Safety Science 70 (2014) 58–62

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Potential crash risks of expressway on-ramps and off-ramps: A case study in Beijing, China

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ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form 22 January 2014
Accepted 23 April 2014

Keywords:
Crash risk
On-ramps and off-ramps
Urban expressways

ABSTRACT

Objective: This paper aims to assess the potential crash risks across different traffic lanes (shoulder lane, median lane, and middle lane) near to ramps (before on-ramps, between ramps, and after off-ramps).
Methods: Field data are collected at seven locations (90 min for each location) during peak hours. Two risk indices based on time to collision, individual risk and societal risk are proposed to represent the distinct interpretations of risks to transport agencies and individual motorists. One-way ANOVA is applied to analyze the risk impact of ramps in various types of locations across distinct traffic lanes.
Results: Median lanes and sections after off-ramps have relatively lower risks compared to other lanes and sections. The individual and societal risks might not always be consistent since the two risk indices are proposed based on distinct perspectives: transport agencies focus on the crash/conflict frequencies in a road section and individual motorists concern more about the probability of being involved in a crash/conflict during their journey.
Conclusions: The differences in risks mainly result from the frequent lane-changing and merging activities. This model could be used to evaluate the performance of expressway ramp design.
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1. Introduction

Urban expressways are important infrastructures serving intra-city transport needs. Vehicle crashes on expressways are one of the world's largest public health problems, especially in the sense that the victims are overwhelmingly healthy prior to the crashes (Pei et al., 2012; Qu et al., 2014). Indeed, road accidents are the leading cause of deaths for those under 45 years old (BITRE, 2006). Traffic safety issues are the most severe in developing countries, and simple prevention measures could halve the number of deaths. In this regard, traffic safety management has become an over-riding issue in developing countries, especially in populous cities (Zhao and Deng, 2012; Qu and Meng, 2014; Jin et al., 2011).

Understanding the crash mechanism is a high priority in improving the traffic safety of urban expressways. On urban expressways, vehicles entering from on-ramps and exiting to off-ramps are the major factors that result in traffic interruptions, which play an essential role in many of the vehicle crashes on urban expressways. According to AASHTO (2001), the arrangement of on-ramps and off-ramps has a significant impact on road safety. A few scholars have carried out pioneering studies evaluating the safety effects of highway ramps and acceleration lanes. For example, Bared et al. (1999) examined the impact of acceleration and deceleration lane lengths on traffic safety; Chen et al. (2009) evaluated the safety effects of the number and arrangement of lanes on freeway off-ramps; Liu et al. (2010) discussed three types of lane arrangements on freeway sections with closely spaced ramps and their safety effects; Pulugurtha and Bhatt (2010) analyzed the role of geometric characteristics and traffic on crashes in weaving sections. All the existing studies acknowledge that vehicles entering from on-ramps and leaving to off-ramps significantly change drivers' behavior (e.g. encourage lane changing) and thus result in safety issues.

In this study, field observations are conducted in order to understand the impact of ramps. According to the field survey, we find (1) many drivers change from the shoulder lane to the middle lane before on-ramps in order to avoid having to decelerate and give way to merging vehicles, and (2) the traffic flows cross various traffic lanes and locations are thus unbalanced. Evidently, ramps

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http://dx.doi.org/10.1016/j.ssci.2014.04.016
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have an impact on the potential crash risks across locations (before on-ramps, between ramps, and after off-ramps) and lanes (shoulder lane, middle lane, and median lane). Unfortunately, to date, the safety effects of the ramps at various locations and across traffic lanes have not been explored.

In this study, two types of potential crash risks based on time to collision (TTC) are applied to analyze the risk impact of ramps at various locations across traffic lanes. TTC is the time that remains until a collision between two vehicles would occur if the collision course and speed difference were maintained (Hayward, 1972). TTC is a well-recognized safety indicator for traffic conflicts on highways (Meng and Qu, 2012a) and similar concepts have been applied to maritime safety analysis (Qu et al., 2011; Li et al., 2012). Minderhoud and Bovy (2001) pointed out that the TTC is inversely related to vehicle crash frequencies in road sections. It is widely accepted as a safety indicator for highways. A TTC threshold value is usually chosen to distinguish relatively safe situations from dangerous scenarios exposed to traffic conflicts (or critical encounters). For example, a car-following scenario is considered to be a traffic conflict or dangerous encounter if its corresponding TTC value is smaller than the predetermined threshold. Note that other well-recognized safety indicators (e.g. time integrated time-to-collision and time exposed time-to-collision) could also be used to estimate the potential crash risks.

The contribution of this paper is threefold. First, this is the first study to look at the lane distribution of crashes on expressways. The drivers could be better aware of the potential risks when they drive along various traffic lanes. Second, two potential risk indices are proposed to evaluate the safety effects of expressway on-ramps and off-ramps. The two indices could be applied by transport agencies to better design the expressway ramps. Third, the different perspectives of drivers and transport agencies are discussed and analyzed, which could be very useful for helping transport agencies to control potential risks from the viewpoints of not only road managers but also road users.

2. Data description

2.1. Site description

The field data analyzed in this paper were collected from road sections on the Beijing North Ring III expressway, China. The data were collected at seven locations (each location has three lanes: a shoulder lane, middle lane and median lane) for 90 min during peak hours (see Fig. 1) through a traffic management system (based on processing traffic videos). During the observation periods, no traffic crash occurred. The speed limit was 80 km/h. The observed data included the vehicle length, speed, headway, and vehicle type of each vehicle in various traffic lanes across these locations. As can be seen in Fig. 1, Locations 3, 5, and 7 refer to expressway sections following off-ramps (50 m downstream of the off-ramps). Locations 1 and 6 are two expressway sections occurring before on-ramps (50 m upstream of the on-ramps). Locations 2 and 4 are two weaving sections in between two ramps.

2.2. TTC data collection

Fig. 2 illustrates a car-following scenario. Let L_{leader} and L_{follower} be the positions of the leading and following vehicles at a particular time, respectively; $\dot{L}_{\text{leader}}$ and $\dot{L}_{\text{follower}}$ denote the speeds of the leading and following vehicles at a particular time. According to the TTC definition, namely, the time that remains until a collision between two vehicles would occur if the collision course and speed difference were maintained, the TTC can be mathematically expressed by Eq. (1):

$$TTC = \begin{cases} \frac{L_{\text{leader}} - L_{\text{follower}} - l_{\text{leader}}}{\dot{L}_{\text{follower}} - \dot{L}_{\text{leader}}}, & \text{if } \dot{L}_{\text{follower}} > \dot{L}_{\text{leader}} \\ \infty, & \text{otherwise} \end{cases}$$

where l_{leader} is the length of the leading vehicle.

The procedure for measuring the TTC with respect to a particular car-following scenario is as follows. First, the length of the leading vehicle (l_{leader}), the spot speeds of the two vehicles $\left(\dot{L}_{\text{follower}} \text{ and } \dot{L}_{\text{leader}}\right)$, and the time headway ($h$) between the leading and following vehicles can be measured by traffic management systems. Then, according to Vogel (2003), the gap size ($L_{\text{leader}} - L_{\text{follower}} - l_{\text{leader}}$) can be estimated by ($\dot{L}_{\text{follower}} \times h - l_{\text{leader}}$). Finally, the TTC for this particular car-following scenario can be calculated according to Eq. (1). Note that this estimation is based on the assumption that the average speeds can be approximated by the spot speeds.

3. Potential crash risks

In order to assess the risks on various traffic lanes in different locations, we propose potential crash risks from the perspectives of the transport agencies and individual motorists. Transport agencies tend to evaluate road safety in terms of crash/conflict frequencies for a given road section during a particular time period (Meng et al., 2011; Meng and Qu, 2012b). From their perspective, the risk is interpreted as the overall number of conflicts on a survey road section in a one-hour time period, mathematically,

$$SR_i = \frac{N_{i,TTC<\tau}}{t} \tag{2}$$

where $N_{i,TTC<\tau}$ denotes the number of TTC samples with a value of τ or less in road section i, and t is the time period of the survey. This risk is termed societal risk in this paper. By contrast, an individual motorist would be more concerned about the risks to which he or she is exposed during a journey. In other words, a motorist might interpret the risk as the probability of being involved in a conflict during a journey, mathematically,

$$IR_{i,j} = \frac{N_{i,TTC<\tau}}{v_j \cdot N_i} \tag{3}$$

where v_j is the speed of vehicle j, and N_i is the total number of TTC samples in road section i during the survey period. The risk to an individual motorist is termed the individual risk in this paper. According to Eq. (3), the individual risk is estimated by the product of the probability of a dangerous TTC sample $\left(\frac{N_{i,TTC<\tau}}{N_i}\right)$ and the exposure time $\left(\frac{1}{v_j}\right)$. The speed has a dual effect on the individual risk. On the one hand, higher speed might result in higher risks in individual car-following scenarios. $N_{i,TTC<\tau}$ thus becomes greater. On the other hand, higher speed implies a shorter journey time for an individual traveler. As a result, the exposure to the risk is for a shorter time. Thus, Eq. (3) takes into account not only the risk levels of individual car-following scenarios but also the exposure time. It should be pointed out that the probability of a dangerous TTC sample is calibrated based on the TTC samples under particular conditions.

4. Crash risk impact analysis

4.1. Individual and societal crash risks

In this study, the locations are categorized into three types: before on-ramps, between on-ramps and off-ramps, and after off-ramps. For each location, the risks for various traffic lanes (shoulder lane, middle lane, and median lane) are calculated separately according to Eqs. (1) and (3). As suggested in Meng

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