Potential Maximum Benefits of Controlled Vehicle Braking in Reducing Pedestrian Ground Contact Injury

Zou Tiefang, Liu Zhuzi, Zhou Jing, Zhao Yunlong, Wang Danqi

I. INTRODUCTION

As pedestrians are among the most vulnerable road users, the protection of pedestrians in vehicle-pedestrian collisions has become a research focus in recent years. According to existing research, while pedestrian injury is mainly caused by the impacting vehicle, ground-related injuries cannot be ignored [1-3]. A recent study found that the total injury cost could be reduced by two-thirds if ground-related injury were avoided in low speed collisions [4], demonstrating the value of studying methods for reducing such injuries in vehicle-pedestrian collisions. Further research found that controlled vehicle braking shows significant potential to reduce the overall burden of pedestrian ground-contact injuries, and simulation results show substantial median reductions in Weighted Injury Cost (WIC) and head impact velocity for all vehicle shapes, except the Van [5]. This research raises interesting questions, including how much WIC can be maximally reduced and whether the injury caused by the vehicle will be more severe when controlled vehicle braking is applied in vehicle-pedestrian collisions?

II. METHODS

The Controlled Braking Method

The method proposed in [5] (shown in Fig. 1) was employed in this study to control the vehicle braking in each simulation. At t_0 the pedestrian first makes contact with the vehicle, and t_1 is the first head-vehicle contact time. The vehicle is fully braked until $t_{1,}$ to minimize the vehicle-head impact velocity, and then the braking is reduced to 0 at t_1, with a lag time of 0.2 s until $t_{2,}$ when full braking is resumed (accounting for lag time).

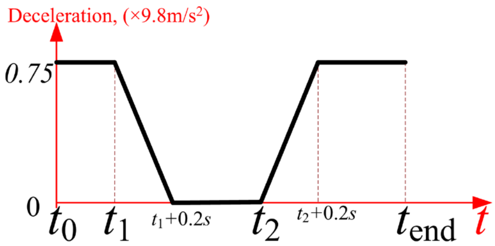

Fig. 1. Curve of the deceleration of the controlled braking method.

In order to obtain optimal t_2, the method of exhaustion was used. The interval [t_1+0.2, 1.4] was divided into 100 sub-intervals and then each end point was considered as a t_2. In practice, we found that 1.6 s after t_1 is enough time for a vehicle to achieve a level of braking sufficient to reduce pedestrian ground-contact injury, which is why we selected 1.4 s as an upper boundary here. Obviously, 100 simulations are required for each controlled braking test.

Design of Experiments

The design described in [5-6] was employed in this study. For each Basic Simulation Test Sample (BSTS), 24 simulations with three velocities (21, 31 and 41km/h), four pedestrian sizes (90th%Male, 50th%Male, 5th%Male and 5th%Female) and two pedestrian gaits (50% and 100%) were included. As controlled vehicle braking does not reduce ground-related injury when the vehicle is a Van and the ground-related injury occurrence is low when the vehicle is a Sportscar, we opted to include only the Bigcar, Highsuv, Compactcar and Smallsuv in this study (see Fig. 2).

In order to analyze the maximum benefits of controlled vehicle braking for four vehicle shapes* BSTS (2 pedestrian gaits*3 vehicle velocities*4 pedestrian sizes) = 96 tests were conducted. In each test, two braking methods were applied. In the first situation the vehicle was braking fully during the whole process, while in the

Z. Tiefang (e-mail: tiefang@163.com; tel: +86 731 85258630) is Professor and W. Danqi is a lecturer and Z. Jing and Z. Yunlong are graduate students in Changsha University of Science and Technology. L. Zhuzi is a lecturer in Changsha Social Work College.

second situation the vehicle was controlled by the braking method shown in Fig. 1. There were 101 simulations in each test, hence there were 96*(100+1) =9,696 simulations in total.

In order to analyze whether the pedestrian injury caused by the vehicle would be more severe after the braking was starting to reduce to 0 at t_1, the time at which the braking was starting to reduce to 0 was set to 0, t_1, t_1+0.15s, t_1+0.3s and ∞. If the time was set to ∞, this meant the vehicle was braking fully during the whole process. If the time was set to 0, this meant the vehicle was not braking during the whole process. Obviously, we needed four vehicle shapes*5 time steps=20 tests. In each test, the BSTS (3 vehicle velocities*4 pedestrian sizes*2 pedestrian gaits) were included, therefore we had to conduct 480 simulations in total.

All simulations were conducted by MADYMO. In each simulation, similar to previous studies [6], the friction coefficients of pedestrian to vehicle and pedestrian to ground contact were set to 0.3 and 0.6, respectively. A single stiffness level for each vehicle front structure was used.

The crash scenario with a pedestrian being hit laterally accounts for about 80% of accidents in the German In-Depth Accident Study (GIDAS) and was taken as the baseline simulation condition for varying vehicle speed and pedestrian size, gait [7]. The pedestrian was offset by 400 mm from the vehicle centreline (opposite to the pedestrian's walking direction), since a specific walking speed was defined for a given pedestrian model [6], and this maintained the head contact on the vehicle front body.

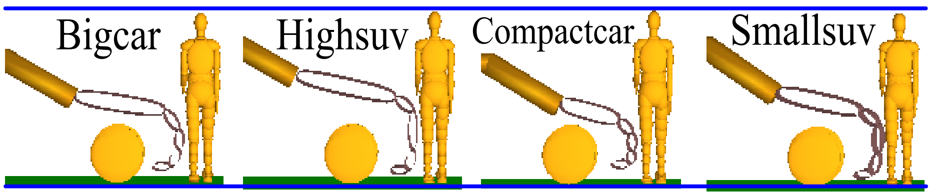

Fig. 2. The vehicle shape versus 50th%Male pedestrian model.

Evaluation Indices and Analysing approaches

In the study, only the Weighted Injury Cost (WIC) proposed in [6-7] was employed as an index. The WIC was calculated by:

$$\mathrm{WIC} = \sum_{i=1}^{N} \mathrm{IC}_i * p_i \tag{1}$$

where

$$p_i = p_{si} * p_{hi} * p_{gi}, \qquad \sum_{i=1}^{N} p_i = \sum_{i=1}^{N} p_{si} = \sum_{i=1}^{N} p_{hi} = \sum_{i=1}^{N} p_{gi} = 1. \tag{2}$$

N is the number of simulations in a BSTS and it is equal to 24 in the research. p_{si}, p_{hi} and p_{gi} are the proportion of the vehicle velocity, the pedestrian height and the pedestrian gait, respectively. Their value is determined by the distributions of the corresponding impact parameters observed from accident data in GIDAS. IC_i (sum of the medical cost and auxiliary cost of all injuries to a pedestrian's head, thorax, pelvis and legs) is the predicted injury cost for a crash scenario. In each simulation, the HIC (head), Thoracic Trauma Index (TTI) (thorax), impact force (pelvis), bending moment (long bone in lower limbs) and bending angle (knee) were extracted first, and then the thresholds of these injury criteria were applied to assess AIS levels of the predicted injuries. Finally, the IC_i can be calculated based on AIS levels of injuries suffered in the corresponding body regions. Thus the WIC for the BSTS (N=24), defined as the sum of the product of the injury cost (IC_i) and the proportion (p_i) for a given impact scenario in the BSTS (Eq. (2)), is the weighted average cost of all injuries recorded per impact in the BSTS.

As we know, although the MADYMO is a popular and well-established software in analyzing injury in vehicle-pedestrian collisions, the model is not well validated in analyzing pedestrian-ground contact injury. In order to reduce the influence of this factor, graphing and tabulation methods were employed to carry out the comparative study.

III. INITIAL FINDINGS

The influence of the Time at which Braking starts to reduce

Figure 3 shows the WIC caused by the vehicle versus the different times at which braking started to reduce. This shows clearly that the WIC caused by the vehicle did not be more severe if the braking started to reduce after the time t_1. This tells us that there is no evidence of an a-priori risk to pedestrians in reduced vehicle braking after t_1, which means we can try to reduce the ground-related injury by controlling the vehicle braking.

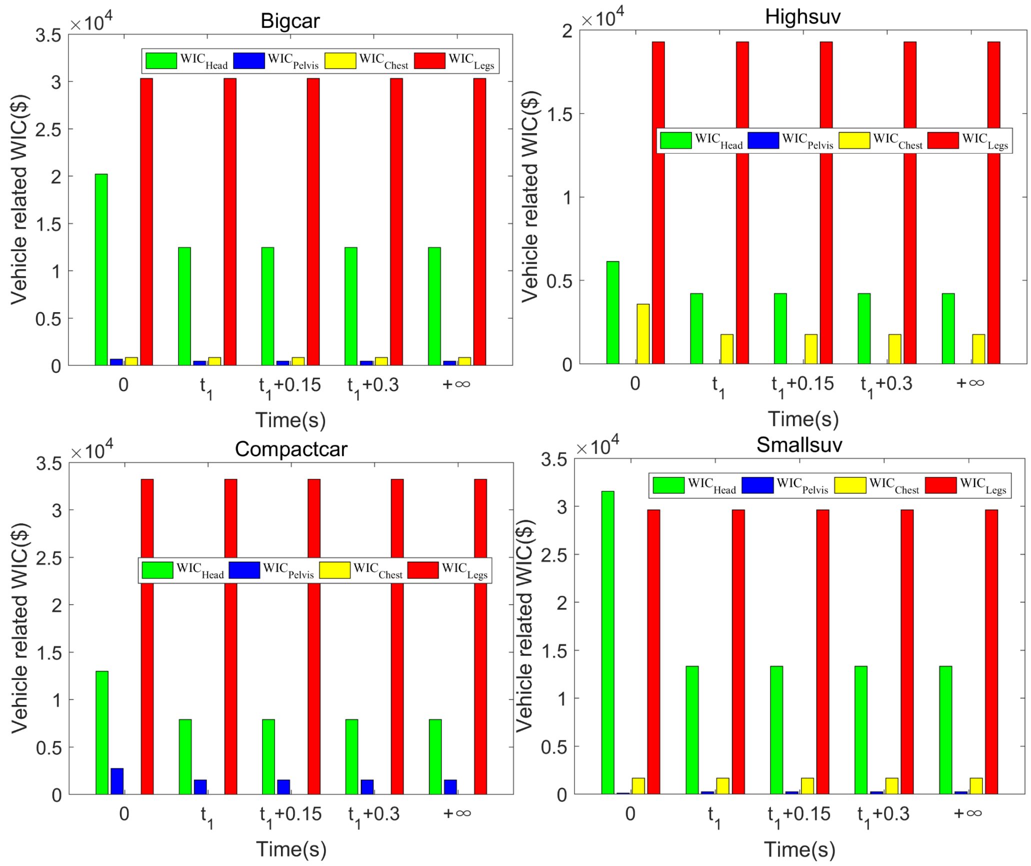

Fig. 3. WIC caused by the Bigcar, Highsuv, Compactcar and Smallsuv versus the different times at which braking is starting to reduce.

The Maximum Benefits of Controlled Vehicle Braking

Table I shows these results, in which the reduction rate is calculated by Equation (3):

$$\text{Reduction rate} = \frac{\text{WIC}_{\text{full-braking}} - \text{WIC}_{\text{controlled-braking}}}{\text{WIC}_{\text{full-braking}}} * 100\% \tag{3}$$

TABLE I

THE GROUND-RELATED WIC IN FULL BRAKING AND CONTROLLED BRAKING SIMULATIONS

Vehicle shape	Full braking, WIC（$）	Controlled braking, Minimum WIC（$）	Reduction rate
Bigcar	9308.7	1502.3	83.9%
Highsuv	14513	1613.5	88.9%
Compactcar	21381	566.0	97.4%
Smallsuv	9501.9	2417	74.6%
Average	13676.15	1524.7	88.9%

Table I shows that the maximum benefits of controlled vehicle braking are substantial. The ground-related WIC in the controlled braking group can be reduced by 88.9% on average and by a maximum of 97.4%.

IV. DISCUSSION

The analysis reported two findings. One finding is that we can reduce the vehicle braking to 0 after t_1 in order to reduce the ground-related injury to the pedestrian and this will not make the vehicle-related injury be more severe. The second finding is that the maximum benefits of controlled vehicle braking are substantial. This proves that this field of research –reducing ground-related injury by controlling vehicle braking – is a worthwhile pursuit for future studies.

One of the questions raised here is whether we can find t_1 and t_2 easily in practice. t_1 is the time the pedestrian head first contact the vehicle. Figure 4(A) shows that t_1 decreases as the speed increases, its median changed from 0.22 s to 0.12s. Such kinds of small values tells us that high quality vehicle sensors are needed in order to detect t_1. t_2 is the time the vehicle is starting to full brake again. In those simulations we found many t_2 can results a minimum ground related injury, which means that it is not hard for us to find out a optimal value in practice. And then we subtract the t_1 from the minimum value of those optimal t_2, results were shown in Figure 4(B). We found that range of t_2-t_1 increases as the speed increases. But values of t_2-t_1 are in a narrow interval when the impact velocity is 21km/h, which means that we may propose simple method to determine t_2 in practice under lower impact speed condition.

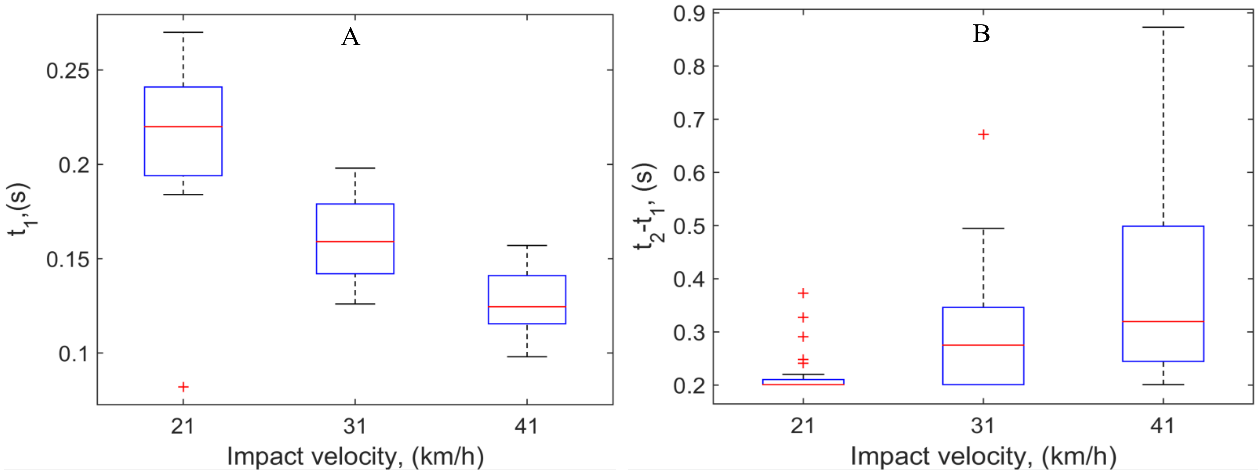

Fig. 4. The box plot of t_1 (A) and t_2 (B) versus impact velocity.

V. CONCLUSIONS

Through these simulations, we found that the vehicle-related injury to the pedestrian would not be increased if the vehicle braking were reduced to 0 after t_1 and that the ground-related injury could be reduced by 88.9% on average and by a maximum of 97.4%. Through a further analysis we found that the optimal t_2 is not hard to obtain especially under lower impact speed condition, the t_1 is small hence high quality vehicle sensor is needed in order to detect it. The limits of this study are that the reasons why ground-related injury was reduced through controlled vehicle braking were not analysed and that the means of achieving the controlled braking method in practice was not addressed. Further research will be required to answer these questions.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

[1] Otte D., *et al*., IRCOBI, 2001.
[2] Kendall, R., *et al*., SAE Technical Paper, 2006.
[3] Badea-Romero, A., *et al*., *Accid Anal Prev*, 2013.
[4] Shang, S., *et al*., *Accid Anal Prev*, 2018.
[5] Zou, T., *et al*., *Accid Anal Prev*, 2019.
[6] Li, G., *et al*., *Traffic Inj Prev*, 2016.
[7] Li, G., et al., Accid Anal Prev, 2017.