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A note on hotspot identification for urban expressways

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ABSTRACT

Hotspot identification (HSID) is of great importance to land transport authorities (e.g. the Land Transport Authority (LTA) of Singapore) in their efforts to improve the safety of highways. According to a survey of experienced engineers at the LTA of Singapore, we draw the conclusion that the severity of crashes should not be neglected in the HSID process. Accordingly, in this technical note, societal risk-based simple ranking and empirical Bayesian methods are proposed to identify the hotspots in a Singapore expressway on the basis of the detailed three-year casualty data in the Historical Crash Damage (HCD) database. We further conduct a consistency analysis to compare the societal risk-based method and the conventional frequency-based method. The consistency analysis reports that (1) the frequency-based method is more consistent than the societal risk-based method, and (2) the empirical Bayesian method is more consistent than the simple ranking method.

1. Introduction

A crash hotspot, also referred to as a high-risk location or black spot, is a term used in highway safety management systems to denote road sites at which crashes are concentrated (PIARC, 2004). The identification of hotspots is of great importance to land transport authorities and other decision makers in their attempts to enhance the safety of highways. Precise localizations of crashes are essential if decision makers are to implement cost-effective risk reduction solutions. By contrast, inaccurate localizations, namely misidentifications of hotspots, will result in the inefficient use of limited resources (Monsere et al., 2006, 2008; Cheng and Washington, 2005; Montella, 2010; Oh et al., 2010). The identification of crash hotspots is the first step in the highway safety management process (AASHTO, 2010; PIARC, 2004; TRB, 2013).

Several hotspot identification (HSID) approaches have been developed on the basis of accident frequency, accident rate, accident reduction potential, and other variables (e.g. Cheng and Washington, 2005, 2008; Elvik, 2008; Huang et al., 2009; El-Basyouny and Sayed, 2006). In addition to those HSID methods that are based on the crash count without taking into account the severity of the crashes, a few HSID methods involving both crash count and severity have been proposed. The typical equivalent property damage only method is to convert all crashes into the equivalent number of property damage only (PDO) crashes on the basis of their severity or the damage caused (PIARC, 2004). However, these PDO-based approaches are unable to represent the economic impact of hotpots on society. It would be more straightforward to represent the consequences/severity of a crash in terms of the monetary cost.

It is of high priority for land transport authorities to reduce the number of "high-risk" or "high-potential for safety improvement" highway sections, and not necessarily those with high crash frequencies, with a limited budget (Qu et al., 2014). That is, the "risk" should be evaluated by taking into account the severity of the crashes. For example, the crash records on two sections of the Central Expressway (CTE) in Singapore (from 2 km to 3 km and from 9 km to 10 km in the southbound direction) in 2007 were 111 and 176, respectively. The latter section can be judged far more dangerous than the former if we only consider the number of crashes. However, there were 6 serious injuries and 59 slight injuries involved in the crashes that occurred on the former section, while only 28 slight injuries were caused by the crashes on the latter. This is because the spot speed in the latter section is significantly lower than that in the former (the latter section is a merging area from an on-ramp to the expressway). Accordingly, on the one hand, there are much fewer traffic conflicts in the former section than the latter (i.e. more conflicts are likely to occur between vehicles on the on-ramp and those on the main expressway). On the other hand, the severity of the crashes that occur on the former section is significantly higher than those on the latter.

If the severities of crashes are assumed to be randomly distributed along the crash spots on a highway, the "risk" will be appropriately represented by the crash frequency without incorporating

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the severities of the crashes. This assumption is invalid for the urban expressways in Singapore, however. There are 11 expressways in Singapore, acting as traffic corridors connecting different urban areas, and these expressways are non-homogeneous in terms of the traffic condition as well as the road geometries. For example, the 15-km CTE has 19 on-ramps and 24 off-ramps. More importantly, the expressway connects the Central Business District (CBD) area in the south with the residential area in the north. Accordingly, the traffic volume on the southern part of the expressway is significantly higher than that on the northern part. Correspondingly, the severities of crashes cannot be assumed to be randomly distributed along the expressways due to the non-homogeneous traffic flow and spot speeds. Therefore, a new approach needs to be developed to identify hotspots by taking into account not only the crash frequencies but also the severities on the urban expressways of Singapore.

The objective of this note is to propose a comprehensive HSID method by taking not only crash frequency but also crash severity (evaluated by the monetary losses caused by different crashes) into account from the perspective of the land transport authorities. The Historical Crash Damage (HCD) database (2006–2008) is used in this study. After that, a consistency analysis is used to compare the conventional HSID method to the proposed HSID method. Discussions and conclusions are presented on the basis of the data analyses.

2. Societal risk-based crash hotspot identification

Let $\{1, 2, \ldots, I\}$ be the set of road sections of a target non-homogeneous urban expressway. Assuming that there are J types of crash denoted by $1, 2, \ldots, J$, let f_{ij} and m_{ij} denote the yearly number of crashes of type j occurring on section i and the estimated monetary loss from one crash of type j, respectively. As an example of the sorts of losses that might occur, the National Safety Council (NSC, 2009), the Highway Safety Manual (AASHTO, 2006), and the Federal Highway Administration (FHWA, 1994) have respectively estimated the monetary losses of four types of motor-vehicle crash using insurance and hospital records, and these are presented in Table 1.

The above values are all based on the "willingness-to-pay" approach, estimating the amounts that individuals are prepared to pay to reduce a risk to their lives, which is the value to the individual on an ex-ante basis, or before the fact. In other words, the willingness-to-pay approach attempts to capture trade-offs between wealth and small reductions in risk. People's preferences (either stated or revealed) demonstrate the value they place on reducing a risk to their life. As can be seen in Table 1, the crashes costs estimated from different studies are quite consistent.

Societal risk has been proposed and used in a number of quantitative risk assessment models to represent risks incorporating both accident frequency and the severity of dangerous scenarios (see Meng et al., 2011a,b; Meng and Qu, 2012). The societal risk is defined as the annual monetary loss due to crashes on one particular section i of an expressway, denoted by R_i, namely,

$$R_i = \sum_{j=1}^{J} (f_{ij} m_{ij}), \quad \forall i \in \{1, 2, \ldots, I\} \tag{1}$$

Table 1
Comprehensive costs of motor-vehicle crashes with different severities.

Crash category	Loss (USD) (NSC, 2009)	Loss (USD) (HSM, 2010)	Loss (USD) (FHWA, 1994)
Fatal	4,300,000	3,000,000	2,600,000
Serious injury	55,300	42,000	36,000
Possible injury	26,300	22,000	19,000
PDO	2400	2300	2000

3. Applications and discussion

3.1. Data description

The HCD database of the CTE is used to conduct this study. As shown in Fig. 1, the CTE links the north and the south of Singapore via the CBD. There are 19 on-ramps and 24 off-ramps connecting to the expressway, causing non-homogeneous traffic volume among the sections. Clearly, the safety performance of the expressway is homogeneous neither in terms of crash frequency nor crash severity: the CBD area probably has a higher crash frequency but a lower crash severity due to the slower traffic speeds there. The crash records in the HCD database are collected by the Land Transport Authority (LTA) of Singapore. According to the Motor Claims Framework introduced by the General Insurance Association of Singapore (GIA), in the event of a crash on an expressway, everyone involved must inform the insurance company within one day using the GIA Motor Accident Report form. In addition, in accordance with the Road Traffic Act of Singapore, another report must be made within 24 h of a crash if an injury has occurred. The HCD database (2006–2008) includes the reported crash records occurring on the CTE from 2006 to 2008, detailing the start time of the crash, its location, the crash type (e.g. rear-end, skidded, chain collision, etc.), the vehicle type (e.g. car–car, car–truck, etc.), the number of slight injuries, number of serious injuries, and number of fatalities. To summarize, there was a total of 6382 vehicle crashes (3305 southbound and 3077 northbound) on the CTE from 2006 to 2008.

In the HCD database, crashes are classified into four types in accordance with their severity: fatal, serious injury, possible injury and PDO. Similar classifications have been used in a number of previous studies (e.g., Wang and Abdel-Aty, 2008). Recently, some institutions have conducted studies estimating the comprehensive losses due to crashes of different types.

3.2. Results and analysis

3.2.1. Simple ranking approach

The comprehensive costs of various crash types estimated by the NSC are applied in this study. Horizontal alignment characteristics and traffic conditions are used to divide the expressway into 26 sections (southbound: S1 to S13; northbound: N1 to N13) with an average length of 1.04 km. Detailed casualty data from crashes occurring on the CTE are obtainable from the HCD database. Fig. 2 reports the longitudinal hotspot distributions along the highway.

As can be seen in Fig. 2, Site N8 is considered risky according to the simple ranking method (crash count > 100 per year per km). However, out of the 353 reported crashes at the site, only 47 involved slight injuries and the remaining 306 were categorized as PDO. The societal risk of the site is thus low (<1 million USD per year per km) in terms of the monetary loss. Accordingly, it may not be a high priority for the land transport authorities to implement risk reduction solutions at this site.

To summarize, the hotspots identified by the two methods are presented in Table 2. It shows that the results generated by the two methods are not exactly consistent for the two consecutive years.

3.2.2. Empirical Bayesian approach

The highly consistent results of the empirical Bayesian (EB) method can be attributed to its use of a predictive model, typically based upon the road geometry, which addresses the regression-to-the-mean bias present in simpler methods (Persaud et al., 1999; Liu et al., 2013). This model forms a baseline from which the