EVALUATION OF REAR-END COLLISION RISK IN CAR-HEAVY VEHICLE MIXED TRAFFIC FLOW ON FREEWAYS USING SURROGATE SAFETY MEASURES

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Introduction

As economy is globalized in recent few decades, demand for freight transportation has dramatically increased. In particular, road transportation is a major mode of freight transportation. According to the United States Department of Transportation (U.S. DOT) report, the tonnage of goods by heavy vehicles (in millions tons) increased from 12,778 in 2007 to 13,182 in 2012, and this tonnage will increase to 18,786 by 2040 (U.S. DOT, 2014). Similarly, Transport Canada reported that the tonnage of goods by heavy vehicles increased to 251.4 billion tonne-kilometers in 2013, which is a 4.1% increase from 2012 (Transport Canada, 2015).

Consequently, as more passenger cars and heavy vehicles share the same road, keeping roads safe becomes a big challenge. In the U.S., 4,186 large trucks and buses were involved in fatal crashes in 2013 and, large truck and bus fatalities per 100 million vehicle miles traveled by all motor vehicles remained steady at 0.142 from 2012 to 2013 (U.S. FMCSA, 2015). Thus, it is essential to analyze the safety of car-heavy vehicle mixed traffic flow condition.

Conventionally, the relationships between crash frequency and factors have been analyzed using statistical models and historical crash data. However, this approach has the following limitations. First, safety problems can be identified only after crashes occur. Second, as drivers' driving behaviors are not generally recorded in details in crash data, it is difficult to identify how driving behaviour is associated with crash occurrence or collision risk. Third, due to rare occurrence of crashes, it usually takes several years to collect the crash data with sufficient sample size.

In this regard, surrogate safety measures have been developed to estimate collision risk using trajectory data to access road safety performance. Vehicle trajectory data provide detailed information on driving behaviors such as instantaneous speed, acceleration, deceleration and the gap between two successive vehicles. In addition, trajectory data could be collected in a short period of time unlike crash data.

However, in previous studies, cars and trucks were not differentiated in safety evaluation using surrogate safety measures. In car-heavy vehicle mixed traffic flow, vehicle-following behaviours of car drivers and heavy vehicle drivers are different. Car driver behavior is affected by the size of large trucks due to visibility and difference in speed. Also, car drivers are more likely to suffer severe injury if they collide with a large truck compared to colliding with a car. Thus, it is essential to estimate safety surrogate measures for different types of vehicles separtely.

The objective of this study is to analyze rear-end collision risk on a freeway using two surrogate safety measures: time-to-collision (TTC) and post-encroachment-time (PET). These measures were estimated for different types of lead and following vehicles (car or heavy vehicle) using the individual vehicle trajectory data. The differences of these two safety surrogate measures were also discussed.

Literature Review

Conventionally, the relationships between crash frequency and the related factors have been identified using statistical models. For instance, Zhang et al. (2012) applied the generalized additive model (GAM) to explore potential non-linear relationships between crash frequency and exposures using the crash data (1996-2000) in Texas. Eustace et al. (2015) developed separate crash prediction models for merging and diverging areas. The results showed that left-side merging and diverging increased crash frequency on the ramps. Anastasopoulos & Mannering (2009) applied random-parameters count models to analyze the 5-year crash data from the rural interstate highways in Indiana. The results showed that there exist heterogeneous effects of factors on crash frequencies among different sites.

However, these crash prediction models require long-term crash data. Thus, safety surrogate measures have been developed. In particular, time-to-collision (TTC) has been used to classify the conflict between two vehicles. TTC was first introduced by Harward (1972) and further discussed by Hyden (1987). TTC is the minimum time for the following vehicle to reach the position of the lead vehicle with the initial constant velocity at the time instant when the following vehicle begins braking to avoid the collision with the lead vehicle (Gettman & Head, 2003).

Many researchers have expressed TTC in different equations. For instance, Gettman & Head (2003) defined TTC in the Surrogate Safety Assessment Model (SSAM) as the time it takes for the following vehicle to reach the position of the lead vehicle if the following vehicle's speed remains the same. TTC is calculated as follows:

$$TTC_i = \frac{X_{i-1}(t)-X_i(t)}{V_i} \qquad \text{(Eq. 1)}$$

where TTC_i is the time-to-collision at the i^{th} time frame, $X_{i-1}(t)$ is the position of the lead vehicle, $X_i(t)$ is the position of the following vehicle, and V_i is the velocity of the following vehicle.

However, Bachmann et al. (2011) criticized that the TTC in Eq. 1 does not account for speed of the lead vehicle. Thus, they revised the definition of TTC assuming that both lead and following vehicle continue moving at their present speeds and on the same trajectory. The revised TTC is calculated as follows:

$$TTC_i = \begin{cases} \frac{|X_{i-1}(t)-X_i(t)|}{V_i-V_{i-1}}, & V_i \geq V_{i-1} \\ \infty, & V_i < V_{i-1} \end{cases} \qquad \text{(Eq. 2)}$$

where V_{i-1} is the velocity of the lead vehicle.

On the other hand, some researchers defined TTC considering both gap and speed difference between two vehicles (Minderhoud & Bovy, 2001; Vogel, 2003, Astarita et al., 2012). Unlike Gettman & Head (2003) and Bachmann et al. (2011) which assume front end of the vehicle as the positions of both lead and following vehicles, this TTC specifically focuses on the conflict between rear end of the lead vehicle and front end of the following vehicle as follows:

$$TTC_i = \frac{X_{i-1}(t)-X_i(t)-L_{i-1}}{V_i-V_{i-1}} \qquad \text{(Eq. 3)}$$

where L_{i-1} is the length of the lead vehicle. In this equation, TTC can be calculated only if the lead vehicle's speed is lower than the following vehicle speed ($V_{i-1} < V_i$).

Besides TTC, there are other surrogate safety measures such as the post-encroachment-time (PET). PET is defined as "the minimum post-encroachment time observed during the conflict" according to Gettman & Head (2003). The post-encroachment time is the time difference between the lead vehicle last occupied a position and the following vehicle first reached the same position.

Some researchers have evaluated safety using safety surrogate measures. They defined the frequencies of TTC shorter than a given threshold of TTC as the number of conflicts. For instance, Habtemichael & Santos (2012) evaluated the effect of different types of aggressive driving behaviors on conflicts using a microscopic traffic simulation model and TTC. It was found that TTC values were shorter for speeding, following too close, and unsafe lane change in a weaving section. It was also found that the numbers of conflicts for these three dangerous behaviors will increase by up to 2.36, 6.16, and 7.02 times, respectively, compared to the normal driving behavior.

Nezamuddin et al. (2011) also tested the safety of variable speed limits (VSL) and peak-hour shoulder use based on the number of conflicts as defined in the SSAM. They found that both VSL and peak hour shoulder use decreased the average vehicle delay and the number of conflicts by reducing speed variability.

EI-Tantawy et al. (2009) evaluated safety for different scenarios of truck lane restrictions and dedicated truck lanes using the Paramics traffic simulation model and the SSAM. The results showed that the number of lane-change conflicts decreased but the numbers of merging conflicts and rear-end conflicts increased. In particular, designating the innermost lane as the dedicated truck lane or restricting trucks in the two innermost lanes significantly reduced the interactions between trucks and passenger cars, and lane change conflicts.

St-Aubin et al. (2013) evaluated safety of the protected highway on-ramps using TTC. This treatment prohibits lane change from inner lanes to outer lanes immediately downstream of on-ramps in the weaving zone. This will help avoid conflicts between exit vehicles to off-ramps and merging vehicles from on-ramps. Based on the cross-sectional comparison of statistics and distribution of TTC, it was found that rear-end conflicts are more likely to occur than lane-change conflicts in merging area.

However, there is a limitation in the safety evaluation using the number of conflicts. Although TTC less than 1.5 seconds has commonly been used as a conflict (EI-Tantawy, et al., 2009; Nezamuddin, et al., 2011; Bachmann, et al., 2011, and Habtemichael & Santos, 2012), there is no clear objective criterion for determining this threshold value of TTC. Since surrogate safety measures reflect the probability of crash occurrence, they can be directly used for safety evaluation instead of the number of conflicts. For instance, lower values of TTC and PET indicate higher likelihood of crash occurrence and lower level of safety.

Description of Data

The trajectory data used in this research were retrieved from the Next Generation Simulation (NGSIM) website. In the NGSIM project, individual vehicle trajectories were obtained from a 640-meter (2100 feet) section of US-101 freeway in Los Angeles, California, U.S.A for the three time periods: 1) 7:50 a.m. - 8:05 a.m.; 2) 8:05 a.m. - 8:20 a.m.; and 3) 8:20 a.m. - 8:35 a.m.

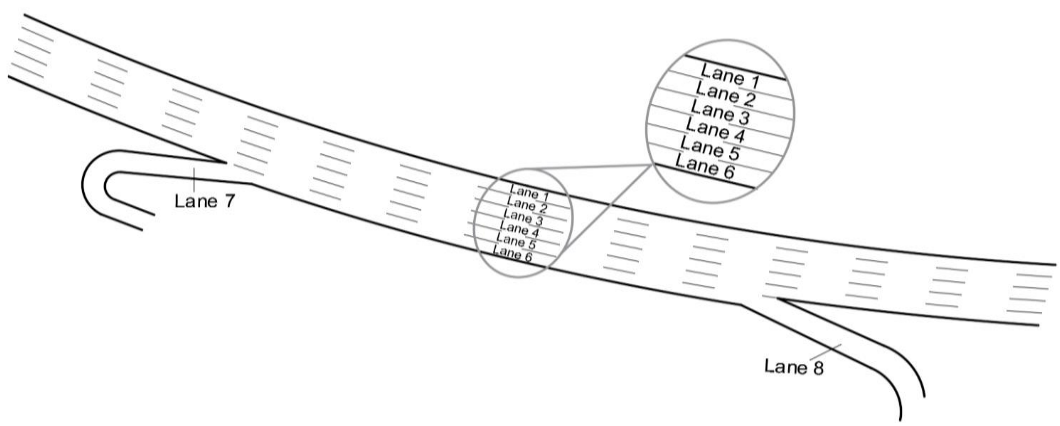

Figure 1. US-101 freeway

The study area consists of five lanes in the mainline freeway (Lanes 1-5) with one auxiliary lane between the on-ramp and off-ramp (Lane 6) as shown in Figure 1. The vehicle trajectory data were collected for every one-tenth second (0.1s) using 8 digital cameras spaced throughout the section.

To estimate the risk of rear-end collision between the lead and following vehicles, the trajectories of the vehicles which did not change lanes were only extracted from the data. Also, the trajectories of the vehicles in the three innermost lanes (Lanes 1-3) were only extracted to minimize the effects of merging and diverging vehicles on the vehicles in the mainline freeway.

Vehicles in the data set are classified into motorcycles, automobiles (cars) and heavy vehicles (trucks and buses). The numbers of the four vehicle pair types (a car following a car (Car-Car), a car following a heavy vehicle (Car-HV), a heavy vehicle following a car (HV-Car) and a heavy vehicle following a heavy vehicle (HV-HV)) in the three time periods are shown in Table 1. The table shows that a car followed by a car is the most common vehicle pair type on this freeway segment. However, due to a lack of data, the case of heavy vehicle followed by a heavy vehicle could not be considered in this study.

Table 1. Number of different vehicle pair types

Vehicle pair types	Car-Car	Car-HV	HV-Car	HV-HV
Number of observations	4440	63	94	2

Method

Two safety surrogate measures - Time-to-collision (TTC) and post-encroachment-time (PET) were estimated in this study. The TTC formula used in this study contains the distance between the rear end of the lead vehicle and the front end of the following vehicle, and the velocity of the following vehicle. This is because a rear-end collision occurs when the front end of the following vehicle hits the rear end of the lead vehicle. Also, this will better reflect actual spacing between the two vehicles than the front-to-front distance since the length of the lead vehicle varies. Figure 2 illustrates an example that although the front-to-front distance is the same for two vehicle pairs – car followed by car and truck followed by car, actual spacing is shorter for truck followed by car than car followed by car.

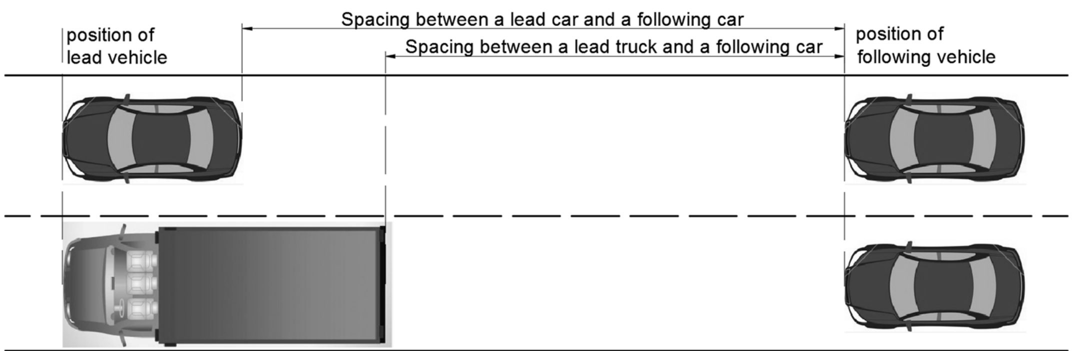

Figure 2. Comparison of spacing between two vehicles for different length of lead vehicle

In this study, TTC was calculated using the following equation:

$$TTC_i = \frac{X_{i-1}(t)-X_i(t)-L_{i-1}}{V_i} \quad \text{(Eq. 4)}$$

The equation of TTC was adapted by Kusano & Gabler (2011). This TTC denotes the time it takes for the front end of following vehicle to reach the rear-end of the lead vehicle if the lead vehicle suddenly stops at a given time instant and the following vehicle maintains the same speed. This TTC does not consider the speed of the lead vehicle unlike the TTC in Eq. (3).

The TTC in Eq. (4) was used in this study because of the following limitations of the TTC in Eq. (3). First, Eq. (3) implicitly assumes that the spacing at a given time instant remains constant until the front-end of the following vehicle reaches the position of rear-end of the lead vehicle. However, since the lead vehicle is assumed to continue moving (instead of stopping) at the instantaneous speed for a given time instant, this spacing is not constant. Second, Eq. (3) cannot be used when the lead vehicle's speed is higher than the following vehicle's speed. Since the lead vehicle's instantaneous speed can significantly fluctuate (particularly at very short time frames), the TTC may not be measured in some time frames. This makes difficult to observe general distribution of TTC.

Figure 3 illustrates how the TTC in Eq. (4) can be measured in the time-distance diagram of the lead and following vehicles. The horizontal axis of the figure indicates the time whereas the vertical axis indicates the positions of the vehicles. Two curves represent the trajectories of the lead and following vehicles.

After TTC_i is calculated for each time frame i, a minimum value of TTC in the car-following condition was determined as the TTC for each vehicle pair. A minimum time headway in the car-following condition was determined as the PET for each vehicle pair.

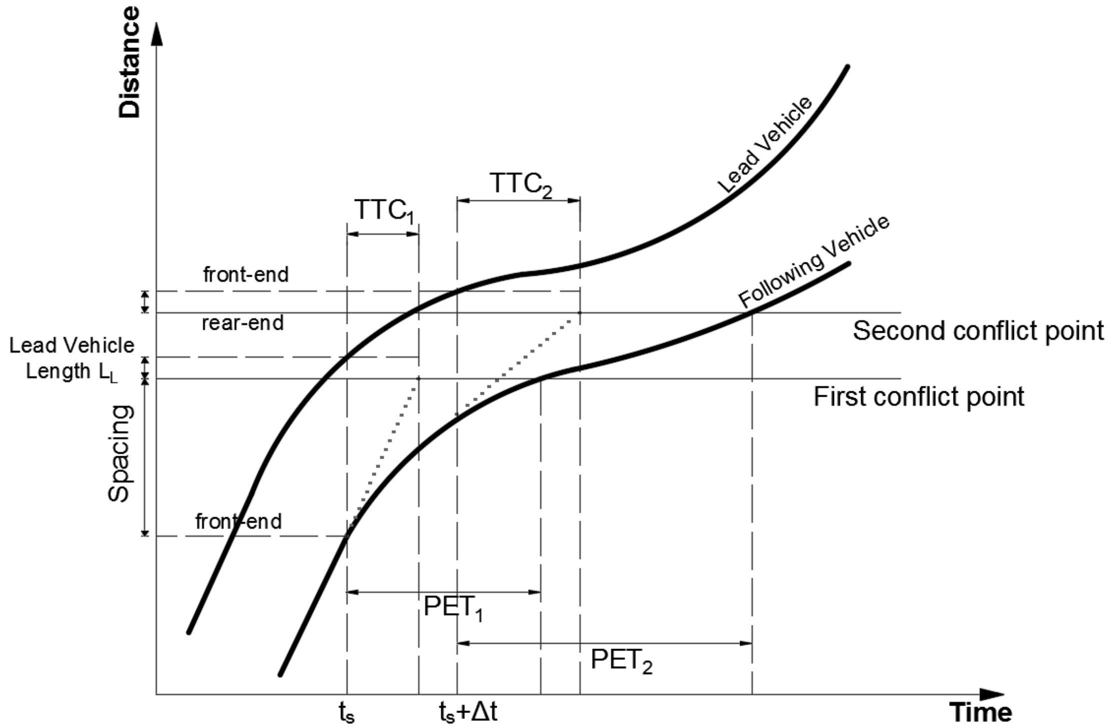

Figure 3. Time-distance diagram of rear-end conflict

Results and Discussion

Distribution of TTC by vehicle pair type

Table 2 and Figure 4 show the descriptive statistics of TTC for different vehicle pair types.

Table 2. Descriptive Statistics of TTC

Vehicle pair type	Min (s)	Max (s)	Mean (s)	SD (s)
Car-Car	0.0013	20.5884	1.2952	0.9031
Car-HV	0.2641	5.5266	1.4123	0.9110
HV-Car	0.2410	8.0437	2.2797	1.6735

It was found that mean TTC for Car-Car is shorter than that of Car-HV. This indicates that the rear-end collision risk is higher for cars when they follow cars rather than heavy vehicles. This is mainly because car drivers tend to maintain a longer spacing with the lead heavy vehicle (mean spacing = 57.4 ft) than the lead car (mean = 52.4 ft). Similarly, heavy vehicle drivers maintain substantially longer spacing with the lead vehicle than car drivers considering lower maximum deceleration of heavy vehicles. Thus, TTC for HV-Car was the longest. These results indicate that the collision risk varies by not only the following vehicle type, but also the lead vehicle type.

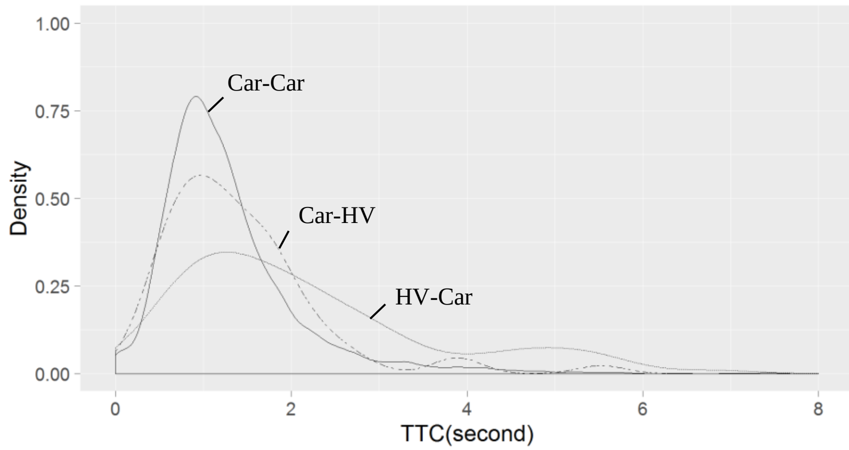

Figure 4. Distribution of TTC by vehicle pair type

In order to check if these TTC values are statistically different between two different vehicle pair types, non-parametric statistical tests were performed. Mann-Whitney U–test (Zheng, et al., 2015) was adapted with the assumption that the distribution of the samples is unknown.

It was found that TTCs are not statistically different between Car-Car and Car-HV (p-value = 0.234) whereas TTCs are statistically different between Car-Car and HV-Car (p-value < 0.001). Thus, although the collision risk is slightly higher for Car-Car than Car-HV, the difference is not statistically significant. This result also indicates that rear-end collision risk is significantly different between the following car and heavy vehicle drivers.

Distribution of PET by vehicle pair type

Table 3 and Figure 5 show the descriptive statistics of PET for different vehicle pair types.

Table 3. Descriptive Statistics of PET

Vehicle pair type	Min (s)	Max (s)	Mean (s)	SD (s)
Car-Car	0.0100	39.3600	1.6743	1.1400
Car-HV	0.8500	6.0200	2.2076	0.9116
HV-Car	0.6800	9.2700	2.6989	1.6419

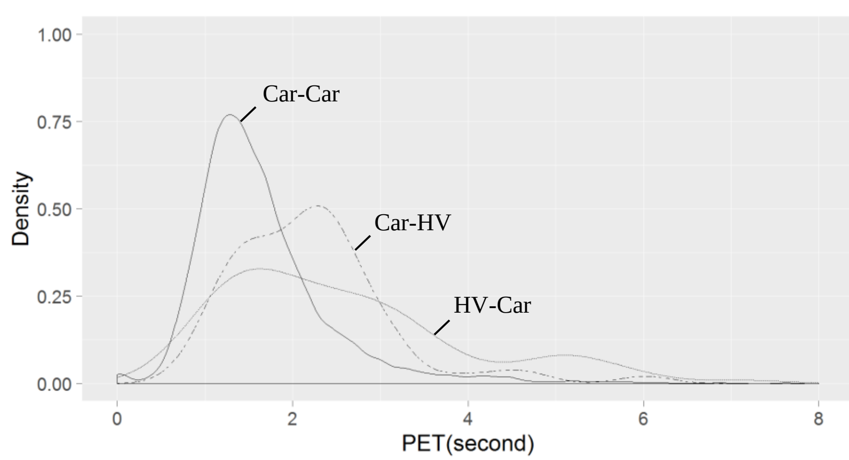

Figure 5. Distribution of PET by vehicle pair type

PET considers the speed variance of the lead and following vehicles, and the difference in acceleration between the two vehicles during the car-following condition. In general, when the spacing with the lead vehicle is small, the following vehicle's driver will decelerate to maintain the enough safety distance. However, in the definition of TTC, the following vehicle's driver is assumed to continue traveling at the same speed regardless of the spacing. Therefore, for a given vehicle pair, the value of PET is greater than the value of TTC. Similar to mean TTC, mean PET was the longest for HV-Car and the shortest for Car-Car. This implies that heavy vehicle drivers actually maintained a longer time headway than car drivers.

The PETs were also compared between the three different vehicle pair. The Mann-Whitney U–test result shows that the PET for Car-Car is statistically different from the PETs for Car-HV and HV-Car (p-value < 0.001). This result indicates that the difference between Car-Car and Car-HV is significant for PET, but not TTC. This indicates that car drivers are more likely to adjust their speeds to avoid collisions when they follow heavy vehicles compared to following cars.

Conclusions and Recommendations

This study analyzed rear-end collision risk in car-heavy vehicle mixed traffic flow on a freeway using two surrogate safety measures: time-to-collision (TTC) and post-encroachment-time (PET). TTC and PET were calculated for cars and heavy vehicles separately using the individual vehicle trajectories on US-101 freeway in California, U.S.A. The two surrogate measures were also calculated for different types of lead and following vehicles – a car following a car (Car-Car), a car following a heavy vehicle (Car-HV), and a heavy vehicle following a car (HV-Car).

The result shows that TTC and PET were the longest for HV-Car and the shortest for Car-Car. This indicates that rear-end collision risk is lower for heavy vehicle drivers than car drivers when they follow cars.

The result also shows that TTC and PET were shorter for Car-Car than Car-HV. This indicates that rear-end collision risk is higher for car drivers when they follow cars than heavy vehicles. This is mainly because car drivers feel less safe when they follow heavy vehicles and maintain a longer spacing with the lead heavy vehicles. However, this difference was statistically significant only for PET, but not TTC.

This difference between PET and TTC is due to the difference in the assumption. TTC is a "conceptual" measure of rear-end collision risk calculated based on the assumed maneuver of the lead and following vehicles. On the other hand, PET is an "observed" measure of rear-end crash risk which reflects actual time headway between the lead and following vehicles. Thus, PET is a more practical measure which accounts for the following vehicle driver's reaction during the car-following condition. However, PET cannot be used to predict rear-end collision risk in advance unlike TTC which predicts when a rear-end collision would occur with the assumed maneuvers of vehicles.

Nevertheless, this study demonstrated that rear-end collision risk is significantly different among different types of lead and following vehicles on a freeway. The findings suggest that rear-end collision risk should be estimated for cars and heavy vehicles separately in car-heavy vehicle mixed traffic flow.

In the future studies, it is recommended that a microscopic traffic simulation model is calibrated to replicate the observed distributions of these surrogate safety measures in the simulation. Then the effects of various traffic control methods on reduction in car-heavy vehicle conflicts can be evaluated using the calibrated simulation model. It is also recommended that these surrogate safety measures are validated using actual crash data.

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