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Citation for the original published paper (version of record):

Jing, X., Pei, X., Yan, S. et al (2022). Safety benefit of cooperative control for heterogeneous traffic on-ramp merging. Transportation Safety and Environment, 4(4).
http://dx.doi.org/10.1093/tse/tdac031

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Transportation Safety and Environment, 2022, **4**: tdac031

DOI: 10.1093/tse/tdac031

Research Article

Safety benefit of cooperative control for heterogeneous traffic on-ramp merging

Xiao Jing[1], Xin Pei[1,*], Song Yan[1], Chunyang Han[1], Selpi[2], Eleonora Andreotti[2] and Jishiyu Ding[1]

[1]Department of Automation, Beijing National Research Center for Information Science and Technology, Tsinghua University, Beijing 100084, China;
[2]Division of Vehicle Safety, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden.
*Corresponding author. E-mail: peixin@mail.tsinghua.edu.cn

Abstract

The safety of heterogeneous traffic is a vital topic in the oncoming era of autonomous vehicles (AVs). The cooperative vehicle infrastructure system (CVIS) is considered to improve heterogeneous traffic safety by connecting and controlling AVs cooperatively, and the connected AVs are so-called connected and automated vehicles (CAVs). However, the safety impact of cooperative control strategy on the heterogeneous traffic with CAVs and human-driving vehicles (HVs) has not been well investigated. In this paper, based on the traffic simulator SUMO, we designed a typical highway scenario of on-ramp merging and adopted a cooperative control method for CAVs. We then compared the safety performance for two different heterogeneous traffic systems, i.e. AV and HV, CAV and HV, respectively, to illustrate the safety benefits of the cooperative control strategy. We found that the safety performance of the CAV and HV traffic system does not always outperform that of AV and HV. With random departSpeed and higher arrival rate, the proposed cooperative control method would decrease the conflicts significantly whereas the penetration rate is over 80%. We further investigated the conflicts in terms of the leading and following vehicle types, and found that the risk of a AV/CAV followed by a HV is twice that of a HV followed by another HV. We also considered the safety effect of communication failure, and found that there is no significant impact until the packet loss probability is greater than 30%, while communication delay's impact on safety can be ignored according to our experiments.

Keywords: Traffic safety, heterogeneous traffic flow, cooperative control, on-ramp merging, communication failure, traffic simulation

1. Introduction

Automated driving is believed to significantly improve traffic efficiency and traffic safety [1]. However, the safety of heterogeneous traffic consisting of human-driven vehicles (HVs) and autonomous vehicles (AVs) has not been theoretically verified in the process of the introduction of automated driving. The safety benefits of AVs lie in accurate acceleration control and shorter reaction time. However, the advantages of AVs related to accurate micro control may not be enough to improve the characteristics of macroscopic heterogeneous traffic flows, particularly when the number of AVs is still less than that of HVs [2]. In addition, the inconsistent driving patterns of AVs and HVs bring new risks to heterogeneous traffic. Conflict may occur when HVs interact with AVs, due to the difference in vehicle performance and driving habits.

As the most important part of the cooperative vehicle infrastructure system (CVIS), cooperative control algorithms are designed to guarantee the traffic efficiency and safety from a macroscopic perspective. They interact with vehicles and roadside sensors, and guide the microscopic driving behaviour of vehicles. The cooperative control algorithms control CAVs and provide driving advice to HVs by displaying information on traffic flow. There are two main methods for solving the cooperative control problem. The first is by calculating the exact solution based on optimization [3,4], but it is difficult to build optimization models for heterogeneous traffic flows. The second is to use rule-based approaches [5,6], which can improve the time efficiency of calculation, and this is necessary in simulations and applications.

A lot of research has been carried out through simulation experiments. Bjärkvik et al. [7] used simulation based on the Simulation of Urban Mobility (SUMO) to obtain the impact of AVs on traffic flow in terms of energy consumption and efficiency. Nilsson [8] investigated the potential improvement in traffic efficiency when AVs are introduced with different penetration rates, based on the traffic flow data collected by detectors on highways. Andreotti et al. [2] further researched the safety of heterogeneous traffic with different penetration rates of AVs. The studies mentioned above found that, although AVs can improve the efficiency of traffic, traffic risk shows a non-monotonic variation with the increase of AV penetration rate. Richter et al. [9] studied the joint effect of penetration rate of AVs and the length of highway acceleration lane on traffic safety. They conducted simulations of an on-ramp merging scenario and found that a longer acceleration lane is better to reduce the risk of merging. These previous works summarized the changes in risk with different penetration rates, but did not consider the impact of CVIS.

When considering inter-vehicle cooperation, previous research has focused on local cooperation between vehicles, e.g. analysing the impact of cooperative adaptive cruise control (CACC) on the safety of heterogeneous traffic. CACC maintains smaller headway within traffic flows and improves efficiency and safety by

Received: December 31, 2021. **Revised:** April 25, 2022. **Accepted:** May 16, 2022

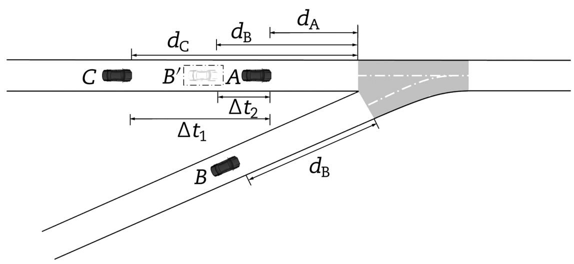

Fig. 1. Schematic diagram of the on-ramp merging scenario.

coordinating the speed of vehicles within a fleet. Studies have shown that the application of CACC has demonstrated the potential to improve traffic capacity and safety at low penetration rates [10–12]. However, relying solely on the control of cruising speed cannot eliminate the risks associated with merging in traffic scenarios such as ramps. Although researchers [13–15] proposed cooperative control algorithms based on on-ramp merging scenarios and performed numerical simulations to show that the control algorithms are effective at different penetration rates, reasonable and comprehensive experimental validations are still lacking.

This paper makes two main contributions. The first is an improvement on the cooperative control algorithm proposed in [13,16], by reducing the adjustment rules from four to two. The second is the analysis of potential impact of this improved control algorithm (i.e. with and without this control algorithm) on the safety of the heterogeneous traffic with different penetration rates of AVs or CAVs. We used the traffic simulator SUMO, and chose on-ramp merging as the simulation scenario.

The paper's outline is as follows: in Section 2, we introduce the methodology, including simulator, parameters setting, cooperative control algorithm and so on. In Section 3, we list the results of our simulation experiments and conduct some analysis. In Section 4, we make conclusions and propose future work.

2. Methodology

2.1 Simulator and traffic scenario

We used the SUMO to investigate the risk of heterogeneous traffic, which is widely used in research on traffic control problems. It integrates many models, such as Krauss and Intelligent Driver Model (IDM), and provides Application Programming Interface (API) for the user to control vehicle behaviour directly, which is essential for studying the effects of the cooperative control algorithm. We selected a simple but representative traffic scenario, i.e. an on-ramp merging scenario. Specifically, we considered a one-lane main road merged with a one-lane ramp, where both the length of the main road and the ramp before the junction are 200 m, and the length of the main road after the junction is 50 m. The reason that we chose a one-lane main road and a one-lane ramp is that when merging, vehicles on the outside lane of the main road are those in danger of colliding with vehicles from the ramp. Especially, in some on-ramp merging scenarios, there are solid lines between the outside lane and the other lanes of the same direction main road, which limit lane-change behaviour. The road's speed limit is 30 m/s (108 km/h), and the schematic diagram of the simulation scenario is shown in Fig. 1.

The risk source of this traffic scenario consists of two main aspects, including the unstable traffic flow caused by the fluctuation of vehicle speed during the following process on the long straight road, and the conflicts during the merging process. In addition, vehicles' merging may lead to blockage, which will affect the driving behaviours of upstream vehicles. Considering that the process of lane change in a multi-lane road and passing the junction are essentially complex forms of the mentioned scenario, the analysis of this scenario can lead to representative and meaningful conclusions.

2.2 Introduction of the cooperative control algorithm

The algorithm we adopted is a centralized cooperative control algorithm [13]. The region with a length of 200 m of the main road and the ramp before the junction is the cooperative control region, where conflicts need to be eliminated during merging. The centralized controller communicates with CAVs entering the cooperative control region and with roadside sensors to obtain all vehicles' position and speed, and assigns right-of-way for each CAV to pass the junction, thus dissipating the conflicts that may arise during the merging process. Then, CAVs control their own acceleration according to the assigned time. In other words, the cooperative control algorithm decomposes the control problem into two subproblems: right-of-way planning and motion planning.

The objective of right-of-way planning is to maximum traffic efficiency, which can be formulated as,

$$J = \omega_1 \max(T_a) + \omega_2 \sum_{i=1}^{n} \left(t_a^i - t_{\min}^i \right), i = 1, 2, \ldots, n \tag{1}$$

where $t_{\min}^i$ is the minimum time for the ith vehicle to pass the ramp merge area without other vehicles, and t_a^i is the right-of-way of the ith vehicle planned by the centralized controller. $T_a = \{t_a^i, i = 1, 2, \ldots, n\}$ is the set of all vehicles' right-of-way. The optimization problem is modelled as follows:

$$\begin{aligned}
& \min_{T_a, u} J \\
\textbf{s.t.}\quad & v_{\min} \le v_i \le v_{\max} \\
& t_a^i - t_a^j \ge \Delta t_1, \forall i > j, i, j \in \mathcal{M} \textbf{ or } i, j \in \mathcal{R} \\
& t_a^i - t_a^j + M u_{i,j} \ge \Delta t_2, \forall i \in \mathcal{M} \textbf{ and } \forall j \in \mathcal{R} \\
& t_a^i - t_a^j + M(1 - u_{i,j}) \ge \Delta t_2, \forall i \in \mathcal{M} \textbf{ and } \forall j \in \mathcal{R} \\
& u_{i,j} \in \{0, 1\}
\end{aligned} \tag{2}$$

where $\mathcal{M}$ and $\mathcal{R}$ indicate the collection of main road vehicles and the collection of ramp vehicles in order of proximity to the junction. $u_{i,j}$ is a Boolean variable, which indicates whether ramp vehicle j passes before main road vehicle i. Δt_1 and Δt_2 indicate the safe headway constraints. In the actual driving process, merging into the traffic flow brings greater risk, compared with following vehicles on the same road when passing the junction. So it is reasonable that Δt_1 and Δt_2 satisfy $\Delta t_1 \le \Delta t_2$, similar to Ref. [17], and this setting encourages vehicles to form a fleet. M is a sufficiently large positive number. The notations of parameters are listed in Table 1.

To solve this mixed-integer linear programming problem, the cooperative control algorithm uses a rule-based adjustment strategy in the right-of-way planning to obtain a near-optimal solution while ensuring the real-time calculation, which has been proved by experiments in our previous research [16]. The algorithm uses a virtual vehicle mapping technique [4,18] to map the ramp vehicles to the main road by position, as shown in Fig. 1. Since vehicles A and B, and C and B, are located on different roads, B's headway following A and C's headway following B when passing the junction

Table 1. Notations.

Notation	Indication
n	The number of vehicles
$\mathcal{M}$	The collection of main road vehicles
$\mathcal{R}$	The collection of ramp vehicles
t_a^i	The right-of-way of the ith vehicle planned by centralized controller
T_a	The set of all vehicles' right-of-way
$t_{\min}^i$	The minimum time for the ith vehicle to pass the ramp merge area
ω_1, ω_2	Weights of different objections
$u_{i,j}$	A Boolean variable
$\Delta t_1, \Delta t_2$	The safe headway

should be greater than Δt_2, while the headway between vehicles A and C should be greater than Δt_1.

Compared with the four adjustment rules proposed by the algorithm [16], we removed case 3 and case 4 in the algorithm, because they delay the right-of-way of vehicles ahead, which may lead to instability of the fleet in a heterogeneous traffic flow, and generalized case 1 and case 2. The rule-based algorithm can be described as follows. As shown in Fig. 1, suppose the distances to the junction of the last vehicle A on the main road and the new vehicle C arriving at the cooperative control region are d_A and d_C, and the distance of the last vehicle on the ramp is d_B, satisfying $d_C > d_B > d_A$, as shown in Fig. 1. We record C's right-of-way as t_a^{AC} if C follows A passing the section. Similarly, B's right-of-way is t_a^{AB} if B follows A passing the section. When

$$\begin{aligned} t_a^{AC} &< t_a^{AB} \\ t_a^{AC} &= \max\left\{t_a^A + \Delta t_1, t_{\min}^C\right\} \\ t_a^{AB} &= \max\left\{t_a^A + \Delta t_2, t_{\min}^B\right\} \end{aligned} \tag{3}$$

namely if C passes the section before B there will be time benefits. The variation in overall travel time is:

$$\Delta T = \max\left\{t_a^A + \Delta t_1, t_{\min}^C\right\} - \max\left\{t_a^A + \Delta t_2, t_{\min}^B\right\} \tag{4}$$

When there are HVs in the traffic flow, the algorithm cannot get the t_a of HVs. However, based on the vehicle position and speed obtained by the sensors, the algorithm predicts the time for HVs to reach the junction based on the car-following model. In reality, the behaviour of HVs will not exactly match the car-following model, so the cooperative control algorithm observes the global vehicles in real time and updates the right-of-way assignment in time so that the CAVs actively avoid HVs.

In the motion planning problem, optimal motion control is used with the objective of minimizing the vehicle energy consumption of

$$\min J = \frac{1}{2}\int_{t_0^i}^{t_a^i} a_i^2(t)\mathrm{d}t \tag{5}$$

where $a_i(t)$ is the acceleration of ith vehicle at moment t.

In actual traffic control, there is time consumption during the communication between roadside controller and vehicles, and the basic communication framework is shown in Fig. 2, where t^s is the step length of simulation, t^u and t^d are upload time and download time and t^c is calculation time. Communication delay is the sum of t^u, t^d and t^c, and CAVs do not get the control command until the calculation is finished and the communication is completed.

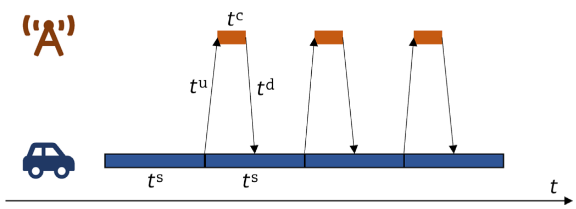

Fig. 2. Communication framework.

Due to the synchronous cooperative control framework, the time for CAVs to execute the control command is reduced from t^s to $t^s - t^u - s^c - t^d$. In addition, packet loss would occur and affect the vehicle controlling process when the communication quality is poor. Though our cooperative control algorithm does not consider communication delay and packet loss, we analysed their impacts.

2.3 Parameter settings of vehicles and controller

There is a difference between HVs' and AVs' driving behaviours, which can be seen in their reaction times and some other characteristics. Different vehicles should have different driving parameters in simulations, and those of HVs are influenced by the driver's expectation of speed, their habit of controlling the throttle and brake pads and their perception of risk, while AVs have more consistent control of speed and acceleration/deceleration due to the unification of algorithms. Compared to HVs, AVs can keep a smaller safe headway and gap when following another vehicle. The relevant parameters of the HV and AV were collected from the real road in Gothenburg, Sweden, as shown in Table 2.

We adopted Krauss as the car-following model of HV and IDM for AV, in which the former is the default model used in SUMO and the latter matches the car-following model used in the cooperative control algorithm. Different car-following models may lead to instability and risk, but we also noted that the car-following behaviours of HVs and AVs are different in real life. In the Krauss model, the parameter *tau* is the minimum time gap between the rear bumper of the front vehicle and the front bumper of the following vehicle, while in IDM it is the minimum time headway. And the parameter minGap is the minimized distance between two vehicles excluding vehicles' length for both car-following models.

In CVIS, the central controller obtains the global vehicles' information and controls vehicles' motion by interacting with CAVs and roadside devices. HVs are not controlled. Note that CAV is the AV communicating with CVIS, so CAV shares the vehicle's driving parameter setting with AV. However, CAVs will not follow the driving parameters while under the control of the central controller. In addition, although the central controller will optimize the vehicles' driving speed to enable them to pass the merging area quickly and improve the efficiency of the traffic flow, we are able to trade-off the efficiency and safety by setting parameters such as the safe headway of the controller algorithm. In particular, the vehicles' following behaviours and the safety threshold of the headway in different scenarios, such as driving on a long straight road and passing a junction, should be different. Therefore, we set different safe headway parameters for the control algorithm. When the leading vehicle and following vehicle come from the same road, the *tau* is the same as AVs (i.e. 0.9 s), while the *tau* is bigger when they come from different roads, for example 1.2 s.

Table 2. Parameters setting of vehicles.

Parameter	HVs	AVs	CAVs
length (m)	Norm(4.9,0.2)	Norm(4.9,0.2)	Norm(4.9,0.2)
accel (m/s^2)	Norm(1.4976, 0.0555)	1.5000	1.5000
decel (m/s^2)	Norm(4.0522, 0.9979)	6.0000	6.0000
car-following model	Krauss	IDM	/
tau (s)	Gamma(33.6166, 40.6236)	0.9	0.9
minGap (m)	Norm(1.5401, 0.2188)	1.5014	1.5014
speedFactor	Norm(1.2081, 0.1425)	1	1

2.4 Simulation settings

We used the Python-based Traci interface to call SUMO as the main programme of simulation, and the cooperative control algorithm is coded in MATLAB. The communication between the two is done through TCPIP. The vehicle arrival rate is set to 720 vehicles per hour for both the main road and the ramp. There are four streams of traffic flow on the road: HVs from the main road, HVs from the ramp, AVs/CAVs from the main road and AVs/CAVs from the ramp. And each traffic flow's departure is decided by three parameters: Begin, DepartSpeed and DepartPos. Begin decides the departure time of the first vehicle. When the default value of 0 is used for all streams, the main road and ramp will generate traffic flow at the same time, which could enhance the probability of conflict at the junction of the main road and the ramp. In order to conform to the real traffic flow, we set Begin following an exponential distribution $Exp(1/\lambda)$, where λ is the arrival rate of this kind of flow, namely the product of the road vehicle arrival rate and the penetration rate. DepartSpeed decides the vehicles' initial speed when entering the network. DepartPos represents the initial position of the vehicle when it enters the road network, and the value of 'base' represents that the vehicle would be generated at the start of the network. We investigated the effect of departSpeed value on the safety of the simulated heterogeneous traffic.

3. Results

3.1 Effect of cooperative control algorithm

In order to study the variation of the safety of heterogeneous traffic with the penetration of AV and CAV, and understand the effects of the cooperative control algorithm, we performed 50 experiments for each combination of parameters and each experiment represents a 10-minute simulation by SUMO. We considered the lead-follow situation and assumed that the leader decelerated to stop with maximum deceleration. Then, the leader's braking distance can be calculated by Eq. (6), and the follower's travel distance can be calculated by Eq. (7):

$$d_l = \frac{1}{2}\frac{v_l^2}{a_l} \tag{6}$$

$$d_f = \frac{1}{2}\frac{v_f^2}{a_f} + v_f t_r \tag{7}$$

where t_r is the follower's reaction time, a_l and a_f are the maximum deceleration of leader and follower and v_l and v_f are the initial velocities of leader and follower. Encounters are then classified as conflicts when $(p_l + d_l) - (p_f + d_f) < \delta$, where p_l and p_f are the initial positions of leader and follower and δ is a distance threshold. This metric takes into account the differences between AV/CAV and HV in terms of reaction time and vehicle performance. In our experiments, we set δ as the leader's length. Considering the severity of injury and traffic accident responsibility identification, we treat the conflict as a risk to the follower.

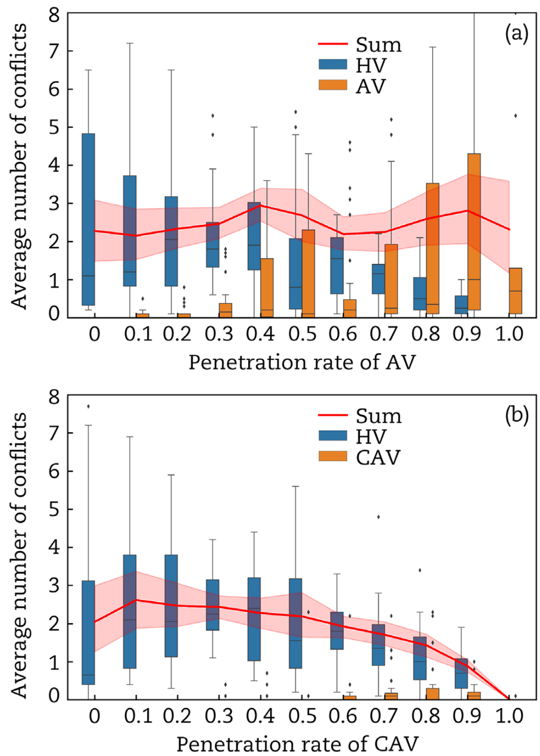

Fig. 3. Average number of conflicts per minute when the vehicles' departSpeed is set to 30 m/s and arrival rate is set to 720 vehicles per hour per lane: (a) results of heterogeneous traffic flow of AVs and HVs; (b) results of heterogeneous traffic flow of CAVs and HVs.

With the metric mentioned above, we calculated the average number of conflicts per minutes, and plotted box plots with different penetration rates and vehicle types, as shown in Fig. 3. The red line indicates the sum of all conflicts.

From Fig. 3, we are able to see that the risk of HVs in the two heterogeneous traffic flows has a similar trend. The number of conflicts shows a non-monotonic variation with the increase of penetration, and the risk of HVs is highest when the penetration rate of AV and CAV is in the range of 10%-50%. On the other hands, the risk of AV and CAV increases gradually with the penetration rate, because there are more AVs and CAVs in the traffic flow. In Fig. 3(a), we can see that AVs have less risk compared with HVs with a similar number of vehicles, i.e. the penetration rate of AVs is 0.5. This is probably because AVs have a shorter reaction time t_r and bigger deceleration a_f.

After we introduced cooperative control algorithms to control the driving behaviour of CAVs, as shown in Fig. 3(b), the risk is

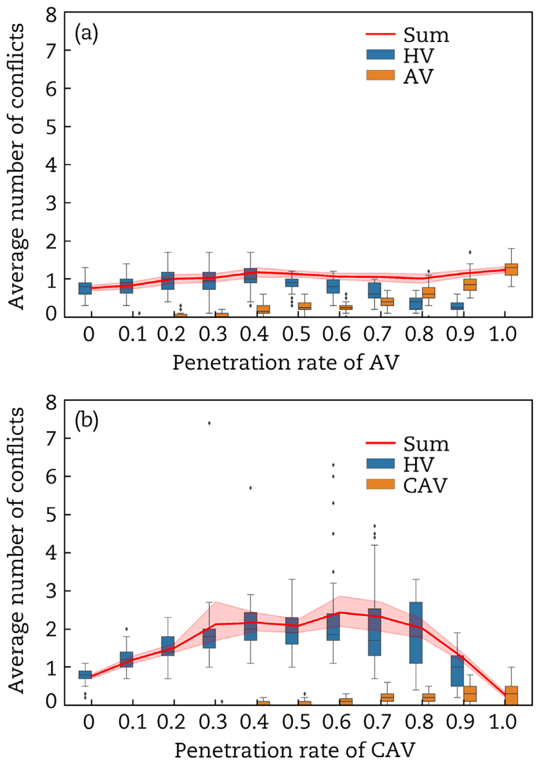

Fig. 4. Average number of conflicts per minute when the vehicles' departSpeed is set to random and arrival rate is set to 720 vehicles per hour per lane: (a) results of heterogeneous traffic flow of AVs and HVs; (b) results of heterogeneous traffic flow of CAVs and HVs.

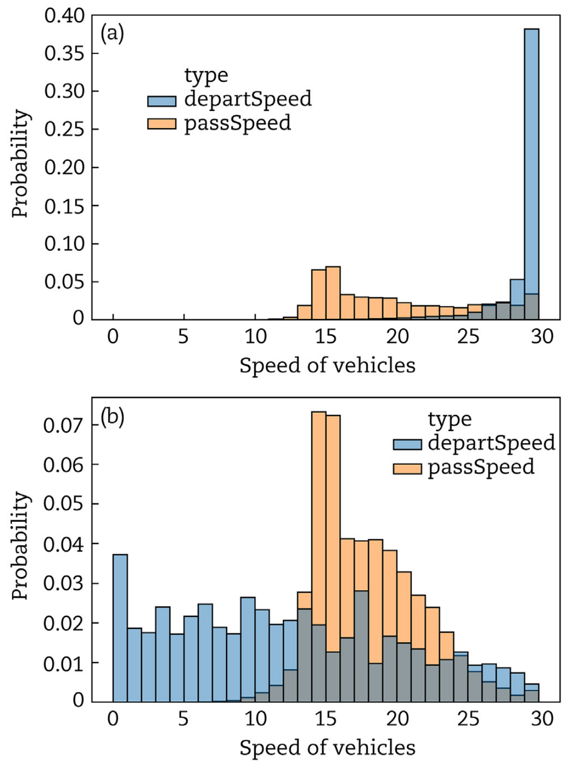

Fig. 5. Distribution of initial speed and passing speed: (a) departSpeed is 30 m/s; (b) departSpeed is random.

significantly reduced. Especially when the penetration rate is 0.9999, there are few conflicts in Fig. 3(b), while AVs without cooperative control still generate some conflicts.

In addition, we analysed the effect of the initial speed parameter departSpeed to find more generalized conclusions. In particular, we changed the initial speed to random, i.e. to follow a uniform distribution from 0 m/s to 30 m/s. Although in real life, vehicles rarely travel with a uniformly distributed speed on the road, we can check the effect of the cooperative control algorithm on traffic flow with a large speed variance.

From Fig. 4(a), we can see that the total number of conflicts generated by the heterogeneous traffic flow of HV and AV is basically constant, while it is relatively safe compared to the departSpeed of 30 m/s. This experimental result is a little counter-intuitive. Considering that both the magnitude and variance of speed have an impact on traffic safety, we recorded the speed of vehicles passing through the junction as passingSpeed, and plotted the speed distribution of departSpeed and passingSpeed as Fig. 5. We used the Wasserstein metric [19] of departSpeed and passingSpeed to evaluate the degree of speed change during driving, and when DepartSpeed is 30 m/s, the metric is 8.98, and 5.99 when DepartSpeed is random. This may be the reason that there are fewer conflicts when DepartSpeed is random.

However, the risk of the heterogeneous traffic with random DepartSpeed increases at higher penetration rates when we adopt cooperative control algorithm to control CAVs, which reminds us to pay attention to the influence of initial speed variance when designing cooperative control algorithms.

We also conducted extra experiments to study the traffic safety with bigger arrival rates. We increased the vehicle arrival rate from 720 to 1,000 vehicles per hour per lane when the vehicle's initial speed is 30 m/s. The statistical results are shown in Fig. 6. As the figure highlights, when the vehicle arrival rate increases, the number of conflicts also increases significantly. However, the cooperative control algorithm is still effective in increasing traffic safety when the penetration rate is high.

Comparing the two heterogeneous traffic flows, we find that the introduction of cooperative control algorithms worsens the traffic environment when penetration rate is low, e.g. between 0.1 and 0.7. A possible explanation is that the cooperative control algorithm performs a more aggressive acceleration and deceleration behaviour when controlling to make the vehicle pass the junction according to its right-of-way, without considering the HVs before and after the CAV. This characteristic is more evident when the traffic flow is less stable, such as with a large arrival rate or large departSpeed variance, and seriously affects the safety of HVs. The driving behaviours of AVs are instead relatively conservative as they only observe the vehicles in front of them. This increases the need to design an effective cooperative strategy at low penetration rates and pay more attention to the impact of CAVs on HVs.

3.2 Conflicts analysis

In order to gain a deeper understanding of the risks of heterogeneous traffic, especially the different influence that AV/CAV and HV make, we distinguished the type of leader in each conflict. We classified all conflicts into four types, i.e. HV-AV/CAV conflict, HV-HV conflict, AV/CAV-HV conflict and AV/CAV-AV/CAV conflict, in which HV-AV means HV is the leader and AV is the follower in the conflict. In Fig. 7, the biggest difference between (a) and (b) is the number of conflicts where AV follows AV. While AVs suffer from more risks with the increase of the penetration rate, CAVs are still safe with the help of a cooperative controller.

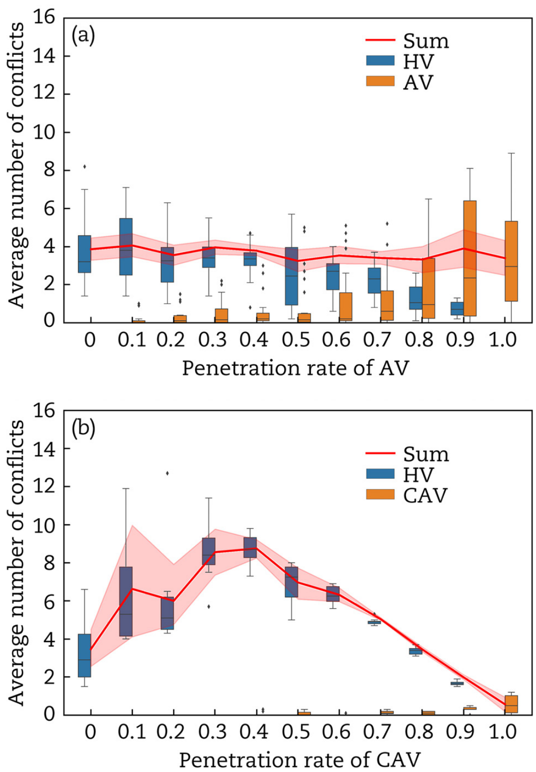

Fig. 6. Average number of conflicts per minute when the vehicles' departSpeed is set to 30 m/s and arrival rate is set to 1,000 vehicles per hour per lane: (a) results of heterogeneous traffic flow of AVs and HVs; (b) results of heterogeneous traffic flow of CAVs and HVs.

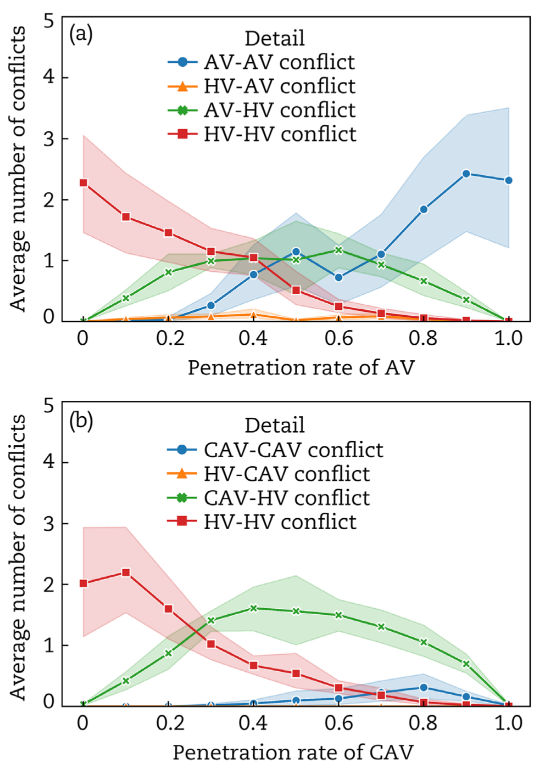

Fig. 7. Number of the four types of conflict events when the vehicles' departSpeed is set to 30 m/s and arrival rate is set to 720 vehicles per hour per lane: (a) results of heterogeneous traffic flow of AVs and HVs; (b) results of heterogeneous traffic flow of CAVs and HVs.

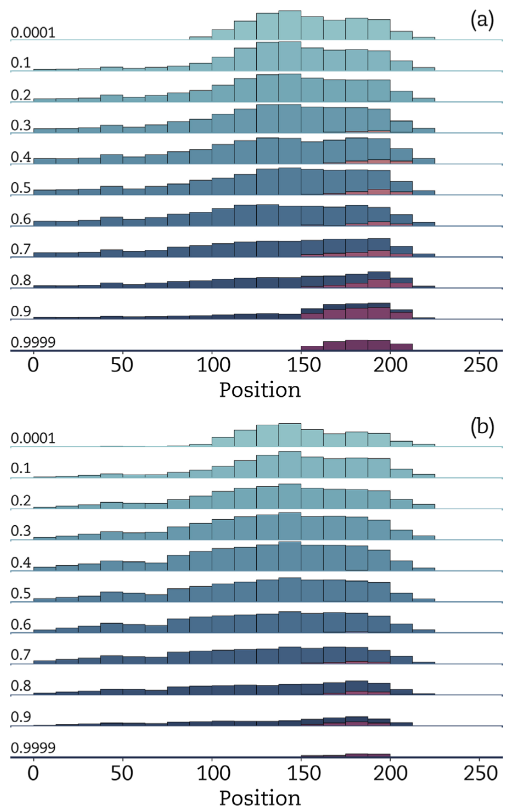

Fig. 8. Distribution of conflicts along the road when the vehicles' departSpeed is set to 30 m/s and arrival rate is set to 720 vehicles per hour per lane: (a) results of heterogeneous traffic flow of AVs and HVs; (b) results of heterogeneous traffic flow of CAVs and HVs.

From Fig. 7(a), we can find that AVs can avoid risks with more accurate control performance on acceleration and shorter reaction time as a follower, because the number of conflicts when AV follows HV is basically 0. However, when AV is the leader, it may pose a threat to the follower. When the penetration rate is 0.5, the number of conflicts when HV follows AV is about 1, which is twice that of conflicts where HV follows HV. Comparing Fig. 7(a) and Fig. 7(b), we can see that the cooperative control algorithm mainly reduces the risk of heterogeneous traffic by reducing the number of conflicts where CAV follows CAV. The number of conflicts where HV follows CAV is even more than that of HV following AV in Fig. 7(a), which is because the cooperative algorithm mentioned in Section 2.2 does not consider the followers when controlling CAVs.

3.3 Distribution of conflicts along the road

We counted the conflicts at each position with departSpeed set to 30 m/s and plotted the distribution of conflicts along the road at different penetration rates, as shown in Fig. 8. The x-axes of the figure are the distance along the road, where 0-200 m is the ramp segment and the main road before the junction, the position 200 m is the junction and 200 m-250 m is the road segment after merging. The blue shaded area is the number of conflicts of HV, and the red shaded area is the number of conflicts of AV/CAV. Note that some conflicts may last for a period of distance due to the continuity of the driving process.

The figures show that HVs not only generate more conflicts, but are also exposed to risks for longer distances; and HVs also increase the degree of risk propagation upstream to the road from

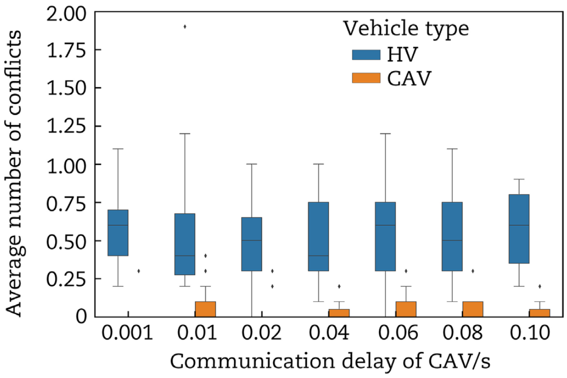

Fig. 9. Average number of conflicts per minutes with different communication delays.

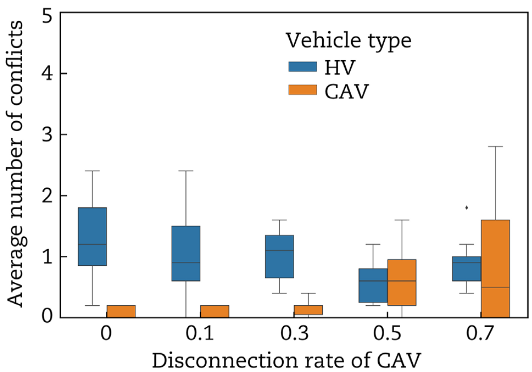

Fig. 10. Average number of conflicts per minute with different disconnection rates.

the junction. Although the previous figures, such as Fig. 3, tells us that AVs and HVs generate a similar number of conflicts, AVs keep the risk within 150 m-200 m. Comparing Figs. 8(a) and (b), we can also see that CAVs bring benefits on the number of conflicts and reduce the impact of risk compared to AVs.

3.4 Communication failure analysis

Considering that communication is necessary for cooperative control, we analysed the impact of communication failure on safety. The communication between vehicles and the roadside central controller is frequent and bidirectional, as shown in Fig. 2. In order to study the impact of communication delay, i.e. $t^u + t^c + t^d$, on the effectiveness of the cooperative control algorithm, we divided different levels of delay and conducted simulation experiments with the penetration rate of CAV as 80%. We selected the scales of delay duration as 1 ms, 10 ms, 20 ms, 40 ms, 60 ms, 80 ms and 100 ms, and plotted the average number of conflicts for CAVs and HVs, as shown in Fig. 9. From the results, we did not observe significantly increased risk with increased delays. Considering that our algorithm does not require high real-time performance, the impact of communication delay on cooperative control needs to be studied in more depth.

Further, packet loss may occur when the quality of communication becomes worse. We assumed that the packet loss obeys the uniform distribution alone time, namely each CAV may fail to receive control command with probability p in every simulation step. And in this case, CAV have to drive following the SUMO's built-in car-following model. With the penetration rate of CAV at 80%, the average number of conflicts per minutes is shown in Fig. 10. When disconnection rate, i.e. the probability of packet loss, is smaller than 0.3, the number of conflicts slightly increases, which means that the cooperative control still has safety benefits when the communication environment is a little worse.

4. Conclusions

In this paper, we used simulation techniques to investigate the conflict risk of heterogeneous traffic specifically for the on-ramp traffic scenario. We improved an existing cooperative algorithm and conducted a number of simulations with different departSpeed and arrival rates. We paid attention to the difference safety performances of two different heterogeneous traffic in terms of AV and HV, as well as CAV and HV.

For heterogeneous traffic of CAV and HV, we found that the cooperative control algorithm improved traffic safety when the penetration rate of CAV was large enough, e.g. 50% when arrival rate is 1,000 vehicles per hour per lane and departSpeed is 30 m/s. However, the safety performance of CAV and HV flow is not always outperformed by that of AV and HV flow upon different penetration rates of AVs/CAVs. With a random departSpeed and a higher arrival rate, the proposed cooperative control method should be adopted whereas the penetration rate of AVs/CAVs is over 80%. Therefore, when introducing cooperative control, the penetration rate of controllable vehicles needs to be considered; and the cooperative control algorithm needs to pay more attention to the control strategies for scenarios with lower penetration rates.

By analysing the conflicts in terms of the leading and following vehicle type, we found that the cooperative control algorithm mainly reduces the risk by alleviating the conflict where CAV follows CAV, and the risk of HV following a AV/CAV is twice that of HV following a HV. With these results, further research is needed to investigate the impact of AVs and CAVs on HVs, especially the tailgating events of HVs that might be caused by the aggressive strategies of AVs and CAVs.

We also analyse the impacts of communication delay and packet loss. It is found that when the penetration rate of a CAV is 0.8, communication delay's impact on safety is not significant and there is no significant impact until the packet loss probability is greater than 30%.

Compared with the scenario shown as Fig. 1, in more complex scenarios such as the multi-lane main road case, conflicts will propagate to the inner lanes due to lane change behaviour, which makes the design of the cooperative control algorithm and the analysis of safety more difficult and requiring further research. When considering the lane change behaviour of vehicles on the main road, the cooperative control algorithm may control the vehicles to travel along the outer lane or to change lanes to the inner side, and the different actions will bring different risks. On the other hand, we plan to test more cooperative control algorithms to examine the role of different control algorithms for risk reduction in heterogeneous traffic, which will also guide us in designing cooperative strategies. And more complex but real models of communication delay and packet loss will be used, to find the communication failure's impacts. We also plan to design and use multiple safety criteria, especially those that reflect the characteristic differences between different vehicles, to measure the risk of traffic under cooperative control.

Acknowledgements

This work was jointly supported in part by the Collaboration Project between China and Sweden regarding Research, Development and Innovation within Life Science and Road Traffic Safety (Grant No. 2018YFE0102800), in part by the Key Program of National Natural Science Foundation of China (Grant No. U21B2089), in part by the National Natural Science Foundation of China (Grant No. 71671100) and in part by the Swedish Innovation Agency Vinnova (Grant No. 2018-02891).

Conflict of interest

No potential conflict of interest was reported by the authors.

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