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Analysis of work zone rear-end crash risk for different vehicle-following patterns

Jinxian Weng[a,*], Qiang Meng[b], Xuedong Yan[a]

[a] MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, Beijing 100044, China
[b] Department of Civil and Environmental Engineering, National University of Singapore, 117576 Singapore, Singapore

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ABSTRACT

This study evaluates rear-end crash risk associated with work zone operations for four different vehicle-following patterns: car–car, car–truck, truck–car and truck–truck. The deceleration rate to avoid the crash (*DRAC*) is adopted to measure work zone rear-end crash risk. Results show that the car–truck following pattern has the largest rear-end crash risk, followed by truck–truck, truck–car and car–car patterns. This implies that it is more likely for a car which is following a truck to be involved in a rear-end crash accident. The statistical test results further confirm that rear-end crash risk is statistically different between any two of the four patterns. We therefore develop a rear-end crash risk model for each vehicle-following pattern in order to examine the relationship between rear-end crash risk and its influencing factors, including lane position, the heavy vehicle percentage, lane traffic flow and work intensity which can be characterized by the number of lane reductions, the number of workers and the amount of equipment at the work zone site. The model results show that, for each pattern, there will be a greater rear-end crash risk in the following situations: (i) heavy work intensity; (ii) the lane adjacent to work zone; (iii) a higher proportion of heavy vehicles and (iv) greater traffic flow. However, the effects of these factors on rear-end crash risk are found to vary according to the vehicle-following patterns. Compared with the car–car pattern, lane position has less effect on rear-end crash risk in the car–truck pattern. The effect of work intensity on rear-end crash risk is also reduced in the truck–car pattern.

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1. Introduction

Various routine road maintenance and construction activities, which are referred to as work zone projects, have to be implemented in order to maintain a good level of service in expressways. For example, there are 43 work zone projects planned for the Singapore's Pan Island Expressway (PIE) in 2014. In order to ensure the safety of workers, a work zone usually requires closing a part of the traffic lanes. However, lane closure could increase traffic conflicts, therefore the rear-end crash rate at work zones is generally higher than at non-work zones (Wang et al., 1996; Rouphail et al., 1988; Khattak et al., 2002). Hence, traffic engineers wish to evaluate crash risk for the duration of roadwork operations. Hereafter, rear-end crash risk refers to the probability that a vehicle will be involved in a rear-end crash in a work zone.

In general, there are two types of data available to assess rear-end crash risk. One is historical crash data, which have been widely in previous studies used to establish the relationship between injury severity and its influencing factors. The other is vehicle trajectory data, which can be utilized to evaluate rear-end crash risk. Compared with historical crash data, vehicle trajectory data has two advantages. First, it is possible that there may be no crash accident data available for traffic safety analysis in a work zone. However, it should be pointed out that having no crash accident data does not mean that the work zone is necessarily risk free. In this situation, vehicle trajectory data can be used as an alternative data source for the assessment of work zone traffic crash risk. Second, the quality of vehicle trajectory data is sometimes better than historical crash accident data because traffic police may wrongly record crash accidents. For these reasons, this study uses vehicle trajectory data to evaluate work zone rear-end crash risk.

Currently, there is an increasing trend for more and more vehicles to be equipped with a collision avoidance system, which could detect an imminent rear-end crash and take the corresponding action automatically. An accurate assessment of the potential for a rear-end crash is a key step toward improving system performance. However, rear-end crash risk might be affected by vehicle-following patterns. Many researchers (e.g., Hoogendoorn

* Corresponding author. Tel.: +86 18612036889.
E-mail address: jxweng@bjtu.edu.cn (J. Weng).

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and Bovy, 1998; Weng et al., 2014; Aghabayk et al., 2014) have reported that the time headway, acceleration and deceleration behavior for cars are significantly different from that of heavy vehicles, owing to the differences of their physical and operational characteristics, especially in work zones with reduced lanes. In this situation, the collision avoidance system may detect an imminent crash with low accuracy. Therefore, there is a critical need to show that the work zone rear-end crash risks for different vehicle-following patterns are not the same and it is necessary to develop separate rear-end crash risk models for each vehicle-following pattern.

1.1. Literature review

A number of studies have been conducted for the analysis of work zone crashes using historical accident data (e.g., Abdel-Aty and Abdelwahad, 2004; Wang and Abdel-Aty, 2006; Kim et al., 2007; Srinivasan et al., 2007; Harb et al., 2008; Meng et al., 2010; Qi et al., 2013; Lao et al., 2014). According to these studies, one useful data source for estimating the crash risk is historical traffic crash accident data with high quality and reliability (Kamalasudhan et al., 2002). However, these data may sometimes have poor quality when a part of traffic accidents are unreported or when traffic police record accidents incorrectly. Obviously, poor data quality could lead to biased or incorrect results. In addition, there is a possibility that there may be no crash accident records available for the analysis of work zone risk.

Many researchers have used another data source, vehicle trajectory data, to estimate rear-end crash risk. For example, Hu et al. (2004) proposed a probabilistic model for the prediction of traffic accidents using a 3D model based on vehicle tracking. In their study, a fuzzy self-organizing neural network algorithm was applied to learn trajectory patterns. Hourdos et al. (2006) used individual speeds and headways over each lane to detect crash-prone traffic conditions on a Minnesota freeway. They also established a relationship between fast-evolving real time traffic conditions and the likelihood of a crash. Oh et al. (2006) developed a methodology to identify real-time rear-end collision likelihood by using inductive loop detector data. Cunto and Saccomanno (2008) used deceleration rate to avoid the crash (*DRAC*) to evaluate individual vehicle risk. Oh and Kim (2010) developed methodologies to evaluate freeway safety performance and rear-end crash potential in real time based on the analysis of vehicular movements. Weng and Meng (2014) investigated the relationship between rear-end work zone crash risk and influencing factors at work zone merging areas. Gao et al. (2013) analyzed freeway work zone safety using two safety surrogate measures (*SSM*): time to collision (*TTC*) and *DRAC* based on the collected vehicle trajectory data.

However, it should be pointed out that these vehicle trajectory data-based studies did not take into account the effect of vehicle-following patterns on rear-end crash risk. As argued by Peeta et al. (2005), transportation capacity and safety can be significantly affected by large vehicles (i.e., trucks), because of their physical and operational characteristics. In comparison with cars, trucks are much larger and have reduced emergency brake ability. Several researchers, e.g., Hoogendoorn and Bovy (1998), Ye and Zhang (2009) and Weng et al. (2014), have already shown that the time headway between two successive vehicles can be affected by different vehicle-following patterns (i.e., pairs of the following vehicle and leading vehicle). Therefore, it is necessary to examine rear-end crash risk for different vehicle-following patterns in work zones. In addition, to the best of our knowledge, none of the existing studies took into account the effect of work intensity on rear-end crash risk, despite the fact that different work intensities do actually exhibit varying influences, owing to their unique work zone configurations.

1.2. Objectives and contributions

The first objective of this study is to demonstrate that the work zone rear-end crash risks for different vehicle-following patterns are not the same. The second objective is to develop separate rear-end crash risk models for each vehicle-following pattern, which can then be used to examine the relationship between work zone rear-end crash risk and its influencing factors, including work intensity, lane position, lane traffic flow and heavy vehicle percentage.

The contributions of this study are twofold. First, it confirms that rear-end crash risk in work zones varies significantly according to different vehicle-following patterns. Second, it examines in depth the impacts of work intensity, lane traffic flow rate, heavy vehicle percentage and lane position on rear-end crash risk in work zones.

2. Methodology

The vehicle pairs are first classified into four patterns according to different pairs of vehicle types: (i) car–car, (ii) car–truck, (iii) truck–car, and (iv) truck–truck. Surrogate safety measures (SSM) are any events that can be correlated with crash rates. They represent an indirect measure of safety, which is especially useful for evaluating the safety performance of new roadways. In general, a surrogate safety measure should have the following two properties: (i) the causal mechanism for surrogates and crashes are the same or similar; (ii) there is a strong association between the frequency of surrogate measures and crashes under different settings (Guo et al., 2010). There are a number of surrogate safety measures available for analysis. Archer (2005) has explicitly recognized the superiority of the deceleration rate to avoid the crash (*DRAC*) as a safety measure indicator, compared to the other surrogate safety measures, such as time to collision (*TTC*) and the post encroachment time (PET), which is the time between end of encroachment and arrival of a conflicting vehicle at the potential point of collision. The *DRAC* indicator could reflect the following vehicle's required deceleration to come to a timely stop or attain the corresponding leading vehicle's speed, in order to avoid a rear-end crash. According to Cunto and Saccomanno (2008), rear-end crash risk between two vehicles can be determined as the probability that a given *DRAC* exceeds its maximum available deceleration rate (*MADR*), namely:

$$R_{\text{follower}}^{\text{lead}} = p(DRAC_{\text{follower}}^{\text{lead}} > MADR_{\text{follower}}) \quad (1)$$

$$DRAC_{\text{follower}}^{\text{lead}} = \begin{cases} \dfrac{(v_{\text{follower}} - v_{\text{lead}})^2}{2d_{\text{follower}}^{\text{lead}}}, & \forall v_{\text{follower}} > v_{\text{lead}} \\ 0, & \forall v_{\text{follower}} \le v_{\text{lead}} \end{cases} \quad (2)$$

where $R_{\text{follower}}^{\text{lead}}$ is the probability of a rear-end crash between the following and leading vehicles, $DRAC_{\text{follower}}^{\text{lead}}$ is the deceleration rate of the following vehicle to avoid the crash with the leading vehicle, v_{follower} represents the speed of the following vehicle, v_{lead} represents the speed of the leading vehicle, $d_{\text{follower}}^{\text{lead}}$ is the gap distance between the following and leading vehicles and $MADR_{\text{follower}}$ is the maximum available deceleration rate for the following vehicle. It should be pointed out that the *MADR* depends on such factors as vehicle type. In this study, the *MADR* is assumed to follow a truncated normal distribution and the parameters for *MADR* distributions are listed in Table 1. Statistical test techniques are then used to statistically compare the differences in the mean rear-end crash risk between any two of the four vehicle-following patterns. Graphical comparison is also employed to determine whether rear-end crash risk for each pattern differs significantly when work intensity and lane position change. Next, for each vehicle-following pattern, a rear-end crash risk model is developed to describe the meaningful relationship between rear-end crash risk and influencing factors, including lane traffic flow rate, the heavy vehicle percentage, work

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