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A disaggregate model for quantifying the safety effects of winter road maintenance activities at an operational level

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ABSTRACT

This research presents a disaggregated modeling approach for investigating the link between winter road collision occurrence, weather, road surface conditions, traffic exposure, temporal trends and site-specific effects. This approach is unique as it allows for quantification of the safety effects of different winter road maintenance activities at an operational level. Different collision frequency models are calibrated using hourly data collected from 31 different highway routes across Ontario, Canada. It is found that factors such as visibility, precipitation intensity, air temperature, wind speed, exposure, month of the winter season, and storm hour have statistically significant effects on winter road safety. Most importantly, road surface conditions are identified as one of the major contributing factors, representing the first contribution showing the empirical relationship between safety and road surface conditions at such a disaggregate level. The applicability of the modeling framework is demonstrated using several examples, such as quantification of the benefits of alternative maintenance operations and evaluation of the effects of different service standards using safety as a performance measure.

1. Introduction

Winter snow storms have a significant impact on the safety and mobility of highway users. Highway collision rates often increase considerably during snow storms due to slippery road conditions and poor visibility (Andrey et al., 2001; HASTE report, 2002; Knapp et al., 2000; Andrey and Knapper, 2003; Eisenberg and Warner, 2005; Velavan, 2006; Qiu and Nixon, 2008). Weather related collisions are costly to the society. Andrey et al. (2001) estimated that injury and property damage accidents occurring due to inclement weather cost around $1 billion per year in Canada. Winter storms can cause substantial delay due to reduced traffic speeds and road capability as well as 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. Canadian road officials spend around $1 billion each year on winter road maintenance and put around five million tons of salt on Canadian roads (Transport Association of Canada, 2003). This amount excludes other related costs such as damage to the environment, road infrastructure, and vehicles due to salt use (Environment Canada, 2002; Perchanok et al., 1991). While important for maintaining road safety in Ontario, road salting has also raised significant concerns due to its potential damage to the environment, roadside infrastructure, and vehicles (Perchanok et al., 1991; Environment Canada, 2002). A recent study by Environment Canada concluded that road salts at high concentrations pose a risk to plants, animals and aquatic systems (Transport Canada, 2001).

While there is a 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, only a few efforts have been devoted to the problem of quantifying the safety and mobility benefits of winter road maintenance (Hanbali, 1992; Norrman et al., 2000; Fu et al., 2006; Usman et al., 2010). Furthermore, most of the few existing studies have adopted highly aggregated approaches in terms of temporal and spatial levels (e.g. by month, season or year and over a city or region-wide). Usman et al. (2010) was among the first to develop collision models at a disaggregate level with the objective of linking the number of collisions on highways over individual snow storms to the average road weather and surface characteristics and road characteristics. While this level of disaggregation is sufficient for evaluating the average effects of various storm-wise factors, including those of bare pavement policies and standards currently being used in practice, it is not applicable for quantifying the safety effects of specific maintenance treatments deployed over a given storm.

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This paper describes a disaggregate modeling framework proposed for quantifying the impact of road surface conditions and weather factors on winter collision occurrence controlling for traffic exposure and site-specific characteristics. The significance of this effort is twofold. First, this work fills the knowledge gap on the quantitative understanding of how different road weather and surface conditions and traffic factors influence the road safety. Second, the disaggregate accident frequency model developed in this research is the first in the winter road safety literature, providing a foundation for allowing quantification of the safety effects of individual winter road maintenance operations. Given the limited resources available and the growing concern about negative environmental effects associated with some of the winter road maintenance practices such as salting, the ability to perform such detailed analyses is needed in order to develop outcome oriented performance measurement systems for evaluating winter road maintenance related policies and decisions. The paper illustrates the two potential applications of the developed models, namely, evaluation of the safety benefit of particular maintenance operations and maintenance standards. The developed models are expected to be used by local agencies for assessing different decisions related to winter road maintenance.

The paper is organized as follows. The next section provides a literature review of winter maintenance operations, weather and road safety. The proposed methodology, model structure and data, is explained in Section 3. Modeling results, their interpretation and application are given in Section 4. Section 5 highlights the main conclusions and outlines some directions for future research.

2. Literature review

Limited efforts have been devoted to the problem of quantifying the safety benefits of winter road maintenance under various weather conditions. Most of the past research is directed towards establishment of a link between weather and safety (Knapp et al., 2000; Andrey et al., 2001; Andrey and Knapper, 2003; Eisenberg and Warner, 2005; Hermans et al., 2006; Qin et al., 2006, 2007; Qiu and Nixon, 2008; Stern et al., 2011). Hanbali (1992) was among the first who studied effectiveness of winter road maintenance (salting) on safety. A before-after analysis was conducted on undivided and divided highways randomly selected in New York, Minnesota, and Wisconsin, USA. Accidents rates were compared over varied number of hours before and after salting and it was found that for divided highways there was a significant difference in accident rate two hours before and after salting while for undivided highways the difference was significant over four hours. It was found that on 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, ignoring the fact that other important factors such as storm characteristics and traffic volume could be different over the periods before and after salting.

Norrman et al. (2000) were among the first to attempt to quantify the relationship between road safety and road surface conditions. They classified road surface conditions into ten different types based on slipperiness, and then compared the crash rates associated with the different road surface types. The accident risk for a specific road surface condition type was defined as the ratio of the accident rate under the specific road surface conditions to the expected number of accidents for each month. These rates were then compared with percent of time maintenance was done when an accident occurred under some specific road surface conditions. This comparison showed that the frequency of maintenance operations associated with high accident risks is low. From this they concluded that in general, increasing maintenance operation frequency could reduce the number of accidents. However, the approach taken in that study has several limitations. Firstly, it is an aggregate analysis, considering roads of all classes and locations together. This approach may mask some important factors that affect road safety. Secondly, 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. Thirdly, the study uses the frequency of maintenance operations only, disregarding differences between various types of maintenance operations. The procedure cannot be used to compare the effect of different maintenance operations.

Fu et al. (2006) 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 plowing, 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 was 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. One of the implications of these limitations is that their results are not directly applicable for quantifying the safety benefit of winter road maintenance of other highways or maintenance routes.

Usman et al. (2010) attempted to establish a link between winter maintenance and winter road safety using data over three winter seasons from four maintenance routes in the province of Ontario, Canada. A generalized linear model was developed for collision frequency over individual snow storms and it was found that, in addition to some weather and traffic related factors, road surface conditions is a significant factor, suggesting that the model could potentially be applied for evaluating the effect of alternative maintenance standards.

Nordic countries have conducted extensive research on issues related to winter road safety and road maintenance. Wallman et al. (1997) 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.

In terms of safety modelling methodology, the most commonly employed approach for modeling accident occurrence is the generalized linear mixed (Poisson) regression. In particular, the standard negative binomial (NB) model with fixed dispersion parameter and its extension, the generalized negative binomial (GNB) model, have been found to be suitable in many road safety studies (Hauer, 2001; Shankar et al., 1995; Miaou and Lord, 2003; Miranda-Moreno, 2006; Sayed and El-Basyouny, 2006). Both models help dealing with overdispersion, a common issue in crash frequency data (Maher and Summersgill, 1996; Miranda-Moreno, 2006; Lord and Mannering, 2010). In several applications, the GNB model seems to perform better than the NB in terms of goodness-of-fit. Other model settings have been also used such as the Poisson lognormal (PLN) and zero-inflated negative binomial (ZINB) models. The latter can deal with the over-dispersion problem due to excess of zero crash counts. However, ZINB has been criticised because of the assumption of a permanent safe state, which is against the logic of accident occurrence (Hauer, 1999; Lord et al., 2004, 2007). The NB and PLN models have been also extended within a Bayesian framework, to deal with the spatial correction among locations as well as the correlation among crash outcomes, e.g. correlation of accident frequency