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Research Article

Vehicle safety analysis at non-signalised intersections at different penetration rates of collision warning systems

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Abstract: The market penetration of intelligent vehicles is a long-term process. In recent years, significant attention has been paid to the influence of technology market penetration rate (MPR) on efficiency at signalised intersections, but little attention has been given to such an influence on safety at non-signalised intersections. In this study, the influence of the intersection collision warning (ICW) system MPR on safety at non-signalised intersections is investigated. The authors built a Matlab-based simulation platform where an ICW algorithm was implemented. The simulation was firstly conducted to verify their models. Then the simulation results of different MPRs were obtained and compared statistically. Collision probability, conflict index, and collision rate were analysed for safety evaluation. The overall results showed that vehicle safety at non-signalised intersections improves with the increase of the ICW system MPR. Without considerations of inappropriateness and otherness of driver reaction to warnings, when the MPR is 20% and all vehicles are connected by vehicle-to-everything, the collision probability, conflict index, and collision rate can be reduced by around 20, 20, and 35%, respectively. The simulation method can establish a mapping relation between the ICW system MPRs and vehicle safety indices at non-signalised intersections.

1 Introduction

1.1 Motivation and contribution

Intersections are essential but risky elements of the road network, where potential conflicts between vehicles occur. In reality, a considerable portion of traffic accidents takes place at the intersection all around the world. More than 40% of traffic accidents occur at or near intersections in the United States, while more than 30% of fatality and 40% of serious injuries also occur at intersections in Canada [1]. According to [2], the number of traffic accidents at intersections accounts for more than 20% of the total number of traffic accidents in China, more than half of which is ascribed to the four-leg intersection. Specifically, the majority of intersection accidents occur at non-signalised intersections. The statistics of the specific critical events show, taking the EU as an example, that no action, premature action, and late action are recorded more frequently in those accidents and sum up to around 60% of total events [3]. The main cause is drivers' inaccurate estimation of the position, speed, and intention of other vehicles [4].

The intersection collision warning (ICW) system is an in-vehicle warning system that uses sensors (such as detecting radar) on vehicles and equipment located at intersections to detect obstacles and alert drivers of an impending collision [5]. In recent years, researchers gradually found that vision and radar were not qualified enough to provide the warning signal in all the scenarios [6]. As a result, more researchers focused on applying communication technology into ICW algorithms [7]. Avino *et al.* [8] compared the performance of 802.11p and LTE-V2V in considering the ICW algorithm deployment. Takatori and Takeo [9] conducted a research on vehicle information sharing performance, which meant the vehicle should send out its information or along with all the vehicles' information around it. ICW systems can warn drivers in terms of inaccurate estimation, urge drivers to take action timely, and have the potential to improve intersection safety. Compared to vehicle automatic control, ICW systems only assist drivers with information and warnings rather than actively intervening in the driving task. Drivers may not trust vehicle automatic control and may not be willing to release vehicle control, even in situations where the system may gain safety advantages [10]. Besides, vehicle automatic control can face more difficulties in regulations and ethics. Therefore, the ICW system has a more promising market penetration prospect and is worth studying.

The great bulk of research works on intelligent vehicles at intersections are presented under a critical assumption: all vehicles are with intelligent vehicle technologies. In the near future, the market penetration rate (MPR) of any intelligent vehicle technologies cannot jump from 0 to 100% all of a sudden [11]. One of the greatest challenges to ICW's potential ability to improve intersection safety is that the market penetration of the ICW systems will be a long-term process. There will be a mixed traffic situation where vehicles with or without the ICW systems will co-exist for a transitional period of time. The MPR is bound to affect the benefit of the ICW systems on intersection safety. The existing literature of intersection traffic control technology MPRs mainly focuses on efficiency and vehicle control approaches at the signalised intersection. Feng *et al.* [12] proposed an intersection signal control method based on connected vehicles' location and speed estimation at different MPRs to minimise total vehicle delay and queue length. Du *et al.* [13] proposed a control method for a group of connected vehicles mixed with human-driving vehicles at signalised intersections to achieve better fuel economy and traffic efficiency. Zhao *et al.* [14] proposed an intelligent vehicle control method based on the platooning idea to deal with the mixed traffic environment at a signalised intersection, which also focused on efficiency. Nevertheless, a relatively small amount of literature is concerned with intersection safety. Validi *et al.* [15] presented a safety improvement of the signalised intersection at different MPRs of vehicle-to-vehicle (V2V) and the technology of adaptive cruise control (ACC), and found that a medium MPR results in considerable safety improvement. Njobelo *et al.* [16] proposed an advisory system to assist drivers in minimising rear-end collisions at signalised intersections and conducted a safety evaluation at different MPRs. There also exists research on the safety benefits of vehicle intervention or control systems instead of warning systems at different MPRs such as in [17, 18]. Sander and Lubbe [18] analysed the safety improvement of the intersection emergency braking system during the penetration process, along with the influence of the field-of-view of the sensors on-board. However, it is quite surprising that little focus has been placed on the vehicle safety analysis at the non-signalised intersection, which is a more hazardous traffic scenario than the signalised one.

To fill the above-mentioned research gaps, this study proposed a relatively complete simulation method (which will be introduced in Section 3) to investigate the influence of MPR of ICW systems on safety at non-signalised intersections. This study was conducted on a highly flexible Matlab-based simulation platform where two representative ICW algorithms were implemented. The simulation was firstly conducted to verify our models, then to obtain and compare the safety evaluation results of different MPRs statistically.

The contributions of this paper are as follows:

- The proposed simulation method, which models randomness, driver characteristics, ICW systems, vehicle dynamics, and statistical analysis separately and then analytically combine them, which provides an effective means to analyse vehicle safety at non-signalised intersections.
- A mapping relation between the MPRs of the ICW systems and the indices of vehicle safety at non-signalised intersections is revealed, which is a useful reference for the not-too-distant future when a mixed traffic situation is likely to show up.
- The simulation indicated that even a relatively low MPR of the ICW systems brings notable safety benefits for vehicles at non-signalised intersections, which generally echoes the law revealed in [15] concerning the MPR of ACC systems and safety improvement at the signalised intersection.

1.2 Brief literature review

1.2.1 ICW algorithms: ICW algorithms have been relatively mature both in theory and in practice. In early studies, Miller and Huang [19] designed and developed a peer-to-peer ICW algorithm based on the V2V communication. They determined a potential collision point by predicting the trajectories of conflicted vehicle pairs based on the current state. The time to reach the potential collision point was computed and compared to calibrate the risk of a potential collision. This algorithm has been widely cited by later researchers, including [20, 21]. Such a method can be easily implemented but the accuracy of the collision detection results may be compromised, for it does not consider the vehicle size. Most of the later studies improved it. For example, based on the idea of proposed by Miller and Huang [19], Huang *et al.* [21] proposed an improved ICW algorithm based on the V2V communication considering the current vehicle state as well as the vehicle size. They transformed the potential collision point into an area. The previous methods were mainly based on the assumption that the vehicles in conflict would keep the current speed and heading angle. Such methods may compromise the accuracy of predicting the collision since the vehicles could alter their trajectories such that the previously predicted risks diminish or new risks appear. Some studies have considered this while designing the ICW algorithms. Wang and Chan [22] introduced an ICW algorithm that could better predict the collision circularly based on the current and expected states of the vehicles. Some studies used a Bayesian network to assess the collision risks of vehicles approaching the intersection, such as [23, 24]. However, building an effective model to predict the vehicle states by this approach can be complicated and computational costly [22].

The way of releasing warnings is also an important factor. The hierarchical warning can link conflict risks with warning levels and provide drivers with more sufficient warning information. However, too many warning levels may confuse and annoy drivers, or even worse, be ignored by drivers. The safety improvement by the warning system thus could be reduced. Wang *et al.* [25] developed a collision warning system that proved to be able to provide two-stage warnings timely and effectively corresponding to different driving risks. As to the warning timing, a common method of comparing the time to collision (TTC) and the time to avoidance (TTA) is provided in [19, 26]. Although comparing TTC with TTA is widely used to design the multi-level warning mechanism in many studies, some other criteria exist as well. For example, Wang *et al*. [27] used TTC and post encroachment time (PET) simultaneously for warning criteria, which still belongs to the category of time. Wang and Chan [22] devised the 'minimal future distance (MFD)' and compared it with a two-level dynamic threshold to determine the normal warning or the emergency warning.

1.2.2 Driver behaviour models: Modelling drivers' crossing behaviour at intersections is an important basis for exhaustive and realistic simulation in the transitional period. Prevailing modelling methodology mainly contains game theory, gap acceptance theory, and pre-emptive status theory. Liu *et al.* [28] analysed drivers' crossing behaviour at non-signalised intersections with consideration of risk perception based on the game theory. However, they only focused on two straight-moving vehicles from the orthogonal direction but neglected all turning vehicles. The basic assumption of the gap acceptance theory is that the major stream vehicles have absolute priority over the minor stream vehicles, and the minor stream vehicles have to seek an opportunity to pass through non-signalised intersections [29]. Drivers strictly abiding by the priority of main roads and branch roads to pass through non-signalised intersections are not common, particularly in China where road priority is not obvious and gap-forcing behaviour often occurs. To overcome this limitation, Xiao *et al.* [30] proposed the pre-emptive status theory using virtual field graph methodology. The results showed that more than 80% Chinese drivers' crossing behaviour at non-signalised intersections can be interpreted through their model according to collected field conflict data. However, vehicle width is ignored in the analysis of pre-emptive status. Improving model accuracy is possible with the consideration of vehicle width.

1.3 Organisation

In this paper, we present a simulation study that focuses on vehicle safety improvement at non-signalised intersections brought by two representative ICW algorithms at different MPRs. The remainder of this paper is organised as follows: Section 2 clarifies the exact scenario definition and basic assumptions in the simulation; Section 3 states and describes our simulation methodology and design, including road structure, vehicle physical characteristics, intelligent and CV (ICV) technology and MPR, driver behaviour characteristics, and vehicle safety evaluation and analysis; Section 4 presents the simulation results and analyses safety improvement at different MPRs; Section 5 provides a discussion on the results compared to the related research; Section 6 gives the concluding remarks.

2 Scenario definition and basic assumptions

2.1 Scenario definition

Non-signalised intersections have no traffic lights. Drivers traditionally have to make eye contact with each other to pass the intersections safely. The exact research scenario of this study consists of a non-signalised intersection and multiple vehicles of different types. A schematic diagram is presented in Fig. 1. The intersection is set to be a very common four-leg dual-lane non-signalised intersection without obstacles, just as in [31, 32]. Its shape and size are determined according to relevant Chinese National Standards [33]. Normally, vulnerable road users (VRUs) appear at the signalised intersections in urban areas. We do not consider the involvement of VRUs here during the vehicle safety analysis, which is a major scenario setup for non-signalised intersections [32].

From each direction, multiple vehicles of different types are approaching the stop line at the beginning. In terms of vehicle types, the U.S. Department of Transportation's Connected Vehicles Initiative to improve the performance of cooperative advanced driving assistance systems at low MPRs is to equip as many vehicles as possible with a vehicle awareness device (VAD) [34], which is capable of broadcasting vehicles' information to the surroundings. Such a vehicle type is also considered in this study. To sum up, three types of vehicles are taken into account:

- *Human-driving vehicle (HDV)*: The vehicle is completely under the driver's control without interference, ICW system, or VAD.
- *Connected vehicle (CV)*: The vehicle is completely under the driver's control without interference or ICW system but equipped with VAD and with its help, the vehicle can broadcast its position, speed etc. to the surroundings.
- *ICV*: The vehicle is under the driver's control, but equipped with the ICW system, which enables it to exchange information with the surroundings and alert the driver.

2.2 Basic assumptions

To simplify the complexity of the research problem without losing its essence of revealing the potential ability of ICW systems at different MPRs to improve vehicle safety at non-signalised intersections, we make the following basic and common assumptions in this study, just as how Chen and Englund [32] summarised:

- Each driver's driving direction can be inferred or obtained by others from the turn light, trajectory around the intersection etc.
- It is assumed that both vehicles and the intersection are equipped with communication devices that can facilitate information exchange among them.
- The vehicle-to-everything (V2X) communications among all relevant vehicles as well as infrastructure are ideal, without the consideration of transmission delay or packet loss influence.
- The inappropriateness and otherness of driver reaction to warnings are not considered after the signals are received by the drivers.
- No overtaking, reverse or lane-changing manoeuvres are considered around the intersection.

3 Simulation methodology and design

Simulation plays an important role in evaluating the performance of a system when it has not yet penetrated the market, especially for a vehicle's ICW system whose MPR influence on safety is difficult to be revealed by field tests. In this study, the simulation is conducted in Matlab. In contrast to other frequently-used traffic simulation software such as Vissim, Sumo, and Prescan, Matlab is more flexible in models and algorithms implementation as well as data extraction and processing. This flexibility will contribute to exhaustive and realistic simulation.

3.1 Simulation framework and structure

In this study, we introduce a simulation framework as shown in Fig. 2 to figure out the mapping relation between the MPRs of the ICW systems and the vehicle safety indices at the non-signalised intersection through multiple simulations. The framework contains several necessary parts as follows:

- *Road structure*: The structure of the road should be determined before any simulation begins, including its type, shape, size, communication equipment etc. This study focuses on the non-signalised intersection as defined in Section 2.1. The Cartesian coordinates should be used to accurately determine the position of the elements around the road.
- *Vehicle physical characteristics*: The vehicles are the only elements that move during each simulation, which results in the risks at the intersection. Their properties, such as the vehicle mass, length, width, initial states, acceleration, and deceleration limits, should be determined individually. To update their motion, vehicle dynamics should also be modelled.
- *ICV technology and MPR*: The MPR of the ICV technology can influence the risks of the vehicles at the intersection. In this study, the ICW system and VAD are selected, and the ICW algorithm should be implemented. To study the influence of MPR, the ICW system and VAD should be allocated to different vehicles in each simulation according to the MPR.
- *Driver behaviour characteristics*: The drivers are in full control of the vehicles as the ICW systems only assist them. Hence, their nature, such as the perception-response time, should be determined. Besides, the pattern of the drivers' decision-making while following the preceding vehicle, facing conflict at the intersection, and receiving the warning signals should also be modelled.
- *Vehicle safety evaluation and analysis*: To evaluate vehicle safety at the intersection, several representative indices should be selected before the simulation. The corresponding data used to calculate the safety indices should be measured and collected during each simulation. After all the simulations, statistical analysis should be conducted to present the mapping relation between the MPRs of the ICW systems and these indices.

The overall structure and the flow chart of the simulation are presented in Fig. 3.

The overall structure consists of five main segments: (i) random initialisation; (ii) driver module; (iii) ICW algorithm; (iv) vehicle dynamic model; and (v) evaluation module. At the beginning of the simulation, some parameters are randomly initialised to generate corresponding scenarios, and vehicles and driver characteristics in the simulation platform. For the second step, every driver's conflict resolution strategy is obtained based on the pre-emptive status model. For the third step, combining the conflict resolution strategy and possible warnings provided by the ICW system, the driver's desired acceleration is calculated based on the driver behaviour model. For the fourth step, the desired acceleration is fed into the

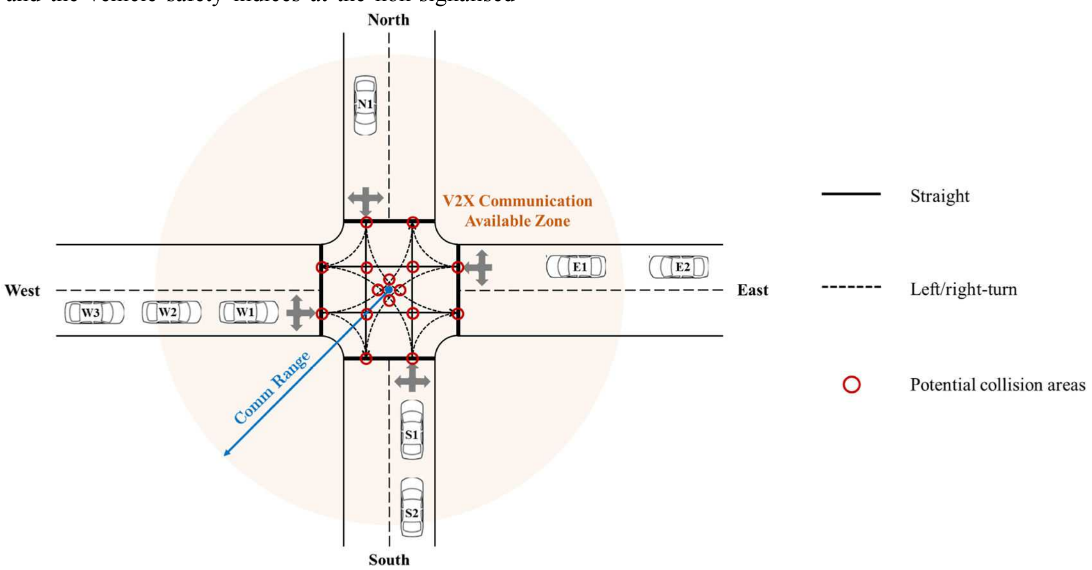

Fig. 1 *Illustration of the scenario setup of the non-signalised intersection*

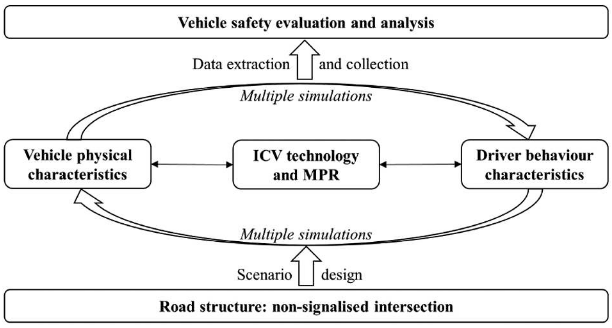

Fig. 2 *Simulation framework*

vehicle dynamic model to control the vehicle movement. Finally, all information is used by the evaluation module to monitor collision occurrence in real-time. The safety of vehicles without collision is evaluated at the end of each simulation.

3.2 Road structure

In this study, the road structure is designed to be a non-signalised intersection, as presented in Fig. 1. The shape and the size of this four-leg dual-lane non-signalised intersection are determined according to the relevant Chinese National Standards [33]. In addition, the road is equipped with a V2X communication device that can exchange information with ICVs and CVs. The communication range as a critical factor, which defines the V2X zone at the intersection, is identified as a radius of 100 m within the limit in [35]. The information broadcasting frequency is set to be 10 Hz. To better calibrate the intersection shape, V2X communication range, as well as potential moving vehicles, the Cartesian coordinates are established. Its origin is set to be the centre of the intersection, the x-axis is the East direction, and the y-axis is the North direction.

3.3 Vehicle physical characteristics

In every single simulation, a total of 12 vehicles are evenly arranged in the four approaching directions of the non-signalised intersection. The properties of these vehicles should be determined as below. Vehicle mass (kg) is assumed to conform to $U(1100, 1700)$. Similar to [36], we also assume a linear relation between vehicle length and vehicle mass, as well as between the vehicle's maximum deceleration and the vehicle mass. Precisely, the vehicle length (m) varies from 3.5 to 5 and the maximum deceleration (m/s^2) varies from 5.5 to 6.5. The width (m) of all vehicles is fixed at 2. In each direction, the distance between the lead vehicle and the stop line (m) is set to obey $U(50, 60)$. The initial speed of all vehicles and the initial car-following distance of the following vehicles are consistent with the desired values of corresponding drivers, which will be introduced in Section 3.5.

As to update the motion of the vehicles, the vehicle dynamics should be modelled. The motion update frequency for all vehicles is adopted as the common value of 10 Hz. A linear time-invariant system is used to model vehicle dynamics in the simulation. Deeper theoretical characteristics such as lateral dynamics of the vehicle are not addressed here, as they are beyond the focus of this study. Equation (1) is enough to represent the vehicle dynamic system abstractly

$$\begin{bmatrix} \dot{p} \\ \dot{v} \\ \dot{a} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/\tau \end{bmatrix} \cdot \begin{bmatrix} p \\ v \\ a \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/\tau \end{bmatrix} \cdot a_{\text{des}}, \qquad (1)$$

where p denotes the vehicle's distance to the stop line, v is the velocity, a is the acceleration, and τ represents the vehicle inertia lag, which is set to be 0.45 s.

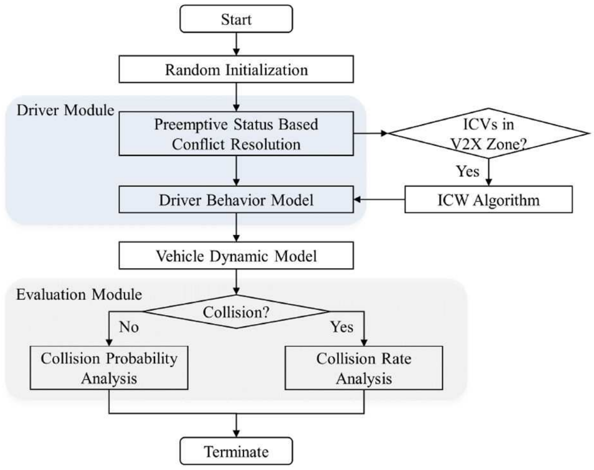

Fig. 3 *Flow chart of the simulation*

3.4 ICV technology and MPR

Vehicles in the simulation are probable to be HDV, CV, and ICV depending on MPR. The HDV has no intelligent vehicle technologies and is completely under the driver's control. The CV is only equipped with VAD and can exchange its basic information (such as position, speed etc.) with the surroundings. The ICV here has the ICW system on-board and is also able to exchange information with the surroundings. The ICW algorithm and the MPR allocation method are introduced in this subsection.

3.4.1 ICW algorithm: ICW algorithms have been relatively mature both in theory and in practice. The collision warning algorithm proposed in [19] is an early but classical solution to the collision detection of an ICW system. Many ICW algorithms that were studied later on were theoretically based on it with some improvements. However, this type of method was mainly based on the assumption that the vehicles in conflict would keep the current speed and heading angle. The accuracy of collision prediction could be compromised. Hence, this study uses a more recent ICW algorithm from [22] that has considered accuracy.

For every step in a simulation, the algorithm can predict the future velocity of the vehicle. The predictions are according to the following equation:

$$v_k(p) = \beta(p) v_{\text{KM},k}(p) + [1 - \beta(p)] v_{\text{EM},k}(p), \qquad (2)$$

where k is the present simulation step, $k + p$ is the present prediction step, and the time between two consecutive steps is set to be 0.1 s; $v_k(p)$ is the predicted vehicle velocity at the step of $k + p$; $v_{\text{KM},k}(p)$ is the predicted vehicle velocity based on the current acceleration; $v_{\text{EM},k}(p)$ is the predicted vehicle velocity based on the predefined speed profile; $\beta(p)$ is the time-varying weighted coefficient and is considered to be monotonically decreasing according to Wang and Chan [22].

Based on the velocity prediction, the MFD between any two vehicles that are in conflict can be calculated by

$$D_{\min}^{i,j}(k) = \min \left[D_k^{i,j}(1), \ldots, D_k^{i,j}(p), \ldots, D_k^{i,j}(N_\text{p}) \right], \qquad (3)$$

where $D_{\min}^{i,j}(k)$ is the MFD of the conflicted vehicle i and vehicle j at the present step k; $D_k^{i,j}(p)$ is the predicted future distance (Euclidean distance) at the step of $k + p$; N_p is the total prediction steps, and the prediction horizon is set to be 5 s in this study.

The warning timing is also a critical factor that should be determined to construct a complete ICW system. A hierarchical warning can link conflict risk with the warning level and provide more sufficient warning information for drivers. However, too many warning levels can confuse and annoy drivers, or worse, be ignored by them. In this study, a two-stage warning system as in

[22] is used. The warnings are provided by comparing the MFD with two dynamic thresholds, which can be formulated as follows:

$$\mathrm{WL}(k)=\begin{cases}1, & \text{if } D_{\mathrm{EW}}^{i,j}(k)<D_{\min}^{i,j}(k)\le D_{\mathrm{NW}}^{i,j}(k)\\ 2, & \text{if } D_{\min}^{i,j}(k)\le D_{\mathrm{EW}}^{i,j}(k)\end{cases}, \tag{4}$$

where k is the present simulation step, $\mathrm{WL}(k)$ denotes the warning level; $D_{\mathrm{NW}}^{i,j}(k)$ and $D_{\mathrm{EW}}^{i,j}(k)$ are the dynamic thresholds of 'normal warning' and 'emergency warning' for the conflicted vehicles i and j, respectively, and are determined by conflicted vehicles and potential collision scenarios according to Wang and Chan [22].

Additionally as to two conflicted ICVs, the warnings of vehicle 1 caused by vehicle 2 will be discarded if (5) is satisfied, and vice versa

$$\mathrm{TTC}_1-\mathrm{TTC}_2<0, \tag{5}$$

where this criterion shows a reasonable cooperative mechanism of the cooperative warning system.

3.4.2 MPR allocation method: The MPR is an important variable in the simulation, where the proportion of the vehicles with the ICW system should coincide with the target MPR.

Let N_{V} be the total number of vehicles in a society or a region, among which N_{ICW} is the number of vehicles equipped with the ICW system (i.e. the ICVs). Then the MPR of the ICW system can be expressed as

$$\mathrm{MPR}_{\mathrm{ICW}}=\frac{N_{\mathrm{ICW}}}{N_V}, \tag{6}$$

where $\mathrm{MPR}_{\mathrm{ICW}}$ denotes the MPR of the ICW system in the society or region.

In each simulation, there exist multiple vehicles. For any vehicle, whether it is allocated as an ICV should obey the probability equation presented in (7)

$$P\left(\mathrm{Veh}^i=\mathrm{ICV}\right)=\mathrm{MPR}_{\mathrm{ICW}},\quad i=1,2,\ldots,n_{\mathrm{veh}}, \tag{7}$$

where Veh^i represents the type of vehicle i; n_{veh} is the number of vehicles in a simulation, 12 in this study; each vehicle has an independent probability setting.

For a given MPR as a variable, the number of ICVs in a simulation could vary. However, the statistical simulation results after multiple simulations can reflect the given MPR. Moreover, we also study the influence of VAD. At any given MPR, all the vehicles without the ICW system are set to be pure HDVs without VAD or to be CVs with VAD.

3.5 Driver behaviour characteristics

The nature of drivers, while they are approaching the intersection, should be determined first. Driver reaction time (s), according to the experiment results conducted by Olson and Sivak [37], is set to follow the normal distribution of $N\left(0.7,0.2^2\right)$. Driver desired speed (km/h) is assumed to accord with the uniform distribution of $U(20,30)$. We refer to [36] and choose a driver desired time headway (THW, s) for car-following to be $N\left(1.5,0.1^2\right)$. The driving direction of each driver is considered as an invariable random choice among left-turning, straight-crossing, and right-turning with the same probability.

The patterns of the drivers' decision-making around the intersection are also modelled as below, including the patterns of conflict resolution, following the preceding vehicle, and reacting to the possible warning signals.

3.5.1 Conflict resolution based on pre-emptive status: From an overall perspective, several vehicles from different directions may conflict in trajectory simultaneously or in pairs at the non-signalised intersection. This complex conflict relation can be illustrated in Fig. 4. In the figure, there are three types of vehicles with different trajectories in each direction. The L, S, and R in the figure represent the flow direction of the trajectories, left-turning, straight-crossing, and right-turning, respectively. For example, the trajectory from the east turning left to the south is denoted by E–L in short. A link represents a trajectory conflict between the corresponding pair of vehicles, such as between E–L and S–S. Whilst no conflict exists between trajectories without a link.

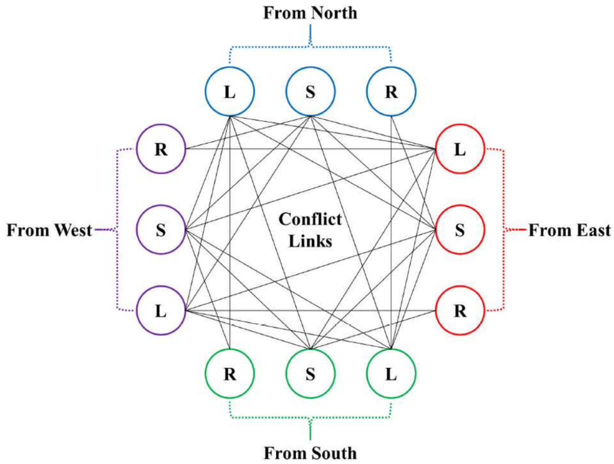

Fig. 4 *Conflict links among the vehicles with different trajectories*

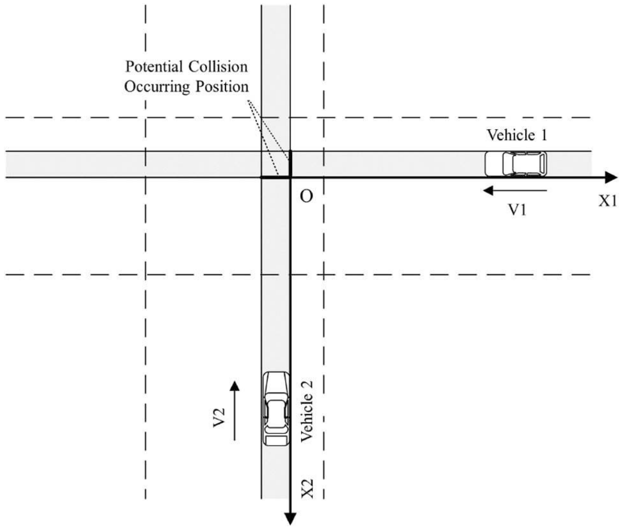

Fig. 5 *Schematic diagram of the PL calculation*

As for a pair of vehicles in trajectory conflict as shown in Fig. 5, the pre-emptive level (PL) is calculated on the basis of the pre-emptive status model proposed in [30]. In addition, vehicle width is considered in the calculation for improvement of model accuracy. Assuming that vehicle 1 is in the pre-emptive position, the PL calculation of both vehicles can be formulated as shown in (8) and (9), and vice versa. It is worth pointing out that the two vehicles will not collide at the intersection if the absolute PL is >1

$$\mathrm{PL}_1=\frac{|x_1(t_c)|}{l_1+w_2} \tag{8}$$

$$\mathrm{PL}_2=-\mathrm{PL}_1, \tag{9}$$

where x_1 denotes the distance to the potential collision occurring position for vehicle 1 that is in the pre-emptive position; t_c is the time when vehicle 2 reaches the potential collision occurring position; due to the pre-emptive status assumption, $x_2(t_c)=0$, $x_1(t_c)<0$; l_1 is the length of vehicle 1 and w_2 is the width of vehicle 2.

For drivers of two conflicted vehicles, whether they consider themselves in a pre-emptive status depends on the relation between objective PL and psychological critical PL (CPL). According to the experiment results of [20], the CPL follows the normal distribution of $N(0, 0.2^2)$. The CPL is related to driver characteristics and does not change with time. Only when PL is greater than CPL, drivers consider themselves in a pre-emptive status.

Driver's desired acceleration, as the output of the driver behaviour model, is dependent on the driver's conflict resolution strategy and possible warnings from ICW systems. Drivers do not judge their pre-emptive status for a long time in advance but begin to judge it when the time to intersection is firstly <3 sapproximately [30].

3.5.2 Conflict exists after the pre-emptive status judgement: If drivers consider themselves in a pre-emptive status over all conflicted vehicles, they will conform to their desired speed. The desired acceleration is calculated by (10) based on the basic form of a stimulus–response linear model in [38]

$$a_{\text{des}} = \gamma(v_{\text{des}} - v_{\text{e}}), \tag{10}$$

where a_{des} is the driver's desired acceleration, γ denotes the sensitivity of driver's reaction to stimulus following $N(0.85, 0.1^2)$, v_{des} is the driver's desired speed, and v_{e} is the current speed of the ego-vehicle.

On the contrary, if drivers consider themselves not in a pre-emptive status, they will decelerate and yield the right-of-way. The action point model considers driver psychology and is consistent with the real traffic situation [39]. The desired acceleration is thus obtained by

$$a_{\text{des}} = c \cdot e \cdot \text{TTC}^f + d, \tag{11}$$

where c, e, and f are parameters, which are set to be 1.264, 1.04, and 0.72, respectively, according to Wang *et al*. [39], and d is the maximum deceleration (negative value).

3.5.3 No conflict or before the pre-emptive status judgement: For drivers of the lead vehicles, they also accord with a stimulus–response linear model. Likewise, their desired acceleration is calculated by (12). For drivers of following vehicles, the calculation of the desired acceleration by (12) and (13) is based on a safe distance model [40]

$$s_{\text{safe}} = T_{\text{THW}} \cdot v_{\text{e}} + s_0 \tag{12}$$

$$a_{\text{des}} = \frac{v_{\text{p}}^2 - v_{\text{e}}^2}{2(s_{\text{actual}} - s_{\text{safe}})}, \tag{13}$$

where T_{THW} is the driver's desired THW, s_0 is the stop distance to the preceding vehicle set to be 1 m, and s_{actual} is the current relative distance.

3.5.4 Warnings provided: Driver behaviour is modelled to give priority to react to the received warnings. An indicator named comfortable braking deceleration a_{c} was proposed by Krishnan *et al.* [41] to evaluate whether warnings are provided too early for drivers. Considering the driving comfort, here we assume that drivers will decelerate at a_{c} when the lower-level warning is provided. Take a two-stage warning mechanism into account, the desired acceleration for drivers under warning is thus determined as follows:

$$a_{\text{des}}(t) = \begin{cases} \min\,[a_{\text{c}}(v(t)), a_{\text{des}}(t)], & \text{WL}(t - t_{\text{r}}) = 1 \\ a_{\text{extreme}}, & \text{WL}(t - t_{\text{r}}) = 2 \end{cases}, \tag{14}$$

where t is the present time, t_{r} is the driver's reaction time, WL is the warning level, a_{c} is the comfortable deceleration based on the speed of the vehicle according to [41], and a_{extreme} is the maximum deceleration (negative value).

3.6 Vehicle safety evaluation and analysis

The safety of vehicles both in a collision and passing through the non-signalised intersection is evaluated from not only micro but also macro angles. Several indices are used to improve the accuracy of safety evaluation, including collision probability, conflict index, and collision rate (CR). For the vehicles passing through the intersection, the collision probability and the conflict index are used to evaluate the probability and the degree of the conflicts. For the vehicles in collision at the intersection, the CR is calculated.

3.6.1 Collision probability: The collision probability of a vehicle at non-signalised intersections can be calculated as (19) based on the very commonly-used evaluation index TTC according to Chen and Hsiung [42]

$$\mathscr{P}^i = \begin{cases} 1, & \text{if } x \le a \\ 1 - 2\left(\dfrac{\min_{j \in \mathbb{M}_i} \text{TTC}_{\min}^{i,j} - a}{b - a}\right)^2, & \text{if } a \le x \le \dfrac{a+b}{2} \\ 2\left(\dfrac{\min_{j \in \mathbb{M}_i} \text{TTC}_{\min}^{i,j} - b}{b - a}\right)^2, & \text{if } \dfrac{a+b}{2} \le x \le b \\ 0, & \text{if } x \ge b \end{cases}, \tag{15}$$

where $\mathscr{P}^i$ is the collision probability of vehicle i, $\mathbb{M}_i$ denotes the set of all conflicted vehicles of vehicle i, $\text{TTC}_{\min}^{i,j}$ is the minimum TTC during the conflict between vehicle i and vehicle j, and the parameters a and b are set as 0.5 and 2.5, respectively, according to Chen and Hsiung [42].

In a single simulation, we define average collision probability (ACP) and critical collision probability (CCP) to describe vehicle safety from average and critical perspectives, which can be formulated as (16) and (17), respectively

$$\mathscr{ACP} = \frac{1}{\text{card}(\mathbb{S})} \sum_{i \in \mathbb{S}} \mathscr{P}^i \tag{16}$$

$$\mathscr{CCP} = \min_{i \in \mathbb{S}} \mathscr{P}^i, \tag{17}$$

where $\mathbb{S}$ denotes the set of all the vehicles that pass through the intersection.

In multiple simulations, we define ACP_{m} and CCP_{m} to describe vehicle safety from a macro angle, which can be calculated by (18) and (19), respectively

$$\mathscr{ACP}_{\text{m}} = \frac{1}{N} \sum_{i=1}^{N} \mathscr{ACP}^i \tag{18}$$

$$\mathscr{CCP}_{\text{m}} = \frac{1}{N} \sum_{i=1}^{N} \mathscr{CCP}^i, \tag{19}$$

where N is the number of simulations, $\mathscr{ACP}^i$ is the ACP value in the simulation, and $\mathscr{CCP}^i$ is the CCP value in the simulation.

3.6.2 Conflict index: The previous collision probability index mainly focuses on TTC and does not address the degree of the potential conflict. As a supplement, the conflict index based on the PET and the kinetic energy change in the potential collision is used for safety evaluation according to [43]. The conflict index can be calculated as

$$\mathscr{CI}^i = \min_{j \in \mathbb{M}_i} \frac{\alpha \Delta K_{\text{e}}^{i,j}}{\mathrm{e}^{\beta \text{PET}^{i,j}}}, \tag{20}$$

where $\mathscr{CI}^i$ is the conflict index of vehicle i; $\mathbb{M}_i$ denotes the set of all conflicted vehicles of vehicle i; $\Delta K_e^{i,j}$ is the change in total kinetic energy before and after the potential collision between vehicle i and vehicle j; $\text{PET}^{i,j}$ is the PET of vehicle i and vehicle j; and the adjustment parameters α and β are set to be 1 according to [43].

Similarly, as the collision probability, we can define the average conflict index (ACI) and critical conflict index (CCI) in a single simulation, and the way of calculation is just as (16) and (17). In multiple simulations, the indices ACI_m and CCI_m to describe vehicle safety from a macro angle can also be calculated in a similar way as presented in (18) and (19).

3.6.3 Collision rate: We define CR to reflect the scale and severity of collision as a whole. The CR can be formulated as (21) which holds in a single simulation as well as in multiple simulations

$$\mathscr{CR} = \sum_{i=1}^{N} \sum_{j=1}^{n_{\text{veh}}^i} \mathscr{C}_j^i / \sum_{i=1}^{N} n_{\text{veh}}^i, \tag{21}$$

where n_{veh}^i is the number of vehicles in the ith simulation and $\mathscr{C}_j^i$ is the collision logical value for vehicle j in the ith simulation.

4 Simulation results

To verify the rationality and effectiveness of algorithms implementation and simulation design is the premise of convincingly studying the improvement of vehicle safety at non-signalised intersections brought by ICW systems at different MPRs. Therefore, a one-time simulation is conducted for verification in the first place. Then the effect of MPR on safety is analysed by statistical simulation.

4.1 One-time simulation for verification

Several one-time simulations are carried out to verify that the algorithms and the simulation process are reasonable. Three scenarios for simulation are generated randomly according to the methodology. In these scenarios, the vehicles are set to be HDVs and ICVs, respectively. Except for the vehicle types, other initialisation conditions of each simulation remain unchanged to ensure the consistency of the simulation scenario. Therefore, the influence of the ICW system on the trajectories of the vehicles can be presented by comparison. The simulation figures in Fig. 6 illustrates the motion characteristics of vehicles when they belong to the HDV in the three example scenarios. In each direction, there are three sequential vehicles (sequentially denoted by the solid line, the dotted line, and the dashed line in one colour) approaching the intersection in order. All the vehicles in the simulation figures in Fig. 7 are the ICVs with the ICW system.

As can be seen from the figures, for some vehicles, the ICW system can alert the drivers to slow down in advance according to the collision risk. Compared to HDVs, some ICVs start to gently decelerate slightly farther away from the intersection. Therefore, the ICW systems can influence the time and sequence of each vehicle's arrival at the intersection. This ability enables the ICW system to help drivers to reduce the risk that the ICVs take while the vehicles are approaching and crossing the non-signalised intersection.

Based on the ‘safety evaluation and analysis’ part of the simulation method, necessary data can be extracted and collected during each simulation. After each simulation, the safety indices, including ACP, CCP, ACI, CCI, and CR, can be calculated automatically. Table 1 presents the numerical results of the safety evaluation indices under these different simulation conditions, respectively. It can be seen from the data that in scenarios 1, 2, and 3, the vehicles with the ICW system have lower ACP, CCP, ACI, and CCI. From Section 3.6, lower ACP, CCP, ACI, CCI, and CR correspond to better vehicle safety. In these random scenarios, no collision occurred in simulations of all the two vehicle types. From the safety indices of the random simulations, the ICW system presents a positive effect on improving vehicle safety at the non-signalised intersection in this simulation.

4.2 Statistical simulation at different MPRs

To find out the influence of the ICW system MPR on vehicle safety, the representative MPRs of 0, 20, 40, 60, 80, and 100%

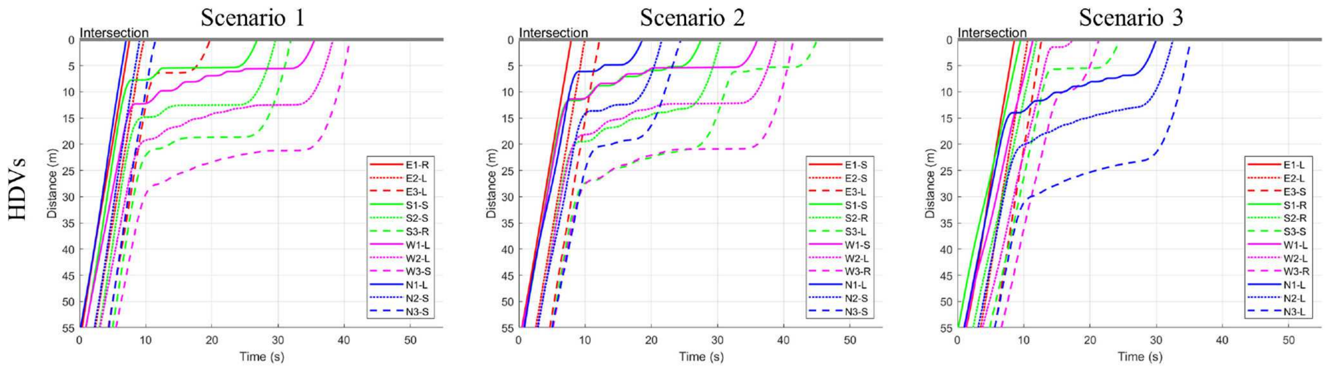

Fig. 6 *Several one-time simulations of HDVs as examples*

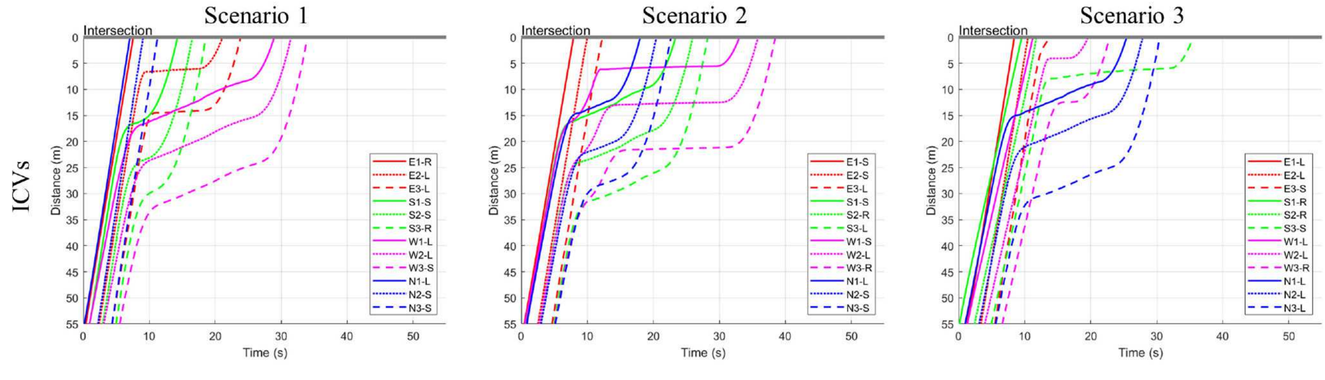

Fig. 7 *Several one-time simulations of ICVs as examples*

Table 1 Numerical results of the safety evaluation indices in several one-time simulations

Scenario	Vehicle type	$\mathscr{ACP}$	$\mathscr{CCP}$	$\mathscr{ACI}$	$\mathscr{CCI}$	$\mathscr{CR}$
1	HDV	0.29	1.00	4026	8171	0
	ICV	0.04	0.37	1495	2759	0
2	HDV	0.12	0.63	849	2866	0
	ICV	0.09	0.48	338	950	0
3	HDV	0.16	0.81	3819	7756	0
	ICV	0.10	0.62	2144	3413	0

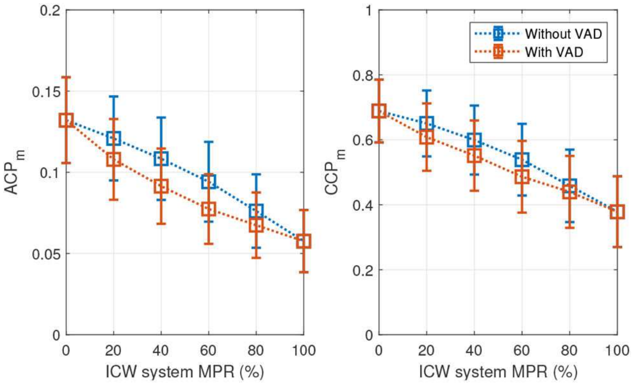

Fig. 8 *Collision probability at different MPRs*

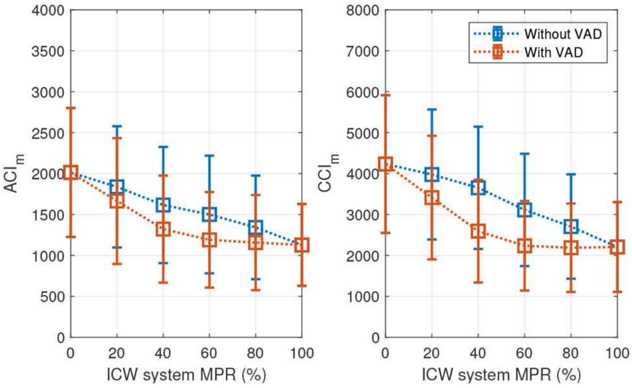

Fig. 9 *Conflict index at different MPRs*

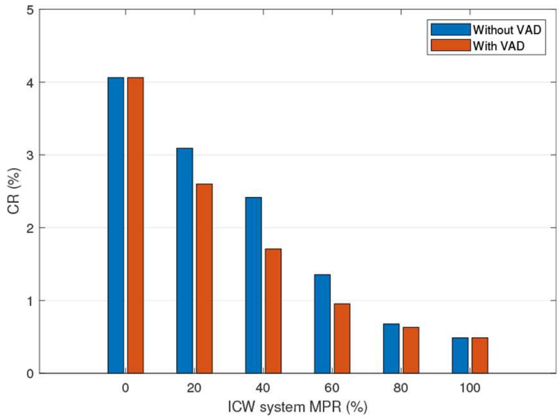

Fig. 10 *CR at different MPRs*

were selected for the statistical simulation. At any selected MPR, ICVs with the ICW system are the objects of study. Besides, at each MPR of either types of ICVs, we consider two types of vehicles in addition to ICV in the simulation. One is that all HDVs without VAD and the other is that all CVs are equipped with VAD.

Since the MPR is a macroscopic concept, if the number of simulations is small, the simulation results do not possess statistical effectiveness and are unable to reflect the MPR's influence on safety at the intersection. After many experiments, we found that the influence of MPR on safety tends to reach a steady-state when the number of simulations reaches 500. Therefore, in the statistical simulation, 500 random but repeatable simulations were carried out under four conditions of each MPR. After that, the collision probability and the conflict index are analysed for vehicles passing through the intersection, and the CR is analysed for vehicles in collision at the intersection.

4.2.1 Collision probability analysis: The simulation results of collision probabilities are shown in Fig. 8, which illustrates vehicle safety at different MPRs from average and critical perspectives. The uncertain range in the figures is coordinated with the standard deviation of the corresponding data. The two figures are quite similar except for the different ranges of their vertical axes.

It is reflected in Fig. 8 that with other conditions unchanged, not only the collision probability of vehicles as a whole but also the collision probability of high-risk vehicles can be reduced with MPR increasing of the ICW system. This trend means that the safety of the vehicles passing through the non-signalised intersection is improved with MPR increasing of ICW systems.

Besides, we can also observe that at the same MPR, whether the rest vehicles are CVs (that is, whether they are equipped with VADs) can affect the ability of ICW systems to improve vehicle safety at the intersection. The VAD of a CV can enable the ICW systems in conflicted ICVs, which is beneficial to improve the safety and is reflected in the additional reduction of $\mathrm{ACP_m}$ and $\mathrm{CCP_m}$ caused by VADs in the figures.

It is worth pointing out that at zero MPR, all CVs and all HDVs have no difference because VADs can only broadcast self-information to surroundings instead of exerting any influence on drivers. When MPR is 100%, obviously no other types of vehicles exist except ICVs, so the VAD makes no difference.

4.2.2 Conflict index analysis: The conflict index, which includes the PET and the kinetic energy change in the potential collision, provides another way to evaluate the safety of the vehicles passing through the intersection in addition to the collision probability index. The results are presented in Fig. 9, which also illustrates vehicle safety at different MPRs from average and critical perspectives.

From the figure, we can observe that both $\mathrm{ACI_m}$ and $\mathrm{CCI_m}$ decrease, as the MPR of the ICW system increases. The tendency of the conflict index change reflects that the penetration of the ICW system can stagger the time that two vehicles arrive at the conflict area or reduce the severity of the potential collision. Similarly, the VAD in CVs can influence the capability of the ICW system on vehicle safety at the intersection. In the average and the critical cases, the ICW system at different MPRs achieves an additional safety improvement in $\mathrm{ACI_m}$ and $\mathrm{CCI_m}$ if all the other vehicles are CVs. However, the VAD benefits are more evident when the MPR of the ICW system is at a medium level. In addition, with the help of the VAD, the conflict index corresponding to the medium to high MPRs can be reduced to a fairly low level, which is close to the conflict index when the ICW system has fully penetrated the market.

4.2.3 CR analysis: The simulation results of the CR are shown in Fig. 10, which is concerned with vehicles in collision at the intersection. The influence of MPR of ICW systems and the VAD on the safety of vehicles passing through the intersection can also be reflected in the safety evaluation index CR of vehicles in a collision.

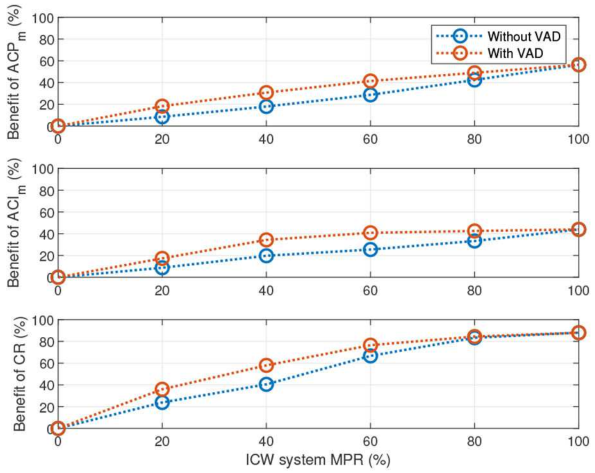

Fig. 11 *Safety improvement at different MPRs*

With the increase of MPR of the ICW system, the proportion of vehicles in collision at the intersection decreases significantly. At 100% MPR, the ICW system makes the CR reduced to a very low level, with nearly 90% collisions being avoided compared to the 0% MPR case according to Fig. 11. The results reflect that without considerations of inappropriateness and otherness of driver reaction to warnings, high MPR of the ICW system has a great potential to avoid vehicle collision occurring at non-signalised intersections. Meanwhile, VADs also help ICW systems to play a bigger role in collision avoidance.

5 Discussion

The market penetration of the ICW system has been shown in the simulation results that it strongly relates to vehicle safety at the non-signalised intersection. The ICW system can benefit the safety observably at medium to low MPRs, especially with the help of V2X communication devices. This characteristic calls for the deployment of the ICW systems as well as the V2X communication devices swiftly in the not-too-distant future, as even a portion of vehicles equipped with the system could improve vehicle safety as a whole at the intersection.

To the best of our knowledge, there is not much research on the influence of the ICW system MPR on intersection safety. Sander and Lubbe studied the market penetration of intersection automatic emergency braking (AEB) in terms of accident avoidance in [18], which can be used for comparative discussion. They found that around 80% of the accidents could be avoided for a 180° field-of-view sensor at 100% market penetration of the AEB system. The evaluated collision avoidance potential of the ICW system with the 100% MPR is of the same magnitude as the potential concluded in their research according to Fig. 11. The simulation results of both studies indicate that the ability of collision avoidance is with higher gains at lower MPRs and lower gains at higher MPRs. However, there is also some difference between these two studies. The ICW system in this study can only provide warning signals instead of intervening in the vehicle control, while the intersection AEB does not alert drivers but brake automatically. Due to the two-level warning mechanism and the assumption that the drivers are in fully compliance with the warning in this study, the improvement of CR at 100% MPR of the ICW system is a bit higher than that of the intersection AEB, which could also relate to the timing of the AEB system. Besides, the MPR model in [18] was mainly based on probability calculation with two vehicles in conflict at the intersection, while this study allocates the ICW system for a group of vehicles at the intersection according to the MPRs.

6 Conclusion

In this paper, without considerations of inappropriateness and otherness of driver's reaction to warnings, the overall simulation results indicate that the collision probability, the conflict index and the CR at non-signalised intersections will theoretically fall to a relatively low level when the ICW system has fully penetrated the market. Even a relatively low ICW system MPR (20%) brings notable safety benefits for vehicles at non-signalised intersections. Overall, vehicle safety at non-signalised intersections improves with the increase of ICW system MPR. Finally, with the help of V2X communication devices in CVs, the integral vehicle safety at non-signalised intersections can benefit additionally at different ICW system MPRs.

However, under the mixed traffic circumstance in the not-too-distant future, the uncertainty and heterogeneity of human driving behaviour may make a dent in the benefits of the ICW system. For example, not all drivers would accept and use the system even if it is available in their cars, and not all the drivers that accept the system would react to warnings appropriately and homogeneously. Such an influence of human driving behaviour will be worth further study in the future. After all, the experiment of this study was carried out in a full simulation environment, and field testing was difficult and risky. In the future, real data will be collected and included to further study the influence of the MPR of ICV technologies on intersection safety.

In addition, a simulation method was proposed to analyse vehicle safety at non-signalised intersections at different ICW system MPRs. This method modelled randomness, driver characteristics, ICW systems, vehicle dynamics, and statistical analysis separately, and then analytically combined them. Such a method can establish a mapping relation between the ICW system MPRs and vehicle safety indices at non-signalised intersections. Furthermore, this simulation method would also be applicable to the research in the influence of MPRs of other intelligent vehicle technologies on vehicle safety after being expanded in the future.

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