A Multilevel Disaggregate Model for Quantifying the Safety Effect of Winter Road Maintenance

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ABSTRACT

This research presents disaggregated models linking accident frequency to road surface condition and other influencing factors of road winter safety. Multilevel Poisson Lognormal Models (PLN) are developed using hourly-based data from patrol routes in Ontario. As part of the contributions, an original and comprehensive road surface index was developed representing the road surface condition during winter storms. Factors such as visibility, precipitation, air temperature, wind speed, exposure and road surface conditions were found to have a statistically significant effect on winter road safety. The models developed are capable of quantifying benefits of maintenance operations and evaluating maintenance standards using safety as a performance measure, which have been demonstrated through some examples.

KEYWORDS

Winter road safety / Multilevel PLN models

1. INTRODUCTION

Winter storms have a significant impact on the safety and mobility of highway users. Highway collision rates often increase considerably during a snow storm due to slippery road conditions and poor visibility [1]. Winter storms can also create unsafe travel environments for travelers and can cause substantial delay due to reduced traffic speeds and road capability and increased collisions.

To reduce the negative impacts of winter storms, transportation agencies spend significant resources every year to keep roads and highways clear of snow and ice for safe and efficient travel. Canada spends $1 billion each year on winter road maintenance. This sum includes the application of over five million tonnes of salt [2]. While essential for maintaining road safety, road salting has also raised significant concerns due to its potential damage to the environment, roadside infrastructure, and vehicles [3-4]. A recent study by Environment Canada concluded that road salts at high concentrations pose a risk to plants, animals and aquatic systems [5].

While there is consensus that winter road maintenance is beneficial to the nation’s economy in general and to the safety and mobility of our highway system in particular, little research has been done into quantifying the safety and mobility benefits of winter road maintenance, nor into identifying contributory factors. Knowledge on the potential impacts of improved winter road maintenance on traffic incidents and travelers is critical for policy makers and transportation agencies and for supporting decisions on where to invest limited road maintenance resources. For example, what maintenance policies and standards should be adopted by a given city or province? How much salt application could be considered as sensible for maintaining the safety of a given highway or network? This research summarizes the results of our recent efforts aimed at addressing some of these questions along with the major findings of past studies.

Limited efforts have been devoted to the problem of quantifying the safety benefit of winter road maintenance under various weather conditions. Most of the past research is directed towards establishment of a link between weather and safety [1, 6 - 8]. Hanbali et al. [9] was among the first who studied effectiveness of winter road maintenance on safety. A before-after analysis was conducted on undivided and divided highways randomly selected in New York, Minnesota, and Wisconsin, U.S.A. It was found that on the average the accident rate was reduced by 87% and 78% for divided and undivided highways respectively. This study assumes that reductions in accident rates are only due to maintenance, which seems to be a major shortcoming.

Norrman et al. [10], was among the first to attempt to quantify the relationship between road safety and road surface conditions. Norrman classified road surface conditions into ten different types based on slipperiness, and then compared the crash rates associated with the different road surface types. Norrman et al. [10] concluded that in general, increasing maintenance reduces the number of accidents. However, the approach taken in that study has several limitations. First, it is an aggregate analysis, considering roads of all classes and locations together. This approach may mask some important factors that affect road safety. Second, the simple categorical method of determining crash rates may introduce significant biases if confounding factors exist, which is likely to be the case for a system as complex as highway traffic. Furthermore, the procedure cannot be used to compare the effect of different maintenance operations.

Recently, Fu et al. [11] investigated the relationship between road safety and various weather and maintenance factors, including air temperature, total precipitation, and type and amount of maintenance operations. They concluded that anti-icing, pre-wet salting with ploughing, and sanding have statistically significant effects on reducing the number of accidents. Both temperature and precipitation were found to have a significant effect on the number of crashes. Their study also presents several limitations. First, the data used in were aggregated on a daily basis, assuming uniform road weather conditions over the entire day for each day of record. Second, their study did not account for some important factors due to data problems, such as traffic exposure and road surface conditions.

Nordic countries have conducted extensive research on issues related to winter road safety and road maintenance. However, most of these studies were published in the form of project reports in the local language and few were published in academic journals. Wallman et al. [12] provided a comprehensive review on this body of work. In terms of research methodology, most of these studies relied on simple comparative analyses instead of rigorous statistical modeling. Nevertheless, the findings were in general consistent, showing that winter weather increases the risk of accidents by virtue of poor road surface conditions and that maintenance lowers the crash risk by improving road surface conditions.

The objective of this research is to develop statistical models linking safety effects to maintenance operations through road surface conditions (RSC) with the intention to use the developed models for evaluation of alternative maintenance policies.

2. PROPOSED METHODOLOGY

There are a large number of factors that influence the safety of a highway under winter conditions [13-14]. The major factors affecting winter road safety can be grouped into three categories, namely, weather characteristics, traffic, and maintenance operations, as schematically illustrated in Figure 1. Models can be developed by establishing a relationship between collision frequency and these factors. Analyses could be performed at an aggregate level e.g. event-based analysis [15] or at a disaggregate level – time-based analysis. This research will focus on the latter approach with the following five steps:

1. Selection of study sites
2. Data source identification (traffic, weather, maintenance and accident data)
3. Data processing (hourly data and storm-event data)
4. Modeling road surface conditions
5. Exploratory data analysis and development of statistical models

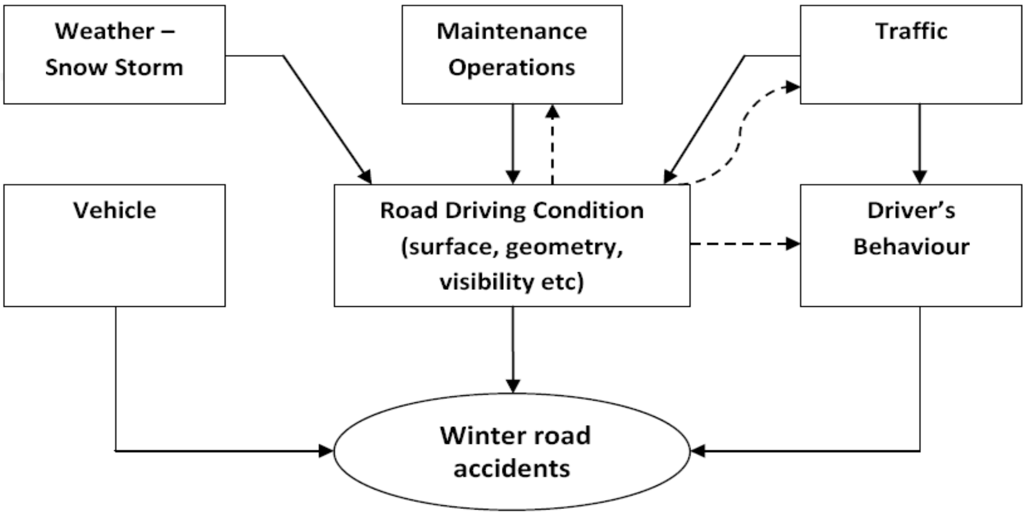

Figure 1- Relation between maintenance, weather, traffic and safety

2.1. Study Sites

Based on data availability, four patrol routes, two each on Highway 401 and Queen Elizabeth Way (QEW) in the Province of Ontario, Canada, were selected as study sites, as shown in Figure 2:

- Hwy 401-R1: Hwy 400 to Morningside Ave (28.0 Km)
- Hwy 401-R2: Trafalgar Road to Hwy 400 (31.1 Km)
- QEW-R1: Burloak Drive to Erin mills parkway (17.4 Km)
- QEW-R2: Erin mills parkway to Eastmall (13.1 Km)

Figure 2- Site Map Showing Location of Selected Patrol Routes

These are major inter-urban freeways with multiple lanes in each direction and AADT from 100,000 to more than 400,000.

2.2. Data sources

Data was obtained for accidents, traffic and weather (RCWIS, RWIS and EC) from October 2003 to April 2006 for the four selected sites. A description of each data source is given below:

- Traffic Volume Data: Traffic volume data was obtained from loop detectors from the Ministry of Transportation of Ontario (MTO), which was then processed and converted into hourly traffic volume data.
- Traffic Accident Data: The Ontario Provincial Police (OPP) maintains a database of all collisions occurring on Ontario highways. A database including all collision records for the study routes was obtained from MTO. The database includes detailed information on each collision including; accident time, accident location, accident type, impact type, severity level, vehicle information, driver information, and road conditions – surface and geometry, weather conditions, speed, visibility, passenger information, etc.
- Road Condition Weather Information System (RCWIS) data: This data contains information about road surface conditions, maintenance, precipitation type, accumulation, visibility and temperature. RCWIS data is collected by MTO maintenance personnel, who patrol the maintenance routes during a storm event 3 ~ 4 times on the average. One of the most important pieces of information in this data source is the road surface condition description, which is used in this study as a predictor of accidents.
- Road Weather Information System (RWIS) data: This data contains information about temperature, precipitation, visibility, wind speed, road surface conditions, etc., recorded automatically by RWIS stations near the selected maintenance routes. This dataset is used to supplement and cross validate the RCWIS data.
- Environment Canada (EC) data: Weather data is available from Environment Canada, which is also used to supplement the data from RCWIS. This data contains information about temperature, precipitation, visibility, wind speed etc.

2.3. Modeling of Road Surface Conditions

The RCWIS records classify road surface conditions into a total of 7 major classes that are further subdivided into 160 sub classes. In this research we introduced a road surface condition index (RSI), similar to the commonly used friction measure, to represent different road surface conditions described in RCWIS. Each category in the major classes is assigned with a specific range of RSI values, as shown below [12, 16]:

Road Surface Condition major Classes	**RSI Range**
Bare and dry	0.9~1.0
Bare and wet	0.8 ~ 0.89
Snow packed	0.5 ~ 0.79
Partly snow covered	0.25 ~ 0.49
Snow covered	0.2 ~ 0.24
Slushy	0.16 ~ 0.19
Icy	0 ~ 0.15

2.4. Data Processing

The data obtained from all the data sources were subsequently pre-processed and merged to form a data set of hourly records on weather, traffic, and accidents. Snow storm events are then identified based on weather conditions and road surface conditions, as shown in Figure 3. The following assumptions were considered in the event identification process:

- An event starts at the time when snow/freezing rain is observed;
- An event ends when snow/freezing rain stops and certain predefined road surface condition is achieved after that time.
- Precipitation must be greater than zero (0)
- Air temperature must be less than 5 ^{0}C
- Road surface conditions must not be bare-dry

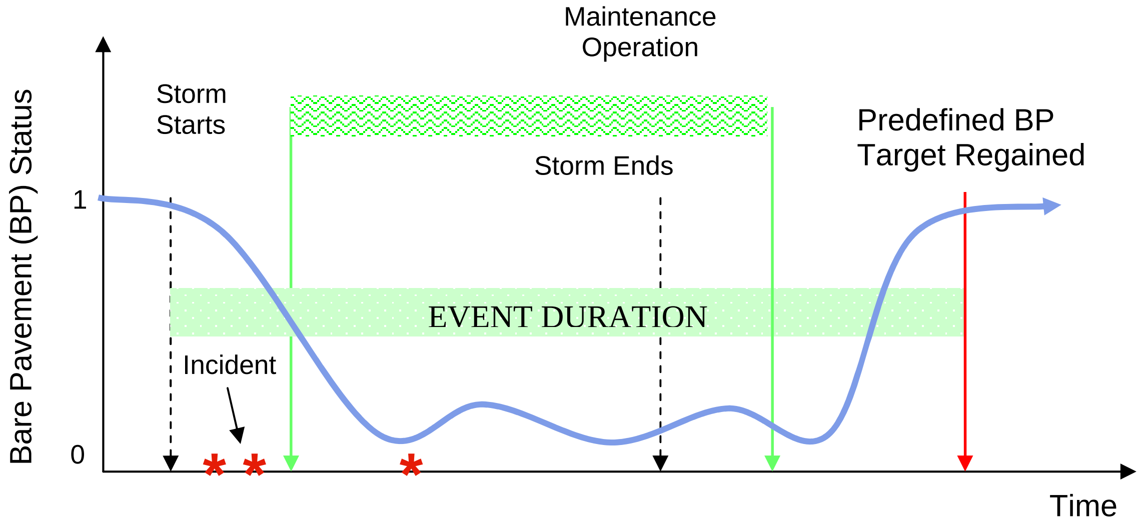

Figure 3- Road Surface Conditions over a Snow Storm Event

3. MODEL DEVELOPMENT

In road safety literature, the most commonly employed approach for modeling accident frequencies is the generalized linear regression analysis. Specifically, the Negative binomial (NB) model and its extensions have been found to be the most suitable distribution structures for road accident frequency [17-19]. The modelling approach considered in this research is a multilevel Poisson lognormal model (PLN). PLN differs from NB model in the sense that instead of gamma distributed error a lognormal distributed error term is added to the Poisson model to capture the unobserved heterogeneity. The multilevel model structure is necessary because the hourly data set is longitudinal in nature with the hourly records within each storm event forming a time series of observations. The potential within-storm correlation can only be captured by a multilevel model [18].

3.1. Exploratory Data Analysis

Five sets of data were formed: one for each patrol route and one including all patrol routes together. The combined data set has a total of 6260 observations recorded over 761 snow storm events. All the data sets were checked for any outliers using box plots of individual data fields in the database.

A correlation analysis was conducted for each patrol dataset and the combined dataset. It was found that precipitation type and maintenance operations were consistently correlated with RSC across all datasets (with a correlation coefficient greater than 0.60) and were therefore removed from further analysis.

4. MODEL CALIBRATION AND APPLICATION

An exploratory analysis indicated that there appeared to be a trend in the observed collisions over individual storms. To statistically test this observation four models with different trend forms were tested, namely, model without a trend, model with a linear trend component, model with a dummy variable indicating whether or not the hour under consideration is the first hour of the storm (S1E2 for first hour, S1E1 otherwise), and model with a dummy variable indicating if the hour is the first or second hour of the storm (S2E2 for first or second hour, S2E1 otherwise).

A dummy variable was also included in the combined data set to capture the possible effect of other route specific factors, such as location, driver population, and road geometry, on road safety.

A stepwise elimination process was followed to identify the significant factors. STATA[1] (Version 9) was used for this analysis. The best fit model was identified using likelihood ratio test and Akaike Information Criterion (AIC). The AIC statistic is defined as -2LL+2p, where LL is the log likelihood of a fitted model and p is the number of parameters, which is included to penalize models with higher number of parameters: a model with smaller AIC value represents a better overall fit. Based on both the likelihood ratio test and AIC criterion, the model considering the effect of the first two hours of a storm was found to be

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[1] http://www.stata.com/

the best fitted model for the combined data set. The resulting model includes eight factors that were statistically significant at $p<0.05$, as shown in Table 1.

Table 1- Summary results for hourly based analysis – combined dataset

Variable	**Coeff**	**Sig**
Intercept	-3.566	0.000
visibility (km)	-0.030	0.000
S2E1	-0.409	0.000
S2E2	0.000	
Wind speed (Km/Hr)	0.008	0.043
Air temperature	-0.038	0.000
hourly Ppt (mm)	0.050	0.004
RSC	-0.670	0.000
Ln exposure	0.218	0.000
401 – R1	2.705	0.000
401 – R2	1.795	0.000
QEW – R1	-0.235	0.589
QEW – R1	0.000	
LL	-3122.863	

4.1. MODEL INTERPRETATION

In general, results from the models are consistent, as shown in Table 1. The following specific observations could also be made from the modeling outcome:

- The most interesting result is perhaps that the road surface condition index (RSI) was found to be a statistically significant factor influencing road safety across all sites. The negative sign associated to the factor suggests that higher accident frequencies are associated with poor road surface conditions. Because of the exponential functional form, the exponent in the model is a measure of sensitivity of crash frequency to the corresponding variable. The coefficient -0.67 associated with RSC suggests that a 10% improvement in RSC would lead to approximately a 6.7% reduction in the expected number of accidents.

- The analysis also confirmed the significance of a trend component in road collisions over the duration of individual storms. Specifically, it was found that the first two hours of an event had a statistically higher collision rate than the remaining hours of the event, which is consistent with findings reported in the literature.

- Visibility is found to have a statistically significant effect on accident frequency during a snow storm. The negative model coefficient also makes intuitive sense, as it suggests that reduced visibility was associated with increased number of accidents.

- As expected, exposure, defined as total vehicle-kilometres traveled (product of the traffic volume per hour and route length, in MVKm), was found to be significant, suggesting that an increase in traffic volume or route length would lead to increase in number of accidents.

- The models also suggest that, controlling for other factors (RSC, Visibility and Exposure), Highway 401 (401-R1 and 401-R2) is more susceptible to crashes than the QEW (QEW-R1 and QEW-R2). The difference in risk between the maintenance routes on the same Highway appears to be quite small.

- Both air temperature and precipitation have a statistically significant effect on accident frequency. The negative sign of the coefficient associated with air temperature suggests that higher number of collisions were associated with lower temperatures. Furthermore, precipitation intensity has a negative effect on road accidents.

- Wind speed was found statistically significant and the positive sign indicates that higher wind speeds were associated with higher numbers of accidents.

4.2. MODEL APPLICATION

The previous section has described a model that links between road safety to RSC and other factors such as precipitation, visibility and air temperature, as shown in Table 1. This section uses two case examples to illustrate how this model can be applied for evaluating different maintenance policies and decision variables. The first example shows the potential effect of a specific winter road maintenance operation on collision frequency while the second example shows the effect of a maintenance policy variable - bare pavement (BP) recovery time on safety. BP recovery time is defined as the time elapsed after the end of a snow storm until bare pavement is achieved through maintenance treatments.

4.2.1 Effect of winter road maintenance operation on road safety

This example is to show how the developed model can be applied to quantify the potential effect of a particular winter road maintenance operation on collision frequency. For this purpose, the patrol route on Highway 401 (R1), as shown in Figure 2, is considered with a uniform traffic flow rate of 10,000 vehicles per hour. A specific snow storm is assumed with the following characteristics:

- Precipitation = 20 mm/hr
- Wind speed = 15 Km/hr
- Air temperature = -5 C
- Visibility = 4 Km
- Duration = 8 hours

Furthermore, the road surface conditions of this route, as represented by RSI, are assumed to vary over the event as follows (Figure 4):

- At the start of the event, the road surface is bare and dry with a RSI of 1.0 for the first hour.

- Due to precipitation, RSI drops (linearly) to 0.2 at the start of the second hour and it remains at this level until the end of the 4th hour.
- A ploughing and salting operation is completed at the 5th hour which brings the RSC back to bare-wet state with a RSI of 0.8
- Due to the combined effect of precipitation, residual salt and traffic, the RSI is assumed to decrease linearly to a value of 0.2 in the eighth hour.

The solid line in Figure 4 shows the estimated number of accidents that is expected to occur over each hour of the storm duration. The benefit of this particular maintenance operation could be quantified by comparing the average collision frequencies before and after the operation. For example, if we consider four hours before and after the operations, the average reduction in collision frequency due to the maintenance operation is 25%. It is important to note that the magnitude of the reduction, thus benefit, is dependent on the nature of the snow storm, the timing and effect of the maintenance operations. It is however feasible to derive an estimate on the overall benefit over a winter season by simulating the typical snow storms that could occur for the winter season.

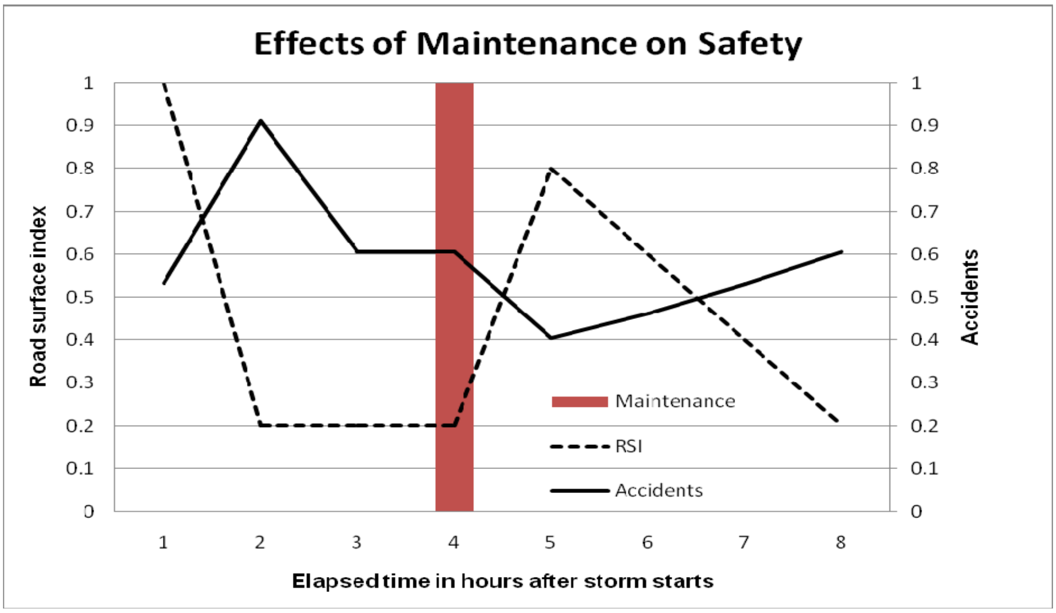

Figure 4 – Effects of Maintenance on safety

4.2.2 Effects of bare pavement recovery time on safety

According to the current MTO maintenance standards, the BP recovery time for class 1 highways is eight hours [20]. What is the safety implication of changing this BP recovery standard? This section attempts to answer this question through an example application of the model developed in the previous section. The same highway section and snow storm used in the previous example are assumed; however, the analysis focuses specifically on the period after the precipitation stops. Furthermore, it is assumed that the road surface at the end of the snow storm is covered by snow and ice with a RSI of 0.2 and the conditions remain the same until some maintenance work is done and BP is recovered. The BP RSI is assumed to be 0.8. Figure 5 shows the increase in the expected number of accidents as a function of the BP recovery time, considering the case with a BP recovery time of one hour as the base case. From Figure 5, the safety implication of different BP recovery time standards could be estimated. For example, the expected safety benefit of reducing BP recovery time from eight hours to six hours would be a reduction of 0.45 accidents for this highway section over this particular snow storm. These values can be easily converted to monetary values by multiplying them by average accident cost. Similar analysis can be conducted for other policy scenarios.

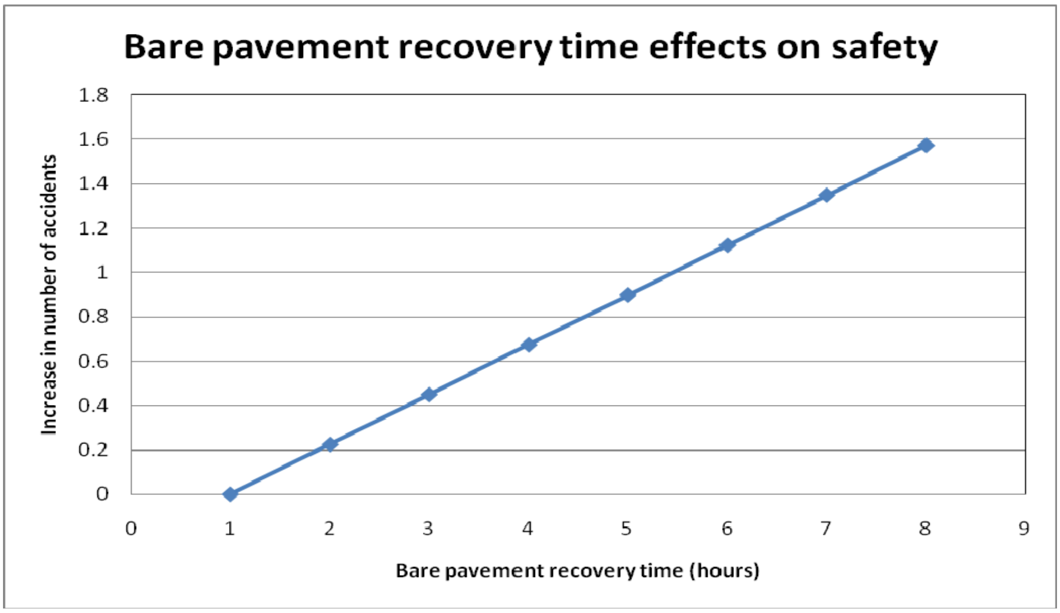

Figure 5 – Effects of Bare pavement recovery time on safety

5. CONCLUSIONS AND FUTURE WORK

This paper has presented the results of a modeling approach aimed at explaining the variation of road accidents and quantifying the effect of winter road maintenance on road accidents during snow storm events. The proposed approach introduces a comprehensive road surface condition measure called road surface condition index (RSI) to model some of the major effects that the weather (precipitation), traffic and maintenance treatments (e.g., ploughing and salting) have on road safety. Detailed hourly data on road weather and surface conditions, traffic, and collision history on four instrumented freeway sections in Ontario, Canada, were obtained. A multilevel Poisson lognormal model (PLN) was applied to fit the data. It was found that the four key weather factors, including visibility, precipitation, air temperature and wind speed, all have a statistically significant effect on road safety. The model also shows that there is a statistically significant link between road surface conditions and road safety. The paper has also illustrated the two potential applications of the developed models, namely, evaluation of the safety benefit of particular maintenance operations and maintenance standards. Using a similar approach, effectiveness of alternative maintenance operations can also be evaluated.

Our future efforts will concentrate on examining the validity of these findings across a wider spectrum of weather, highway, traffic and maintenance conditions, and exploring new model structures such as simultaneous equation models for addressing potential endogeneity problems between traffic and accidents.

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