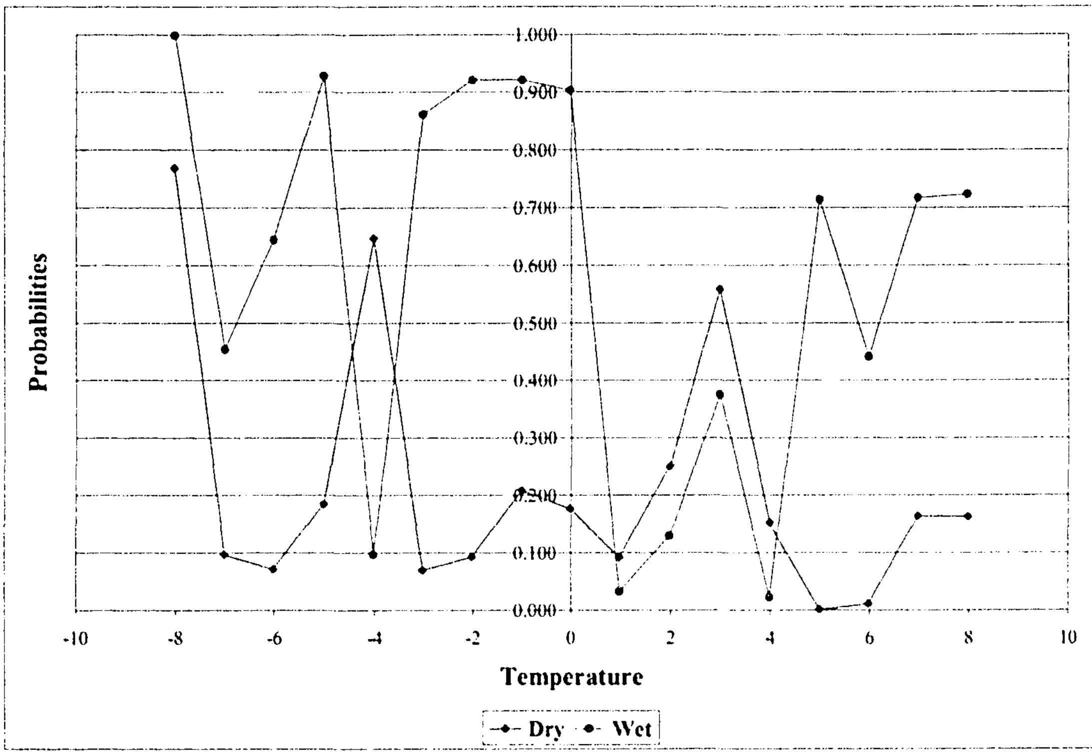


Figure 4.20: Posterior probabilities of rear-end collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

To study the effect of surface temperature during the peak period on the risk of collisions on dry and wet surfaces separately, the average and variance of the rates of rear-end collisions on dry surface during the peak period were given in the 3rd column of Table 3.17 as 0.98 and 0.14 respectively. Solving Equations 4.3 and 4.4, the estimated prior parameters α and β for rear-end collisions on dry surface were 7.03 and 7.11 respectively. Similarly, the average and variance of the rates of rear-end collisions on wet surface were given in the 4th column of Table 3.17 as 1.03 and 0.11 respectively. The estimated values of the parameters α and β of the prior distribution were 10.00 and 9.67. Table 4.19 gives the estimated values of the posterior parameters α_i and β_i, and probabilities on dry and wet surfaces separately during the peak period, which are calculated by substituting the prior parameters and values in Tables 3.6 and 3.16 in

Equations 4.10, 4.11, and 4.14. The posterior probabilities of rear-end collisions indicate, at 95% confidence level, that there were no above average collision rates on dry or wet surface when compared to all other temperatures within the dry or wet surface respectively.

Table 4.19: Posterior parameters and probabilities of rear-end collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	18.03	17.11	0.57	27.00	22.67	0.74
-7	17.03	13.11	0.84	27.00	18.67	0.94
-6	16.03	13.11	0.77	20.00	19.67	0.44
-5	19.03	20.11	0.39	20.00	21.67	0.28
-4	21.03	17.11	0.81	22.00	29.67	0.04
-3	20.03	21.11	0.40	30.00	31.67	0.29
-2	12.03	18.11	0.06	45.00	45.67	0.35
-1	21.03	23.11	0.32	61.00	48.67	0.92
0	16.03	19.11	0.22	34.00	34.67	0.36
1	13.03	22.11	0.02	35.00	41.67	0.09
2	18.03	26.11	0.04	43.00	37.67	0.72
3	15.03	18.11	0.22	30.00	26.67	0.65
4	17.03	21.11	0.17	19.00	19.67	0.35
5	25.03	25.11	0.49	25.00	20.67	0.76
6	25.03	21.11	0.79	18.00	19.67	0.27
7	20.03	16.11	0.82	21.00	19.67	0.53
8	23.03	22.11	0.57	14.00	17.67	0.13

Figure 4.21 presents the posterior probabilities for hazardous road-driving conditions on wet and dry surfaces during the peak period when calculated separately. It shows that the posterior probabilities on wet surface were higher than on dry surface during the peak period between –2°C and +5°C.

During the off-peak period, the average and variance of the rates of rear-end collisions on dry surface were given in the 7th column of Table 3.17 as 0.46 and 0.04 respectively. The estimated values of the parameters α and β of the prior distribution were 5.39 and 11.74.

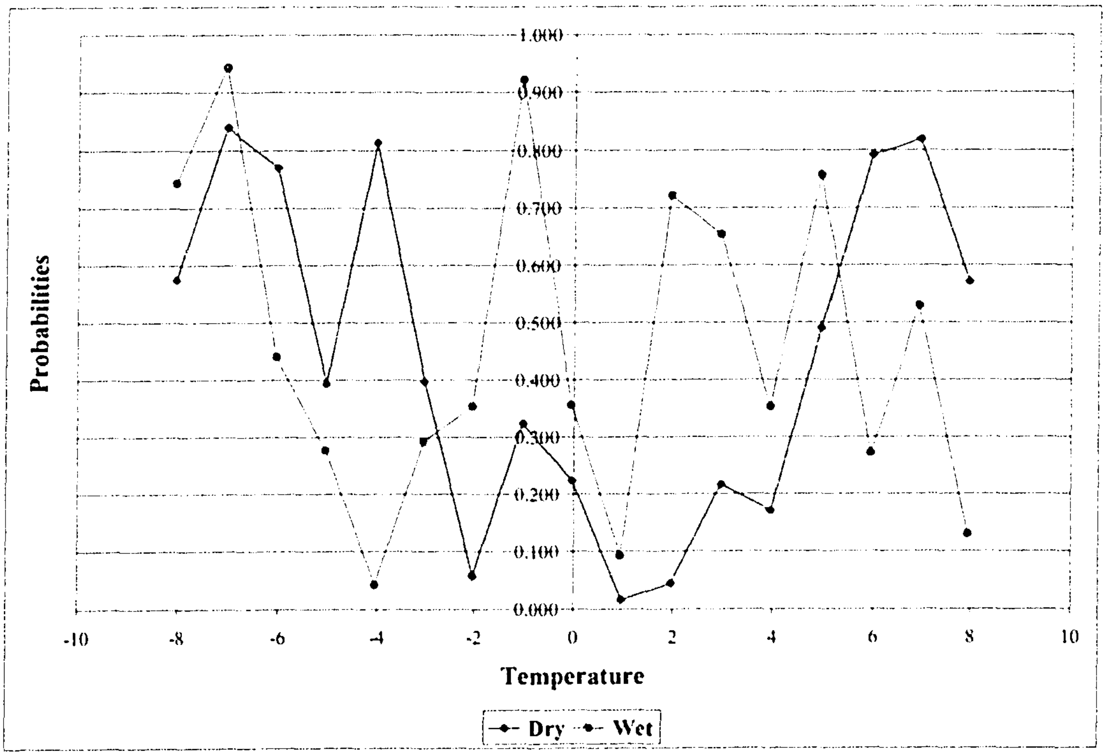


Figure 4.21: Posterior probabilities of rear-end collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

Similarly, the average and variance of the rates of rear-end collisions on wet surface were given in the 8th column of Table 3.17 as 0.79 and 0.21 respectively. The estimated values of the parameters α and β of the prior distribution were 2.90 and 3.69. Table 4.20 gives the estimated parameters α_i and β_i and the posterior probabilities on dry and wet surfaces.

Table 4.20: Posterior parameters and probabilities of rear-end collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	11.39	17.74	0.83	14.90	8.69	0.99
-7	10.39	25.74	0.30	7.90	11.69	0.29
-6	11.39	28.74	0.27	11.90	15.69	0.41
-5	8.39	19.74	0.37	14.90	14.69	0.80
-4	16.39	26.74	0.85	7.90	17.69	0.03
-3	15.39	36.74	0.33	29.90	37.69	0.50
-2	7.39	19.74	0.24	30.90	36.69	0.63
-1	17.39	35.74	0.56	30.90	36.69	0.63
0	16.39	34.74	0.51	42.90	54.69	0.47
1	14.39	33.74	0.36	27.90	60.69	0.00
2	13.39	27.74	0.54	21.90	42.69	0.01
3	19.39	32.74	0.84	25.90	42.69	0.07
4	14.39	31.74	0.45	11.90	30.69	0.00
5	10.39	38.74	0.02	25.90	35.69	0.32
6	9.39	29.74	0.09	13.90	21.69	0.19
7	12.39	27.74	0.42	11.90	14.69	0.50
8	18.39	38.74	0.53	9.90	11.69	0.55

The probabilities show that, at 95% confidence level during the off-peak period, there were no above average rates of rear-end collisions on dry surface at any temperature, while on wet surface, the rate of rear-end collisions was higher than the average only at – 8°C. The posterior probabilities for rear-end collisions on dry and wet surfaces separately during the off-peak period are presented in Figures 4.22. It shows that the posterior probabilities on wet surface were higher than on dry surface during the off-peak period between –3°C and –1°C, and that the posterior probabilities on dry surface were higher than on wet surface during the off-peak period between 0°C and +4°C.

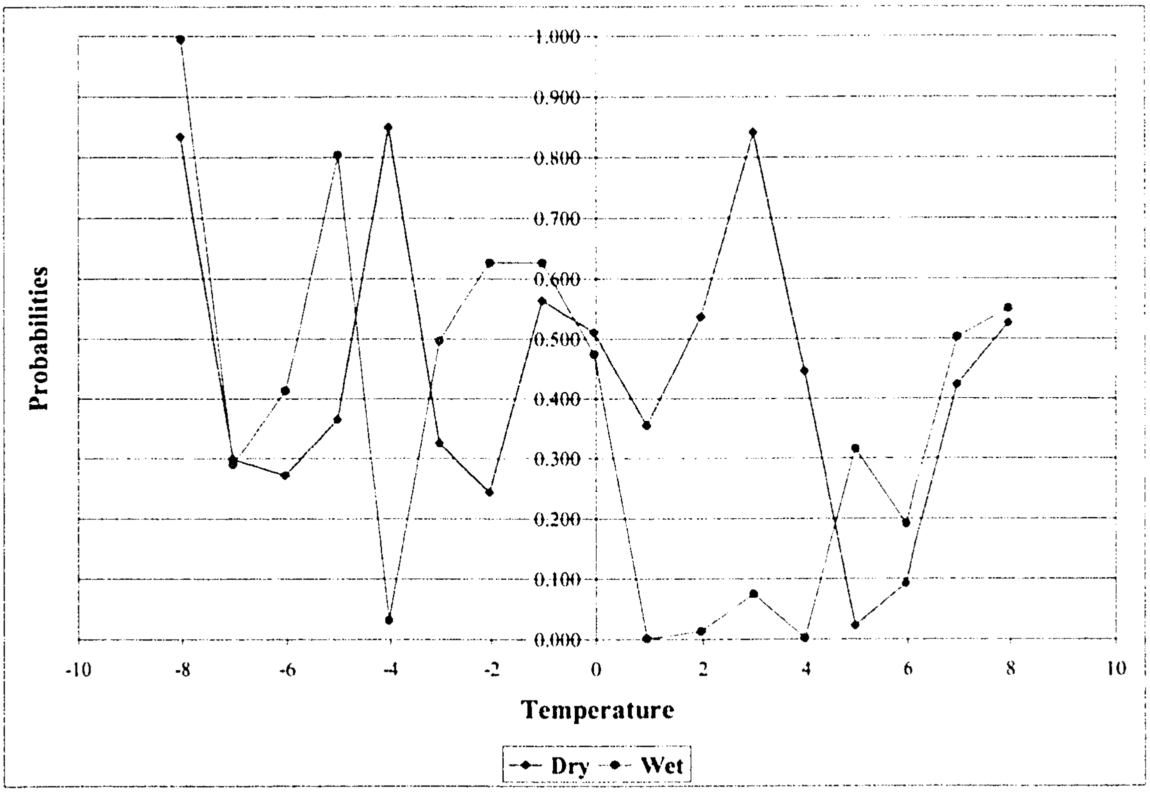


Figure 4.22: Posterior probabilities of rear-end collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

4.3.3.c. Other Types of Vehicle Collisions

The average and variance of the rates of collision involving other types of initial impact per hour of exposure on dry and wet surfaces combined during the peak period were given in Table 3.19 as 1.33 and 0.15. The estimated values of the prior parameters α and β were 11.96 and 9.01 respectively. The estimated posterior parameters α_i and β_i for collisions involving other types of initial impact were obtained by substituting the prior parameters and from Tables 3.6 and 3.18 in Equations 4.10 and 4.11. Table 4.21 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14. These probabilities show that at 95% confidence level during the peak period, there were no above average rates of collisions involving other types of initial impact on dry surface at any temperature, while on wet pavement surface, the rate of collision was higher than the average at – 5°C, –2°C and –1°C. Figure 4.23 shows that the posterior probabilities of collision rates involving other types of initial impact were higher on wet than on dry surfaces between -2°C and 0°C. The distributions of the posterior probabilities of other types of initial collisions on wet and dry surfaces during the peak period in Figure 4.23 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the peak period in Figure 3.31.

Similarly, Table 3.19 gives the average and variance of the rates of collisions involving other types of initial impact per hour of exposure on dry and wet surface combined during the off-peak period as 1.10 and 0.38 respectively. Solving Equations 4.3 and 4.4, the estimated values of the prior parameters α and β were 3.14 and 2.87. The estimated posterior parameters α_i and β_i for collisions involving injury during the off-peak period were obtained by substituting the estimated prior parameters and corresponding values from Tables 3.6 and 3.18 in Equations 4.10 and 4.11. Table 4.22 presents the posterior parameters and probabilities calculated from the Bayes posterior gamma distribution in Equation 4.14 during the off-peak period.

Table 4.21: Posterior parameters and probabilities of other types of collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	23.96	19.01	0.37	31.96	22.01	0.67
-7	24.96	15.01	0.85	29.96	18.01	0.87
-6	18.96	15.01	0.38	26.96	19.01	0.61
-5	22.96	22.01	0.10	38.96	21.01	0.97
-4	29.96	19.01	0.80	32.96	29.01	0.16
-3	28.96	23.01	0.36	37.96	31.01	0.29
-2	25.96	20.01	0.43	79.96	45.01	0.99
-1	28.96	25.01	0.21	91.96	48.01	1.00
0	22.96	21.01	0.15	40.96	34.01	0.25
1	26.96	24.01	0.17	39.96	41.01	0.02
2	26.96	28.01	0.03	48.96	37.01	0.47
3	25.96	20.01	0.43	30.96	26.01	0.25
4	27.96	23.01	0.30	24.96	19.01	0.45
5	27.96	27.01	0.08	26.96	20.01	0.50
6	27.96	23.01	0.30	21.96	19.01	0.23
7	24.96	18.01	0.56	25.96	19.01	0.53
8	31.96	24.01	0.48	23.96	17.01	0.59

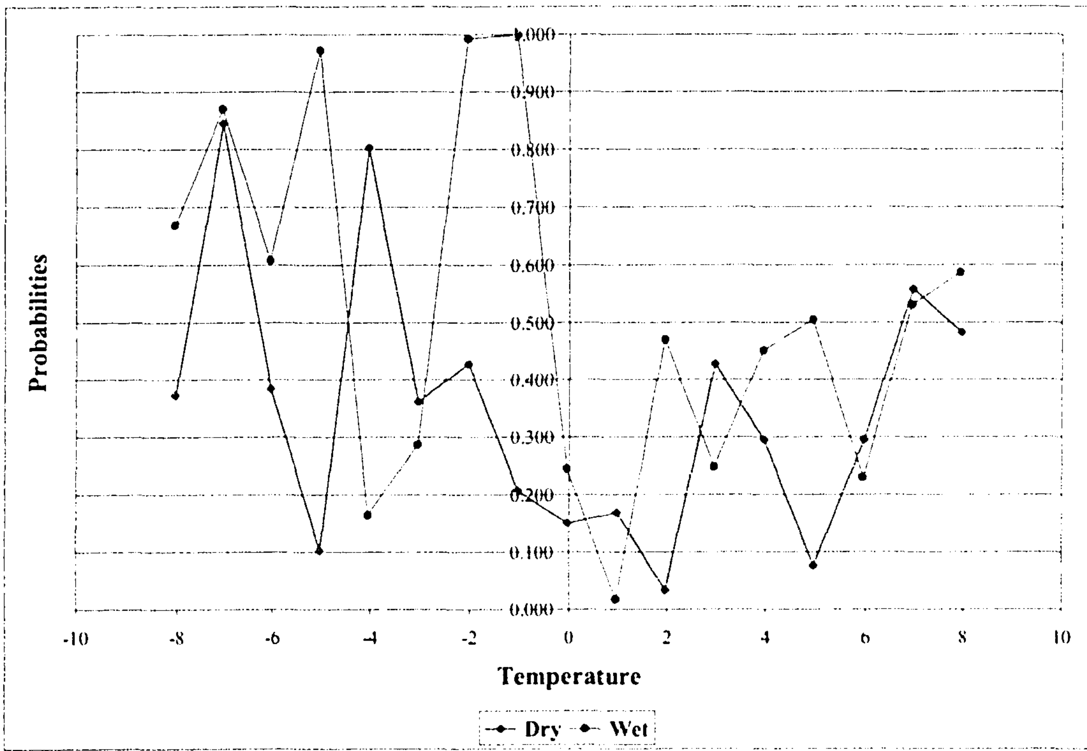


Figure 4.23: Posterior probabilities of other types of collisions on dry and wet surfaces combined in the City of Ottawa during the peak period

The probabilities in Table 4.22 show that at 95% confidence level during the peak period, there were no above average rates of collisions involving initial types of impact on dry surface at any temperature, while on wet surface, the rate of collision was higher than the average at – 8°C, – 5°C, and –1°C. Figure 4.24 shows that the posterior probabilities for risk of collisions involving other types of initial impact on wet surface during the off-peak period were larger than on dry surface at all temperatures between – 8°C and +8°C except at -3°C.

The distributions of the posterior probabilities of other types of initial collisions on wet and dry surfaces during the off-peak period in Figure 4.24 are similar to the distributions of the collision rates per hour of exposure on wet and dry surfaces during the off-peak period in Figure 3.33.

Table 4.22: Posterior parameters and probabilities of other types of collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	4.14	8.87	0.01	22.14	7.87	1.00
-7	12.14	16.87	0.05	14.14	10.87	0.71
-6	12.14	19.87	0.01	19.14	14.87	0.73
-5	11.14	10.87	0.37	25.14	13.87	0.99
-4	13.14	17.87	0.05	24.14	16.87	0.88
-3	27.14	27.87	0.25	36.14	36.87	0.23
-2	10.14	10.87	0.27	43.14	35.87	0.71
-1	22.14	26.87	0.07	67.14	35.87	1.00
0	24.14	25.87	0.19	66.14	53.87	0.81
1	19.14	24.87	0.04	66.14	59.87	0.51
2	19.14	18.87	0.34	44.14	41.87	0.38
3	23.14	23.87	0.25	50.14	41.87	0.72
4	18.14	22.87	0.06	30.14	29.87	0.30
5	14.14	29.87	0.00	43.14	34.87	0.77
6	15.14	20.87	0.04	23.14	20.87	0.50
7	12.14	18.87	0.02	15.14	13.87	0.46
8	25.14	29.87	0.07	16.14	10.87	0.86

In the above analysis, rates of other types of initial collisions per hour of exposure on dry and wet pavement surfaces were compared to their overall combined average and variance to calculate the posterior probabilities. This analysis suggests that, with 95% confidence level, driving on dry surface was not hazardous at any surface temperature and was hazardous at the (–5°C, wet), (–1°C, wet) combinations irrespective of the traffic volume. There were also hazardous driving conditions during the peak period at (–2°C, wet), and during the off-peak period at (–8°C, wet). The risk of collision was, in general, higher on wet surface than on dry surface between –2°C and 0°C irrespective of the traffic volume.

To study the effect of surface temperature during the peak period on the risk of collisions on dry and wet surfaces separately, the average and variance of the rates of collisions involving other types of initial impact on dry surface during the peak period were given in the 3rd column of Table 3.19 as 1.21 and 0.12 respectively. Solving Equations 4.3 and 4.4, the estimated prior parameters α and β for collisions involving other types of initial impact on dry surface were 12.33 and 10.15 respectively.

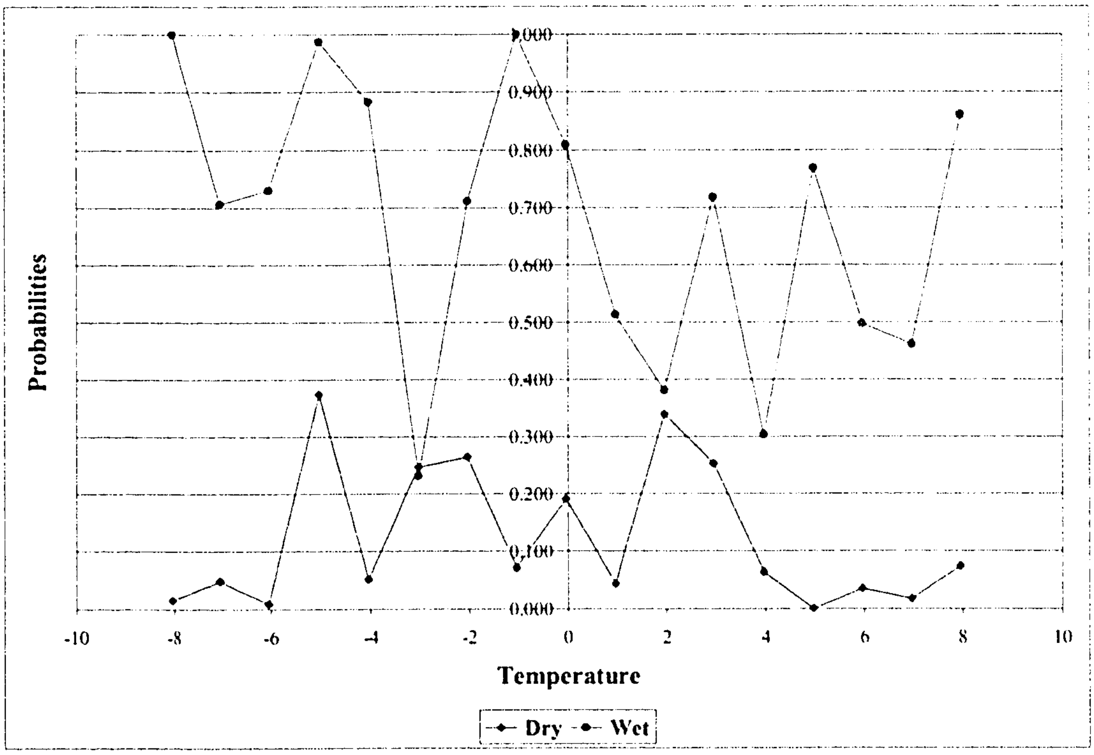


Figure 4.24: Posterior probabilities of other types of collisions on dry and wet surfaces combined in the City of Ottawa during the off-peak period

Similarly, the average and variance of the rates of collisions involving other types of initial impact on wet surface were given in the 4th column of Table 3.19 as 1.44 and 0.16 respectively. The estimated values of the parameters α and β of the prior distribution were 13.20 and 9.16. Table 4.23 gives the estimated values of the posterior parameters α_i and β_i, and probabilities on dry and wet surfaces separately during the peak period, which were calculated by substituting the prior parameters and values in Tables 3.6 and 3.18 in Equations 4.10, 4.11 and 4.14. The posterior probabilities show that there were no above average rates of collisions involving other types of initial impact on dry surface at any temperature at 95% confidence level during the peak period, while on wet surface, the rate of collision was higher than the average at – 8°C, – 5°C, and –1°C.

Figure 4.25 shows that there was no specific trend between the posterior probabilities of collisions involving other types of impact on wet or dry surface when calculated separately and the surface temperature during the peak period, however, the probabilities on wet surface were higher than on dry surface between –2°C and 0°C.

During the off-peak period, the average and variance of the rates of collisions involving other types of initial impact on dry surface were given in the 7th column of Table 3.19 as 0.73 and 0.05. The estimated values of the parameters α and β of the prior distribution for collisions on dry surface are 10.43 and 14.27 respectively.

Similarly, the average and variance of the rates of collisions involving other types of initial impact on wet surface were given in the 8th column of Table 3.19 as 1.46 and 0.45 respectively. The estimated values of the parameters α and β of the prior distribution were 4.68 and 3.21. Table 4.24 gives the estimated parameters α_i and β_i and the posterior probabilities on dry and wet surfaces separately during the off-peak period. The posterior probabilities indicate that there were no above average rates of collision involving other types of initial impact on dry surface at any temperature with 95% confidence level relative to all temperatures within the dry surface condition.

Table 4.23: Posterior parameters and probabilities of other types of collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	24.33	20.15	0.43	33.20	22.16	0.99
-7	25.33	16.15	0.80	31.20	18.16	0.86
-6	19.33	16.15	0.25	28.20	19.16	0.58
-5	23.33	23.15	0.56	40.20	21.16	1.00
-4	30.33	20.15	0.86	34.20	29.16	0.30
-3	29.33	24.15	0.87	39.20	31.16	0.03
-2	26.33	21.15	0.80	81.20	45.16	0.94
-1	29.33	26.15	0.61	93.20	48.16	1.00
0	23.33	22.15	0.62	42.20	34.16	0.17
1	27.33	25.15	0.46	41.20	41.16	0.00
2	27.33	29.15	0.57	50.20	37.16	0.11
3	26.33	21.15	0.81	32.20	26.16	0.15
4	28.33	24.15	0.62	26.20	19.16	0.09
5	28.33	28.15	0.05	28.20	20.16	0.36
6	28.33	24.15	0.54	23.20	19.16	0.11
7	25.33	19.15	0.54	27.20	19.16	0.34
8	32.33	25.15	0.52	25.20	17.16	0.63

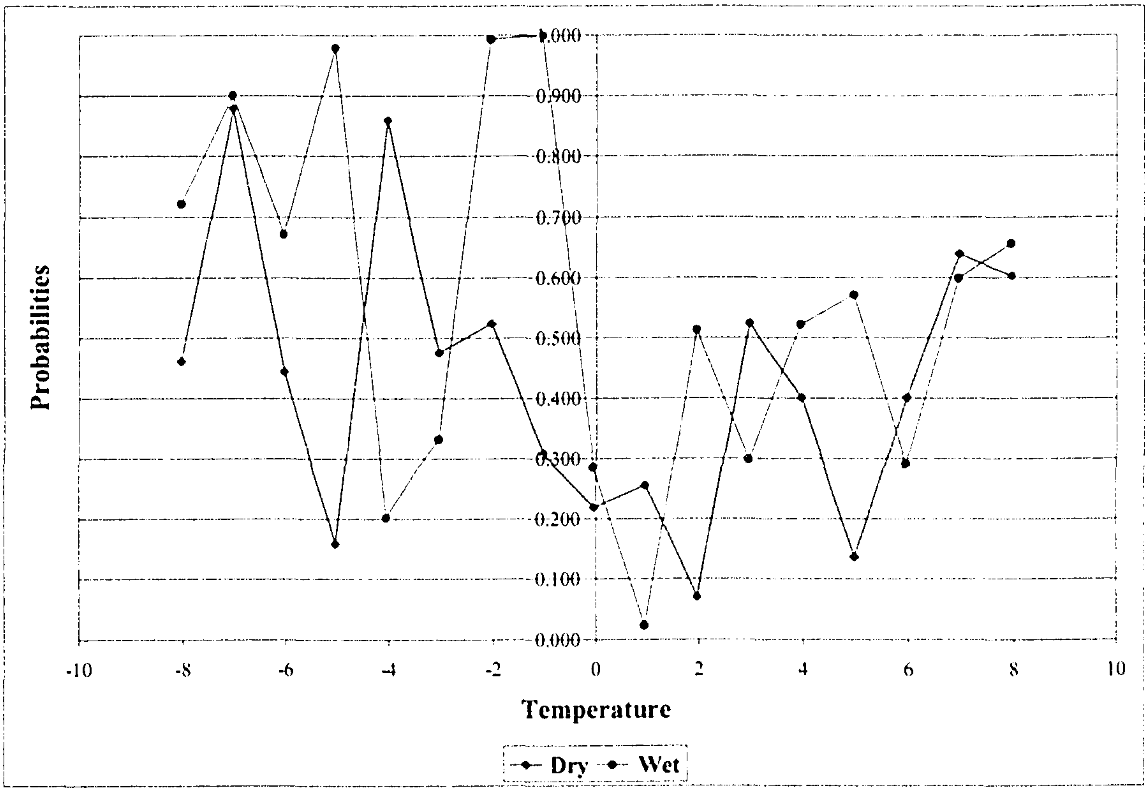


Figure 4.25: Posterior probabilities of other types of collisions on dry and wet surfaces separately in the City of Ottawa during the peak period

There were above average collision rates were, however, on wet surface at –8°C and –1 °C relative to the all temperatures within the wet surface condition. The posterior probabilities for collisions involving other types of initial impact on dry surface were higher than on wet surface during the off-peak period between 0°C and +8°C.

4.4. Summary

This chapter applies the EB method to identify the hazardous pavement surface temperature and pavement moisture condition combinations at which above average collision rates occur, in each of the categories discussed in Chapter 3 during the peak and off-peak periods. The posterior probabilities were calculated for two cases. The first compared the collision rates on dry and wet surfaces to their combined average at each temperature. This allows for comparing the effect of pavement moisture condition on the risk of collisions at different temperatures. Results showed that for all categories during the peak and off-peak periods there was no above average collision rates on dry surface at any temperature, and that the (−1°C, wet) combination was hazardous irrespective of the traffic volume, except for rear-end collisions.

Table 4.24: Posterior parameters and probabilities of other types of collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

Temperature	Dry surface			Wet surface		
	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.	$\alpha_i = \alpha + n_i$	$\beta_i = \beta + h_i$	Prob.
-8	11.43	20.27	0.16	23.68	8.21	1.00
-7	19.43	28.27	0.36	15.68	11.21	0.40
-6	19.43	31.27	0.21	20.68	15.21	0.35
-5	18.43	22.27	0.67	26.68	14.21	0.88
-4	20.43	29.27	0.39	25.68	17.21	0.52
-3	34.43	39.27	0.84	37.68	37.21	0.01
-2	17.43	22.27	0.58	44.68	36.21	0.11
-1	29.43	38.27	0.58	68.68	36.21	0.98
0	31.43	37.27	0.77	67.68	54.21	0.09
1	26.43	36.27	0.47	67.68	60.21	0.01
2	26.43	30.27	0.79	45.68	42.21	0.01
3	30.43	35.27	0.80	51.68	42.21	0.09
4	25.43	34.27	0.50	31.68	30.21	0.02
5	21.43	41.27	0.04	44.68	35.21	0.16
6	22.43	32.27	0.38	24.68	21.21	0.11
7	19.43	30.27	0.25	16.68	14.21	0.16
8	32.43	41.27	0.64	17.68	11.21	0.60

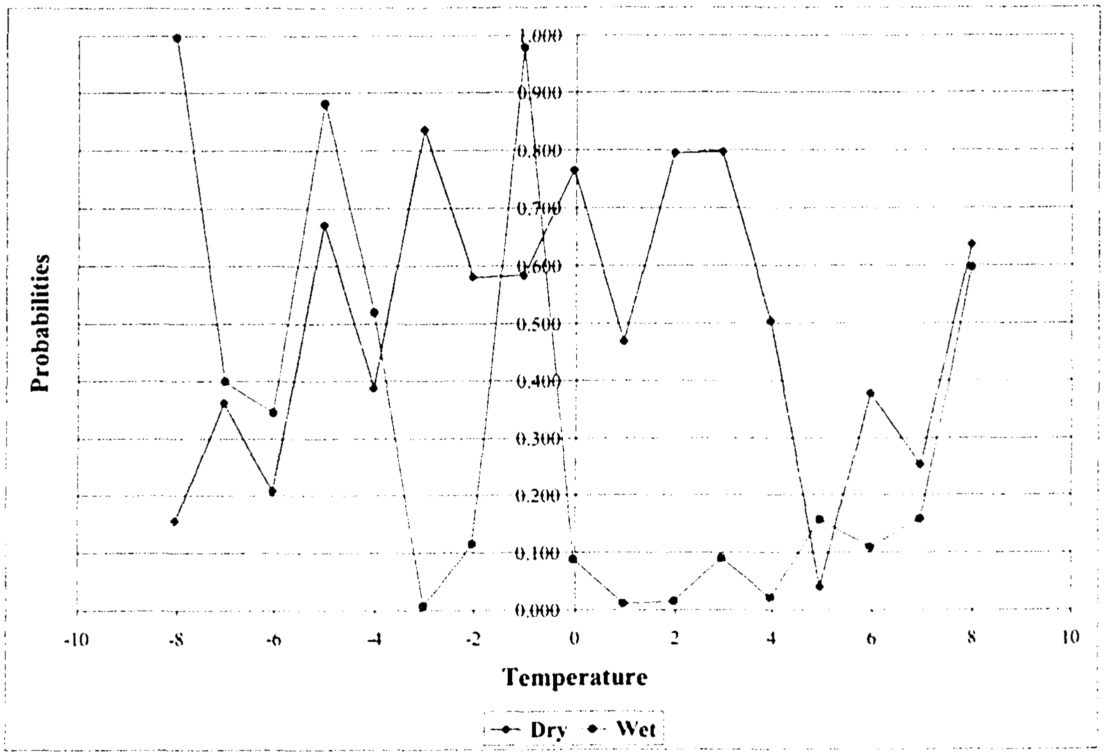


Figure 4.26 : Posterior probabilities of other types of collisions on dry and wet surfaces separately in the City of Ottawa during the off-peak period

There were other different sub-zero temperatures during which above average collision rates occurred, all of them on wet surface. In addition, the posterior probabilities of higher than average collision rates were, in general, greater on wet surface than on dry surface at the sub-zero temperatures. For example, posterior probabilities of total collisions were higher on wet surface than on dry surface during the peak period between –8°C and +5°C, except at – 4°C. During the off-peak period, these probabilities were higher on wet surface than on dry surface between –8°C and +8°C, except at +4°C and +3°C. This result concluded that posterior probabilities of total collisions were higher on wet surface than on dry surface between –8°C and +0°C irrespective of the traffic volume. Similar results were shown for the single-vehicle collisions. Other categories had smaller sub-zero ranges for above average collision rates irrespective of traffic volume, (–1°C, 0°C) for collisions with injury, (–2°C, 0°C) for rear-end and other types collision rates, and (–3°C, 0°C) for collision rates involving PDO.

The above analysis concluded that moisture on pavement surface at sub-zero temperatures, particularly close to the freezing temperature, had a large effect on the risk of collision during the wintertime as all hazardous driving conditions occurred in this condition.

The distributions of the EB posterior probabilities on wet and dry surfaces during the peak period were similar to the distributions of the rates of collisions on wet and dry surfaces used in Chapter 3 to calculate the pavement moisture risk factors. That is, results from both methods are in agreement in identifying the effect of pavement moisture condition on the risk of driving. Similar conclusions were obtained from results of analyzing the off-peak data.

The analysis also revealed that the posterior probabilities during the off-peak period were, in general, higher on dry surface than on wet surface at above zero temperatures. This supports the assumption that other factors including driving speed and the human factors affecting the risk of collisions at these temperatures.

5. PAVEMENT TEMPERATURE MODEL DEVELOPMENT

Accumulation of snow and ice on pavement surface during wintertime substantially increases the risk of road vehicle collisions. Therefore, road and highway winter maintenance operations are vital for the safety of citizens and for enabling emergency and security services to perform their essential functions. Recent practices for the application of anti-icers and deicers are moving toward the use of pavement surface temperature as a guide to control the snow and ice on roads (Blackburn *et al.*, 2004). The prediction of this temperature is therefore very important to plan and execute winter maintenance operations.

In this chapter, statistical analysis is used to develop low cost, highly accurate models capable of predicting pavement surface temperature from the knowledge of the weather variables such as air temperature, dew point, precipitation, relative humidity, and wind speed. These models can provide local authorities with an additional tool to develop their winter maintenance programs more efficiently while minimizing the effect of road salts on the environment.

A three-step modelling framework is used to achieve this objective: model formulation, model estimation, and model verification. In the model formulation, the form of the model is developed based on the graphical shape of the relationships between variables and previous research studies. Plotting data of pavement temperature versus air temperature concluded that the linear model is adequate. In model estimation, the coefficients of the model are estimated using regression analysis, to achieve the best fit of the available data to the formulated model. The regression analysis starts with the Multivariate Stepwise Linear Regression, to eliminate those independent variables whose coefficients are not statistically different from zero using the t-statistic. Next, those variables that do not significantly contribute to the coefficient of determination (corrected R^2) were dropped from the model. Model verification is used to test and evaluate the model accuracy by further examination of the chosen variables according to their contribution to the goodness of fit and their physical relationships to each other; i.e. the problem of multicollinearity. In addition, the Durbin-Watson statistic was used to test the autocorrelation in the error structure to improve the predictability of the models. Finally, the time-lag dependent variables were used to improve the predictability of the models. Different number of lags was tried only the estimated coefficients of the first two lags were significantly different from zero at 5% level of significance.

This chapter starts with a description and detailed analysis on data collected by the RWIS stations at the City of Ottawa for the winter season of 2001-2002. It explains the process through which the raw data were tested for consistency and manipulated until a final usable dataset is reached. An objective of this process was also to maximize the utilization of the data, which contained complete, partially complete, and unusable observations, in order to study the relationship between the pavement surface temperature and weather variables. Then the methodology of developing the models is presented and finally, the results of the relevant statistical tests are given. Of particular interest are the tests for autocorrelation and multicollinearity, which are used to produce more statistically, sound models.

5.1. Data Description and Analysis

Data on weather variables, pavement surface temperature and pavement moisture condition for the Ottawa Region were obtained from the City of Ottawa for the 2001-

2002-winter season. The variables and their definitions as included in the database and used in this thesis are listed below.

5.1.1. *Weather Variables Recorded by the RWIS Stations*

- ***Air Temperature (AirT):*** is the temperature measured in degrees Celsius at 1.5 metres above ground.
- ***Dew Point (DewPt):*** is the temperature at which the air becomes saturated as it cools down. If the road temperature drops to or below the dew point, moisture will develop on the surface. The form that the moisture takes (e.g. ice or frost) depends upon the surface temperature and the amount of chemicals present.
- ***Relative Humidity (RH):*** is the percentage of moisture in the air. A relative humidity of 0% shows that the air contains no moisture and 100% shows that the air is completely saturated and cannot absorb any additional moisture.
- ***Wind Direction (WDir):*** is the average wind direction during a one-minute period. Wind direction is in degree format whose value ranges from 1 to 360.
- ***Wind Speed (WSpd):*** is the average wind speed (km/h) during a one-minute period.
- ***Gust (Gust):*** is the maximum wind speed measured during a one-minute period. The RPU averages the wind speed every four seconds and collects 15 four-second averages in one minute. The largest of these 15 values is the gust value.

5.1.2. Pavement Condition Variables Recorded by the RWIS Stations

- ***Surface Temperature (SfT)*:** is measured in degrees Celsius roughly 3 mm below the surface. If the sensor does not record temperature, a code of 327.66 is reported.
- ***Pavement Surface Condition (SfCond)*:** a categorical variable: No Report (32); Dry (33); Wet (34); Chemical Wet (36); Snow/Ice Watch (35); Slush, Snow/Ice Warning (38); Black Ice warning, Wet above Freezing, Wet below freezing, and Damp (39); Frost (40).
- ***Chemical Wet Surface (Chem)*:** is the relative indication of chemicals present in the moisture on the surface. This factor uses a relative scale ranging from 5 to 95 in increments of 5.
- ***Snow/Ice Warning*:** The continuous film made of water and ice mixture at or below freezing temperature, with insufficient amount of chemicals to keep the mixture from freezing.
- ***Chemical Percent (Chem%)*:** Measures the percent of chemical saturation in the moisture. This field is reported when the surface status is Wet, Chemical Wet, or Snow/Ice Warning.
- ***Ice Percent (Ice%)*:** is the percent of ice in the moisture. When ice percentage is roughly 50% to 85%, the surface moisture is typically called "slush". This field is reported when the surface status is Wet, Chemical Wet, or Snow/Ice Warning.
- ***Subsurface Temperature (SubT)*:** Typically, it is the pavement temperature measured in degrees Celsius approximately 43 cm below the top of the surface.

Additional subsurface sensors may also be installed at different depths to monitor frost depth.

5.1.3. Data Recorded by the RWIS Stations in Ottawa

Data on the weather and pavement temperature analyzed in this chapter were extracted from nine stations in the RWIS system at the City of Ottawa for the winter season of 2001-2002. The stations are located at Acres road, Vars, Trim Road, North Gower, Hawthorne road, Plaza Bridge, Walkley road, Kinburn, and Ashton (Figure 5.1). Each RWIS station consists of a set of pavement sensors that collect information on pavement condition and then transmit it to an adjacent tower. Some of these sensors are installed at a maximum of 0.75 km away from the tower, others are located on a bridge deck and approach, and some are located very far away from the tower. For example, a sensors installed at the city of Orleans is connected to the RPU at Hawthorne and sensors installed at Greenbank/Hunt Club and Riverside/Hunt Club locations are connected to the RPU at North Gower. The main functions of the towers are to collect weather data, to receive data from the sensors measuring pavement surface condition, and then transmit these data to a central location for analysis. Figures 5.2 and 5.3 show examples of two data samples collected at a station with tower and a station without tower, respectively.

Because an objective of this thesis is to develop a pavement temperature prediction model usable for winter maintenance, only data collected during the winter season (from November 1, 2001 to March 31 2002) will be discussed in this section. The RWIS stations can be detailed further as follow:

- A tower and sensors at Vars Southbound (VARSB). The complete observations from November 1, 2001 at 1 am until March 31, 2002 at 12 am were available from this site on the pavement surface temperature, pavement subsurface temperature, air temperature, dew point, relative humidity, and wind speed. The data on the pavement surface condition, wind direction and wind gust were missing. The number of observations recorded at this site is 3,624.

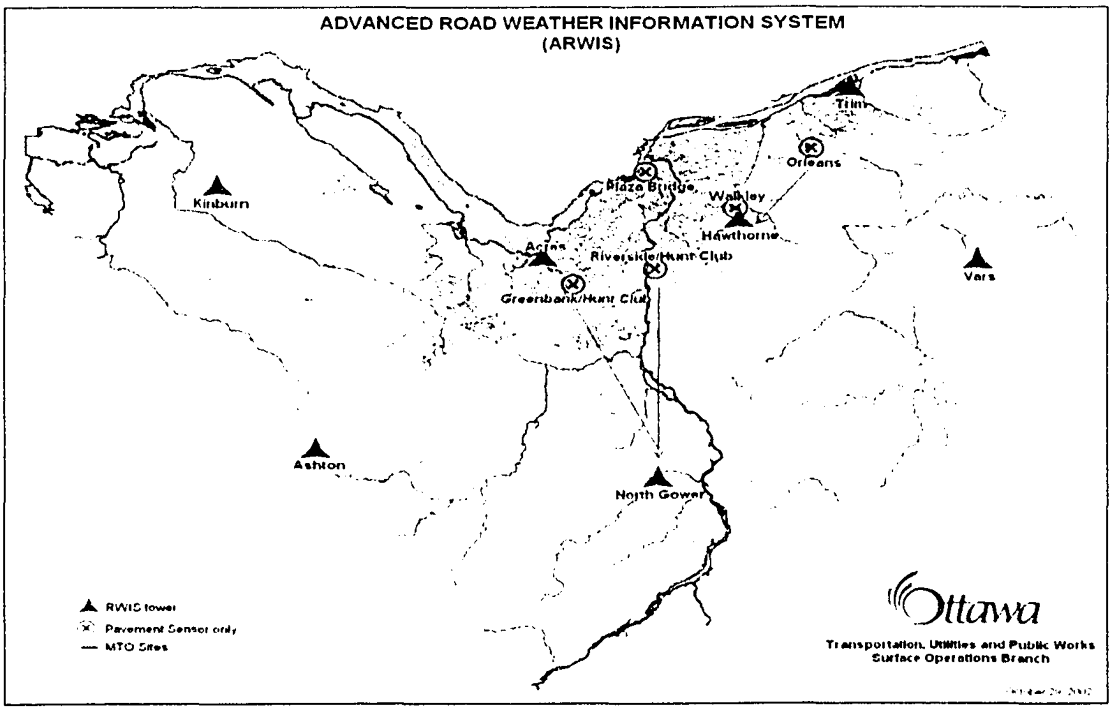


Figure 5.1: Locations of RPU's in the City of Ottawa used in this study.

```
# This report was generated on Jul 23 2002  2:50PM.
# ------------------------------------------------
# Station=Kinburn
#
# Sysid=276
# Rpuid=0
# Senid=0
# Start Date=Oct  1 2001 12:00AM
# End   Date=Apr 30 2002 11:59PM
# ------------------------------------------------
# Obervations ...
# EST = UTC - 5 HOURS
# ------------------------------------------------
```

Date/Time (UTC)	Air T	Dew Pt	Rh	Pcp	WDir	WSpd	Gust	Pav Cond	Cond Code	Sf T	Sub T	Frz T	Chem	Chem%	Ice%
Oct 21 2001 7:26PM	11.96	-1.68	39	0	215	24	28	Dry	33	20.65	11.70	327.67	255	255	255
Oct 21 2001 7:35PM	12.38	-1.65	38	0	220	16	19	Dry	33	21.33	11.62	327.67	255	255	255
Oct 22 2001 12:44PM	6.99	3.00	76	1	160	15	20	Wet	34	7.44	12.21	0.00	5	0	0
Oct 22 2001 12:53PM	6.94	3.14	77	1	170	12	15	Wet	34	7.39	12.16	0.00	5	0	0
Oct 22 2001 1:03PM	6.99	3.37	78	1	155	11	16	Wet	34	7.47	12.16	0.00	5	0	0
Oct 22 2001 1:13PM	6.92	3.48	79	1	175	12	18	Wet	34	7.61	12.21	0.00	5	0	0
Oct 22 2001 1:23PM	6.99	3.55	79	1	150	11	15	Wet	34	7.70	12.21	0.00	5	0	0

Figure 5.2: Sample of data collected at a RPU.

```
# This report was generated on Jul 23 2002  2:50PM.
# -----------------------------------------------------
# Station=Acres Road
#
# Sysid=276
# Rpuid=5
# Senid=1
# Start Date=Oct  1 2001 12:00AM
# End   Date=Apr 30 2002 11:59PM
# -----------------------------------------------------
# Obervations ...
# EST = UTC - 5 HOURS
# -----------------------------------------------------
```

sysid	rpuid	senid	Date/Time (UTC)	Pav Cond	Cond Code	Sf T	Frz T	Chem	Chem%	Ice%
276	5	1	Feb 10 2002 3:15PM	Dry	33	-2.77	327.67	255	255	255
276	5	1	Feb 10 2002 3:16PM	Dry	33	-2.51	327.67	255	255	255
276	5	1	Feb 10 2002 3:18PM	Dry	33	-2.17	327.67	255	255	255
276	5	1	Feb 10 2002 3:23PM	Dry	33	-2.00	327.67	255	255	255
276	5	1	Feb 10 2002 3:25PM	Dry	33	-2.00	327.67	255	255	255
276	5	1	Feb 10 2002 3:30PM	Dry	33	-2.09	327.67	255	255	255
276	5	1	Feb 10 2002 3:35PM	Dry	33	-1.83	327.67	255	255	255

Figure 5.3: Sample of data collected at a RWIS station without a tower

- Sensors at Acres road Southbound (ACRSB), Acres road Northbound (ACRNB), Acres road Transitway (ACRTW), and Acres road Westbound at highway 417 (ACR417) are connected to a RPU tower at ACRSB. The observations from November 1, 2001 at 4 pm until March 31, 2002 at 12 am were available from the first three locations. Missing, were observations on the first 17 hours. Data from the ACR417 location were missing observations from January 29, 2002 at 1 am to March 6, 2002 at 1 am. Therefore, it was excluded from the study to allow for a full utilization of the other three locations. The variables measured at the ACRSB location were pavement surface temperature, pavement surface condition, air temperature, dew point, relative humidity, wind direction, wind speed, and wind gust. The variables measured at the ACRNB and ACRTW locations were pavement surface temperature and pavement surface condition. The number of observations recorded at this site is 3,609.
- Sensors at Trim Road Southbound (TRMSB) and Trim Road Northbound (TRMNB) are connected to a RPU tower at TRMSB. Observations from

November1, 2001 at 1 am until March 31, 2002 at 12 am were available from these locations, but missing 67 observations, from February 1, 2002 at 1 pm to February 4, 2002 at 7 am. The variables measured at the TRMSB location were the pavement surface temperature, pavement subsurface temperature, pavement surface condition, air temperature, dew point, relative humidity, wind direction, wind speed, and wind gust. The variables measured at the TRMNB location were the pavement surface temperature and pavement surface condition. The number of observations recorded at this site is 3,557.

- Sensors at North Gower Westbound (NGWB), North Gower Eastbound (NGEB), Riverside/Hunt Club Westbound (NGRHWB), Greenbank/Hunt Club Northbound (NGGHNB), Riverside/Hunt Club 1500 mm (NGRH15), and Greenbank/Hunt Club 1500 mm (NGGH15) are connected to RPU at NGWB. Observations from November 1, 2001 at 1 am until March 31, 2002 at 12 am were available for the first four locations, but missing 767 observations from January 30, 2002 at 2 am to March 2, 2002 at 12 pm. The variables measured at the NGWB location were pavement surface temperature, pavement subsurface temperature, pavement surface condition, air temperature, dew point, relative humidity, wind direction, wind speed, and wind gust. The variables measured at the NGEB, NGRHWB, and NGGHNB locations were the pavement surface temperature, pavement subsurface temperature, and pavement surface condition. The sensors at the NGRH15 and NGGH15 locations did not record any pavement surface temperature observations and therefore, these two locations were excluded from the study. The number of observations available for this site is 2,857.

- Sensors at Hawthorne Northbound (HANB), Hawthorne Southbound (HASB) and Orleans Westbound (OWB) are connected to the RPU at HASB. Sensors at OWB did not record any observations. Observations from November 1, 2001 at 1 am to March 31, 2002 at 12 am were available from HANB and HASB. The variables measured at the HASB location were pavement surface temperature, pavement surface condition, air temperature, dew point, relative humidity, wind speed, wind gust, and wind direction. Only pavement surface temperature was measured at HANB. There were 793 missing observations for all the variables at the two locations from January 30, 2002 at 1 am until and including March 3, 2002 at 12 pm. The number of observations recorded at this site is 2,831. There was a third location at this site where all the sensors had failed to record any observations.
- Sensors at Plaza Bridge Eastbound deck (PBEBD) and Plaza Bridge Eastbound approach (PBESA) are connected to a RPU tower at PBEBD. Observations available from these locations were from December 14, 2001 at 1 pm until March 31, 2002 at 12 am. Observations from December 26, 2001 at 4 am to December 28, 2001 at 9 am, and from January 30, 2002 at 1 am to March 5, 2002 at 12 pm were missing. The variables measured at the PBEBD location were the pavement surface temperature, pavement subsurface temperature, pavement surface condition, air temperature, dew point, and relative humidity. No other weather variables were available at this location. The variables measured at the PBEBA location were pavement surface temperature, pavement subsurface temperature, and pavement surface condition. The number of observations recorded at this site is 1,686.

- A tower and sensors at Walkley road (weather variables included only the air temperature). Therefore, this site was excluded from the study.
- Sensors at Kinburn Southbound (KSB) and Kinburn Northbound (KNB) are connected to the RPU at KSB. Data from these locations were missing large number of observations at many different time periods, and therefore this site was excluded from the study.
- Sensors at Ashton Southbound deck (ASHSBD), Northbound deck (ASHNBD), and Ashton Southbound approach (ASHSBA) are connected to the RPU at ASHSBD. Data from these locations were the same as in Kinburn, and therefore this site was also excluded from the thesis.

Table 5.1 below summarizes the data availability and the missing observations.

Table 5.1: Data availability for the 2001/2002-winter season at the City of Ottawa.

Locations	Missing Period(s)	Missing Hours	Independent variables‡	Site used/ excluded	Number of observations
Vars	N/A	N/A	1, 2, 3, 4	Used	3,624
Acres	01/11/2001	15	1, 2, 3, 4, 5, 6, 7	Used	3,609
Trim	01/02 – 04/02/2002	67	1, 2, 3, 4, 5, 6, 7	Used	3,557
North Gower	30/01 – 02/03/2002	767	1, 2, 3, 4, 5, 6, 7	Used	2,857
Hawthorne	30/01 – 03/03/2002	792	1, 2, 3, 4, 5, 6, 7	Used	2,831
Plaza Bridge	01/11 – 14/12/2001 & 26/12 – 28/12/2001 & 30/01 – 05/03/2002	1,938	1, 2, 3, 7	Used	1,686
Walkley	Many	Many	N/A	Excluded	N/A
Kinburn	Many	Many	N/A	Excluded	N/A
Ashton	Many	Many	N/A	Excluded	N/A

‡ 1 = air temperature, 2 = dew point, 3 = relative humidity, 4 = wind speed, 5 = gust, 6 = wind direction, 7 = surface condition.

Since the measurements were taken approximately every 10 minutes or less for twenty-four hours a day, the use of the observations in this format would have distorted the statistical model. This is because the changes in weather and pavement conditions between any two consecutive periods of ten minutes or less will usually be very small. Therefore, the data were transformed into hourly measurements by averaging all consecutive observations within each hour. Table 5.2 shows a sample of the hourly-averaged data recorded at the Acres road during January 1, 2002.

Figure 5.4 gives an example of the trend of hourly average air temperature and surface temperature at the Acres Road RPU during the month of January 2002. It is clear from the graph that both temperatures follow closely the same pattern, which indicates a very close relationship between the two variables. The graph also clearly shows the daily temperature cycles, which reach their minimum at about 6:00 am and their maximum at about 3:00 pm.

Table 5.2: Sample of hourly-averaged data recorded at Acres station.

Date	Hour	SfT	AirT	RH	DewPt	WDir	WSpd	Gust	SfCond
01/01/2002	1	-10.33	-10.38	85	-12.47	355	10.33	12.00	35
	2	-10.61	-10.09	86	-12.00	355	10.27	12.73	35
	3	-11.04	-10.63	87	-12.35	355	5.64	7.91	35
	4	-11.60	-11.31	89	-12.83	355	8.60	11.50	35
	5	-12.01	-12.11	89	-13.59	355	6.40	9.10	35
	6	-12.54	-13.03	91	-14.22	355	6.00	7.89	35
	7	-12.83	-13.14	92	-14.20	355	8.78	11.56	35
	8	-12.92	-12.98	91	-14.16	355	11.83	16.17	35
	9	-11.64	-12.63	89	-14.11	355	11.60	16.20	35
	10	-8.65	-11.65	84	-13.84	355	12.55	17.30	33

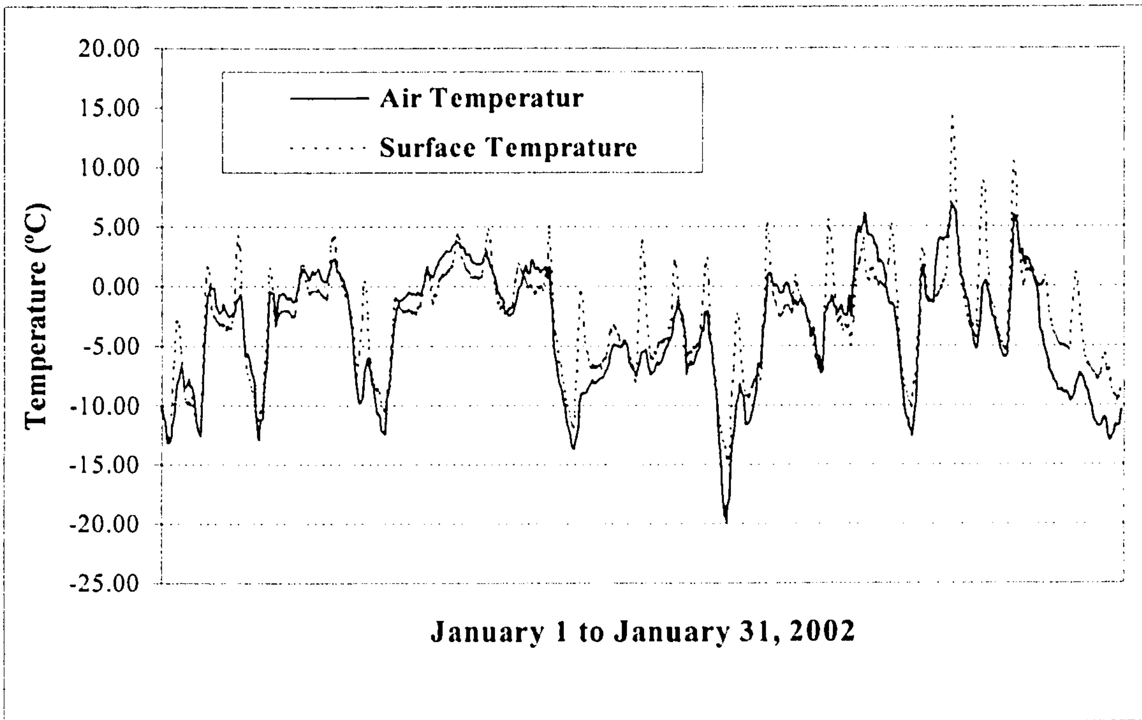


Figure 5.4: Example of hourly average air and surface temperatures (Acres Road RPU; January 2002)

The minimum pavement temperature in the City of Ottawa during the winter of 2001/2002 was –17.04 °C recorded by a sensor at Acres road RPU on February 5, 2002. On that day, the pavement temperature fell during the early hours of the day to reach its minimum at 6:00 am, then started to climb until it reached its maximum of –2.22 at 3:00pm. Then started to cool again.

Before averaging the data, the original data were inspected to ensure that they did not include any of the code 327.66, which is used by the sensor for missing readings. In examining the data further, it was noticed that more data were missing for pavement sensors that were farther away from the RPU. For the cases where there were too many missing observations on any of the variables, particularly the pavement surface temperature, the location was excluded. As mentioned earlier, three locations (Walkley, Kinburn, and Ashton) were excluded. The impact of this exclusion is minimal since the available data were sufficient to establish the existence of relationships between the pavement surface temperature and the weather and pavement surface conditions.

5.1.4. RWIS Data Consistency Test

As seen earlier, all stations had suffered from dropout periods when the sensors or the weather recording instruments were unable to function due to unexpected technical difficulties. In some cases, it required few days or weeks to fix the problem, and in others it took over one month to get the station back in working conditions. Some of them were left idle due to lack of maintenance funds. In this thesis, an attempt was made to optimize the utilization of the data available under these severe restrictions.

It was expected that readings on pavement surface temperatures reported by closely located sensors, would be very close. Small random differences might have occurred due to traffic conditions (sensors were contacted with vehicle tires or covered with slush). Bernstein et al. (2004) used time series charts to examine the temperature differences between any two adjacent pavement sensors and concluded that overall, the comparison was quite good. In this thesis, a simple statistical *t*-test was undertaken to examine and identify these differences and then verify which locations would be used to develop the regression models based on their relative reliability. The differences between hourly readings at different close locations were calculated and the average differences per hour are summarized in Table 5.3 (note that the Vars RPU was not included in this comparison as only one sensor is connected to the RPU). Additional indicators such as the maximum and minimum of hourly differences were also calculated. Column four gives the average difference per single hourly observations and column five gives the standard deviation of the differences from their means. The sixth column gives the calculated t-values for testing the null hypothesis H_0: $\mu = 0$.

It is clear that all the average differences between any two sensors connected to the same RPU are not significantly different from zero at 5% level of significance as given by the t-statistics, which are less than the tabulated value of 1.96. For the purpose of this research, models using pavement data from sensors adjacent to the tower will be used with the weather information collected at this tower to develop a regression model, which will be able to forecast the pavement surface temperature at this location.

Table 5.3: Differences in pavement surface temperatures (°C) for different sensors at same RPU.

Location	Minimum	Maximum	Mean	Standard deviation	t-statistic	p-value
Acres Road (AC)						
ACSB – ACNB	-3.93	5.50	0.033	0.604	0.05	0.960
ACSB – ACTW	-6.90	7.90	0.051	0.655	0.08	0.936
Trim (TR)						
TRSB – TRNB	-2.82	2.47	0.030	0.456	0.07	0.944
North Gower (NG)						
NGWB – NGEB	-7.56	2.05	0.682	0.805	-0.85	0.395
NGWB – NGEB	-5.90	8.29	0.209	1.231	-0.17	0.865
NGWB – NGEB	-7.18	7.61	0.239	1.152	0.21	0.834
Hawthorne (HA)						
HASB – HANB	-2.59	4.16	-0.063	0.439	-0.14	0.889
Plaza Bridge (PB)						
PBEBD – PBEBA	-2.20	8.15	0.263	0.902	0.29	0.772

‡ EB = Eastbound, WB = Westbound, NB = Northbound, SB = Southbound, NBD = Northbound Deck, SBA = Southbound Approach.

5.2. Development of Surface Temperature Prediction Models

Another objective of this thesis was to develop statistical models capable of predicting the pavement surface temperature from the knowledge of weather variables such as air temperature, relative humidity, dew point, precipitation, wind speed, etc. Prediction models of pavement temperature are developed at six different locations in the City of Ottawa (Vars road, Acres road, Trim road, North Gower, Hawthorne road, and Plaza Bridge). Another model is developed for the City of Ottawa by combining data from all locations. Multivariate regression analysis is used to estimate the pavement temperature as a function of the weather variables. A three-step framework is used to develop these models: model formulation, model estimation, and diagnostic checking.

In the model formulation, the form of the model is developed based on previous research studies, multivariate correlation analyses, and graphical shape of the relationships between variables.

In model estimation, the coefficients of the model are estimated using regression analysis, to achieve the best fit of the available data to the formulated model. The regression analysis starts with the multivariate stepwise linear regression, to eliminate those independent variables whose coefficients are not statistically different from zero using the t-statistic. Next, those variables that do not significantly contribute to the coefficient of determination (R^2) were dropped from the model.

Diagnostic checking is used to test and evaluate the model accuracy by further examining the chosen variables according to their contribution to the goodness of fit and their physical relationships to each other; i.e. the problem of multicollinearity. In addition, the Durbin-Watson statistic was used to test the serial correlation in the error structure to improve the predictability of the models.

5.2.1. Model Formulation

The form of the model has to be developed based on the functional relationships between the pavement surface temperature and the independent variables, e.g. the choice of the independent variables and the mathematical form of the relationship (linear versus non-linear). Previous research studies to estimate the pavement surface temperature as function of weather variables have used the linear regression models (Bosscher et al., 1998). As shown in Figure 5.5, the graphical shape of scatter data between the pavement surface temperature and the air temperature indicates that the linear form is adequate for modelling this relationship. If the Least Squares Estimation Method is used to fit a linear regression model for observations from two random variables, the ratio of the variance explained by the linear relationship to the total variance of the dependent variable is called the coefficient of determination (R^2), where r is the correlation coefficient between the two variables. If both explained variance and total variance are equal, the correlation coefficient is equal to ± 1, which means a perfect relationship. If the explained variance is zero, then the correlation coefficient is zero and no relationship exists between the two variables.

5.2.2. Model Estimation

Model estimation is the process of fitting the tentative model to the data and estimating its parameters and testing their statistical significance. The parameters are estimated using one of the well-known statistical methods such as the Ordinary Least Squares (OLS) method or the Maximum Likelihood (ML) method. The estimation criterion usually is based on achieving the best fit of the available data to the formulated model. The model estimation method used in thesis starts with the Multivariate Stepwise Linear Regression to eliminate those independent variables whose coefficients are not statistically different from zero.

5.2.2.a. Multiple Linear Regression Analysis

In many engineering problems, two or more variables are inherently related, and it is necessary to explore the nature of this relationship. *Regression analysis* is a statistical technique for modelling and investigating the relationship between two or more variables. If the relationship between a dependent variable Y and an independent variable X is linear (in parameter), then the model is called "*simple linear regression model*". The general form of the model can be represented by:

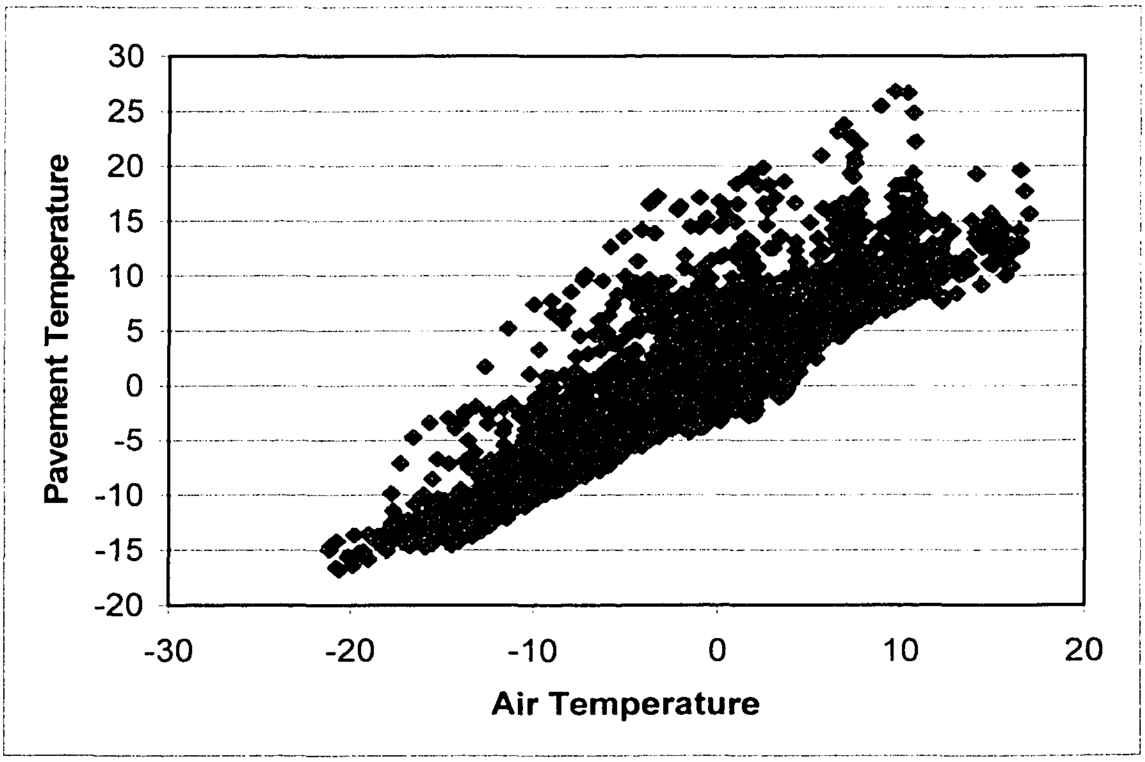


Figure 5.5: Plotting pavement temperature versus air temperature.

$$Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, \qquad i = 1, ..., n, \qquad (5.1)$$

where ε_i is a random uncorrelated error term with mean zero and a variance σ^2, which can be estimated from the given data.

The estimates b_0 and b_1 of the *regression coefficients* β_0 and β_1 should result in a straight line that is (in some sense) "best fit" the data. One of the methods of determining these estimates is the "*Least Squares Method*", and the estimated coefficients are therefore called the "*Least Squares Estimates*". The fitted model can be written as:

$$Y_i' = b_0 + b_1 x_i, \qquad i = 1, ..., n. \qquad (5.2)$$

Many applications of regression analysis involve more than one independent variable. A regression model that contains more than one independent variable is called "*multiple linear regression model*". The general form of a linear model relating a dependent variable Y to k independent variables $x_1, x_2, ..., x_k$, can be represented by:

$$Y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + ... + \beta_k x_{ki} + \varepsilon_i \qquad (5.3)$$

The estimated Least Squares regression model is

$$Y_i' = b_0 + b_1 x_{1i} + b_2 x_{2i} + ... + b_k x_{ki} \qquad (5.4)$$

where b_0, b_1, b_2, ... , b_k, are the Least Squares estimates of β_0, β_1, β_2, ..., β_k.

An important problem in many applications of regression analysis involves selecting the set of independent variables to be used in the model. Sometimes various experience or underlying theoretical considerations can help determine which of the independent variables should be used in a particular situation. Usually the problem consists of selecting the appropriate independent variables from a set that is quite likely to include many important variables, but not all of them are necessary to adequately estimate the model. In this case, the candidate independent variables are screened to obtain a regression model that contains the "best" subset of the independent variables. However, in most problems, no single regression model is "best" in terms of the various statistical evaluation criteria and a great deal of judgment and experience with the system being modelled is usually necessary to select the most appropriate set of the independent variables.

There are different methods of selecting those independent variables, which are most suitable for model development, including the forward selection method, the backward elimination method, and the stepwise regression method. In this research, the stepwise regression method was applied using the software package of *Statistical Package for Social Sciences* (SPSS - version 10.0).

5.2.2.b. The Stepwise Regression Method

Stepwise regression is probably the most widely used variable selection technique. It iteratively constructs a sequence of regression models by adding or removing independent variables at each step. The criterion of adding or removing a variable at any step is expressed in terms of pre-specified values of the partial F-test. It begins with forming a one-variable model using the independent variable that has the highest correlation with the dependent variable Y. This will also be the independent variable that produces the largest F-statistic. At the next step, the remaining independent variables are examined and the variable with largest partial F-statistic is added to the equation, provided that its partial F-statistic is larger than that of the pre-specified value for adding a variable. Then, the stepwise regression algorithm check if the first variable determined in the first step should be removed. This is done by calculating the partial F-statistic of the first variable in the regression model that contains both, the first and the added variables. If the partial F-statistic is smaller than that of the pre-specified value for removing a variable, then the first variable should be removed. Otherwise it is retained. The procedure continues until no other independent variable can be added to or removed from the model.

5.2.3. Diagnostic Checking

Diagnostic checking is the stage in which the estimated model is evaluated to determine how well it fits the data. The model accuracy is tested by further examining the chosen variables according to their contribution to the goodness of fit statistic and their physical relationships to each other; i.e. the problem of multicollinearity. In addition, the Durbin-Watson statistic is used to test the serial correlation in the error structure to improve the predictability of the models.

Methods used at this stage include statistics describing the residual series and plots describing the behaviour of the standardized predicted values of the pavement surface temperature. This information determines whether the model can be used with confidence, or whether another model should be identified.

5.2.3.a. Multicollinearity

The term multicollinearity is used to denote the presence of linear (or near linear) relationships among the independent variables. If two or more of the independent variables are perfectly correlated, that is, if the correlation coefficient for these variables is equal to unity, the parameters' estimates become indeterminate and the OLS method breaks down (Koutsoyiannis, 1967). The main consequences of multicollinearity are the following:

1. The precision of estimation falls so that it becomes very difficult, if not

impossible, to disentangle the relative influences of various independent variables. This loss of precision has three aspects: specific estimates may have very large errors; these errors may be highly correlated, one with another; and the sampling variances of the coefficients will be very large.

2. Investigators are sometimes led to drop variables incorrectly from the analysis because their coefficients are not significantly different from zero.
3. Coefficient estimates become very sensitive to a particular set of sample data, and the addition or subtraction of a few more observations can sometimes produce dramatic shifts in some of the coefficients.

To conduct collinearity diagnostic on the linear model, the eigenvalues can first be calculated by factoring the scaled (so that diagonal elements are 1's) and uncentered cross-products matrix of the independent variables. Eigenvalues provide an indication of how many distinct dimensions there are among the independent variables. When several eigenvalues are close to 0, the variables are highly intercorrelated and the matrix is said to be *ill conditioned*; small changes in the data values may lead to large changes in the estimates of the coefficients (SPSS, 2001). Secondly, condition indices (the square roots of the ratios of the largest eigenvalue to each successive eigenvalue) are checked. A condition index greater than 15 indicates a possible problem and an index greater than 30 suggests serious problem with Collinearity. A third test is to examine the variance proportions (the proportions of the variance of the estimate accounted for by each principal component associated with each of the eigenvalues). Collinearity is a definite problem when a component associated with a high condition index contributes substantially to the variance of two or more variables. In this case, the model structure should be re-examined.

5.2.3.b. *Autocorrelation*

The use of the Ordinary Least Squares Method to estimate a linear regression model of the form given by Equation (5.3) requires that the stochastic error ε_i satisfies the following three assumptions:

1. The mean of the stochastic error ε_i is zero.
2. The values of the stochastic error ε_i are uncorrelated.
3. The variance of the stochastic error ε_i is constant; equal to σ^2 (homoscedasticity).

While most engineers tend to rely only on the value of R^2, which is fairly high for all developed models, one should check the validity of these assumptions. The second assumption requires that the covariance of any two-error values at two different periods is zero, that is

$$Cov(\varepsilon_i, \varepsilon_j) = 0, \quad i \neq j \tag{5.5}$$

If this assumption is violated, i.e. errors are correlated, then the values of the error term are said to be autocorrelated and this phenomenon is known as autocorrelation (or serial correlation).

Autocorrelation can occur as a result of omitting one of the important explanatory variables, misspecification of the mathematical form of the model, or interpolation in the observations. It causes the sampling variances of the estimated coefficients to be very large as compared to other methods of estimation, resulting in the acceptance of the hypothesis that the estimated coefficients are not significantly different from zero even though it is not true. The most familiar test of autocorrelation in the error term is the Durbin-Watson statistic "d" (Johnston, 1972)

$$d = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2} \tag{5.6}$$

If $d = 2$, there is no serial correlation in the error term, if $d = 0$, there is perfect positive serial correlation.

- If $0 < d < 2$, there is some degree of positive serial correlation which gets stronger as d gets closer to zero.
- If $d = 4$, there is perfect negative serial correlation.
- If $2 < d < 4$, there is some degree of negative serial correlation which gets stronger as d gets closer to 4.

A problem in determining the sampling distribution of d is that it depends on the explanatory variable X. Durbin and Watson were only able to establish upper (d_U) and lower (d_L) limits for the significance levels of d (Johnston 1972). If $0 < d < 2$, these limits are used to test the hypothesis of no autocorrelation against the alternative hypothesis of positive first-order autocorrelation as follows:

- If $d < d_L$, reject the null hypothesis of no autocorrelation in favour of the hypothesis of positive autocorrelation.
- If $d > d_U$, do not reject the null hypothesis.
- If $d_L < d < d_U$, the test is inconclusive.

In case that $2 < d < 4$; the value of $(4 - d)$ is used to test against the alternative hypothesis of negative first-order autocorrelation. While the value of d_L increases as the sample size increases, the value of d_U decreases as the sample size increases. As a result, the gap between the values of the two limits gets closer as the sample size increases. Furthermore, the gap increases with the increase of the number of the explanatory variables.

5.3. Results and Analysis

As explained earlier, this thesis uses data collected by RWIS stations at the City of Ottawa during the winter season of 2001-2002 to study the relationship between the pavement surface temperature and weather variables. Only linear models were constructed since they have produced adequate results.

5.3.1. Location-Specific Models

Statistical models are developed for predicting pavement surface temperature during the winter months at the six locations selected in this thesis. First, the stepwise regression was used to eliminate those variables whose coefficient estimates were not significantly different from zero at 5% level of significance. Then the remaining variables were further examined according to their contribution to the criterion of best fit (coefficient of determination, R^2). Statisticians usually use the R^2 values adjusted with a factor depending on the number of observations and the number of independent variables, called adjusted R^2. Since the numbers of observations used to estimate the models in this thesis are very large, the values of R^2 are almost identical to those of the adjusted R^2 for at least three decimals. Therefore, the term R^2 used instead of adjusted R^2. Only those independent variables having a relatively measurable contribution to the model fitting R^2 were kept in the regression equation, and a final model for each location was recommended.

The model developing process at each location was carried out using the Statistical Package for Social Science (SPSS v10.0). The data from the RPU at Acres are used as an example to illustrate this process. Table 5.4 gives the results of the stepwise regression of pavement surface temperature on six independent variables; air temperature, dew point, relative humidity, wind speed, wind direction, and surface condition. The results show that all coefficients in the six models are significantly different from zero at a 5% level of significance, as given by the *t*-statistics, or alternatively, by the very low *p*-values (the probability of rejecting the null hypothesis H_0: $B = 0$, given it is true).

As shown in Table 5.4, the addition of independent variables beyond Model 2 yields only a minimal improvement in R^2. Based on the analysis presented in this example, it can be stated that air temperature and dew point (Model 2) explain 79% of the variations in the pavement surface temperature, a relatively high R^2 value. Adding more independent variables does not provide significant improvements to the model. The existence of multicollinearity in the model may distort the estimated variance of the random error in the regression equation. Therefore, collinearity diagnostic checking was performed using the SPSS v10.0 on the models estimated by the stepwise regression analysis.

Table 5.5 shows the collinearity diagnostics of those six models presented in Table 5.4. The last condition index of Model 6 is 172.75, significantly larger than 30. In addition, it accounts for 97% of the variance of the constant, 96% of the variance of the air temperature, 97% of the variance of the dew point, and 95% of the variance of the relative humidity.

Table 5.4: Coefficients of stepwise linear regression analysis (Acres RPU).

Model	Dim.	R2	Variables	Coefficients (B)	Std. Error	t-statistic	p-values
1	1	0.71	Constant	1.739	0.062	28.18	0.001
	2		Air Temperature	0.873	0.009	93.88	0.001
2	1	0.79	Constant	- 0.798	0.084	- 9.45	0.000
	2		Air Temperature	1.585	0.020	78.28	0.000
	3		Dew Point	- 0.733	0.019	- 38.15	0.000
3	1	0.80	Constant	13.401	1.131	11.85	0.000
	2		Air Temperature	1.456	0.022	65.25	0.000
	3		Dew Point	- 0.594	0.022	- 27.19	0.000
	4		Surface Condition	- 0.396	0.031	- 12.59	0.000
4	1	0.81	Constant	- 13.979	2.704	- 5.17	0.000
	2		Air Temperature	2.986	0.139	21.41	0.000
	3		Dew Point	- 2.181	0.144	- 15.10	0.000
	4		Surface Condition	- 0.448	0.031	- 14.33	0.000
	5		Relative Humidity	0.300	0.027	11.11	0.000
5	1	0.81	Constant	- 12.918	2.741	- 4.71	0.000
	2		Air Temperature	2.947	0.140	20.99	0.000
	3		Dew Point	- 2.138	0.146	- 14.68	0.000
	4		Surface Condition	- 0.445	0.031	- 14.21	0.000
	5		Relative Humidity	0.289	0.027	10.58	0.000
	6		Wind Speed	- 0.019	0.008	- 2.30	0.022
6	1	0.81	Constant	- 13.738	2.767	- 4.97	0.000
	2		Air Temperature	2.976	0.141	21.11	0.000
	3		Dew Point	- 2.166	0.146	- 14.82	0.000
	4		Surface Condition	- 0.444	0.031	- 14.19	0.000
	5		Relative Humidity	0.295	0.027	10.74	0.000
	6		Wind Speed	- 0.023	0.008	- 2.72	0.006
	7		Wind Direction	0.001	0.001	2.11	0.035

Dependent variable: pavement surface temperature

Table 5.5: Collinearity Diagnostics of stepwise linear regression analysis (Acres RPU).

Model	Dim.	Eigen-value	Cond. Index	Variance Proportions						
				Constant	Air Temp.	Dew Point	Surface Cond.	Rel. Hum.	Wind Speed	Wind Dir.
1	1	1.180	1.00	0.41	0.41					
	2	0.820	1.20	0.59	0.59					
2	1	2.108	1.00	0.03	0.02	0.02				
	2	0.836	1.59	0.31	0.05	0.00				
	3	0.057	6.09	0.66	0.93	0.98				
3	1	2.691	1.00	0.00	0.01	0.01	0.00			
	2	1.246	1.47	0.00	0.04	0.01	0.00			
	3	0.062	6.57	0.00	0.71	0.69	0.00			
	4	0.001	51.49	1.00	0.24	0.29	1.00			
4	1	3.495	1.00	0.00	0.00	0.00	0.00	0.00		
	2	1.415	1.57	0.00	0.00	0.00	0.00	0.00		
	3	0.089	6.26	0.00	0.01	0.01	0.00	0.00		
	4	0.001	49.92	0.03	0.03	0.02	0.99	0.05		
	5	0.0002	140.29	0.97	0.96	0.97	0.01	0.95		
5	1	4.198	1.00	0.00	0.00	0.00	0.00	0.00	0.01	
	2	1.498	1.67	0.00	0.00	0.00	0.00	0.00	0.01	
	3	0.230	4.27	0.00	0.00	0.00	0.00	0.00	0.70	
	4	0.073	7.58	0.00	0.01	0.01	0.00	0.00	0.26	
	5	0.001	54.75	0.03	0.03	0.02	0.99	0.05	0.00	
	6	0.0002	155.87	0.97	0.96	0.97	0.01	0.95	0.03	
6	1	5.079	1.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	2	1.515	1.83	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	3	0.230	4.70	0.00	0.00	0.00	0.00	0.00	0.64	0.00
	4	0.106	6.91	0.00	0.00	0.00	0.00	0.00	0.21	0.80
	5	0.068	8.62	0.00	0.01	0.01	0.00	0.00	0.11	0.18
	6	0.001	60.26	0.03	0.03	0.02	0.99	0.05	0.00	0.00
	7	0.0002	172.75	0.97	0.96	0.97	0.01	0.95	0.02	0.01

These results indicate a serious multicollinearity Model 6 as explained in Section 5.2.3.a. Other models with fewer independent variables were examined. Models 5, 4 and

3 also show serious multicollinearities since their condition indices of 155.87, 140.29, and 51.49 respectively, are larger than 30 and Models 5 and 4 have components that substantially contribute to the variance of two or more variables. Consequently, Model 2 with only air temperature and dew point as independent variables was considered to be statistically more suitable than the other four models.

Stepwise regression analyses performed at the other five locations are presented in Tables A.1 – A.5 of Appendix A. As in the case of Acres road, the addition of independent variables beyond the air temperature and dew point (Model 2) in the other locations, but Plaza Bridge, yields a minimal improvement to R^2. The only two independent variables that were statistically significant for the Plaza Bridge models were the air temperature and the surface condition (Table A.4). The value of R^2 for Model 2 at Vars, Trim, and North Gower RPU locations was 0.83, and was 0.82 at Hawthorne RPU. In case of Plaza Bridge RPU, R^2 was 0.66, which is relatively lower than all other RPU locations. The City of Ottawa officials confirmed that there were technical difficulties with the sensors and equipment at this RPU during 2001/2002. Therefore, data from this location were not included in the calculation of the Ottawa-wide data. Table 5.6 gives the estimated coefficients and test statistics for the six models, which will be referred to as location-specific models.

The collinearity diagnostics of the estimated models at the other five locations are shown in Tables B.1 – B.5 of Appendix. Tables B.2 and B.3 showed that Trim and North Gower RPU locations had similar trends to that of Acres RPU, that is, adding any independent variable other than air temperature And dew point to the model will induce a serious multicollinearity.

Table 5.6: Summary of multiple linear regression of location specific models.

Model	RPU	R^2	D-W statistic	Variables	Coeff. (B)	t-statistic	p-value
I	Vars	0.83	0.14	Constant	- 2.112	- 21.26	0.000
				Air Temperature	1.503	78.60	0.000
				Dew Point	- 0.686	- 36.13	0.000
II	Acres	0.79	0.13	Constant	- 0.806	- 9.55	0.000
				Air Temperature	1.590	78.39	0.000
				Dew Point	- 0.738	- 38.34	0.000
III	Trim	0.83	0.15	Constant	- 0.150	- 2.05	0.041
				Air Temperature	1.386	87.70	0.000
				Dew Point	- 0.527	- 36.02	0.000
IV	North Gower	0.83	0.20	Constant	- 1.085	- 12.20	0.000
				Air Temperature	1.381	86.74	0.000
				Dew Point	- 0.551	- 36.28	0.000
V	Hawthorne	0.82	0.15	Constant	- 0.061	- 0.84	0.402
				Air Temperature	1.446	75.67	0.000
				Dew Point	- 0.602	- 32.78	0.000
VI	Plaza Bridge	0.66	0.10	Constant	42.357	22.04	0.000
				Air Temperature	0.811	45.01	0.000
				Surface Cond.	- 1.175	- 21.28	0.640
VII	Ottawa-wide	0.84	0.12	Constant	- 1.058	- 13.29	0.000
				Air Temperature	1.514	88.47	0.000
				Dew Point	- 0.664	- 40.57	0.000

The collinearity diagnostic results of the estimated stepwise regression models at Vars RPU indicates that the use of wind speed in addition to air temperature and dew point would not cause any serious multicollinearity in the model (Table B.1). However, Table A.1 shows that wind speed does not improve the model since R^2 remains the same in Models 2 and 3.

The collinearity diagnostic of the stepwise regression models at Hawthorne RPU shows that the wind direction, surface condition, and wind speed can be added to the air temperature and dew point without inducing any serious multicollinearity in the estimated model. Again, Table A.5 shows that adding any of these independent variables to Model 2 would not improve R^2.

Finally, the collinearity diagnostic of the stepwise regression models at Plaza Bridge RPU in Table B.4 Shows that only Model 1 with the air temperature can be used as an independent variable to estimate the surface temperature. The condition index of the surface condition in Model 2 is 55.52, which is larger than 30, and the variance proportions of the constant and the surface condition are 1.00. The surface condition is highly collinear with the air temperature at the Plaza Bridge RPU. The model with only air temperature as an independent variable has a low R^2 value of 0.56. Therefore, no further analysis or consideration will be given to modelling the Plaza Bridge RPU.

As a result of the above analysis, model 2 with air temperature and dew point as independent variables was considered to be the most suitable formulation to estimate the pavement surface temperature at all RPU locations.

5.3.2. Ottawa-Wide Aggregate Model

Although each of the models presented in the previous section correspond to a specific location, they all fall in the City of Ottawa, which is not geographically very large. Therefore, it was thought that one model could be developed to represent the whole City of Ottawa by pooling all data corresponding to the five locations, hence referred to as Ottawa-wide model. The Ottawa-wide model is estimated by regressing the average pavement surface temperature on the averages of air temperature and dew point at the five RPU locations as independent variables. The estimated model is presented as Model VII in Table 5.6. The value of R^2 is 0.84 and the estimated coefficients are statistically different from zero at 5% level of significance.

5.3.3. Tests of Autocorrelation

The values of the Durbin Watson statistic for all location-specific models as well as Ottawa-wide model are very low ranging from 0.12 for Ottawa-wide model to 0.20 for North Gower model, which indicates a serious autocorrelation in the six models. A first order autocorrelation correction using the Cochrane-Orcutt (1949) method was tried on all models but did not improve any of them.

The examination of the regression assumptions can also be illustrated visually using the residual plots that can be readily provided by SPSS. All six models have shown same pattern of behaviour. An example is given in Figure 5.6 using the spread of the observed surface temperature for the Ottawa-wide versus the standardized predicted surface temperature.

Figure 5.6 clearly shows that the error of regression increases as the surface temperature increases, indicating that the variance of the regression error is not constant, which is a violation of the third assumption mentioned in Section 5.3.2.b (homoscedasticity).

5.4. Summary and Results

The prediction of pavement surface temperature is very important to plan and execute winter maintenance activities, which in turn impacts on road safety. Previous attempts were undertaken using regression analyses to develop prediction models by relating the surface temperature to weather variables and surface condition

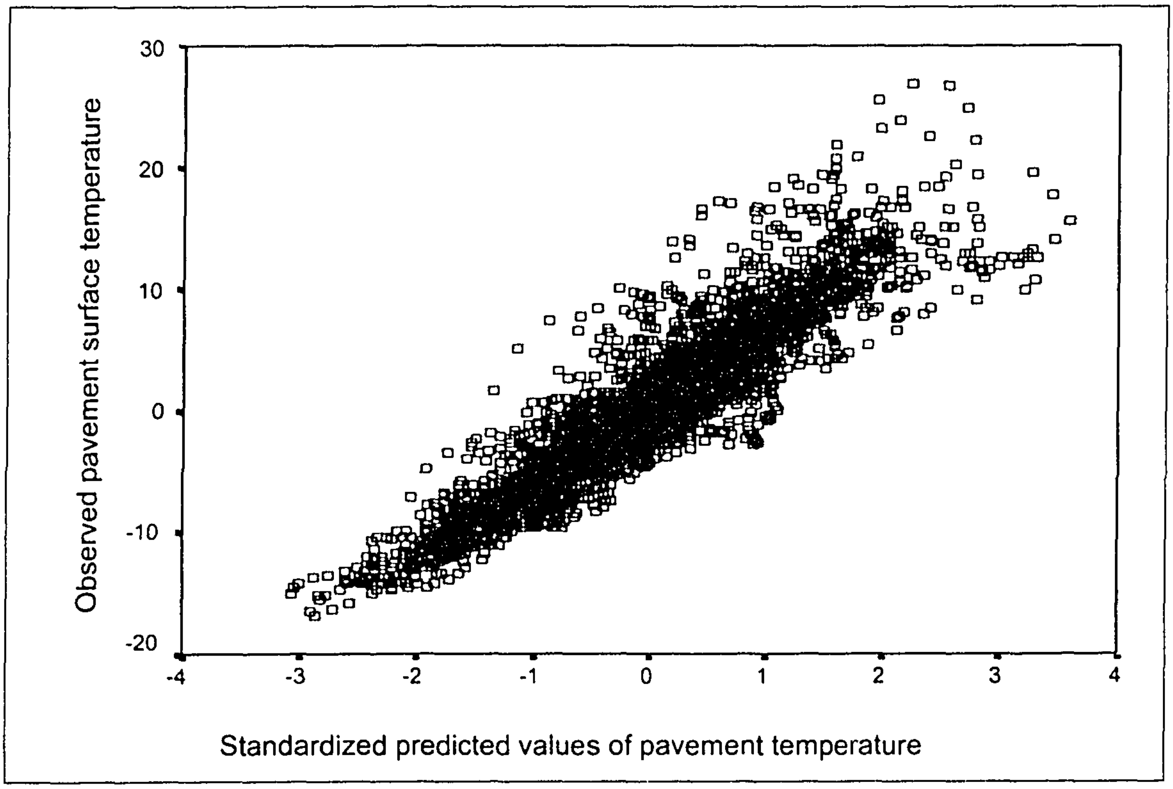


Figure 5.6: Scatter of observed dependent variable versus standardized predicted dependent variable with no LDV (Ottawa-wide)

Many of these models were cumbersome and require an enormous amount of data, which made them very expensive to build and maintain. In addition, a review of the literature did not show any attempt to apply thorough statistical tests to the basic assumptions of the regression methods.

In this chapter, low cost simple linear regression models were developed using data from the RWIS at six different RPU locations in the City of Ottawa. These models are capable of predicting the pavement surface temperature from the knowledge of weather variables. The stepwise regression analysis was first applied to determine those models having coefficients significantly different from zero at 5% level of significance. Then collinearity diagnostic tests were undertaken to improve the predictability of the models by excluding those independent variables that induce serious multicollinearity.

The results concluded that the air temperature and dew point could be used as independent variables in a linear regression model to predict the surface temperature. The value of R^2 was relatively high at about 0.80 for five out of the six RPU locations. Plaza Bridge RPU location had low value of R^2 (0.66) and technical difficulties with the sensors and equipment during the study period were reported at this location. No further consideration will be given to the Bridge Plaza RPU.

The averages of the surface temperature, air temperature, and dew point were calculated at each hour using data from the remaining five RPU locations to obtain Ottawa-wide observations. The Ottawa-wide estimated model had R^2 value of 0.84.

Finally, D-W statistic was used to test for the autocorrelation in the error structure of the models. All location-specific models as well as Ottawa-wide model have shown serious autocorrelations. A first order autocorrelation correction using the Cochrane-Orcutt method was tried on all models but did not improve any of them. In addition, all the models were found to violate the homoscedasticity condition (constant variance of the error term in the linear regression model). The next chapter presents additional measures taken to reduce the autocorrelation in the models and improve their predictability by adding time lag dependent variables to the independent variables.

6. REVISED PAVEMENT TEMPERATURE MODELS: TIME LAG DEPENDENT VARIABLES

Many engineering processes are dynamic and of continuous adjustment. Clearly an adjustment process takes time, and the length of adjusting time period depends upon the nature of the particular phenomenon. For example, in a problem like the one studied in this thesis, it is obvious that the pavement surface temperature at any time will depend not only on the weather variables but also on the surface temperature at earlier times (referred to as lag dependent variable, LDV). Lagged values of the dependent variables are therefore, important explanatory variables in many of the engineering relationships, since the behaviour of the dependent variable in any one period can, to a great extent, be determined by past pattern of the behaviour.

6.1. Lag Dependent Variables

In view of the nature of dynamic behaviour of some engineering materials, realistic model formulation of explaining their behaviour should involve some lag dependent variables among the set of the explanatory variables. This is one way for taking into account the length of time in the adjustment processes of material behaviour and perhaps the most efficient way for rendering them dynamic. The pattern of lags is determined from the available sample observations, by adopting an experimental approach of models including different lags and then choosing the one that gives the most satisfactory fit on the basis of statistical criteria.

Including lagged dependent variables among the set of the explanatory variables, however, causes some of the main assumption for using the Ordinary Least Squares

(OLS) method to break down. First, the error terms in the model will be autocorrelated. Secondly, the lag dependent variables are correlated with the errors, causing the OLS estimates to be biased in small samples, and that these estimates become statistically inconsistent. In general, adding a LDV as an independent variable would invalidate the use of D-W statistic as a measure for autocorrelation. However, when the absolute value of the estimated coefficient of the LDV is less than one, the LDV may be treated as ordinary independent variables for large samples (Theil, 1971). Nerlove and Wallis (1966) found that the classical D-W Statistic is biased towards 2 (its asymptotic value in the absence of autocorrelation) if a lagged dependent variable appears among the set of the independent variables. Malinvaud (1966) has shown that the bias in the D-W statistic tends to decrease if apart from the lagged dependent variable there are exogenous variables in the model. Taylor and Wilson (1964) have tested the power of the D-W statistic in detecting autocorrelation within various models having first and second order lagged dependent variables with various values of R^2 and found that the D-W statistic performs well when the sample size was large or when R^2 is large.

Durbin developed a large sample test for autocorrelation when lagged dependent variables are present (Theil, 1971). A great advantage of that test is that the statistics required for its computation are generated routinely in OLS applications. Let e_t, $t = 1, \ldots, n$, denote the OLS residuals from the fitted regression. Define

$$r = \frac{\sum_{t=2}^{n} e_t e_{t-1}}{\sum_{t=1}^{n-1} e_t^2} \tag{6.1}$$

This is the estimated first-order autocorrelation coefficient of the residuals. An approximation of r can be obtained from

$$r \cong 1 - \frac{1}{2}d \tag{6.2}$$

where d is the conventional Durbin-Watson Statistic given by Equation 5.6. A test statistic h can be computed from r as follows:

$$h = r\sqrt{\frac{n}{1 - n\hat{V}(b_1)}} \tag{6.3}$$

where $\hat{V}(b_1)$ is sampling variance of b_1, *the coefficient of* Y_{t-1}, *in the simple* least-squares regression and the square root is a correction factor to r (Johnston, 1972).

The statistic h is then tested as a standard normal deviate. If $h > 1.645$, the hypothesis of zero autocorrelation is rejected at 5% level of significance. The correction to r that leads to this test merely involves the estimated variance of b_l. This is perfectly general and does not depend on the number of independent variables or the number of other lagged variables of Y, such as Y_{t-2}, Y_{t-3}, … which appear in the equation. Only the variance of the coefficient of Y_{t-1} is required. This test is applicable only for large samples ($n > 30$).

The use of the lag-dependent variables further enhanced the fitting of the models in addition to reducing the autocorrelation in the error structures. The final forms of the estimated models using the lag dependent variables are capable of more accurately predicting pavement surface temperatures from the knowledge of the weather variables.

6.2. Model Development

6.2.1. One Lag Dependent Variable (LDV1)

Table 6.1 gives all the seven models using one LDV, which shows an improvement in the value of R^2 by at least 14% in each model. The values of the t-

statistic also show that the first LDV is in fact the most important predictor among the independent variables in all seven models. However, adding the first LDV to the independent variables has resulted in changes to the significance of the estimated coefficients of the dew point.

Table 6.1: Summary of multiple linear regression models with one LDV.

Model	RPU	R^2	D-W Statistic	Variables	Coeff. (B)	t-statistic	p-value
I	Vars	0.96	0.43	*Constant*	- 0.076	- 1.40	0.163
				Air Temperature	0.124	7.45	0.000
				Dew Point	- 0.040	- 3.42	0.001
				TLDV1‡	0.895	101.89	0.000
II	Acres	0.95	0.44	*Constant*	0.092	2.19	0.029
				Air Temperature	0.074	4.32	0.000
				Dew Point	- 0.011	- 0.95	0.344
				TLDV1‡	0.921	107.49	0.000
III	Trim	0.95	0.47	*Constant*	0.129	3.41	0.001
				Air Temperature	0.087	5.67	0.000
				Dew Point	- 0.011	- 1.17	0.242
				TLDV1‡	0.907	99.33	0.000
IV	North Gower	0.95	0.76	*Constant*	- 0.101	- 1.97	0.049
				Air Temperature	0.209	12.18	0.000
				Dew Point	- 0.073	- 7.05	0.000
				TLDV1‡	0.839	79.61	0.000
V	Hawthorne	0.95	0.46	*Constant*	0.104	2.79	0.005
				Air Temperature	0.097	5.45	0.000
				Dew Point	- 0.019	- 1.71	0.088
				TLDV1‡	0.905	89.95	0.000
VI	Ottawa-Wide	0.96	0.34	*Constant*	0.062	1.46	0.145
				Air Temperature	0.093	5.58	0.000
				Dew Point	- 0.019	- 1.81	0.071
				TLDV1‡	0.910	100.04	0.000

‡ TLDV1 is the surface temperatures one hour before the time the surface temperature is estimated.

The p-values in Table 6.1 can be used to test the hypothesis that an estimated coefficient of any variable is not significantly different from zero at 5% level of significance. Based on the results in Table 6.1, this hypothesis cannot be rejected for the dew point in all models except Vars and North Gower. Therefore, further analysis of the models will be considered. By comparing the values of Durbin-Watson statistic of the models estimated in Table 5.7 to those estimated with one LDV in Table 6.1, there has been a substantial improvement in the reduction of autocorrelation. The improvement ranges from 188% for Ottawa-wide model up to 280% for the North Gower model. Figure 6.1 gives an example of the scatter diagram of the pavement temperature versus the standardized predicted pavement temperature for the Ottawa-wide model with one LDV.

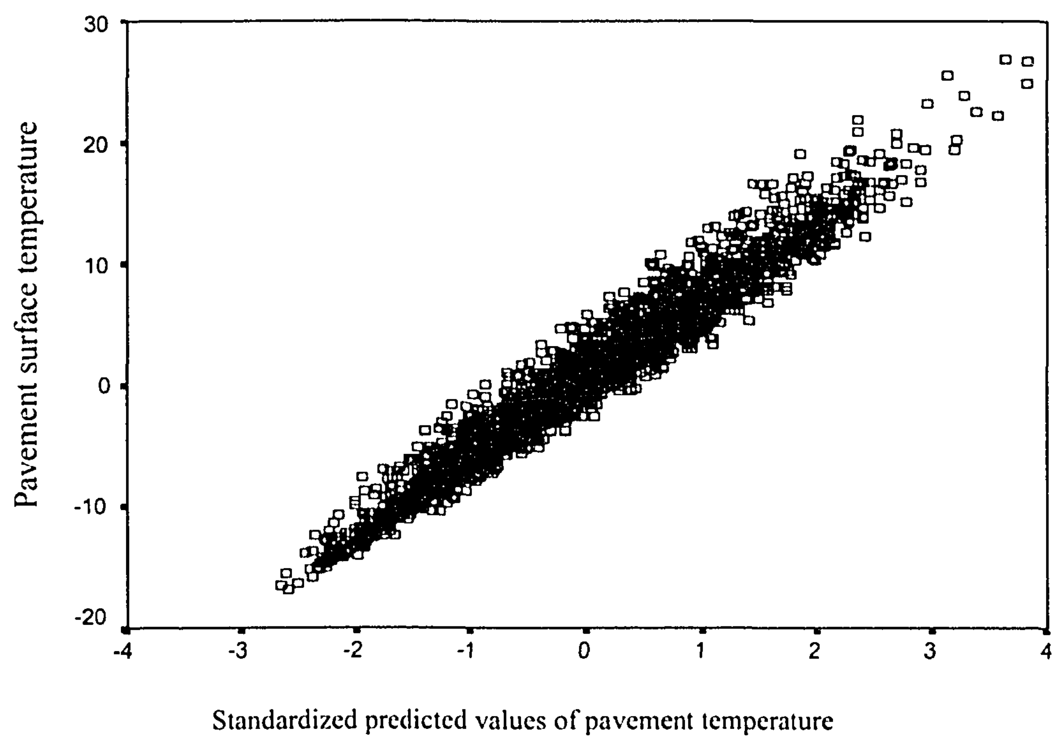


Figure 6.1: Scatter of observed dependent variable versus standardized predicted dependent variable with one LDV (Ottawa)

A comparison of Figure 6.1 to Figure 5.6 shows that the problem of homoscedasticity has been improved substantially and the estimation errors have been reduced. Same pattern of behaviour was repeated in all other model. The collinearity diagnostic of the six models with one LDV is presented in Table 6.2.

Table 6.2: Collinearity diagnostics of models with one LDV

RPU	Dim.	Eigen value	Condition Index	Variance Proportions			
				Constant	Air Temp.	Dew Point	TLDV1
Vars	1	2.672	1.00	0.01	0.01	0.01	0.01
	2	1.126	1.54	0.11	0.00	0.00	0.03
	3	0.181	3.84	0.21	0.03	0.06	0.41
	4	0.021	11.40	0.68	0.97	0.93	0.55
Acres	1	2.542	1.00	0.01	0.01	0.01	0.02
	2	1.202	1.65	0.19	0.00	0.00	0.04
	3	0.230	3.32	0.40	0.01	0.07	0.34
	4	0.026	9.88	0.41	0.98	0.91	0.60
Trim	1	2.562	1.00	0.01	0.01	0.01	0.01
	2	1.209	1.46	0.19	0.00	0.00	0.03
	3	0.200	3.58	0.56	0.01	0.13	0.28
	4	0.029	9.34	0.24	0.98	0.86	0.67
North Gower	1	2.301	1.00	0.00	0.01	0.01	0.02
	2	1.441	1.26	0.13	0.00	0.01	0.02
	3	0.222	3.22	0.44	0.01	0.12	0.28
	4	0.036	8.05	0.43	0.97	0.85	0.68
Hawthorne	1	2.450	1.00	0.00	0.01	0.01	0.02
	2	1.285	1.38	0.26	0.00	0.01	0.02
	3	0.233	3.24	0.54	0.00	0.13	0.28
	4	0.032	8.72	0.20	0.99	0.85	0.68
Ottawa	1	2.597	1.00	0.01	0.01	0.01	0.01
	2	1.184	1.48	0.16	0.00	0.00	0.03
	3	0.196	3.64	0.38	0.01	0.09	0.30
	4	0.023	10.71	0.45	0.98	0.90	0.65

From the examination of the condition indices and the variance proportions, there is no serious multicollinearity in any of the six models. Therefore, these models would be considered superior in predicting the pavement surface condition to those estimated in Table 5.7.

6.2.2. Two Lag Dependent Variables (LDV2)

Another set of regression models were developed using two LDVs. The results of the estimated models are presented in Table 6.3. The t-statistic or alternatively the p-statistic shows that all the coefficients of the six models are significantly different from zero at 5% level of significance. The values of R^2 have further improved reaching 0.99 for the Ottawa-wide model. The h-statistic defined above is used to test the autocorrelation in the estimated models. All models show the continuing existence of autocorrelation, however, the scatter graphs of the observed surface temperature vs. the standardized predicted surface temperature have shown smaller estimation errors and large improvement in homoscedasticity over those of the models with one LDV. An example is shown by comparing the Ottawa-wide model with two LDVs in Figure 6.2 with the Ottawa-wide model with one LDV in Figure 6.1

Finally, Table 6.4 presents the collinearity diagnostic of the models with two LDVs. An examination of the condition indices and the variance proportions indicates that there is no serious multicollinearity in any of the estimated models.

The above results conclude that the models developed in Table 6.3 with two LDVs are far superior to those with one LDV and with no LDV. They include only two independent variables, air temperature and dew point. The historical values of these variables are usually available from a RWIS and their forecasts are produced by the central governments. The cost of estimating and maintaining these models is very low and they possess relatively higher R^2, less autocorrelation, no serious multicollinearity, and relatively stable homoscedasticity.

Table 6.3: Summary of multiple linear regression models with two LDVs.

Model	RPU	R^2	*h*-statistic	Variables	Coeff. (*B*)	*t*-statistic	*p*-value
I	Vars	0.98	7.47	*Constant*	0.004	0.13	0.894
				Air Temperature	0.122	12.45	0.000
				Dew Point	- 0.025	- 3.59	0.000
				TLDV1‡	1.664	156.01	0.000
				TLDV2‡	- 0.797	- 82.45	0.000
II	Acres	0.98	7.93	*Constant*	0.094	3.84	0.000
				Air Temperature	0.134	13.33	0.000
				Dew Point	- 0.034	- 5.09	0.000
				TLDV1‡	1.676	162.57	0.000
				TLDV2‡	- 0.808	- 83.70	0.000
III	Trim	0.98	4.34	*Constant*	0.158	6.89	0.000
				Air Temperature	0.129	13.80	0.000
				Dew Point	- 0.022	- 3.93	0.000
				TLDV1‡	1.648	150.48	0.000
				TLDV2‡	- 0.788	- 78.37	0.000
IV	North Gower	0.97	7.56	*Constant*	0.017	0.42	0.673
				Air Temperature	0.187	14.00	0.000
				Dew Point	- 0.053	- 6.51	0.000
				TLDV1‡	1.437	89.25	0.000
				TLDV2‡	- 0.610	- 43.14	0.000
V	Hawthorne	0.98	6.83	*Constant*	0.137	6.16	0.000
				Air Temperature	0.149	13.98	0.000
				Dew Point	- 0.037	- 5.43	0.000
				TLDV1‡	1.648	137.34	0.000
				TLDV2‡	- 0.795	- 71.50	0.000
VI	Ottawa Wide	0.99	16.93	*Constant*	0.096	4.43	0.000
				Air Temperature	0.120	14.01	0.000
				Dew Point	- 0.022	- 4.11	0.000
				TLDV1‡	1.721	185.91	0.000
				TLDV2‡	- 0.851	-101.30	0.000

‡ TLDV1 and TLDV2 are the surface temperatures one hour and two hours respectively before the time the surface temperature is estimated.

Table 6.4: Collinearity diagnostics of models with two LDVs

RPU	Dim.	Eigen value	Cond. Index	Variance Proportions				
				Const.	Air Temp.	Dew Point	TLDV1	TLDV2
Vars	1	3.417	1.00	0.00	0.00	0.00	0.00	0.00
	2	1.302	1.62	0.09	0.00	0.01	0.00	0.00
	3	0.236	3.81	0.20	0.04	0.05	0.02	0.03
	4	0.027	11.21	0.28	0.31	0.35	0.28	0.61
	5	0.018	13.73	0.42	0.64	0.59	0.69	0.35
Acres	1	3.249	1.00	0.00	0.00	0.00	0.00	0.00
	2	1.407	1.52	0.15	0.00	0.01	0.00	0.00
	3	0.291	3.34	0.42	0.03	0.05	0.02	0.02
	4	0.030	10.41	0.29	0.58	0.59	0.12	0.44
	5	0.023	12.01	0.14	0.39	0.35	0.86	0.53
Trim	1	3.265	1.00	0.00	0.00	0.01	0.00	0.00
	2	1.433	1.51	0.16	0.00	0.01	0.00	0.00
	3	0.246	3.65	0.57	0.03	0.09	0.02	0.02
	4	0.034	9.79	0.23	0.74	0.71	0.02	0.26
	5	0.021	12.34	0.04	0.23	0.18	0.96	0.71
North Gower	1	3.053	1.00	0.00	0.01	0.00	0.00	0.01
	2	1.600	1.38	0.10	0.00	0.02	0.00	0.00
	3	0.278	3.31	0.41	0.04	0.08	0.02	0.03
	4	0.045	8.20	0.37	0.63	0.63	0.02	0.27
	5	0.023	11.51	0.12	0.33	0.26	0.96	0.69
Hawthorne	1	3.223	1.00	0.00	0.00	0.01	0.00	0.00
	2	1.422	1.51	0.21	0.00	0.02	0.00	0.00
	3	0.296	3.30	0.56	0.02	0.10	0.02	0.02
	4	0.037	9.37	0.21	0.82	0.76	0.00	0.19
	5	0.022	12.11	0.02	0.16	0.12	0.98	0.78
Ottawa	1	3.320	1.00	0.00	0.00	0.00	0.00	0.00
	2	1.386	1.55	0.13	0.00	0.01	0.00	0.00
	3	0.247	3.67	0.38	0.03	0.06	0.02	0.03
	4	0.028	10.87	0.29	0.50	0.52	0.12	0.47
	5	0.019	13.27	0.19	0.47	0.41	0.85	0.49

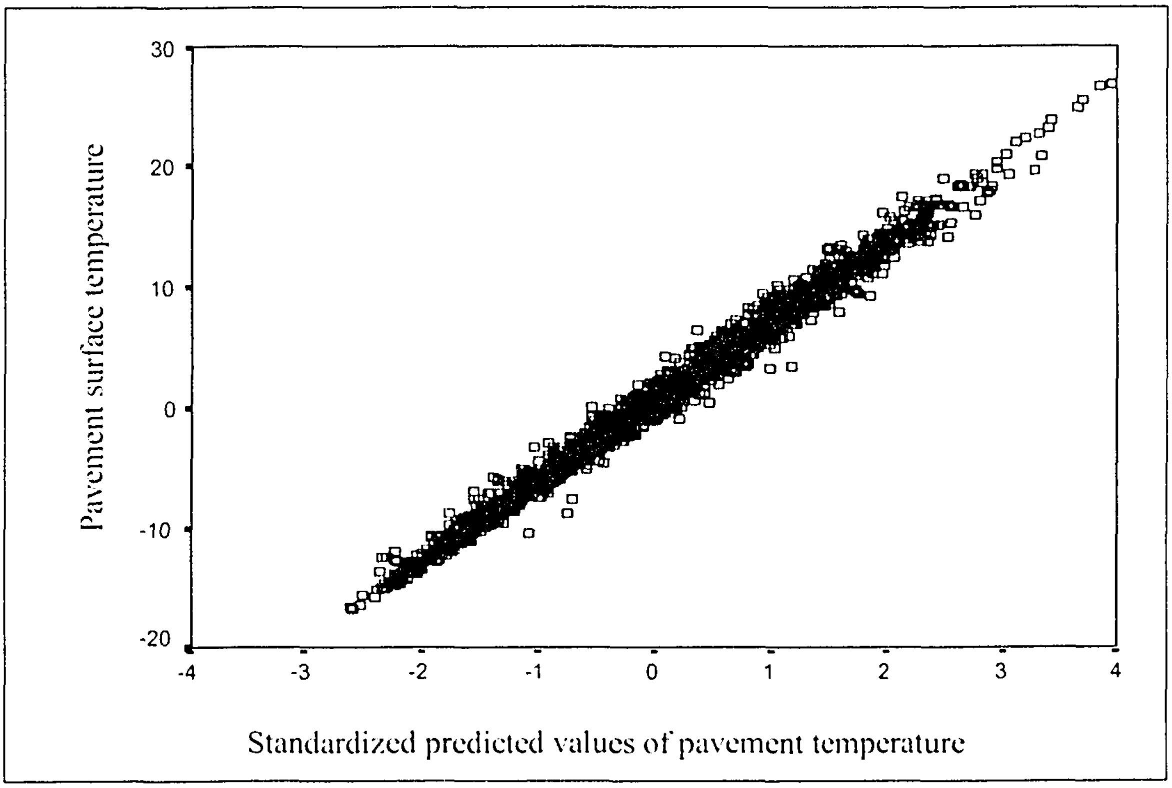


Figure 6.2: Scatter of observed dependent variable versus standardized predicted dependent variable with two LDVs (Ottawa)

7. CASE STUDY

In order to check the applicability and reliability of the models developed in this thesis, officials at the City of Ottawa were asked to choose a day at random during the winter of 2003 and provide the following information:

1. The periodic air temperature and dew point forecast produced by Environment Canada at any RPU location for that specific day.
2. The real hourly pavement surface temperature measured by the RWIS for that day.
3. The collision records in the City of Ottawa during that day.

Data for Monday January 13, 2003 at Trim Road RPU were provided. Environment Canada's weather forecast was issued at 5:33 am for 48 hours from 6:00 am on January 13, 2003, until 6:00 on January 15, 2003. This forecast contained, among other things, the air temperature and dew point for periods of 3 hours each, i.e. 6 am, 9 am, 12 pm, 3 pm, ... etc. The next update was issued at 2:35 pm on January 13, 2003, for a new 48 hours starting at 3:00 pm. A file of vehicle collisions obtained from the police records of the City of Ottawa for January 13, 2003. Copies of the weather forecast and vehicle collisions for the City of Ottawa on January 13, 2003 are given in Appendix C. The weather forecast predicted wet condition during all the day.

7.1. Prediction of Pavement Surface Temperature

In order to predict the pavement surface temperature in the City of Ottawa, the values of the air temperature and dew point were interpolated linearly between each two consecutive observations. Although it is expected that the Trim road models (Models III in Tables 5.6, 6.2 and 6.3) would provide the most accurate results, the case study utilized Ottawa-wide models (Models VII, VI, and VI in Tables 5.6, 6.1, and 6.3 respectively), to predict surface temperatures as a general application. The three models were verified using the hourly-observed pavement surface temperatures on Monday January 13, 2003 and the hourly forecasts of the air temperature and dew point. Table 7.1 gives the predicted values of the surface temperature every hour using the no-lag, one-lag, and two-lag models.

Table 7.1: Predicted surface temperature for the City of Ottawa using hourly-forecast values of air temperature and dew point (January 13, 2003)

Hour	Observed Surface Temp.	Air Temp.	Dew Point	Predicted surface temperature		
				No- Lag Model	One- Lag Model†	Two- Lag Model†
5:00	−6.53	...	...	...	...	...
6:00	−6.20	−8.00	−9.00	−7.19	−6.45	...
7:00	−6.20	−7.67	−8.67	−6.91	−6.13	−5.75
8:00	−6.18	−7.33	−8.33	−6.62	−6.10	−5.99
9:00	−4.94	−7.00	−8.00	−6.34	−6.06	−5.93
10:00	−4.75	−6.00	−8.67	−4.39	−4.83	−3.68
11:00	−3.40	−5.00	−9.33	−2.43	−4.55	−4.27
12:00	−2.33	−4.00	−10.00	−0.47	−3.21	−1.97
13:00	−0.43	−5.67	−12.33	−1.46	−2.35	−1.43
14:00	−0.72	−7.34	−14.66	−2.44	−0.73	0.78
15:00	−0.13	−9.00	−17.00	−3.40	0.20	1.00
16:00	−3.00	−9.67	−18.00	−3.75	−0.61	−1.50
17:00	−6.14	−10.33	−19.00	−4.08	−3.27	−5.78
18:00	−11.38	−11.00	−20.00	−4.43	−6.17	−8.80
19:00	−10.37	−12.00	−20.33	−5.73	−11.02	−15.26
20:00	−11.38	−13.00	−20.67	−7.02	−10.19	−9.17
21:00	−12.04	−14.00	−21.00	−8.31	−11.20	−11.88

† All lags used at each hour were the observed surface temperatures at the previous hour(s).

Table 7.2 shows the errors of prediction in the three cases. For the prediction period, the average of the absolute values of prediction errors in the no-lag model was on average 78.9% and 92.4% higher than those in the one-lag and two-lag models respectively. Similarly, the standard deviation of the absolute values of prediction errors in the no-lag model was 41.9% and 50.0% higher than the standard deviations of the absolute values of prediction errors of the one-lag and two-lag models respectively. It is clear from the results that the two-lag model is superior to both the no-lag and the one-lag models.

Table 7.2: Errors in predicted surface temperature for the City of Ottawa using forecast values of air temperature and dew point and observed values of surface temperature (January 13, 2003)

Hour	Absolute values of prediction errors		
	No-Lag Model	One-Lag Model	Two-Lag Model
6:00	0.99	0.25	...
7:00	0.71	0.07	0.45
8:00	0.44	0.08	0.19
9:00	1.40	1.12	0.99
10:00	0.36	0.08	1.07
11:00	0.97	1.15	0.87
12:00	1.86	0.88	0.36
13:00	1.03	1.92	1.00
14:00	3.16	1.45	0.06
15:00	3.27	0.33	1.13
16:00	0.75	2.39	1.50
17:00	2.06	2.87	0.36
18:00	6.95	5.21	2.58
19:00	4.64	0.65	4.89
20:00	4.36	1.19	2.21
21:00	3.73	0.84	0.16
Average	2.29	1.28	1.19
Std. Deviation	1.83	1.29	1.22

The one-lag model was used to predict hourly pavement surface temperature from the first hour lag value. The predicted values were compared to the observed values and the predicted errors were calculated and presented in Table 7.3. The next hour, as the surface temperature becomes available, it replaces the first predicted value and the remaining surface temperatures are re-calculated. For example, the first value in the 6:00 O'clock prediction of surface temperature was calculated using the observed value of the surface temperature at 5:00 O'clock. The predicted surface temperature at 6:00 O'clock was then used to generate the 7:00 O'clock predicted value, which in turn was used to generate the 8:00 O'clock predicted value, and so on. The difference between the observed surface temperature and the predicted one (prediction error) at each hour was calculated and given in the 2nd column of Table 7.3. After one hour, the observed value of the surface temperature at 6:00 O'clock was available and could be used, instead of the predicted value at 6:00 O'clock, to predict the surface temperature at 7:00 O'clock. The predicted surface temperature at 7:00 O'clock was then used to predict the 8:00 O'clock surface temperature, which in turn was used to generate the 9:00 O'clock predicted value, and so on. The predicted error at each hour was calculated and given in the 3rd column of Table 7.3. The same process was repeated until 12 O'clock.

The prediction errors at each hour in Table 7.3 are, more or less, of the same order of magnitude. This means that the values predicted by the model using observations of surface temperature are very close to those generated within the model itself using the predicted values, and therefore the prediction errors are most likely to have been occurred from the difference between the forecasted values of the air temperature and dew point and the real observations.

Table 7.3: Errors in predicted surface temperature in the City of Ottawa using forecast values of air temperature and dew point updated every hour in the one-lag model (January 13, 2003)

Hour	Errors in predicted surface temperatures†						
	6 O'clock	7 O'clock	8 O'clock	9 O'clock	10 O'clock	11 O'clock	12 O'clock
6:00	0.25	...	...	...	...	...	...
7:00	0.16	−0.07	...	...	...	...	...
8:00	0.07	−0.14	−0.08	...	...	...	...
9:00	1.18	0.99	1.05	1.12	...	...	...
10:00	1.15	0.98	1.03	1.10	0.08	...	...
11:00	2.19	2.04	2.09	2.15	1.22	1.15	...
12:00	2.88	2.74	2.79	2.84	1.99	1.93	0.88
13:00	4.54	4.41	4.46	4.51	3.73	3.68	2.72
14:00	5.58	5.47	5.51	5.56	4.85	4.80	3.93
15:00	4.74	4.64	4.68	4.73	4.08	4.03	3.24
16:00	1.93	1.84	1.87	1.92	1.33	1.28	0.56
17:00	−1.12	−1.20	−1.17	−1.13	−1.66	−1.71	−2.36
18:00	−6.23	−6.30	−6.28	−6.24	−6.72	−6.77	−7.36
19:00	−5.02	−5.08	−5.06	−5.02	−5.46	−5.51	−6.04
20:00	−5.76	−5.81	−5.79	−5.76	−6.16	−6.20	−6.69
21:00	−6.08	−6.13	−6.11	−6.08	−6.45	−6.49	−6.93

† Observed surface temperature was used in first hour lag value only.

Similar process was repeated for the two-lag model and similar conclusion was reached. The results of the two-lag model are presented in Table 7.4.

Finally, the two-lag model was used assuming that no observed lagged values of surface temperature were available. The first value at 6:00 O'clock was predicted from the surface temperature and dew point forecast at 6:00 O'clock using the no-lag model and found to be −7.19°C. This predicted value was used in the one-lag model with the surface temperature and dew point forecast at 7:00 O'clock to predict the 7:00 O'clock surface temperature and was found to be –7.03°C. The two predicted values of surface temperature were then used in the two-lag model to predict the remaining of the hourly surface temperatures and the result is given in Table 7.5. It is again shows that the utilization of the three models was capable of predicting the surface temperature fairly accurate up to 10 hours. The change in sign of the prediction errors is a clear indication of the continuing existence of the autocorrelation in the two-lag model.

Table 7.4: Errors of predicted surface temperature in the City of Ottawa using forecast values of air temperature and dew point and predicted values of surface temperature updated every hour in the two-lags model (January 13, 2003)

Hour	Errors in predicted surface temperatures†						
	6 O'clock	7 O'clock	8 O'clock	9 O'clock	10 O'clock	11 O'clock	12 O'clock
7:00	–0.45	…	…	…	…	…	…
8:00	–0.96	–0.19	…	…	…	…	…
9:00	–0.28	0.66	0.99	…	…	…	…
10:00	–0.74	0.22	0.63	–1.07	…	…	…
11:00	–0.17	0.69	1.11	–0.97	0.87	…	…
12:00	–0.02	0.64	1.02	–1.12	1.14	–0.36	…
13:00	1.11	1.51	1.81	–0.10	2.22	0.38	1.00
14:00	1.87	1.99	2.19	0.72	2.79	0.90	1.66
15:00	1.15	1.01	1.10	0.20	1.79	0.10	0.88
16:00	–1.11	–1.45	–1.47	–1.76	–0.79	–2.09	–1.39
17:00	–3.25	–3.72	–3.83	–3.56	–3.24	–4.04	–3.50
18:00	–7.23	–7.75	–7.92	–7.21	–7.49	–7.76	–7.42
19:00	–4.79	–5.29	–5.48	–4.49	–5.25	–5.03	–4.90
20:00	–4.30	–4.72	–4.90	–3.80	–4.87	–4.26	–4.33
21:00	–3.48	–3.78	–3.93	–2.88	–4.07	–3.21	–3.44

† Observed two-lag surface temperatures were used in first hour only.

Table 7.5: Predicted surface temperature for the City of Ottawa using hourly-forecast values of air temperature and dew point (January 13, 2003)

Hour	Observed Surface Temp.	Air Temp.	Dew Point	Two- Lag Model	
				Predicted Surf. Temp	Prediction Errors
6:00	-6.2	-8.00	-9.00	-7.19†	0.99
7:00	-6.2	-7.67	-8.67	-7.03‡	0.83
8:00	-6.18	-7.33	-8.33	-6.58	0.40
9:00	-4.94	-7.00	-8.00	-5.91	0.97
10:00	-4.75	-6.00	-8.67	-5.00	0.25
11:00	-3.40	-5.00	-9.33	-3.87	0.47
12:00	-2.33	-4.00	-10.00	-2.57	0.24
13:00	-0.43	-5.67	-12.33	-1.44	1.01
14:00	-0.72	-7.34	-14.66	-0.75	1.47
15:00	-0.13	-9.00	-17.00	-0.68	0.55
16:00	-3.00	-9.67	-18.00	-1.20	-1.80
17:00	-6.14	-10.33	-19.00	-2.21	-3.93
18:00	-11.38	-11.00	-20.00	-3.57	-7.81
19:00	-10.37	-12.00	-20.33	-5.16	-5.21
20:00	-11.38	-13.00	-20.67	-6.85	-4.53
21:00	-12.04	-14.00	-21.00	-8.52	-3.52

† Predicted using the no-lag Model.
‡ Predicted using the one-lag Model.

7.2. Risk of Collisions

The police records for the City of Ottawa on Monday January 13, 2003, contained 79 collisions out of which 10 were excluded; 4 collisions involved unattended vehicles and 6 collisions occurred outside the time limits of the case study. Table 7.6 presents the remaining 69 collisions classified by the categories explained earlier in this thesis. There were no fatal collisions, 9 collisions involved injury and 60 collisions involved PDO. In addition, there were 23 single-vehicle collisions, 20 rear-end collisions, and 26 collisions involved other types of initial impact.

Table 7.6: Number of collision on wet pavement surface in the City of Ottawa (January 13, 2003)

Time	Temp.	Surf. Cond.	Classification by severity			Classification by initial			Total
			Fatal	Injury	PDO	Single	Rear-	Other	
7:00	−7.03	wet	0	0	1	0	0	1	1
8:00	−6.58	wet	0	0	6	3	3	0	6
9:00	−5.91	wet	0	2	11	4	4	5	13
10:00	−5.00	wet	0	2	10	6	4	2	12
11:00	−3.87	wet	0	0	5	1	2	2	5
12:00	−2.57	wet	0	1	2	1	1	1	3
13:00	−1.44	wet	0	1	3	2	2	0	4
14:00	−0.75	wet	0	1	1	1	0	1	2
15:00	−0.68	wet	0	0	2	2	0	0	2
16:00	−1.20	wet	0	1	4	1	0	4	5
17:00	−2.21	wet	0	0	6	1	2	3	6
18:00	−3.57	wet	0	0	4	1	1	2	4
19:00	−5.16	wet	0	0	4	1	1	2	4
20:00	−6.85	wet	0	0	1	1	0	0	1
21:00	−8.52	wet	0	1	0	1	0	0	1
Total			0	9	60	26	20	23	69

To compare the results of Chapters 3 and 4 to this set of real data, the number of collisions were determined at each surface temperature and presented in Table 7.7. As shown in the table, ten more collisions at −15°C, −12°C, and −9°C were outside the temperature range of the study and the therefore, were excluded. The remaining 59 collisions were disaggregated into peak and off peak periods and presented in Tables 7.8 and 7.9. Finally the collision rates during each period were calculated for all categories and presented in Tables 7.10 and 7.11. The effect of pavement moisture condition was not tested because surface was only wet during the day of study.

Table 7.7: Number of collision on wet surface in the City of Ottawa (January 13, 2003)

Temp.	Classification by severity			Classification by initial impact			Hours	Total
	Fatal	Injury	PDO	Single	Rear-end	Other		
- 15	0	0	4	1	1	2	1	4
- 12	0	1	0	1	0	0	1	1
- 9	0	0	5	2	1	2	2	5
- 6	0	2	24	8	9	9	4	26
- 4	0	2	15	7	6	4	2	17
- 2	0	2	6	2	1	5	2	8
- 1	0	1	3	2	2	0	1	4
+ 1	0	1	3	3	0	1	2	4
Total	0	9	60	26	20	23	15	69

Table 7.8: Number of collision on wet surface during the peak period in the City of Ottawa (January 13, 2003)

Temp.	Hours	Classification by severity			Classification by initial impact			Total
		Fatal	Injury	PDO	Single	Rear-	Other	
-6	4	0	2	24	8	9	9	26
-2	1	0	1	4	1	0	4	5
Total	5	0	3	28	9	9	13	31

Table 7.9: Number of collision on wet surface during the off-peak period in the City of Ottawa (January 13, 2003)

Temp.	Hours	Classification by severity			Classification by initial impact			Total
		Fatal	Injury	PDO	Single	Rear-end	Other	
-4	2	0	2	15	7	6	4	17
-2	1	0	1	2	1	1	1	3
-1	1	0	1	3	2	2	0	4
+1	2	0	1	3	3	0	1	4
Total	6	0	5	23	13	9	6	28

Table 7.10: Rates of collision on wet surface during the peak period in the City of Ottawa (January 13, 2003)

Temp.	Classification by severity			Classification by initial impact			Total
	Fatal	Injury	PDO	Single	Rear-end	Other	
-6	0	0.50	6.00	2.00	2.25	2.25	6.50
-2	0	1.00	4.00	1.00	0.00	4.00	5.00
Total	0	0.60	5.60	1.80	1.80	2.60	6.20

Table 7.11: Rates of collision on wet surface during the off-peak period in the City of Ottawa (January 13, 2003)

Temp.	Classification by severity			Classification by initial impact			Total
	Fatal	Injury	PDO	Single	Rear-end	Other	
-4	0	1.00	7.50	3.50	3.00	2.00	8.50
-2	0	1.00	2.00	1.00	1.00	1.00	3.00
-1	0	1.00	3.00	2.00	2.00	0.00	4.00
+1	0	0.50	1.50	1.50	0.00	0.50	2.00
Average	0	0.83	3.83	2.17	1.50	1.00	4.67

According to Table 4.1, driving on wet surface during the peak period was hazardous, that is, the rate of total collisions is higher than average, at –7°C, –2°C, and –1°C. Table 7.10 shows the occurrence of collisions at –6°C and –2°C. During the off-peak period, Table 4.2 showed that driving on wet surface was hazardous at –8°C, –5°C, –2°C, –1°C and 0°C. Table 7.11 shows the occurrence of collisions at –4°C, –2°C, –1°C, and +1°C.

For collisions involving injury, Table 4.5 showed that driving on wet surface during the peak period had above average collision rates at –1°C. Table 7.10 shows the occurrence of collisions at –2°C and –6°C. During the off-peak period, Table 4.6 showed that driving on wet surface was hazardous at –8°C, –1°C and +5°C. Table 7.11 shows collisions involving injury occurred at – 4°C, –2°C, –1°C, and +1°C.

For collisions involving PDO, Table 4.9 showed that driving on wet surface during the peak period was hazardous at –7°C, –5°C, –2°C, and –1°C. Table 7.10 shows the occurrence of collisions at –2°C and –6°C. During the off-peak period, Table 4.10 showed that driving on wet surface was hazardous at –8°C, –5°C, –3°C, –2°C, –1°C and 0°C. Table 7.11 shows collisions involving ODO occurred at – 4°C, –2°C, –1°C, and +1°C.

For single-vehicle collisions, Table 4.13 showed that collision rates on wet surface during the peak period was above average –3°C, and –1°C. Table 7.10 shows the occurrence of collisions at –2°C and –6°C. During the off-peak period, Table 4.14 showed that driving on wet surface was hazardous at –3°C, –2°C, –1°C and 0°C. Table 7.11 shows collisions involving ODO occurred at – 4°C, –2°C, –1°C, and +1°C.

For rear-end collisions, Table 4.17 showed that driving on wet surface during the peak period was hazardous at –7˚C and the posterior probability was 0.94 at –1˚C. Table 7.10 shows the occurrence of collisions at –6˚C and –2˚C. During the off-peak period, Table 4.18 showed that driving on wet surface was hazardous at –8˚C and the posterior probabilities were 0.90 or higher at –5˚C, –2˚C, –1˚C and 0˚C. Table 7.11 shows collisions involving ODO occurred at – 4˚C, –2˚C, –1˚C, and +1˚C.

Finally, for collisions involving other types of initial impact, Table 4.21 showed that collision rates on wet surface during the peak period was above average –5˚C, –2˚C and –1˚C. Table 7.10 shows the occurrence of collisions at –2˚C and –6˚C. During the off-peak period, Table 4.22 showed that driving on wet surface was hazardous at –8˚C, –5˚C, and –1˚C. Table 7.11 shows collisions involving ODO occurred at – 4˚C, –2˚C, –1˚C, and +1˚C.

The above results show that the pattern of vehicle collision on Monday, January 13, 2003, a day chosen at random during the winter months in the City of Ottawa, is extremely close to those identified by the Bayes posterior probabilities as having above average collision rates. In many combinations, the surface temperature having above rates of collision in both cases were either exact or within 1˚C.

This thesis concludes that, given the random nature of vehicle collisions and that one-day observations were compared to the averages of 5-month observations, the Empirical Bayes probability method can be used with high level of accuracy to identify hazardous temperature and pavement moisture condition combinations. The example given below shows the extent of randomness of the collision events even in comparing two sets of observed data. There are large differences due to collision randomness when comparing the observed averages of collision rates on January 13, 2003, with those observed during the 5 winter months of 2001/2002.

1. During the peak period, on wet surface:

- Table 3.8 gives the average of rates of total collisions per hour of exposure as 3.26 as compared to 6.20 in Table 7.10.
- Table 3.11 gives the average of rates of collisions involving injury per hour of exposure as 0.70 as compared to 0.60 Table 7.10.
- Table 3.13 gives the average of the rates collisions involving PDO per hour of exposure as 2.56 as compared to 5.60 in Table 7.10.
- Table 3.15 gives the average of the rates of single-vehicle collisions per hour of exposure as 0.79 as compared to 1.80 in Table 7.10.
- Table 3.17 gives the average of the rates of rear-end collisions per hour of exposure as 1.03 as compared to 1.80 in Table 7.10.
- Table 3.19 gives the average of the rates of collisions involving other types of initial impact per hour of exposure as 1.44 as compared to 2.60 in Table 7.10.

2. During the off-peak period, on wet surface:

- Table 3.8 gives the average of rates of total collisions per hour of exposure as 2.97 as compared to 4.67 in Table 7.11.
- Table 3.11 gives the average of rates of collisions involving injury per hour of exposure as 0.68 as compared to 0.83 Table 7.11.
- Table 3.13 gives the average of the rates collisions involving PDO per hour of exposure as 2.28 as compared to 3.83 in Table 7.11.

- Table 3.15 gives the average of the rates of single-vehicle collisions per hour of exposure as 0.72 as compared to 2.17 in Table 7.11.
- Table 3.17 gives the average of the rates of rear-end collisions per hour of exposure as 0.79 as compared to 1.50 in Table 7.11.
- Table 3.19 gives the average of the rates of collisions involving other types of initial impact per hour of exposure as 1.46 as compared to 1.00 in Table 7.11.

8. CONCLUSIONS AND RECOMMENDATIONS

This thesis used collision data during the winter of 2001/2002 for the City of Ottawa to study the effect of pavement surface temperature and pavement moisture risk on vehicle collisions during the wintertime. Severity of collisions was divided into fatal collisions, collisions involving injury, and collisions involving PDO. Types of initial collision impact were divided into single-vehicle collisions; rear-end collisions, and other types of initial impact. A pavement moisture risk factor was calculated as the ratio of collision rate per hour of exposure on wet surface to collision rate per hour of exposure on dry surface at same temperature. The Empirical Bayes probability method was also utilized in this thesis as a powerful tool to determine the hazardous surface temperature and pavement moisture risk (wet versus dry) combinations. The Bayes posterior probabilities were calculated for two cases, the first was to compare the rates of collision on wet and dry surfaces to the average collision rate calculated from the dry and wet rates combined. This allowed for examining the effect of pavement moisture risk on the risk of collisions at different temperatures. The second method was to examine the effect of the surface temperatures only on road-driving hazardous for each pavement moisture condition separately. That is to determine at which surface temperature the road driving would be hazardous on dry pavement surface by comparing the collision rates on dry surface to their average. The same was repeated for the wet pavement surface.

A second part of this thesis applied stepwise regression method to develop statistical models capable of predicting pavement surface temperature from weather variables. Data collected by the Road Weather Information System (RWIS) in the City of Ottawa during the winter of 2001/2002 were used to develop the models. Advanced statistical tests were performed to reduce multicollinearities among the independent variables and correct for the autocorrelation in the error structure. The addition, the use of two lag-dependent variables substantially improved the fitting and therefore, the predictability of the models.

8.1. Conclusions

The results of this thesis support the following conclusions:

1. The numbers of collisions had their maximums at –1°C on wet pavement for all categories and remained relatively high around this temperature, but they did not show any specific pattern on the dry surface.
2. During the peak period, the pavement moisture risk factor was greater than 1 for total collisions between –3°C and +5°C, for collisions involving injury at –1°C and 0°C, for collisions involving PDO between –3°C and +2°C, for single vehicle collisions between –8°C and +2°C, for rear-end collisions between -2°C and +5°C, and for collisions involving other types of initial impact between –2°C and 0°C. Only singles vehicle collisions had a pavement moisture risk factor greater than 1 at all sub-zero temperatures.
3. During the off-peak period, the pavement moisture risk factor was greater than 1 at all temperatures, between –8°C and +8°C for the total collisions, collisions involving PDO, and collisions involving other types of initial impact. The pavement moisture risk factor was also greater than 1 at temperatures between –8°C and +1°C for collisions involving injury, between –8°C and +2°C for single vehicle collisions, and between –8°C and +1°C (except at –4°C) for rear-end

collisions. The pavement moisture risk factor was grater than 1 at all sub-zero temperatures for all categories, except for rear-end collisions at –4°C.

4. Wet pavement condition increased the risk of collision at all categories at –1°C and 0°C in both the peak and off peak periods, i.e. irrespective of the traffic volume.
5. During the peak and off-peak periods, posterior probabilities showed that there was no above average collision rates on dry surface at any temperature for all categories, and that the (–1°C, wet) combination was hazardous irrespective of the traffic volume, except for rear-end collisions.
6. The posterior probabilities of higher than average collision rates were, in general, greater on wet surface than on dry surface at the sub-zero temperatures.
7. The posterior probabilities of total collisions and the single-vehicle collisions were higher on wet surface than on dry surface between –8°C and +0°C irrespective of the traffic volume. Other categories had smaller sub-zero ranges for above average collision rates irrespective of traffic volume.
8. Posterior probabilities showed that moisture on pavement surface at sub-zero temperatures, particularly close to the freezing temperature, had a large effect on the risk of collision during the wintertime.
9. The distributions of the EB posterior probabilities on wet and dry surfaces during the peak and off-peak periods were similar to the distributions of the rates of collisions on wet and dry surfaces used to calculate the pavement moisture risk factors.

10. Both methods; pavement moisture risk factor and EB, are in agreement for identifying the effect of pavement moisture risk on the risk of collision.

11. Stepwise regression analysis and collinearity diagnostic tests concluded that the air temperature and dew point were the most suitable independent variables in a linear regression model to predict the pavement surface temperature.

12. The value of R^2 was relatively high at about 0.80 for five out of the six RPU locations. Plaza Bridge RPU location had low value of R^2 (0.66) and technical difficulties with the sensors and equipment during the study period were reported at this location. No further considerations were given to the Bridge Plaza RPU. The Ottawa-wide estimated model had R^2 value of 0.84.

13. The Durbin Watson statistic showed that all location-specific models as well as Ottawa-wide model have shown serious autocorrelations. A first order auto-correlation correction using the Cochrane-Orcutt method was tried on all models but did not improve any of them.

14. The addition of a one-lag dependent variable to the air temperature and dew point has increased the R^2 values to 0.95 for Acres, Trim, North Gower, and Hawthorn. The value of R^2 for Vars and Ottawa-wide models was 0.96. It also resulted in substantial reductions in the autocorrelation ranging from 188% for Ottawa-wide model up to 280% for the North Gower location specific model.

15. Scatter of the observed surface temperature versus standardized predicted surface temperature with one-lag surface temperature showed substantial improvement in the lack of homoscedasticity. The estimated errors have been reduced in all models.

16. The examination of the condition indices and the variance proportions in the collinearity diagnostic tests concluded that there was no serious multicollinearity in any of the six models with one-lag dependent variable.
17. The addition of a second-lag dependent variable to the models has further increased the R^2 values to 0.97 for North Gower, 0.98 for Vars, Acres, Trim, and Hawthorn. The value of R^2 for Ottawa-wide models was 0.99.
18. The use of h-statistic to test the autocorrelation showed continuing existence of autocorrelation in all models, however, the scatter graphs of the observed surface temperature versus the standardized predicted surface temperature have shown smaller estimated errors and large improvement in homoscedasticity over those models with one lag-dependent variable.
19. The cost of estimating and maintaining these models is very low and they possess relatively higher R^2, less autocorrelation, no serious multicollinearity, and relatively stable homoscedasticity.

8.2. Recommendations for Future Work

This thesis used collision data during the winter of 2001/2002 for the City of Ottawa to study the effect of pavement surface temperature and condition on vehicle collisions during the wintertime. A collision rate per hour of exposure was used since data on the movements (vehicle-km) were not available. The use of winter months only has caused the collision rates to be sensitive to small changes in the number of hours, particularly at both ends of the temperature spectrum where the numbers of hours of exposure were relatively small. It would be beneficial to use more years to mitigate this problem. This could reduce the fluctuation in the data as a result of the randomness nature of the collision occurrences. However, it would not be an easy task to find reliable data for so many years.

Another important continuation of this work is to undertake benefit/cost analysis to evaluate the impact of improving the winter maintenance activities as a result of the availability of the reliable predicted pavement surface temperature using the statistical models developed in this thesis. Of particular interest is the calculation of those savings resulting from less use of deicing salts and the positive impact on the environment.

Finally, the Box-Jenkins autoregressive integrated moving average (ARIMA) time series analysis can be used to estimate the pavement temperature from the weather variables. Results from the ARIMA models can then be compared to those developed in Chapter 6 using the lag-dependent variables.

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APPENDIX A: COEFFICIENTS OF STEPWISE REGRESSION ANALYSIS

Dependent Variable – Pavement Surface Temperature

Table A.1: Vars RPU

Model	Dim.	Adj. R^2	Variable	Coeff. (B)	Std. Error	t-statistic	p-value
1	1	0.76	Constant	1.038	0.056	18.69	0.000
	2		Air Temperature	0.857	0.008	108.13	0.000
2	1	0.83	Constant	- 2.109	0.099	- 21.24	0.000
	2		Air Temperature	1.502	0.019	78.62	0.000
	3		Dew Point	- 0.686	0.019	- 36.13	0.000
3	1	0.83	Constant	- 1.764	0.111	- 15.84	0.000
	2		Air Temperature	1.546	0.020	76.99	0.000
	3		Dew Point	- 0.723	0.020	- 36.74	0.000
	4		Wind Speed	- 0.045	0.007	- 6.65	0.000

Table A.2: Trim RPU

Model	Dim.	Adj. R^2	Variable	Coeff. (B)	Std. Error	t-statistic	p-value
1	1	0.76	Constant	1.884	0.054	34.64	0.000
	2		Air Temperature	0.876	0.008	107.32	0.000
2	1	0.83	Constant	- 0.149	0.073	- 2.03	0.042
	2		Air Temperature	1.386	0.016	87.76	0.000
	3		Dew Point	- 0.527	0.015	- 36.02	0.000
3	1	0.83	Constant	13.936	1.247	11.18	0.000
	2		Air Temperature	1.303	0.017	76.02	0.000
	3		Dew Point	- 0.445	0.016	- 27.66	0.000
	4		Surface Condition	- 0.403	0.036	- 11.32	0.000
4	1	0.84	Constant	- 7.378	2.074	- 3.56	0.000
	2		Air Temperature	2.551	0.100	25.60	0.000
	3		Dew Point	- 1.745	0.104	- 16.85	0.000
	4		Surface Condition	- 0.504	0.036	- 14.10	0.000
	5		Relative Humidity	0.255	0.020	12.70	0.000
5	1	0.84	Constant	- 5.784	2.098	- 2.76	0.006
	2		Air Temperature	2.475	0.101	24.55	0.000
	3		Dew Point	- 1.664	0.105	- 15.88	0.000
	4		Surface Condition	- 0.484	0.036	- 13.47	0.000
	5		Relative Humidity	0.235	0.021	11.47	0.000
	6		Wind Direction	- 0.002	0.001	- 4.53	0.000
6	1	0.84	Constant	- 5.275	2.113	- 2.50	0.013
	2		Air Temperature	2.448	0.102	24.08	0.000
	3		Dew Point	- 1.633	0.106	- 15.43	0.000
	4		Surface Condition	- 0.474	0.036	- 13.05	0.000
	5		Relative Humidity	0.227	0.021	10.88	0.000
	6		Wind Direction	- 0.002	0.001	- 4.16	0.000
	7		Gust	- 0.012	0.006	- 1.98	0.048

Table A.3: North Gower RPU

Model	Dim.	Adj. R^2	Variable	Coeff. (B)	Std. Error	t-statistic	p-value
1	1	0.75	Constant	1.572	0.061	25.87	0.000
	2		Air Temperature	0.881	0.010	91.54	0.000
2	1	0.83	Constant	- 1.083	0.089	- 12.21	0.000
	2		Air Temperature	1.381	0.016	86.82	0.000
	3		Dew Point	- 0.551	0.015	- 36.32	0.000
3	1	0.83	Constant	11.724	1.172	10.00	0.000
	2		Air Temperature	1.308	0.017	77.18	0.000
	3		Dew Point	- 0.485	0.016	- 30.28	0.000
	4		Surface Condition	- 0.364	0.033	- 10.96	0.000
4	1	0.84	Constant	- 8.488	2.211	- 3.84	0.000
	2		Air Temperature	2.302	0.094	24.40	0.000
	3		Dew Point	- 1.535	0.099	- 15.45	0.000
	4		Surface Condition	- 0.394	0.033	- 12.05	0.000
	5		Relative Humidity	0.224	0.021	10.70	0.000
5	1	0.84	Constant	- 6.361	2.232	- 2.85	0.004
	2		Air Temperature	2.227	0.095	23.50	0.000
	3		Dew Point	- 1.445	0.100	- 14.43	0.000
	4		Surface Condition	- 0.378	0.033	- 11.58	0.000
	5		Relative Humidity	0.200	0.021	9.41	0.000
	6		Gust	- 0.032	0.006	- 5.55	0.000
6	1	0.84	Constant	- 5.610	2.249	- 2.49	0.013
	2		Air Temperature	2.196	0.096	22.99	0.000
	3		Dew Point	- 1.413	0.101	- 14.02	0.000
	4		Surface Condition	- 0.371	0.033	- 11.33	0.000
	5		Relative Humidity	0.192	0.021	8.95	0.000
	6		Gust	- 0.029	0.006	- 5.04	0.000
	7		Wind Direction	- 0.002	0.001	- 2.56	0.010

Table A.4: Plaza Bridge RPU

Model	Dim.	Adj. R^2	Variable	Coeff. (B)	Std. Error	t-statistic	p-value
1	1	0.56	Constant	1.513	0.071	21.36	0.000
	2		Air Temperature	0.912	0.014	65.14	0.000
2	1	0.64	Constant	41.906	1.459	28.72	0.000
	2		Air Temperature	0.825	0.013	63.39	0.000
	3		Surface Condition	- 1.160	0.042	- 27.71	0.000

Table A.5: Hawthorne RPU

Model	Dim.	Adj. R^2	Variable	Coeff. (B)	Std. Error	t-statistic	p-value
1	1	0.75	Constant	1.684	0.059	28.64	0.000
	2		Air Temperature	0.881	0.010	90.97	0.000
2	1	0.82	Constant	- 0.058	0.073	- 0.80	0.424
	2		Air Temperature	1.445	0.019	75.69	0.000
	3		Dew Point	- 0.602	0.018	- 32.78	0.000
3	1	0.82	Constant	1.035	0.127	8.13	0.000
	2		Air Temperature	1.481	0.019	77.73	0.000
	3		Dew Point	- 0.636	0.018	- 34.72	0.000
	4		Wind Direction	- 0.006	0.001	- 10.40	0.000
4	1	0.82	Constant	1.910	0.234	8.17	0.000
	2		Air Temperature	1.480	0.019	77.96	0.000
	3		Dew Point	- 0.633	0.018	- 34.65	0.000
	4		Wind Direction	- 0.006	0.001	- 10.38	0.000
	5		Surface Condition	- 0.025	0.006	- 4.45	0.000
5	1	0.82	Constant	1.758	0.237	7.43	0.000
	2		Air Temperature	1.461	0.020	74.39	0.000
	3		Dew Point	- 0.615	0.019	- 32.59	0.000
	4		Wind Direction	- 0.006	0.001	- 11.01	0.000
	5		Surface Condition	- 0.026	0.006	- 4.54	0.000
	6		Wind Speed	0.033	0.009	3.82	0.000
6	1	0.83	Constant	1.639	0.234	7.02	0.000
	2		Air Temperature	1.500	0.020	75.65	0.000
	3		Dew Point	- 0.627	0.019	- 33.63	0.000
	4		Wind Direction	- 0.006	0.001	- 10.27	0.000
	5		Surface Condition	- 0.020	0.006	- 3.57	0.000
	6		Wind Speed	0.611	0.064	9.56	0.000
	7		Gust	- 0.452	0.049	- 9.13	0.000

APPENDIX B: COLLINEARITY DIAGNOSTICS OF MODELS ESTIMATED BY STEPWISE REGRESSION ANALYSIS

Dependent Variable: Pavement Surface Temperature

Table B.1: Vars RPU

Model	Dim.	Eigen-value	Cond. Index	Variance Proportions			
				Constant	Air Temp.	Dew Point	Wind Speed
1	1	1.204	1.00	0.40	0.40		
	2	0.796	1.23	0.60	0.60		
2	1	2.157	1.00	0.02	0.02	0.02	
	2	0.802	1.64	0.17	0.06	0.00	
	3	0.040	7.32	0.80	0.93	0.98	
3	1	2.603	1.00	0.02	0.01	0.01	0.02
	2	1.205	1.47	0.02	0.04	0.01	0.06
	3	0.153	4.12	0.53	0.02	0.00	0.86
	4	0.039	8.22	0.43	0.93	0.98	0.06

Table B.2: Trim RPU

Model	Dim.	Eigen-value	Cond. Index	Variance Proportions						
				Constant	Air Temp.	Dew Point	Surface Cond.	Rel. Hum.	Wind Dir.	Gust
1	1	1.222	1.00	0.39	0.39					
	2	0.778	1.25	0.61	0.61					
2	1	2.140	1.00	0.04	0.03	0.03				
	2	0.790	1.65	0.33	0.08	0.00				
	3	0.070	5.53	0.64	0.89	0.97				
3	1	2.772	1.00	0.00	0.01	0.01	0.00			
	2	1.151	1.55	0.00	0.06	0.01	0.00			
	3	0.076	6.03	0.00	0.73	0.75	0.00			
	4	0.0007	65.12	1.00	0.20	0.22	1.00			
4	1	3.569	1.00	0.00	0.00	0.00	0.00	0.00		
	2	1.317	1.65	0.00	0.00	0.00	0.00	0.00		
	3	0.114	5.61	0.00	0.01	0.01	0.00	0.00		
	4	0.0009	63.88	0.06	0.09	0.10	0.97	0.14		
	5	0.0003	117.66	0.94	0.89	0.90	0.03	0.86		
5	1	4.354	1.00	0.00	0.00	0.00	0.00	0.00	0.01	
	2	1.370	1.78	0.00	0.00	0.00	0.00	0.00	0.00	
	3	0.190	4.78	0.00	0.00	0.00	0.00	0.00	0.50	
	4	0.084	7.18	0.00	0.01	0.01	0.00	0.00	0.43	
	5	0.0009	71.12	0.06	0.08	0.09	0.98	0.13	0.02	
	6	0.0002	132.29	0.94	0.90	0.90	0.02	0.87	0.04	
6	1	5.063	1.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
	2	1.426	1.88	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	3	0.278	4.27	0.00	0.00	0.00	0.00	0.00	0.02	0.47
	4	0.156	5.69	0.00	0.00	0.00	0.00	0.00	0.74	0.31
	5	0.075	8.20	0.00	0.02	0.01	0.00	0.00	0.20	0.17
	6	0.0008	77.49	0.06	0.07	0.08	0.99	0.12	0.01	0.02
	7	0.0002	144.31	0.93	0.91	0.91	0.01	0.88	0.03	0.02

Table B.3: North Gower RPU

Model	Dim.	Eigen-value	Cond. Index	Variance Proportions						
				Constant	Air Temp.	Dew Point	Surface Cond.	Rel. Hum.	Gust	Wind Dir.
1	1	1.010	1.00	0.50	0.50					
	2	0.990	1.01	0.50	0.50					
2	1	1.924	1.00	0.03	0.04	0.04				
	2	0.991	1.39	0.19	0.11	0.00				
	3	0.085	4.75	0.78	0.86	0.96				
3	1	2.568	1.00	0.00	0.01	0.02	0.00			
	2	1.334	1.39	0.00	0.10	0.02	0.00			
	3	0.097	5.13	0.00	0.72	0.80	0.00			
	4	0.0009	53.25	1.00	0.18	0.17	1.00			
4	1	3.409	1.00	0.00	0.00	0.00	0.00	0.00		
	2	1.441	1.54	0.00	0.00	0.00	0.00	0.00		
	3	0.148	4.80	0.00	0.01	0.01	0.00	0.00		
	4	0.001	50.07	0.03	0.09	0.10	0.91	0.14		
	5	0.0003	107.01	0.97	0.89	0.89	0.09	0.86		
5	1	4.146	1.00	0.00	0.00	0.00	0.00	0.00	0.01	
	2	1.512	1.66	0.00	0.00	0.00	0.00	0.00	0.01	
	3	0.230	4.24	0.00	0.00	0.00	0.00	0.00	0.48	
	4	0.111	6.12	0.00	0.02	0.01	0.00	0.00	0.46	
	5	0.001	55.60	0.03	0.09	0.09	0.93	0.13	0.01	
	6	0.0003	119.92	0.97	0.89	0.89	0.07	0.87	0.03	
6	1	5.021	1.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	2	1.521	1.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.230	4.67	0.00	0.00	0.00	0.00	0.00	0.45	0.00
	4	0.127	6.28	0.00	0.00	0.00	0.00	0.00	0.41	0.50
	5	0.099	7.12	0.00	0.01	0.01	0.00	0.00	0.10	0.47
	6	0.001	61.46	0.03	0.08	0.09	0.94	0.13	0.01	0.01
	7	0.0002	133.17	0.97	0.90	0.90	0.06	0.87	0.02	0.02

Table B.4: Plaza Bridge RPU

Model	Dim.	Eigen-value	Condition Index	Variance Proportions		
				Constant	Air Temp.	Surface Cond.
1	1	1.460	1.00	0.27	0.27	
	2	0.540	1.64	0.73	0.73	
2	1	2.324	1.00	0.00	0.06	0.00
	2	0.675	1.86	0.00	0.88	0.00
	3	0.0008	55.52	1.00	0.05	1.00

Table B.5: Hawthorne RPU

Model	Dim.	Eigen-value	Cond. Index	Variance Proportions						
				Constant	Air Temp.	Dew Point	Wind Dir.	Surface Cond.	Wind Speed	Gust
1	1	1.043	1.00	0.48	0.48					
	2	0.957	1.04	0.52	0.52					
2	1	1.957	1.00	0.03	0.04	0.04				
	2	0.964	1.42	0.38	0.04	0.00				
	3	0.079	4.97	0.59	0.92	0.96				
3	1	2.383	1.00	0.02	0.01	0.02	0.02			
	2	1.454	1.28	0.02	0.06	0.02	0.02			
	3	0.084	5.31	0.50	0.23	0.22	0.87			
	4	0.079	5.51	0.46	0.70	0.75	0.09			
4	1	3.167	1.00	0.00	0.00	0.01	0.01	0.01		
	2	1.602	1.41	0.00	0.06	0.03	0.00	0.00		
	3	0.123	5.08	0.03	0.02	0.02	0.75	0.14		
	4	0.081	6.25	0.00	0.90	0.92	0.14	0.00		
	5	0.027	10.8	0.97	0.01	0.02	0.09	0.86		
5	1	3.920	1.00	0.00	0.00	0.00	0.01	0.00	0.01	
	2	1.648	1.54	0.00	0.06	0.03	0.00	0.00	0.00	
	3	0.211	4.31	0.02	0.01	0.01	0.01	0.04	0.80	
	4	0.119	5.74	0.02	0.00	0.00	0.86	0.10	0.06	
	5	0.075	7.22	0.00	0.93	0.94	0.04	0.00	0.12	
	6	0.027	12.1	0.96	0.00	0.01	0.08	0.85	0.01	
6	1	4.768	1.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
	2	1.683	1.68	0.00	0.05	0.03	0.00	0.00	0.00	0.00
	3	0.324	3.84	0.02	0.00	0.00	0.04	0.03	0.00	0.00
	4	0.120	6.31	0.02	0.01	0.01	0.83	0.11	0.00	0.00
	5	0.076	7.91	0.00	0.89	0.94	0.05	0.00	0.00	0.00
	6	0.027	13.3	0.95	0.00	0.01	0.08	0.84	0.00	0.00
	7	0.002	47.7	0.01	0.04	0.00	0.01	0.01	1.00	1.00

APPENDIX C: ENVIRONMENT CANADA PRECIPITATION FORECAST

January 13, 2003

ENVIRONMENT CANADA

PRECIPITATION FORECAST

FORECAST ISSUED MON JAN 13 AT 6.00 AM
FOR THE CITY OF OTTAWA
NEXT SCHEDULED FORECAST WILL BE ISSUED AT 3.00 PM EST.

OTTAWA REGIONAL CENTRE
CENTRE REGIONAL DE L'OUTAOUAIS
373 SUSSEX DRIVE, OTTAWA (ONTARIO), K1A 0H3
24HR CONSULTATION 1-900-565-5555

WATCHES or WARNINGS IN EFFECT
NONE

Ottawa at 05:00 EST ...
Temp: -5.7 C
Wind: SSW 15
Precip.: -SN

Ottawa : 2003/01/13 01:05 EST
Snow (yesterday / season): TR / 99.4
Temp yesterday (min / avg / max) :
-15.0C / -10C / -5.0C

	TODAY	TONIGHT	TUESDAY	TUESDAY NIGHT
	From 6 AM to 6 PM	From 6 PM to 6 AM	From 6 AM to 6 PM	From 6 PM to 6 AM
Sky Condition	OVERCAST	CLOUDY PERIODS	SUNNY	CLOUDY PERIODS
Sunshine (% period)	0	0	90	0

	06	08	10	12	14	16	18	20	22	00	02	04	06	08	10	12	14	16	18	20	22	00	02	04
FLURRIES	- -	- -	- -	- -	- -	- -	>															<	- -	-

	RAIN	FZ RN	SNOW	RAIN	FZ RN	SNOW	RAIN	FZ RN	SNOW	RAIN	FZ RN	SNOW
Amount (mm|mm|cm)	0	0	6	0	0	TR	0	0	0	0	0	TR

	06h	09h	12h	15h	18h	21h	24h	03h	06h	09h	12h	15h	18h	21h	24h	03h	06h
Prob. of Precip. (%)	80	90	90	90	90	0	0	0	0	0	0	0	0	20	20	40	40
Temperature (C)	-8	-7	-4	-3	-7	-11	-15	-18	-21	-20	-16	-14	-13	-14	-16	-16	-15
Dew Point (C)	-9	-8	-10	-12	-13	-17	-21	-23	-25	-25	-25	-24	-17	-15	-16	-16	-16
Humidity (%)	95	80	55	55	60	60	65	65	70	55	45	55	70	95	95	95	90
Wind dir and speed (km/h)	S 10	S 10	W 20	W 20	W 20	W 20	W 20	VR 05	VR 05	VR 05	W 10	W 10	W 10	VR 05	VR 05	VR 05	VR 05
Gust (km/h)	10	10	20	20	20	20	20	5	5	5	10	10	10	5	5	5	5
Windchill Equivalent T	-13	-12	-10	-9	-14	-19	-24				-22	-20	-19				
Windchill (watts/m2)																	

	TODAY	TONIGHT	TUESDAY	TUESDAY NIGHT
Blowing Snow	NO	NO	NO	NO

OTTAWA-GATINEAU-PRESCOTT AND RUSSELL-CORNWALL.
WEDNESDAY..A MIX OF SUN AND CLOUD. 40 PERCENT CHANCE OF FLURRIES. LOW MINUS 17. HIGH MINUS 7.
THURSDAY..SUNNY WITH CLOUDY PERIODS. LOW MINUS 18. HIGH MINUS 8.
FRIDAY..SUNNY. LOW MINUS 19. HIGH MINUS 11.
NORMALS FOR THE PERIOD..LOW MINUS 15. HIGH MINUS 5.

ENVIRONMENT CANADA — PRECIPITATION FORECAST

FORECAST ISSUED MON JAN 13 AT 3.00 PM
FOR THE CITY OF OTTAWA
NEXT SCHEDULED FORECAST WILL BE ISSUED AT 9.00 PM EST.

OTTAWA REGIONAL CENTRE
CENTRE REGIONAL DE L'OUTAOUAIS
373 SUSSEX DRIVE, OTTAWA (ONTARIO), K1A 0H3
24HR CONSULTATION 1-900-565-5555

WATCHES or WARNINGS IN EFFECT
NONE

Ottawa at 14:17 EST ...
Temp: -4.4 C
Wind: W 26
Precip.: DRSN

Ottawa : 2003/01/13 01:05 EST
Snow (yesterday / season): TR / 99.4
Temp yesterday (min / avg / max) :
-15.0C / -10C / -5.0C

TODAY — From 3 PM to 6 PM

Sky Condition	VARIABLE CLOUDINESS					
Sunshine (% period)	60					
	06	08	10	12	14	16
FLURRIES					-	- -
	RAIN	FZ RN	SNOW			
Amount (mm|mm|cm)	0	0	2			
	06h	09h	12h	15h	18h	
Prob. of Precip. (%)				70	70	
Temperature (C)				-9	-11	
Dew Point (C)				-17	-20	
Humidity (%)				50	45	
Wind dir and speed (km/h)				W 30	W 30	
Gust (km/h)				50	50	
Windchill Equivalent T				-18	-21	
Windchill (watts/m2)						
Blowing Snow	YES					

TONIGHT — From 6 PM to 6 AM

Sky Condition	VARIABLE CLOUDINESS					
Sunshine (% period)	0					
	18	20	22	00	02	04
FLURRIES	- -	>				
	RAIN	FZ RN	SNOW			
Amount (mm|mm|cm)	0	0	2			
	21h	24h	03h	06h		
Prob. of Precip. (%)	10	10	10	10		
Temperature (C)	-14	-18	-21	-21		
Dew Point (C)	-21	-25	-27	-29		
Humidity (%)	55	55	55	50		
Wind dir and speed (km/h)	W 20	NW 20	NW 10	NW 10		
Gust (km/h)	20	20	10	10		
Windchill Equivalent T	-23	-28	-28	-28		
Windchill (watts/m2)						
Blowing Snow	YES					

TUESDAY — From 6 AM to 6 PM

Sky Condition	A MIX OF SUN AND CLOUD					
Sunshine (% period)	60					
	06	08	10	12	14	16
FLURRIES						
	RAIN	FZ RN	SNOW			
Amount (mm|mm|cm)	0	0	0			
	09h	12h	15h	18h		
Prob. of Precip. (%)	10	10	10	10		
Temperature (C)	-20	-18	-16	-16		
Dew Point (C)	-29	-26	-24	-24		
Humidity (%)	45	50	50	50		
Wind dir and speed (km/h)	NW 10	NW 10	NW 10	VR 05		
Gust (km/h)	10	10	10	5		
Windchill Equivalent T	-27	-25	-22			
Windchill (watts/m2)						
Blowing Snow	NO					

TUESDAY NIGHT — From 6 PM to 6 AM

Sky Condition	MAINLY CLOUDY					
Sunshine (% period)	0					
	18	20	22	00	02	04
FLURRIES				<	- -	-
	RAIN	FZ RN	SNOW			
Amount (mm|mm|cm)	0	0	TR			
	21h	24h	03h	06h		
Prob. of Precip. (%)	20	20	40	40		
Temperature (C)	-16	-17	-19	-17		
Dew Point (C)	-23	-22	-23	-18		
Humidity (%)	60	70	80	90		
Wind dir and speed (km/h)	VR 05	VR 05	VR 05	VR 05		
Gust (km/h)	5	5	5	5		
Windchill Equivalent T						
Windchill (watts/m2)						
Blowing Snow	NO					

OTTAWA-GATINEAU-PRESCOTT AND RUSSELL-CORNWALL.
WEDNESDAY..A MIX OF SUN AND CLOUD. 40 PERCENT CHANCE OF FLURRIES. LOW MINUS 17. HIGH MINUS 7.
THURSDAY..SUNNY WITH CLOUDY PERIODS. LOW MINUS 18. HIGH MINUS 8.
FRIDAY..SUNNY. LOW MINUS 19. HIGH MINUS 11.
NORMALS FOR THE PERIOD..LOW MINUS 15. HIGH MINUS 5.

CITY OF OTTAWA
RWIS OBSERVATIONS

TRIM E/B
13-Jan-03

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 11:55PM	-16	-20.4	0	17	[redacted]	-14.7
Jan/13/2003 11:45PM	-15.8	-20.2	0	17	[redacted]	-14.6
Jan/13/2003 11:35PM	-15.7	-20.1	0	17	[redacted]	-14.4
Jan/13/2003 11:34PM	-15.7	-20.1	0	19	[redacted]	-14.4
Jan/13/2003 11:25PM	-15.6	-20.1	0	19	[redacted]	-14.3
Jan/13/2003 11:16PM	-15.5	-19.8	0	13	[redacted]	-14.1
Jan/13/2003 11:14PM	-15.4	-19.7	0	16	[redacted]	-14.1
Jan/13/2003 11:06PM	-15.3	-19.6	0	12	[redacted]	-14
Jan/13/2003 10:56PM	-15.1	-19.6	0	16	[redacted]	-13.9
Jan/13/2003 10:46PM	-15.1	-19.6	0	14	[redacted]	-13.8
Jan/13/2003 10:39PM	-14.9	-19.4	0	19	[redacted]	-13.7
Jan/13/2003 10:36PM	-14.9	-19.4	0	19	[redacted]	-13.6
Jan/13/2003 10:26PM	-14.8	-19.4	0	18	[redacted]	-13.4
Jan/13/2003 10:16PM	-14.7	-19.3	0	18	[redacted]	-13.3
Jan/13/2003 10:08PM	-14.6	-19.4	0	17	[redacted]	-13.1
Jan/13/2003 10:06PM	-14.5	-19.3	0	20	[redacted]	-13.1
Jan/13/2003 9:58PM	-14.3	-19.2	0	23	[redacted]	-12.8
Jan/13/2003 9:57PM	-14.3	-19.2	0	26	[redacted]	-12.8
Jan/13/2003 9:48PM	-14.1	-19	0	21	[redacted]	-12.6
Jan/13/2003 9:47PM	-14.1	-19	0	18	[redacted]	-12.5
Jan/13/2003 9:44PM	-14.1	-19	1	21	[redacted]	-12.4

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 9:40PM	-14	-18.8	1	22	Snow/Ice Watch	-12.2
Jan/13/2003 9:37PM	-13.9	-18.7	1	23	Snow/Ice Watch	-12
Jan/13/2003 9:27PM	-13.7	-18.6	1	21	Snow/Ice Watch	-11.8
Jan/13/2003 9:17PM	-13.6	-18.5	1	21	Snow/Ice Watch	-11.7
Jan/13/2003 9:07PM	-13.6	-18.5	1	24	Snow/Ice Watch	-11.7
Jan/13/2003 8:58PM	-13.8	-18.7	1	21	Snow/Ice Watch	-11.8
Jan/13/2003 8:48PM	-13.8	-18.9	1	21	Snow/Ice Watch	-12
Jan/13/2003 8:46PM	-13.8	-18.8	1	22	Snow/Ice Watch	-12.1
Jan/13/2003 8:37PM	-13.8	-19	0	23	Snow/Ice Watch	-12.1
Jan/13/2003 8:30PM	-13.7	-19.1	0	25	Snow/Ice Watch	-12.2
Jan/13/2003 8:18PM	-13.6	-19	0	20	Snow/Ice Watch	-12.1
Jan/13/2003 8:08PM	-13.4	-18.9	0	27	Snow/Ice Watch	-12
Jan/13/2003 8:07PM	-13.4	-18.8	1	27	Snow/Ice Watch	-12
Jan/13/2003 7:59PM	-13.4	-18.9	1	24	Snow/Ice Watch	-11.9
Jan/13/2003 7:58PM	-13.4	-18.8	1	24	Snow/Ice Watch	-11.9
Jan/13/2003 7:48PM	-13.2	-18.6	1	21	Snow/Ice Watch	-11.8
Jan/13/2003 7:45PM	-13	-18.6	1	28	Snow/Ice Watch	-11.6
Jan/13/2003 7:38PM	-13	-18.6	1	25	Snow/Ice Watch	-11.5
Jan/13/2003 7:30PM	-12.8	-18.6	1	23	Snow/Ice Watch	-11.3
Jan/13/2003 7:28PM	-12.7	-18.5	1	24	Snow/Ice Watch	-11.3
Jan/13/2003 7:18PM	-12.4	-18.6	1	21	Snow/Ice Watch	-11.2
Jan/13/2003 7:17PM	-12.3	-18.6	1	21	Snow/Ice Watch	-11.2
Jan/13/2003 7:08PM	-12	-18.3	1	33	Snow/Ice Watch	-11
Jan/13/2003 7:07PM	-12	-18.3	1	28	Snow/Ice Watch	-11

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 7:06PM	-12	-18.3	1	35	[redacted]	-10.9
Jan/13/2003 6:58PM	-11.8	-18.1	1	30	Snow/Ice Watch	-10.9
Jan/13/2003 6:48PM	-11.6	-17.9	1	24	Snow/Ice Watch	-10.7
Jan/13/2003 6:47PM	-11.6	-17.9	1	20	Snow/Ice Watch	-10.7
Jan/13/2003 6:47PM	-11.5	-17.8	1	28	Snow/Ice Watch	-10.5
Jan/13/2003 6:46PM	-11.5	-17.8	1	28	[redacted]	-10.6
Jan/13/2003 6:45PM	-11.5	-17.8	1	22	Snow/Ice Watch	-10.6
Jan/13/2003 6:44PM	-11.5	-17.8	1	28	[redacted]	-10.6
Jan/13/2003 6:38PM	-11.5	-17.8	1	28	Snow/Ice Watch	-10.4
Jan/13/2003 6:31PM	-11.2	-17.5	1	27	Snow/Ice Watch	-10.3
Jan/13/2003 6:30PM	-11.2	-17.5	1	31	[redacted]	-10.2
Jan/13/2003 6:29PM	-11.2	-17.5	1	25	Snow/Ice Watch	-10.2
Jan/13/2003 6:28PM	-11.2	-17.5	1	23	[redacted]	-10.2
Jan/13/2003 6:27PM	-11.1	-17.4	1	28	[redacted]	-10.1
Jan/13/2003 6:18PM	-10.9	-17.2	1	22	[redacted]	-9.9
Jan/13/2003 6:08PM	-10.5	-16.9	1	33	[redacted]	-9.6
Jan/13/2003 5:58PM	-10.2	-16.6	1	31	[redacted]	-9.4
Jan/13/2003 5:57PM	-10.2	-16.7	1	27	[redacted]	-9.3
Jan/13/2003 5:55PM	-10.1	-16.6	1	27	[redacted]	-9.2
Jan/13/2003 5:53PM	-10.1	-16.6	1	25	[redacted]	-9.2
Jan/13/2003 5:52PM	-10	-16.6	1	28	[redacted]	-9.2
Jan/13/2003 5:48PM	-9.9	-16.5	1	21	[redacted]	-9.1
Jan/13/2003 5:47PM	-9.8	-16.4	1	20	[redacted]	-9.1
Jan/13/2003 5:42PM	-9.6	-16.2	1	23	[redacted]	-8.8

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 5:41PM	-9.6	-16.2	1	23	Snow/Ice Warning	-8.8
Jan/13/2003 5:32PM	-9.1	-16	1	23	Chemical Wet	-8.4
Jan/13/2003 5:26PM	-8.9	-15.7	1	22	Chemical Wet	-8.2
Jan/13/2003 5:19PM	-8.6	-15.7	1	29	Chemical Wet	-8.1
Jan/13/2003 5:18PM	-8.6	-15.7	1	25	Chemical Wet	-8
Jan/13/2003 5:15PM	-8.4	-15.5	1	31	Chemical Wet	-8
Jan/13/2003 5:09PM	-8.2	-15.1	1	24	Chemical Wet	-7.7
Jan/13/2003 4:59PM	-8	-15.1	1	27	Chemical Wet	-7.5
Jan/13/2003 4:54PM	-7.7	-15.1	1	36	Chemical Wet	-7.3
Jan/13/2003 4:50PM	-7.5	-14.8	1	33	Chemical Wet	-7.1
Jan/13/2003 4:49PM	-7.5	-14.8	1	40	Chemical Wet	-7
Jan/13/2003 4:45PM	-7.2	-14.6	1	40	Chemical Wet	-6.8
Jan/13/2003 4:39PM	-7	-14.3	1	37	Chemical Wet	-6.6
Jan/13/2003 4:33PM	-6.6	-13.8	1	24	Chemical Wet	-6.2
Jan/13/2003 4:30PM	-6.5	-13.7	1	24	Chemical Wet	-6
Jan/13/2003 4:29PM	-6.3	-13.5	1	33	Chemical Wet	-5.8
Jan/13/2003 4:26PM	-6.1	-13.3	1	37	Chemical Wet	-5.6
Jan/13/2003 4:19PM	-6.1	-13.1	1	30	Chemical Wet	-5.5
Jan/13/2003 4:15PM	-5.9	-12.7	1	41	Chemical Wet	-5.2
Jan/13/2003 4:09PM	-5.6	-12.2	31	27	Chemical Wet	-4.8
Jan/13/2003 4:01PM	-5.5	-11.9	31	0	Chemical Wet	-4.5
Jan/13/2003 3:54PM	-5.3	-11.3	1	28	Chemical Wet	-4.1
Jan/13/2003 3:52PM	-5.3	-11.1	1	28	Chemical Wet	-4
Jan/13/2003 3:48PM	-5.4	-10.2	1	27	Chemical Wet	-3.7

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 3:47PM	-5.1	-10	1	29	Chemical Wet	-3.5
Jan/13/2003 3:46PM	-5	-9.9	1	30	Chemical Wet	-3.3
Jan/13/2003 3:32PM	-4.3	-9.8	1	32	Chemical Wet	-2.3
Jan/13/2003 3:26PM	-4.3	-9.6	1	29	Chemical Wet	-2.2
Jan/13/2003 3:20PM	-4.2	-9.1	1	22	Chemical Wet	-1.9
Jan/13/2003 3:13PM	-4.5	-8.7	1	24	Chemical Wet	-2.3
Jan/13/2003 3:07PM	-5.2	-8.3	1	23	Chemical Wet	-2.7
Jan/13/2003 2:55PM	-5.5	-8.3	1	31	Chemical Wet	-2.3
Jan/13/2003 2:54PM	-5.5	-8.3	1	36	Chemical Wet	-2.2
Jan/13/2003 2:53PM	-5.5	-8.3	1	34	Chemical Wet	-2.2
Jan/13/2003 2:49PM	-5.3	-8.4	1	36	Chemical Wet	-1.9
Jan/13/2003 2:49PM	-5.3	-8.6	1	32	Chemical Wet	-1.8
Jan/13/2003 2:47PM	-5	-8.8	1	32	Chemical Wet	-1.6
Jan/13/2003 2:46PM	-4.4	-10.3	1	40	Snow/Ice Watch	-0.7
Jan/13/2003 2:45PM	-4.2	-10.5	1	36	Snow/Ice Watch	-0.6
Jan/13/2003 2:44PM	-3.8	-10.8	1	36	Snow/Ice Watch	-0.2
Jan/13/2003 2:40PM	-3.6	-10.9	1	30	Snow/Ice Watch	0
Jan/13/2003 2:39PM	-3.4	-10.8	1	30	[redacted]	0.3
Jan/13/2003 2:38PM	-3.4	-10.8	1	30	[redacted]	0.4
Jan/13/2003 2:33PM	-3.2	-10.6	1	27	[redacted]	1.4
Jan/13/2003 2:30PM	-3.2	-10.6	1	23	[redacted]	1.4
Jan/13/2003 2:28PM	-3.3	-10.7	1	25	[redacted]	1.1
Jan/13/2003 2:27PM	-3.6	-11	1	24	[redacted]	0.4
Jan/13/2003 2:26PM	-3.6	-11	1	31	[redacted]	0.4

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 2:26PM	-3.6	-11	1	25		0.3
Jan/13/2003 2:18PM	-3.8	-11.2	1	32	Chemical Wet	-0.2
Jan/13/2003 2:16PM	-3.6	-11.3	1	34	Chemical Wet	0.2
Jan/13/2003 2:14PM	-3.2	-10.8	1	27		0.8
Jan/13/2003 2:13PM	-3.1	-10.8	1	28		0.9
Jan/13/2003 2:10PM	-3.4	-11	1	27		0.3
Jan/13/2003 2:10PM	-3.4	-11	1	34	Chemical Wet	0.2
Jan/13/2003 2:09PM	-3.2	-10.8	1	33		0.5
Jan/13/2003 2:08PM	-3.1	-10.8	1	24		0.6
Jan/13/2003 2:06PM	-3	-10.5	1	28		0.9
Jan/13/2003 1:55PM	-3.1	-9.9	1	30		0.4
Jan/13/2003 1:53PM	-3.1	-9.5	1	25		0.5
Jan/13/2003 1:52PM	-2.9	-9	1	23		1.1
Jan/13/2003 1:50PM	-2.9	-9	1	18		1.1
Jan/13/2003 1:49PM	-2.8	-8.7	1	21		1.3
Jan/13/2003 1:48PM	-3	-8.5	1	20		1.7
Jan/13/2003 1:47PM	-3	-8.3	1	19		1.4
Jan/13/2003 1:46PM	-3.1	-8.5	1	21		1.2
Jan/13/2003 1:39PM	-3.4	-8.6	1	28		1
Jan/13/2003 1:38PM	-3.5	-8.6	1	25		0.8
Jan/13/2003 1:36PM	-3.6	-8.7	1	22		0.3
Jan/13/2003 1:34PM	-3.7	-9.1	1	30	Chemical Wet	-0.3
Jan/13/2003 1:27PM	-3.6	-8.8	1	21	Chemical Wet	-0.7
Jan/13/2003 1:26PM	-3.6	-8.6	1	27	Chemical Wet	-0.6

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 1:20PM	-3.6	-8.3	1	21	Chemical Wet	-0.2
Jan/13/2003 1:19PM	-3.5	-8	1	23	Chemical Wet	0
Jan/13/2003 1:18PM	-3.5	-8	1	22	Chemical Wet	0.1
Jan/13/2003 1:14PM	-3.6	-7.8	1	24	[redacted]	0.4
Jan/13/2003 1:12PM	-3.6	-7.5	1	24	[redacted]	0.4
Jan/13/2003 1:11PM	-3.6	-7.3	1	22	[redacted]	0.6
Jan/13/2003 1:09PM	-3.6	-7	1	26	[redacted]	1.6
Jan/13/2003 1:07PM	-3.6	-6.2	1	29	[redacted]	2.2
Jan/13/2003 1:04PM	-3.6	-5.4	1	23	[redacted]	2.2
Jan/13/2003 12:59PM	-3.7	-5.6	1	19	[redacted]	1.7
Jan/13/2003 12:58PM	-3.9	-5.9	1	27	[redacted]	1.7
Jan/13/2003 12:57PM	-3.9	-5.9	1	22	[redacted]	1.1
Jan/13/2003 12:55PM	-4	-6.5	1	22	[redacted]	0.4
Jan/13/2003 12:55PM	-4.1	-6.7	1	25	Chemical Wet	-0.2
Jan/13/2003 12:54PM	-4.2	-7.2	1	26	Chemical Wet	-1.1
Jan/13/2003 12:52PM	-4.2	-7.8	1	26	Chemical Wet	-2.2
Jan/13/2003 12:51PM	-4.1	-8.3	1	26	Chemical Wet	-1.9
Jan/13/2003 12:50PM	-3.8	-8.4	1	27	Chemical Wet	-1.6
Jan/13/2003 12:49PM	-2.8	-9.6	1	44	Chemical Wet	0.2
Jan/13/2003 12:48PM	-2.7	-9.5	1	31	Chemical Wet	0.1
Jan/13/2003 12:47PM	-2.6	-9.4	1	31	[redacted]	0.3
Jan/13/2003 12:46PM	-2.7	-9.5	1	38	Chemical Wet	0.2
Jan/13/2003 12:46PM	-2.7	-9.3	1	36	[redacted]	0.4
Jan/13/2003 12:35PM	-2.9	-7.6	1	31	Chemical Wet	-0.4

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 12:34PM	-2.8	-7.2	1	27	Chemical Wet	-0.2
Jan/13/2003 12:31PM	-2.9	-6.4	1	25	Chemical Wet	0.1
Jan/13/2003 12:30PM	-3.1	-6.1	1	23	Chemical Wet	-0.1
Jan/13/2003 12:27PM	-3	-5.6	1	13	Chemical Wet	-0.3
Jan/13/2003 12:26PM	-3.3	-5.7	1	17	Chemical Wet	-0.5
Jan/13/2003 12:25PM	-3.7	-5.6	1	24	Chemical Wet	-1.3
Jan/13/2003 12:14PM	-3.6	-6.2	1	21	Chemical Wet	-2.8
Jan/13/2003 12:13PM	-3.3	-6.3	1	22	Chemical Wet	-2.4
Jan/13/2003 12:08PM	-2.8	-6.8	1	20	Chemical Wet	-1.6
Jan/13/2003 11:59AM	-2.8	-6.7	1	21	Chemical Wet	-1.5
Jan/13/2003 11:54AM	-2.8	-6.3	1	22	Chemical Wet	-1.6
Jan/13/2003 11:45AM	-2.8	-5.8	1	24	Chemical Wet	-2
Jan/13/2003 11:35AM	-2.8	-4.7	1	19	Chemical Wet	-1.6
Jan/13/2003 11:33AM	-2.9	-4.6	1	21	Chemical Wet	-1.8
Jan/13/2003 11:30AM	-3	-4.6	1	21	Chemical Wet	-2.1
Jan/13/2003 11:25AM	-3.2	-4.7	1	19	Chemical Wet	-2.5
Jan/13/2003 11:17AM	-3.5	-4.8	1	21	Chemical Wet	-2.6
Jan/13/2003 11:15AM	-3.5	-4.6	1	14	Chemical Wet	-2.8
Jan/13/2003 11:06AM	-3.9	-5	1	19	Chemical Wet	-3.4
Jan/13/2003 11:05AM	-4	-5.1	1	22	Chemical Wet	-3.7
Jan/13/2003 10:56AM	-4	-4.8	1	17	Chemical Wet	-2.3
Jan/13/2003 10:55AM	-4.1	-5	1	26	Chemical Wet	-2.5
Jan/13/2003 10:49AM	-4.3	-5	1	25	Chemical Wet	-2.8
Jan/13/2003 10:45AM	-4.3	-5	1	23	Chemical Wet	-2.9

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 10:39AM	-4.5	-5.2	1	20	Chemical Wet	-3.6
Jan/13/2003 10:36AM	-4.5	-5.2	1	19	Chemical Wet	-3.8
Jan/13/2003 10:26AM	-4.6	-5.3	1	21	Chemical Wet	-4
Jan/13/2003 10:16AM	-4.7	-5.4	1	28	Chemical Wet	-4.2
Jan/13/2003 10:09AM	-4.7	-5.4	1	22	Chemical Wet	-4.5
Jan/13/2003 9:56AM	-4.8	-5.5	1	22	Chemical Wet	-5
Jan/13/2003 9:50AM	-4.8	-5.5	1	17	Chemical Wet	-5.2
Jan/13/2003 9:36AM	-4.8	-5.6	1	23	Chemical Wet	-5.5
Jan/13/2003 9:30AM	-4.7	-5.5	1	28	Chemical Wet	-5.2
Jan/13/2003 9:19AM	-4.6	-5.4	1	23	Chemical Wet	-4.3
Jan/13/2003 9:17AM	-4.6	-5.4	1	14	[redacted]	-4.2
Jan/13/2003 9:16AM	-4.6	-5.4	1	21	Chemical Wet	-4.2
Jan/13/2003 9:06AM	-4.7	-5.5	1	19	Chemical Wet	-4.4
Jan/13/2003 8:57AM	-4.8	-5.6	1	32	Chemical Wet	-4.5
Jan/13/2003 8:47AM	-4.9	-5.7	1	24	Chemical Wet	-4.7
Jan/13/2003 8:40AM	-4.9	-5.6	1	25	Chemical Wet	-4.8
Jan/13/2003 8:38AM	-5	-5.6	1	26	Chemical Wet	-4.8
Jan/13/2003 8:37AM	-5	-5.6	1	26	Chemical Wet	-4.8
Jan/13/2003 8:27AM	-5	-5.6	1	24	Chemical Wet	-5
Jan/13/2003 8:24AM	-5	-5.6	1	19	Chemical Wet	-5.1
Jan/13/2003 8:17AM	-5	-5.6	1	24	Chemical Wet	-5.3
Jan/13/2003 8:07AM	-5.1	-5.7	1	22	Chemical Wet	-5.5
Jan/13/2003 7:57AM	-5.1	-5.7	1	23	Chemical Wet	-5.7
Jan/13/2003 7:49AM	-5.1	-5.7	1	20	Chemical Wet	-5.9

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 7:47AM	-5.1	-5.7	1	22	Chemical Wet	-6
Jan/13/2003 7:46AM	-5.1	-5.7	1	21	Chemical Wet	-6
Jan/13/2003 7:38AM	-5.1	-5.8	1	19	Chemical Wet	-6.1
Jan/13/2003 7:28AM	-5.1	-5.8	1	20	Chemical Wet	-6.4
Jan/13/2003 7:18AM	-5.1	-6	1	18	Chemical Wet	-6.7
Jan/13/2003 7:08AM	-5.1	-6	1	18	Chemical Wet	-6.6
Jan/13/2003 6:58AM	-5.1	-6.1	1	19	Chemical Wet	-6.3
Jan/13/2003 6:48AM	-5.1	-6.2	1	13	Chemical Wet	-6.2
Jan/13/2003 6:38AM	-5	-6.3	1	18	Chemical Wet	-6.2
Jan/13/2003 6:28AM	-5	-6.5	1	13	Chemical Wet	-6.2
Jan/13/2003 6:18AM	-5	-6.5	1	12	Chemical Wet	-6.2
Jan/13/2003 6:08AM	-5	-6.8	1	11	Chemical Wet	-6.2
Jan/13/2003 5:59AM	-5	-7	1	14	Chemical Wet	-6.2
Jan/13/2003 5:49AM	-5.1	-7.3	1	10	Chemical Wet	-6.1
Jan/13/2003 5:46AM	-5.2	-7.5	1	11	Chemical Wet	-6.2
Jan/13/2003 5:40AM	-5.2	-7.5	1	10	Chemical Wet	-6.2
Jan/13/2003 5:39AM	-5.2	-7.5	0	10	Chemical Wet	-6.2
Jan/13/2003 5:29AM	-5.1	-7.6	0	16	Chemical Wet	-6.2
Jan/13/2003 5:19AM	-5.1	-7.6	0	17	Chemical Wet	-6.2
Jan/13/2003 5:09AM	-5.3	-7.7	0	16	Chemical Wet	-6.3
Jan/13/2003 4:59AM	-5.3	-7.8	0	11	Chemical Wet	-6.3
Jan/13/2003 4:49AM	-5.3	-7.8	0	16	Chemical Wet	-6.4
Jan/13/2003 4:39AM	-5.4	-8	0	15	Chemical Wet	-6.5
Jan/13/2003 4:30AM	-5.3	-7.9	0	11	Chemical Wet	-6.5

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 4:19AM	-5.3	-7.9	0	11	Chemical Wet	-6.6
Jan/13/2003 4:10AM	-5.3	-7.9	0	9	Chemical Wet	-6.7
Jan/13/2003 4:00AM	-5.4	-8	0	16	Chemical Wet	-6.7
Jan/13/2003 3:58AM	-5.4	-8	0	14	Chemical Wet	-6.7
Jan/13/2003 3:50AM	-5.3	-7.9	0	11	[redacted]	-6.7
Jan/13/2003 3:40AM	-5.3	-8.1	0	16	[redacted]	-6.8
Jan/13/2003 3:32AM	-5.2	-8	1	15	[redacted]	-6.8
Jan/13/2003 3:30AM	-5.3	-8.1	1	13	[redacted]	-6.8
Jan/13/2003 3:20AM	-5.2	-8.2	1	15	[redacted]	-6.9
Jan/13/2003 3:10AM	-5	-7.9	1	18	[redacted]	-6.9
Jan/13/2003 3:01AM	-5	-7.8	1	22	[redacted]	-6.8
Jan/13/2003 2:54AM	-5.1	-7.8	1	18	[redacted]	-6.8
Jan/13/2003 2:51AM	-5.1	-7.6	0	20	[redacted]	-6.9
Jan/13/2003 2:51AM	-5.2	-7.6	0	19	[redacted]	-6.9
Jan/13/2003 2:49AM	-5.4	-7.5	0	17	[redacted]	-7
Jan/13/2003 2:40AM	-5.8	-7.7	0	12	[redacted]	-7.2
Jan/13/2003 2:36AM	-6.3	-7.8	0	9	[redacted]	-7.4
Jan/13/2003 2:32AM	-7	-8.6	0	8	[redacted]	-7.5
Jan/13/2003 2:30AM	-7.2	-8.7	0	8	[redacted]	-7.5
Jan/13/2003 2:28AM	-7.5	-9	0	9	[redacted]	-7.6
Jan/13/2003 2:20AM	-8.2	-9.7	0	8	[redacted]	-7.7
Jan/13/2003 2:11AM	-8.2	-9.7	0	4	[redacted]	-7.7
Jan/13/2003 2:01AM	-8.5	-10	0	3	[redacted]	-7.8
Jan/13/2003 1:58AM	-8.6	-10.1	0	2	[redacted]	-7.8

Date	AirTemp	DewPoint	Precip	WindSpeed	Cond	SfcTemp
Jan/13/2003 1:51AM	-8.4	-9.9	0	0	Snow/Ice Warning	-7.7
Jan/13/2003 1:45AM	-8.3	-10	0	0	Snow/Ice Warning	-7.9
Jan/13/2003 1:31AM	-8.2	-9.8	0	3	Snow/Ice Warning	-8
Jan/13/2003 1:25AM	-8.3	-10.2	0	7	Snow/Ice Warning	-8.1
Jan/13/2003 1:12AM	-8.2	-10	0	8	Snow/Ice Warning	-8
Jan/13/2003 1:06AM	-8	-9.8	0	5	Snow/Ice Warning	-7.9
Jan/13/2003 0:52AM	-8	-9.8	0	9	Snow/Ice Warning	-7.9
Jan/13/2003 0:45AM	-8	-9.9	0	6	Snow/Ice Warning	-8
Jan/13/2003 0:33AM	-8.2	-10.2	0	5	Snow/Ice Warning	-8.2
Jan/13/2003 0:32AM	-8.2	-10.2	0	5	Snow/Ice Warning	-8.2
Jan/13/2003 0:26AM	-8.1	-10	0	2	Snow/Ice Warning	-8.1
Jan/13/2003 0:16AM	-8	-9.9	0	5	Snow/Ice Warning	-7.9
Jan/13/2003 0:06AM	-7.8	-9.9	0	6	Snow/Ice Warning	-7.5

Accident ID	Date	Time	Impact Type	Class of Acc.	No. of Veh.
030009635	2003/01/13	19:36	vehicle	P.D. only	1
030009210	2003/01/13	09:50	vehicle	P.D. only	1
030009116	2003/01/13	08:20	vehicle	P.D. only	1
030009737	2003/01/13	22:43	vehicle	P.D. only	1
030009646	2003/01/13	18:30	vehicle	P.D. only	1
030010420	2003/01/13	06:30	vehicle	P.D. only	1
030009292	2003/01/13	08:00	vehicle	P.D. only	1
030009386	2003/01/13	13:50	vehicle	injury	1
030009089	2003/01/13	07:55	vehicle	P.D. only	1
030009481	2003/01/13	15:56	vehicle	P.D. only	1
030009161	2003/01/13	09:12	vehicle	P.D. only	1
030009180	2003/01/13	09:37	vehicle	P.D. only	1
030009546	2003/01/13	17:31	vehicle	P.D. only	1
030009686	2003/01/13	21:00	vehicle	injury	1
030009038	2003/01/13	03:34	vehicle	P.D. only	1
030009208	2003/01/13	09:50	vehicle	P.D. only	1
038000107	2003/01/13	08:45	vehicle	P.D. only	1
038000067	2003/01/13	10:49	vehicle	P.D. only	1
030009430	2003/01/13	14:45	vehicle	P.D. only	1
030009500	2003/01/13	16:20	vehicle	P.D. only	1
030009253	2003/01/13	06:30	vehicle	P.D. only	1
030009276	2003/01/13	11:36	vehicle	injury	1
038000108	2003/01/13	07:25	vehicle	P.D. only	1
030009745	2003/01/13	23:00	vehicle	P.D. only	1
030009204	2003/01/13	09:55	vehicle	injury	1
038000069	2003/01/13	08:15	vehicle	P.D. only	1
038000072	2003/01/13	08:55	vehicle	P.D. only	1
030009455	2003/01/13	15:00	vehicle	P.D. only	1
030009286	2003/01/13	11:30	vehicle	P.D. only	1
030009203	2003/01/13	09:40	vehicle	P.D. only	1
030010225	2003/01/13	11:00	vehicle	P.D. only	1
030009511	2003/01/13	13:00	vehicle	P.D. only	1
030009335	2003/01/13	12:40	vehicle	injury	1
030009156	2003/01/13	09:20	Rear end	P.D. only	2
030009517	2003/01/13	16:45	Approaching	P.D. only	2
030009350	2003/01/13	13:04	Angle	P.D. only	2
030009097	2003/01/13	08:08	Rear end	P.D. only	2
030009114	2003/01/13	08:21	movement	P.D. only	2
030009544	2003/01/13	17:30	Other	P.D. only	2

030009592	2003/01/13	18:34	Rear end	P.D. only	2
030009627	2003/01/13	18:30	Angle	P.D. only	2
030009502	2003/01/13	16:23	movement	P.D. only	2
030009209	2003/01/13	09:25	Rear end	P.D. only	2
030011902	2003/01/13	12:15	Rear end	P.D. only	2
030008982	2003/01/13	00:13	Angle	injury	2
030009724	2003/01/13	22:14	Sideswipe	P.D. only	2
030009506	2003/01/13	16:26	Angle	P.D. only	2
030009246	2003/01/13	10:45	Rear end	P.D. only	2
030009128	2003/01/13	08:43	Rear end	P.D. only	2
030009315	2003/01/13	12:29	Rear end	P.D. only	2
030009168	2003/01/13	08:50	Rear end	P.D. only	2
030009699	2003/01/13	21:23	Rear end	P.D. only	2
030010084	2003/01/13	17:00	Rear end	P.D. only	2
030009285	2003/01/13	11:20	Rear end	P.D. only	2
030009539	2003/01/13	09:10	Rear end	P.D. only	2
030009111	2003/01/13	08:00	Rear end	P.D. only	2
030010108	2003/01/13	19:00	movement	P.D. only	2
030009132	2003/01/13	08:45	Rear end	injury	2
030009130	2003/01/13	08:44	Approaching	injury	2
030009100	2003/01/13	08:07	movement	P.D. only	2
030009145	2003/01/13	08:50	Sideswipe	P.D. only	2
030009509	2003/01/13	16:00	Approaching	P.D. only	2
030009483	2003/01/13	16:00	Approaching	injury	2
030009218	2003/01/13	10:10	Approaching	P.D. only	2
030009070	2003/01/13	07:15	Rear end	P.D. only	2
030009541	2003/01/13	17:26	Angle	P.D. only	2
030009202	2003/01/13	09:55	Other	injury	2
030009179	2003/01/13	08:05	Sideswipe	P.D. only	2
030009160	2003/01/13	09:10	Rear end	P.D. only	2
030013296	2003/01/13	07:55	Rear end	P.D. only	2
038000124	2003/01/13	17:45	Rear end	P.D. only	2
038000068	2003/01/13	10:50	Sideswipe	P.D. only	2
038000071	2003/01/13	09:15	Sideswipe	P.D. only	2
030009291	2003/01/13	11:45	Approaching	P.D. only	2
038000065	2003/01/13	07:00	Sideswipe	P.D. only	2
030009239	2003/01/13	10:36	Rear end	P.D. only	2
030010033	2003/01/13	15:20	movement	P.D. only	2
030009480	2003/01/13	15:55	Other	P.D. only	2
030009487	2003/01/13	16:10	Rear end	P.D. only	3