

Rear-end crash potential estimation in the work zone merging areas

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SUMMARY

This paper proposed a methodology to estimate rear-end crash potential of the merging vehicles traveling in the merge lane, on the basis of the traffic data extracting from the available videotapes. First, we developed a binary logit model to identify drivers' merging behavior in the work zone merging area. Subsequently, the occurrence potential of rear-end crash based on time-to-collision was computed between the merging vehicle and its neighboring vehicles. The overall crash potential of the merging vehicle was finally determined. It was found that the crash potential decreases with the remaining distance to work zone. Moreover, there will be a rear-end crash potential of 4.0% if the merging vehicle fails to complete merging at the end of work zone merging area. If the merging vehicle takes an early merge, there will be a lower rear-end crash potential (1.2%). These findings suggest that we should encourage merging vehicles to take early merges for improving the traffic safety in the work zone merging areas. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: work zone merging area; logit model; rear-end crash; time-to-collision; merging

1. INTRODUCTION

The presence of work zone increases the number of traffic conflicts due to lane closures. However, the increased traffic conflicts cause higher rear-end crash potential. Many past studies reported that the rates and frequency of rear-end crashes in work zones are higher than those in non-work zones [1–5]. As deemed by Srinivasan *et al.* [6], most rear-end crashes occur in the work zone merging areas during the peak periods and bad weather condition. In addition, they pointed out that rear-end crashes in the work zone merging area are likely to be more severe when they are compared with the crashes in other work zone areas. Therefore, the estimation of rear-end crash potential in the work zone merging areas may help prioritize countermeasures aimed at reducing the frequency and injury severity of crashes occurred in work zone merging areas.

A number of studies have been conducted on the analysis of rear-end crashes. Among these studies, the historical accident data are used to identify the casual factors and analyze the injury severity by using statistical techniques. However, it may result in biased results when the historical data have poor quality and reliability because traffic police wrongly record accidents. In addition, it is possible that no historical accident data are available for the analysis of vehicle rear-end crash risk, especially in the work zone merging area. Fortunately, the advanced sensor and communication technology can help us to fully exploit the available traffic data to estimate the rear-end crash potential.

Therefore, the focus of this paper is to estimate the rear-end crash potential of a merging vehicle in the work zone merging area using the traffic data extracted from the available videotapes. Hereafter, a merging vehicle is referred to as a vehicle traveling in the merge lane. In previous traffic safety studies,

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time-to-collision (*TTC*) has been considered as an effective indicator to evaluate the safety of individual vehicles [7,8]. Hence, *TTC* is also adopted in this paper in measuring the occurrence potential of a crash between the merging vehicle and its neighboring vehicles.

1.1. Literature review

On the basis of the historical accident data, numerous studies have been conducted on the analysis of road crashes using statistical approaches. Tay and Rifaat [9] developed an ordinal probit model based on the crash data from 1992 to 2002 to determine the contributing factors affecting the severity of intersection crashes. Barua and Tay [10] proposed an ordered probit model to investigate the factors contributing to the bus crash severity. On the basis of the data for single vehicle crashes for the years 2003–2005, Rifaat *et al.* [11] addressed a logistic model to explore the factors affecting crash occurrences and severity. Srinivasan *et al.* [6] modeled the location of rear-end crash within work zones as functions of the lengths of different work zone segments, traffic volume, weather, and other exogenous factors. The results showed that work zone merging area is particularly unsafe during the peak period and bad weather condition. Harb *et al.* [12] developed a conditional logistic regression model to estimate work zone rear-end crash risk.

With the development of sensor and video technology, recent studies have attempted to exploit the real-time traffic data to estimate crash risk. Hu *et al.* [13] proposed a probabilistic model for the prediction of traffic accidents using 3D model-based vehicle tracking. In their study, a fuzzy self-organizing neural network algorithm was applied to learn trajectory patterns. Hourdos *et al.* [14] used individual speeds and headways over each lane to detect crash-prone traffic conditions on a freeway in Minnesota. They also established a relationship between fast-evolving real-time traffic conditions and the likelihood of a crash. Oh *et al.* [7] developed a methodology to identify the real-time rear-end collision potentials by using inductive loop detector data. Oh *et al.* [15] developed a methodology to evaluate freeway safety performance based on individual vehicle trajectory data and a prototype implementation. Oh and Kim [8] presented another methodology for estimating the rear-end crash potential in real time based on the analysis of vehicular movements.

In summary, the recent video and sensor technology allows us to fully exploit the benefits of available traffic data to estimate the rear-end crash potential in the work zone merging area. The existing literature also provides adequate supports that it could yield reliable and accurate results based on the real-time vehicle trajectory data. However, little efforts have been made to estimate rear-end crash potential in the work zone merging area using this more accessible traffic information.

1.2. Objectives and contributions

The estimation of rear-end crash potential in the work zone merging area may help prioritize countermeasures aimed at reducing the frequency and injury severity of crashes in the work zone. Therefore, this paper aims to present a methodology to evaluate rear-end crash potential in the work zone merging area by using the accessible traffic data. First, a binary logit model is developed to determine the potential of the merging vehicle moving into the through lane. Subsequently, the *TTC* and the occurrence probability of rear-end crash based on *TTC* are computed between the merging vehicle and its neighboring vehicles. The overall potential of the merging vehicle involving in a rear-end crash is finally determined.

The proposed methodology can be applied for either an existing work zone or a newly proposed work zone. It can also be extended to determine the effectiveness of the countermeasures for rear-end crash preventions in the work zone.

2. METHODOLOGY

The presence of work zone causes one or more lanes to be unavailable to traffic. Therefore, vehicles traveling in a lane that is partially closed for work zone activities ultimately have to merge into the adjacent through lane. Hereafter, the lane that is partially closed is defined as the merge lane. A vehicle traveling in the merging lane is defined as the merging vehicle. Figure 1 shows a merging vehicle and its neighboring vehicles. It can be seen that the merging vehicle n follows the lead vehicle $n - 1$ in the

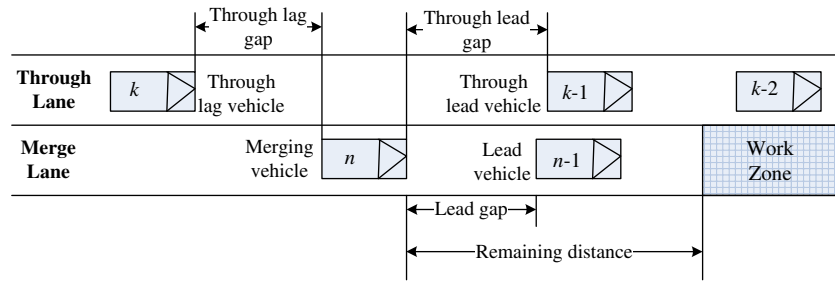


Figure 1. Merging vehicle and the neighboring vehicles.

merge lane with the lead gap (d_n^{n-1}). Note that the lead vehicle $n - 1$ is also a merging vehicle. In order for the merging vehicle to avoid collision with the lead vehicle or work zone, the merging vehicle should either change lane or decrease speed. Otherwise, a rear-end crash may occur when the merge vehicle does not change lane or decelerate its speed. If the merging vehicle enters into the through lane, there is also a probability that the merging vehicle collides with the through lag vehicle k and/or the through lead vehicle $k - 1$ in the through lane. Therefore, the overall crash potential of the merging vehicle is computed as the sum of the probabilities of the merging vehicle colliding with its neighboring vehicles.

Because the *TTC* can directly reflect the potential of rear-end crash between two vehicles, *TTC* is thus used for estimating the rear-end crash potential between the merging vehicle and its neighboring vehicles in this paper. Four stages of the methodology to estimate the rear-end crash potential are depicted in Figure 2, and the detailed description of each stage is elaborated as follows.

2.1. Merging probability calculation

When the merging vehicle considers moving into the through lane, it will first evaluate vehicle movements on the merge and through lanes to determine whether the adjacent gap is accepted. If the adjacent gap is accepted, then it will make a merging maneuver. Otherwise, it will continue traveling in the merge lane. This behavior can be recognized as a sequential gap choice process with two alternatives: “merge into the through lane (*MT*)” if the adjacent gap is accepted and “not merge into the through lane (*NMT*)” if not. This recognition has also been adopted in previous driver behavior studies [16,17]. Because of the advantage of treating the effects of influencing variables on driver choice behavior, a binary logit model is employed to estimate the merging probability and can be formulated as follows:

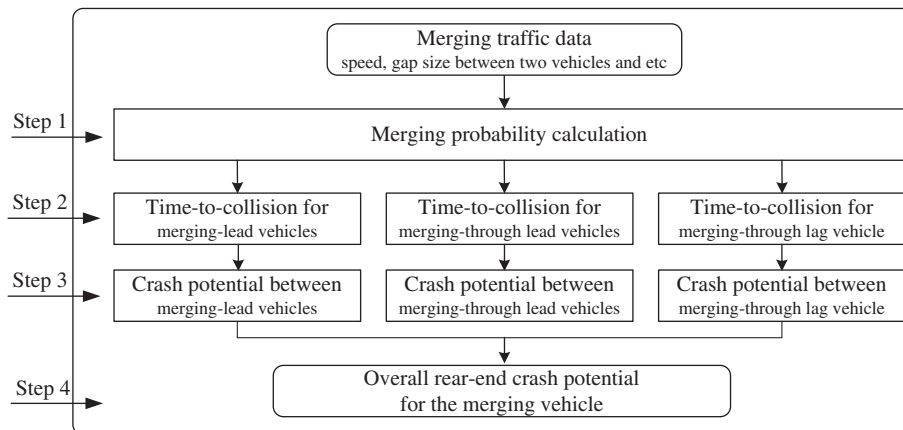


Figure 2. Four stages of the methodology.

$$p(MT_n|X_n) = \frac{\exp(X_n\beta)}{1 + \exp(X_n\beta)} \quad (1)$$

$$p(NMT_n|X_n) = 1 - p(MT_n|X_n) \quad (2)$$

where X_n is a vector of explanatory variables affecting the decision of the merging vehicle n . These explanatory variables include the merging vehicle speed, lead vehicle speed, the through lead and lag vehicle speeds, lead gap, through lead and lag gaps, and so on. β is the parameter vector to be estimated, $p(MT_n|X_n)$ is the probability that the merging vehicle n will merge into the through lane under the given traffic condition X_n , and $p(NMT_n|X_n)$ is the probability that the merging vehicle n will not merge into the through lane under the given traffic condition X_n .

2.2. Time-to-collision calculation

The *TTC* has been applied beneficially as a safety indicator in safety analysis. According to the definition of *TTC* addressed by Hyden [18], a *TTC* value at an instant t is the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained.

As aforementioned, if the merging vehicle decides to keep traveling in the merge lane, it has the probability of collision with the lead vehicle or work zone. Let $TTC_n^{n-1}(t)$ denote the *TTC* between the merging vehicle and the lead vehicle at current time t . $TTC_n^{n-1}(t)$ can be calculated by

$$TTC_n^{n-1}(t) = \frac{d_n^{n-1}(t)}{v_n(t) - v_{n-1}(t)}, \forall v_n(t) > v_{n-1}(t) \quad (3)$$

where $d_n^{n-1}(t)$ is the lead gap between the merging vehicle n and the lead vehicle $n-1$ at time t , $v_n(t)$ is the speed of the merging vehicle n at time t , $v_{n-1}(t)$ is the speed of the lead vehicle $n-1$ in the merge lane.

It should be noted that Equation (3) is available when there is a lead vehicle with respect to the merging vehicle. Actually, the *TTC* function shown in Equation (3) can be also used to determine the *TTC* between the merging vehicle and work zone when there is no lead vehicle as well. Let δ represent the existence of a lead vehicle ($\delta=1$ if there is a lead vehicle and $\delta=0$ if there is no lead vehicle). As $\delta=0$, we can assume that there is a virtual lead vehicle stopped in the work zone. In this case, the lead gap $d_n^{n-1}(t)$ is equal to the remaining distance of the merging vehicle n to work zone, and $v_{n-1}(t)$ is taken as zero at time t .

As mentioned earlier, if the merging vehicle decides to move into the through lane, there will be a potential of collision with the through lead and/or lag vehicles for the merging vehicle. The *TTC* between the merging lead vehicle and the through lag vehicle k , denoted as $TTC_n^k(t)$, can be calculated as

$$TTC_n^k(t) = \frac{d_n^k(t)}{v_k(t) - v_n(t)}, \forall v_k(t) > v_n(t) \quad (4)$$

where $d_n^k(t)$ is the through lag gap between the through lag vehicle k and the merging vehicle n at time t , and $v_k(t)$ is the speed of the through lag vehicle k at time t .

The *TTC* between the merging vehicle and the through lead vehicle $k-1$, denoted by $TTC_n^{k-1}(t)$, can be expressed as

$$TTC_n^{k-1}(t) = \frac{d_n^{k-1}(t)}{v_n(t) - v_{k-1}(t)}, \forall v_n(t) > v_{k-1}(t) \quad (5)$$

where $d_n^{k-1}(t)$ is the through lead gap between the merging vehicle n and the through lead vehicle $k-1$ at time t , and $v_{k-1}(t)$ is the speed of the through lead vehicle at time t .

2.3. Occurrence potential of crash under a given time-to-collision

In general, it could lead to high potential for crash occurrence when a TTC is very small and a large TTC could result in a low occurrence potential of crash. According to the work of Oh and Kim [15], a generalized exponential decay function $y = a + be^{-x/c}$ can be used to describe the relationship between the TTC and the corresponding potential of crash occurrence.

Because the occurrence potential of crash ranges from 0 to 1, we can assume that $a = 0$ and $b = 1$ in this paper. Therefore, the occurrence potential of crash under a given TTC can be expressed by

$$p = e^{-TTC/c} \quad (6)$$

It should be noted that the parameter c in Equation (6) is able to reflect crash frequency of a road segment. For instance, a larger value for c indicates that there is higher crash occurrence frequency for the road segment.

2.4. Overall rear-end crash potential calculation

Given the merging probability and the occurrence potential of crash based on a given TTC , the occurrence potential of rear-end crash between the merging vehicle n and the lead vehicle $n - 1$ can be estimated by

$$p^{(t)}(Crash_n^{n-1}) = p^{(t)}(NMT_n|X_n) \cdot p^{(t)}(C_n^{n-1}|TTC_n^{n-1}) \quad (7)$$

where $p^{(t)}(Crash_n^{n-1})$ is the occurrence potential of rear-end crash between the merging vehicle and the lead vehicle $n - 1$ at time t , and $p^{(t)}(C_n^{n-1}|TTC_n^{n-1})$ is the potential that the merging vehicle collides with the lead vehicle or work zone based on the TTC_n^{n-1} at time t .

The occurrence potential of rear-end crash between the merging vehicle n and the through lag vehicle k at time t , denoted by $p^{(t)}(Crash_n^k)$, can be estimated by

$$p^{(t)}(Crash_n^k) = p^{(t)}(MT_n|X_n) \cdot p^{(t)}(C_n^k|TTC_n^k) \quad (8)$$

where $p^{(t)}(C_n^k|TTC_n^k)$ is the potential that the merging vehicle collides with the through lag vehicle k based on the TTC_n^k at time t .

Similarly, the occurrence potential of rear-end crash between the merging vehicle n and the through lead vehicle $k - 1$, denoted by $p^{(t)}(Crash_n^{k-1})$, can be computed by

$$p^{(t)}(Crash_n^{k-1}) = p^{(t)}(MT_n|X_n) \cdot p^{(t)}(C_n^{k-1}|TTC_n^{k-1}) \quad (9)$$

where $p^{(t)}(C_n^{k-1}|TTC_n^{k-1})$ is the potential that the merging vehicle n collides with the through lead vehicle $k - 1$ based on the TTC_n^{k-1} at time t .

Hence, the overall rear-end crash potential of the merging vehicle is computed as the sum of probabilities of the merging vehicle colliding with the lead vehicle, the through lead and lag vehicles. That is,

$$p^{(t)}(Crash_n) = p^{(t)}(Crash_n^m) + p^{(t)}(Crash_n^k) + p^{(t)}(Crash_n^{k-1}) \quad (10)$$

where $p^{(t)}(Crash_n)$ is the overall potential of the merging vehicle n involving in a rear-end crash at time t .

3. DATA COLLECTION

In order to evaluate the methodology introduced for the estimation of rear-end crash potential, we use the merging traffic data collected from a short-term work zone site located in Ang Mo Kio Avenue 3 in Singapore. The layout of the work zone site is shown in Figure 3. It should be pointed out that driving in Singapore follows the British model. For example, all traffic is generally required to keep left unless overtaking in Singapore. Incoming traffic is seen coming from the right, and the vehicles have the driving seat on the right.

It can be seen from Figure 3 that the advance warning sign is placed upstream and the distance from the advance warning sign to the start of transition taper is about 130 meters. Additionally, the length of transition taper is about 30 meters. There are three lanes in each direction, and the fast lane is blocked for the maintenance activity. Therefore, the fast lane is regarded as the merge lane, and vehicles in the fast lane are considered as merging vehicles.

In the survey, a video camera was used to record vehicular movements in the through and merge lanes. This is because it can cause lower stochastic errors by replaying the collected videotape, compared with other data collection equipments. The completed vehicle trajectory data was extracted every second from the collected videotape by using the Premier Pro CS3 software. Each set of vehicle trajectory data consists of the following information:

- (1) The merging vehicle speed, v_n (km/hour).
- (2) The existence of lead vehicle, δ .
- (3) The lead vehicle speed, v_{n-1} (km/hour). Note that v_{n-1} is assumed as zero when there is no lead vehicle with respect to the merging vehicle ($\delta=0$).
- (4) The through lead vehicle speed, v_{k-1} (km/hour).
- (5) The through lag vehicle speed, v_k (km/hour).
- (6) The lead gap, d_n^{n-1} (m). Note that d_n^{n-1} equals to the remaining distance of the merging vehicle to work zone when there is no lead vehicle ($\delta=0$).
- (7) The through lead gap, d_n^{k-1} (m).
- (8) The through lag gap, d_n^k (m).
- (9) The through lead-lag headway, t_k^{k-1} (s).

4. ANALYSIS OF RESULTS

From the survey, a total of 528 datasets including 332 merging datasets and 196 non-merging datasets are collected from the survey. Table I provides the descriptive statistics of each variable. According to Table I, it can be found that the average lead vehicle speed v_{n-1} is far lower than the merging vehicle speed v_n . This is because the lead vehicle speed is taken as zero when there is no lead vehicle with respect to the merging vehicle ($\delta=0$). In Table I, the mean of δ collected from the survey is 0.45, suggesting that there are more than a half number of datasets containing zero value for v_{n-1} . Hence, the mean of v_{n-1} is very low.

The LOGIT procedure in Statistical Analysis Software [19] is implemented to determine the coefficients of explanatory variables used in the binary logit model. In addition, the backward elimination method, in

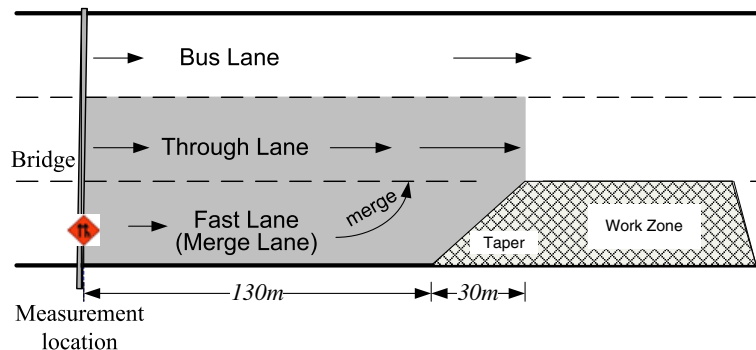


Figure 3. Data collection layout of short-term work zone.

Table I. Descriptive statistics for all variables collected from the work zone site.

Variable	Definition	Mean	Std dev	Min	Max
v_n (km/hour)	The merging vehicle speed	42.14	12.54	8.6	69.1
δ	The existence of lead vehicle	0.45	0.49	0	1
v_{n-1} (km/hour)	The lead vehicle speed	16.98	20.55	0	57.6
v_{k-1} (km/hour)	The through lead vehicle speed	42.24	15.60	5.2	69.1
v_k (km/hour)	The through lag vehicle speed	37.10	14.53	4.5	69.1
d_n^{n-1} (m)	The lead gap size	34.35	24.88	1.3	100.0
d_n^{k-1} (m)	The through lead gap size	17.81	12.54	5.5	56.2
d_n^k (m)	The through lag gap size,	21.82	15.53	4.0	60.2
t_k^{k-1} (second)	The through lead-lag headway	1.99	0.84	0.5	4.6
Number of merging decisions ($y=1$): 332					
Number of non-merging decisions ($y=0$): 196					

Note: v_{n-1} is equal to zero as $\delta=0$.

which the variables are tested for removal from the model one by one based on the significant level of the likelihood ratio, is adopted to choose the variables for the binary logit model. We assume that the least significant variable with level of significance greater than 0.05 should be removed from the binary logit model. The Wald chi-square statistic is used to test the variable significance for the calibrated logit model. Three other statistics including the Akaike information criterion statistic, the Schwarz criterion statistic, and the -2 Log-likelihood statistic are applied to assess the goodness of fit of the calibrated model.

Table II presents the estimated variable coefficients and related statistical results for the binary logit model. According to the table, the intercept and coefficients of the variables in the model are statistically significant. Six variables including the merging vehicle speed v_n , the existence of lead vehicle δ , the through lead vehicle speed v_{k-1} , the through lag vehicle speed v_k , the through lead-lag headway t_k^{k-1} , and the lead gap d_n^{n-1} are found to influence driver's merging choices. Among the six variables, the variable t_k^{k-1} is found to be the most significant variable because of its highest odds ratio. The positive coefficient of the variables t_k^{k-1} , v_n , and v_{k-1} indicates that the larger through lead-lag gap headway, the bigger merging vehicle speed, and through lead vehicle speed would encourage the merging vehicle to merge into the through lane. However, the signs of coefficients for variables δ , d_n^{n-1} , and v_k are negative, suggesting that the merging vehicle is most likely to keep traveling in the current lane (not merge into the through lane) when there is a long lead gap or the through lag vehicle moves too fast. This finding is consistent with the realistic merging maneuver.

Table II. Statistic results for the binary logit model.

Variable	β	Std err	Wald statistic	Odds ratio	p -value
Intercept	−15.3456	1.8192	71.158	0	<0.0001
t_k^{k-1} (second)	4.6541	0.5190	80.401	105.000	<0.0001
δ	−1.5849	0.5410	8.581	0.205	0.0034
v_n (km/hour)	0.0515	0.0248	4.302	1.053	0.0381
d_n^{n-1} (m)	−0.0500	0.0134	13.946	0.951	0.0002
v_{k-1} (km/hour)	1.1040	0.1284	73.901	3.016	<0.0001
v_k (km/hour)	−0.9463	0.1177	64.603	0.388	<0.0010
			Intercept only	Intercept and covariates	
AIC			698.535	223.193	
SC			702.804	253.076	
−2 Log-likelihood:			696.535	209.193	
Testing global null hypothesis: $\beta = 0$					
Likelihood ratio chi-square				<0.001	
Score chi-square				<0.001	
Wald chi-square				<0.001	
Correct classification rate				93.2%	

Note: Odds ratio (OR) is calculated by changing one unit of one variable at a time while controlling for the other variables, where $OR = \exp(\beta)$. For example, one unit increase of v_{k-1} will raise the merging probability to be 3.016 ($=\exp(1.104 \times 1)$) times. AIC, Akaike information criterion; SC, Schwarz criterion.

The correct classification rate is defined as the ratio of the number of correctly identified maneuvers by the binary logit model to the total number of maneuvers observed from the survey. A cut-off 0.5 is used for computing the classification rate. The high correct classification rate (93.2%) indicates that the developed binary logit model can predict driver merging behavior with a high degree of accuracy. Hence, the binary logit model can be written as

$$p(MT_n|X_n) = \frac{\exp(-15.3456 + 4.6541t_k^{k-1} - 1.5849\delta + 0.0515v_n - 0.05d_n^{n-1} + 1.104v_{k-1} - 0.9463v_k)}{1 + \exp(-15.3456 + 4.6541t_k^{k-1} - 1.5849\delta + 0.0515v_n - 0.05d_n^{n-1} + 1.104v_{k-1} - 0.9463v_k)} \quad (11)$$

With the merging traffic data from the survey, we can obtain the *TTC*s between the merging vehicle and its neighboring vehicles. Note that an infinite large value will be assigned to the *TTC* when the speed of the lag vehicle is less than or equal to the corresponding lead vehicle speed. It can be found that the minimum *TTC* between the merging vehicle and the lead vehicle is 1.402 seconds, less than the minimum of 2.487 seconds between the merging vehicle and the through lag vehicle and the minimum of 2.587 seconds between the merging vehicle and the through lead vehicle. Figure 4 presents the

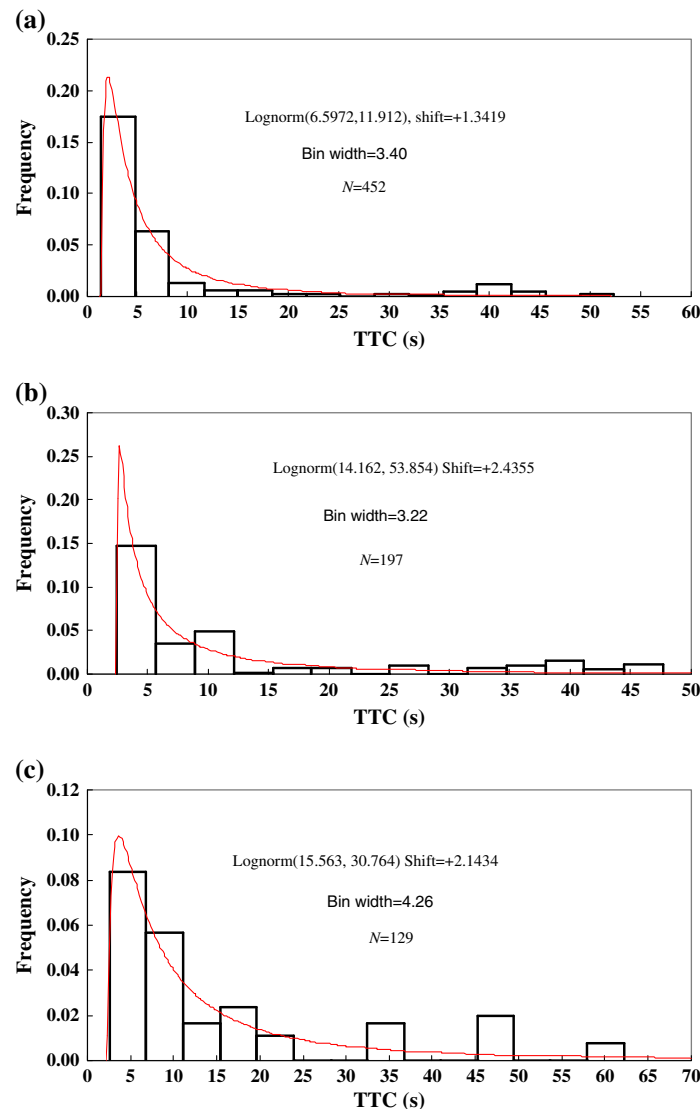


Figure 4. Distributions of *TTC*: (a) between the merging vehicle and the lead vehicle; (b) between the merging vehicle and the through lag vehicle; (c) between the merging vehicle and the through lead vehicle.

best-fitted TTC -frequency distributions between the merging vehicle and its neighboring vehicles by using the @Risk software. It is found that the shifted lognormal distribution can fit the observed three types of TTC best. From Figure 4, an interesting finding is that the majority of merging vehicle speeds is larger than the lead vehicle speeds. Only a small proportion of through lag vehicles are found to travel faster than the merging vehicles.

Next, we calculate the probabilities of merging vehicles involving a rear-end crash in the merge and through lanes, respectively. To estimate the occurrence potential of rear-end crash based on a given TTC , the parameter c in Equation (6) is assumed as 1.2 in this paper. Figure 5 shows the relationship between the remaining distance to work zone and the crash potential for the merging vehicle based on the TTC_n^{n-1} . It should be noted that the values of rear-end crash potential in Figure 5 are calculated using Equation (6) with TTC_n^{n-1} . The curve is a trend line following the logarithmic pattern. From the figure, it can be clearly seen that crash potential in the merge lane for the merging vehicle decreases with the remaining distance to work zone. This is because the lead gap decreases as the remaining distance to work zone decreases. In addition, the merging driver would become more and more aggressive if he or she fails to move into the through lane because of the inadequate through lead-lag headway. Therefore, the crash potential near work zone is relatively larger than that far from work zone. In addition, the rear-end crash potential in Figure 6 is the sum of the values estimated by Equation (6) based on TTC_n^k and TTC_n^{k-1} . Similarly, there will be higher occurrence potential of collision with the through lead and lag vehicles for the merging vehicle even if it decides to merge into the through lane at the end of work zone merging area, shown in Figure 6. This important finding suggests that it will be safer for the merging vehicle if it takes a merging maneuver earlier.

The overall crash potential for the merging vehicle can be estimated according to Equation (10). The rear-end crash potential in this figure is estimated using Equation (10). Figure 7 demonstrates the relationship between the overall crash potential and the positions of merging vehicles. It can be found

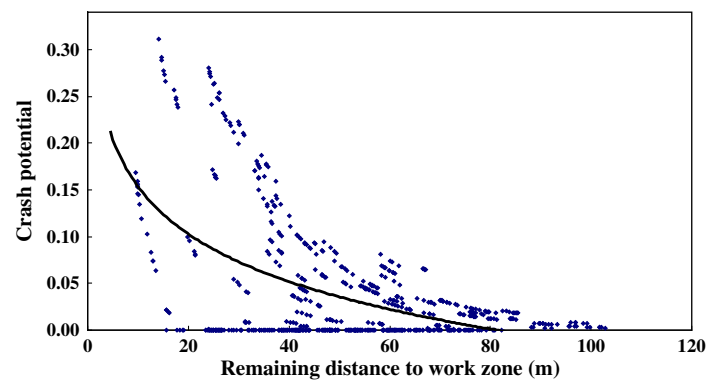


Figure 5. Crash potential in the merge lane based on the TTC_n^{n-1} .

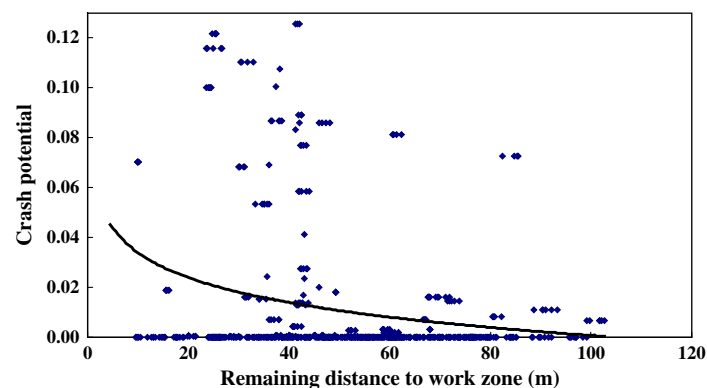


Figure 6. Crash potential in the through lane based on the TTC_n^k and TTC_n^{k-1} .

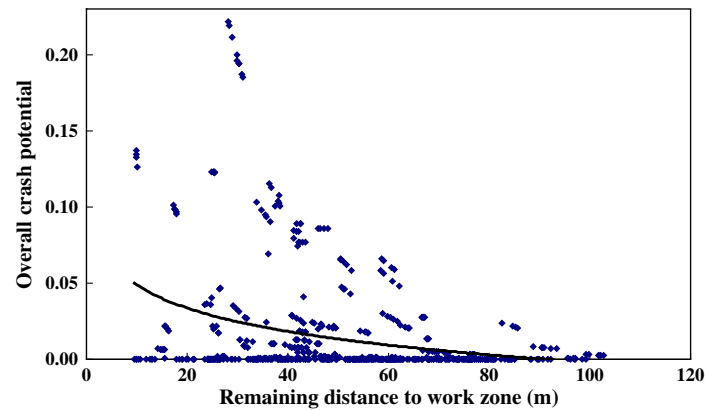


Figure 7. Overall crash potential versus the remaining distance to work zone.

that the merging vehicle far from work zone (=large remaining distance to work zone) has a low occurrence potential of collision with its neighboring vehicles, whereas the merging vehicle near work zone has high overall crash potential whatever it decides to. The average crash potential for all merging vehicles can be expressed in the following form:

$$ACP = \frac{\sum_{n=1}^{N_o} p(Crash_n)}{N_o} \quad (12)$$

where ACP represents the average crash potential, and N_o is the number of observed merging vehicles traveling across work zone.

According to Equation (12), there will be a rear-end crash potential of 4.0% if the merging vehicle fails to complete merging at the end of work zone merging area. If the merging vehicle takes an early merge, there will be a lower rear-end crash potential (1.2%). The overall rear-end crash potential for the merging driver is 1.5%. According to Figure 8, it can be seen that the rear-end crash potential of non-merging behavior is always higher than that of merging behavior as the parameter c increases. These findings suggest that the early merging action could reduce the rear-end crash potential in various road conditions. Therefore, it is an effective method to improve work zone safety by encouraging merging vehicles to take an early merge.

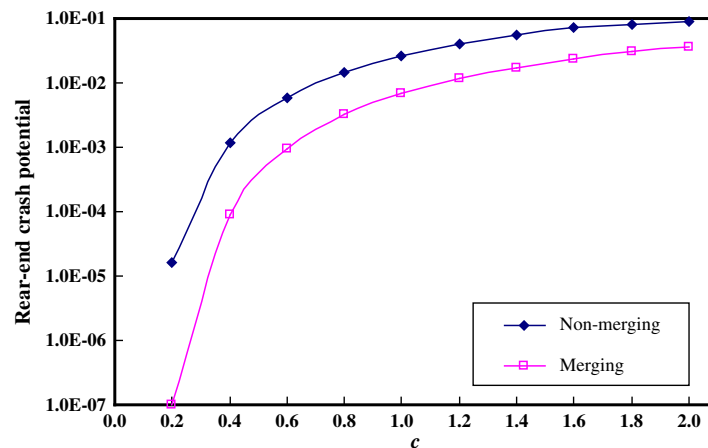


Figure 8. Impacts of driver merging behavior on rear-end crash potential.

5. CONCLUSIONS

In contrast to previous studies measuring crash potential by using historical accident data, this paper presented a methodology to evaluate rear-end crash potential in the work zone merging area using the merging traffic data. The *TTC* was used in measuring the occurrence potential of two-vehicle collision. To estimate the overall crash potential between the merging vehicle and its neighboring vehicles, a binary logit model was developed to determine the probability of the merging vehicle moving into the through lane.

The merging traffic data from the short-term work zone site in Singapore was utilized to test the proposed methodology. Six factors were found to significantly affect driver's merging choice: (i) the merging vehicle speed; (ii) the through lead vehicle speed; (iii) the through lag vehicle speed; (iv) the existence of lead vehicle; (v) the lead gap size; and (vi) the through lead-lag headway. The *TTC* between the merging vehicle and its neighboring vehicle follows the shifted lognormal distribution. It was also found that crash potential of the merging vehicle decreases with the remaining distance to work zone. This suggested that early lane merge control measures should be taken to make merging vehicles merge into the through lane as early as possible for the safety consideration. For example, a series of dynamic "Do Not Pass/When Flashing" signs could be placed in advance of the taper area creating an enforceable no passing zone, to encourage motorists to make an early merge. These signs should also be equipped with sensors that monitor traffic density and congestion. When the density is high or traffic congestion is detected, a signal is transmitted to the next upstream dynamic no passing sign, to activate the sign's flashing signal.

The feasibility of the proposed methodology has been demonstrated and the results from this study are useful for traffic engineers to evaluate traffic control strategies that are adopted for accident preventions. However, this study still has one limitation. Rear-end crash potential may be significantly affected by the following work zone configuration related factors: the number of closed lanes, the number of lanes left available for traffic, types of traffic control device, speed limit, existence of a bus lane, and so on. This study does not take into account the impacts of these factors on the rear-end crash potential. Therefore, future studies might be conducted to examine the impacts of these factors on the rear-end crash potential. It should be pointed out that the early merges could reduce work zone capacity though they can improve the work zone safety. From the traffic throughput consideration, late merges are recommended because they could increase work zone capacity. The combination of early and late merges could be an effective approach to improve both the work zone capacity and safety. Hence, it will be also an interesting topic to determine the optimal merge control scheme maximizing the sum of weighted values between safety and capacity in future.

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