IET Intelligent Transport Systems

Research Article

ISSN 1751-956X
Received on 9th March 2020
Revised 7th September 2020
Accepted on 21st October 2020
E-First on 6th January 2021
doi: 10.1049/iet-its.2020.0146
www.ietdl.org

Coordinated decisions of discretionary lane change between connected and automated vehicles on freeways: a game theory-based lane change strategy

Yuan Zheng[1,2,3], Wanting Ding[4], Bin Ran[1,2,3], Xu Qu[1,2] ✉, Yu Zhang[5]

[1]*School of Transportation, Southeast University, No.2 Southeast University Road, Nanjing, Jiangsu 211189, People's Republic of China*
[2]*Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, Southeast University Road #2, Nanjing 211189, People's Republic of China*
[3]*Department of Civil and Environmental Engineering, University of Wisconsin, Madison, 1208 Engineering Hall 1415 Engineering Drive, Madison WI 53706, USA*
[4]*Shanghai SEARI Intelligent System Co., Ltd, 3/F New Energy Building, No.505 Wuning Road, Shanghai 200063, People's Republic of China*
[5]*Tongji University, Key Laboratory of Road and Traffic Engineering of the Ministry of Education, 4800 Cao'an Road, Shanghai, 201804, People's Republic of China*
✉ *E-mail: quxu@seu.edu.cn*

Abstract: Discretionary lane change is an essential part of connected and automated vehicles (CAVs) on freeway segments. Most existing studies were conducted to optimise the individual decision of discretionary lane change of CAVs. However, the effects of motion states and discretionary lane change decisions from the surrounding vehicles via vehicle to vehicle communication were ignored. To address such a problem, a game theory-based lane change strategy is proposed to collaborate and optimise decisions of discretionary lane change between the CAVs. The payoff functions are formulated for three types of decision games and the payoff of each decision is quantitatively calculated considering the state information of surrounding vehicles. The Nash equilibrium is applied to find the optimal decision set for players. A simulation platform of a CAV environment built is used to conduct the simulation experiments. Various metrics are employed to evaluate the proposed strategy, such as total travel delay, surrogate safety measurement and wave number. The results show that the proposed lane change strategy using a game-theoretical approach can effectively improve traffic operation, safety and oscillations compared to the baseline strategy. The proposed lane change strategy can further benefit the implementations of the CAVs.

1 Introduction

Connected and automated vehicles (CAVs) can drastically improve traffic operation, safety and energy consumption based on better situation awareness collected by the combination of automation and connection technologies [1–6]. Each CAV is an independent system and executes multiple functions of sensing, decision, control, communication etc. CAVs can not only exchange real-time motion state information (i.e. acceleration, speed, and position) but also transmit and receive decision information of the surrounding vehicles via vehicle to vehicle (V2V) communication [7, 8]. Compared to a traditional environment, it provides a potential opportunity to collaborate and optimise their behaviours between multiple vehicles.

Lane change is one of the most essential parts for characterising driving behaviours, which are causing numerous attention by researchers [9–12]. It mainly consists of mandatory lane change (to make drivers keep following their route) and discretionary lane change (to pursue a better driving condition) [13]. Some studies indicated that a lane change is one of the major sources of traffic oscillations and collision risks [14]. In previous studies, traditional lane change models only consider unidirectional effects of surrounding vehicles on the subject vehicle, such as Gipps Model and Minimising Overall Braking Induced by Lane Changes (MOBIL) [9]. However, this assumption is over-simple due to the effects of interactions between the subject vehicle and its surrounding vehicles on lane change decisions actually exist in the lane change process. To better understand the decision-making of a lane change, a game-theoretical approach was used to quantitatively characterise the interactions between human drivers [14]. This approach has been widely applied in recent studies [15–18]. For example, Kita *et al.* [15], Liu *et al.* (2007) and Kang and Rakha (2017) used a game-theoretical approach to characterise merging and yielding interactions between on-ramp vehicles and mainline vehicles. Kim and Langari (2014) [18] applied the mixed-motive game theory into a decision making of lane change for a game of two autonomous vehicles. The results showed that the approach had the larger payoffs compared to non-game theory case. Arbis and Dixit [13] developed an expected utility model for characterising drivers' merge and giveway decisions. The results indicated that the proposed model had considerable prediction accuracy. However, the aforementioned studies made the decisions in the games with the inferred motion states and few studies considered the decision-making analysis of discretionary lane change.

Moreover, the decision-making of a lane change would be impacted and enhanced in a connected and automated environment, based on the exchanged precise state information of the surrounding vehicles. Furthermore, the decision-making system of vehicles can consider the effects of lane change decisions from other vehicles, which is a key topic regarding system improvements. Some notable studies paid attention to the coordinated decision-making problems in a connected and automated environment [10, 19, 20]. Wang *et al.* [10] formulated a differential game approach to model the interactions of mandatory lane change between two CAVs, based on the expected behaviours of the completing vehicle. Talebpour *et al.* [21] proposed a game-theoretical approach to predict lane change behaviour with real-time state information in a connected environment. Meng *et al.* [20] developed a safer and dynamic decision-making strategy for discretionary lane change considering the combined application of receding horizon control and game theory. However, these studies mainly analysed the interactions between the subject vehicle and the new follower. The features of intercommunications will not be

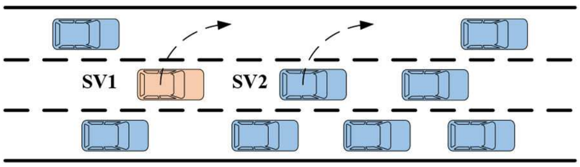


Fig. 1 *Schematic diagram of game type 1*

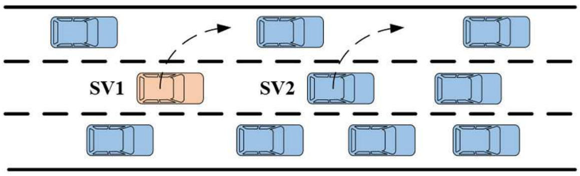


Fig. 2 *Schematic diagram of game type 2*

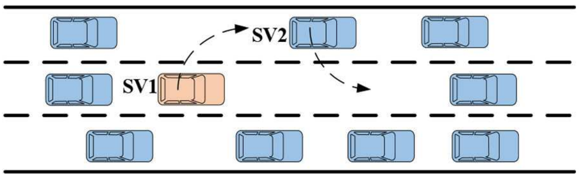


Fig. 3 *Schematic diagram of game type 3*

highlighted in a new environment and the effects of motion state information and lane-change decisions of surrounding vehicles on the decision-making of discretionary lane change were ignored. Therefore, there is a need for analysing coordinated decisions of discretionary lane changes between vehicles with more exchanged state information in a CAV environment.

The study is to propose a game theory-based lane change strategy for coordinated decisions of discretionary lane changes in a CAV environment. The game theory is used to characterise the interactions of discretionary lane change decisions between two CAVs. Three types of decision games of discretionary lane change are defined and the payoff functions for three games are formulated considering the effects of the surrounding vehicles. Based on a simulation platform of the CAV environment, various metrics are used to evaluate the proposed game theory-based lane change strategy from various aspects of traffic operation, safety, and oscillations.

The remainder of the study is organised as follows. Section 'Game theory-based lane change strategy' introduces the game definition, decision game types and payoff function of the proposed strategy. 'Simulation platform for CAVs' section shows that a simulation platform and the various metrics are used to evaluate the proposed strategy. Section 'experiment design' is to describe the experiments in detail. 'Evaluation results' section illustrates the experimental results of the different strategies. In the last section of the study, the conclusions and future research are summarised.

2 Game theory-based lane change strategy

2.1 Game definition

In a CAV environment, a subject vehicle deciding to change lane can receive the decisions of discretionary lane change from the surrounding vehicles. Moreover, these lane change decisions have a mutual effect on each other. In our study, coordinated decision-making of discretionary lane change between the CAVs can be characterised as a decision game. In the game, the payoffs of each decision set can be quantitatively determined. The coordinated decision process of discretionary lane change on freeway segments in a CAV environment includes: (i) two subject vehicles, which pursue a higher speed by performing discretionary lane changes; (ii) current followers, which are the following vehicles on current lane within a communication range; and (iii) putative followers, which are the following vehicles on target lane within a communication range.

To describe the decision game, several elements, first, require to be determined, such as the number of players, a decision set for each player, payoff functions, cooperation or non-cooperation, completed information or non-completed information. A two-person-limited non-zero-sum non-cooperative game under completed information is employed in our study. In this game, it includes two players. A limited game indicates that there are two decisions for each player, including lane change and no lane change. In a non-zero-sum game, the sum of payoffs is generally non-zero in a game. A non-cooperation game means that each player makes its own decision. Completed information is that players can obtain the predicted state information of the other players via V2V communication. The game will re-calculate when the latest traffic states become available.

2.2 Decision game types

In this section, three types of games are defined to represent the cases of the coordinated decision of discretionary lane change. It involves a subject vehicle and a leader with same target gap (type 1), a subject vehicle and a leader with different target gap (type 2) and a subject vehicle and a putative leader/follower (type 3).

2.2.1 Game type 1: For the game type 1, the subject vehicle 1 has the same decision of discretionary lane change with the subject vehicle 2 on the current lane (current leader), which corresponds to the same target gap, as shown in Fig. 1. The subject vehicle and the leading vehicle can possibly perform a coordinated discretionary lane change if the target gap is safe enough for the two vehicles. Or, the target gap is only suitable for a discretionary lane change performed by one of the two vehicles. Thus, it is required to quantitatively determine which decision set can maximise their own payoff for two vehicles and ensure traffic safety with the given traffic conditions.

2.2.2 Game type 2: Both the subject vehicle 1 and subject vehicle 2 (current leader) on the current lane have a decision of discretionary lane change. However, they have a different target gap in the target lane, as shown in Fig. 2. The payoff of the decision of a subject vehicle can be possibly affected by that of another subject vehicle. Therefore, a game-theoretical approach is applied to calculate the payoffs for different decision sets and then determine the optimal decision set.

2.2.3 Game type 3: In Fig. 3, both subject vehicle 1 and subject vehicle 2 (putative leader/follower) decide to perform a discretionary lane change, which corresponds to the switched target lane.

That is, the target lane that a subject vehicle switches into is the current lane of another subject vehicle. Moreover, the target gap of a subject vehicle is the current gap between the leader and the follower of another subject vehicle. To this end, we can calculate the payoffs of different decision sets, and select the optimal one.

2.3 Formulation of payoff functions

In our study, the utility function of acceleration is used to formulate the payoff functions of decision games [18]. To better represent the effects of intercommunication in a CAV environment, the state information of the surrounding vehicles can be considered into the calculation of payoff functions in decision games, which is different from the previous studies. The subject vehicle 1 (sv1) represents the current vehicle, and subject vehicle 2 (sv2) represents the immediate leader or putative leader/follower for different decision games. In all scenarios, the vehicle has two pure decisions: lane change and no lane change. The normalised structure of the decision game is illustrated in Table 1. U_{sv11}, U_{sv12}, U_{sv21} and U_{sv22} indicate the payoff of lane change and no lane change of subject vehicle 1 and subject vehicle 2, respectively. Moreover, the payoff functions for the decision sets can be defined in the following section.

2.3.1 Payoff function for decision set (LC, LC): Game type 1: For the decision set, it means the subject vehicle and immediate

Table 1 Structure of the decision game in normal form

Players		Subject vehicle 2	
—	decision	LC	NLC
subject vehicle1	LC	$(U_{\text{sv}11}, U_{\text{sv}21})$	$(U_{\text{sv}11}, U_{\text{sv}22})$
—	NLC	$(U_{\text{sv}12}, U_{\text{sv}21})$	$(U_{\text{sv}12}, U_{\text{sv}22})$

current leader has a lane change decision simultaneously. The subject vehicle needs to keep a safe distance with the leader. In our study, we define the variations of acceleration before and after a lane change as the payoff of the decision set. The followers on current and target lane within a communication range are considered into the calculations of payoffs since they are affected by the lane change decisions. It is consistent with the calculation of utility in the lane change model, subject to the incentive and safety criteria. The payoffs of the decision set are calculated as follows:

$$U_{\text{sv}11} = \underbrace{\tilde{a}_{\text{sv}1} - a_{\text{sv}1}}_{\text{sv}1} + p \cdot \left[\underbrace{\sum_{i=1}^{N_{\text{cfv}}} (\tilde{a}_{\text{cfv},i} - a_{\text{cfv},i})}_{\text{cfv}} + \underbrace{\sum_{j=1}^{N_{\text{tfv}}} (\tilde{a}_{\text{tfv},j} - a_{\text{tfv},j})}_{\text{tfv}} \right] \tag{1}$$

$$U_{\text{sv}21} = \tilde{a}_{\text{sv}2} - a_{\text{sv}2} + p \cdot \left[\sum_{i=2}^{N_{\text{cfv}}} (\tilde{a}_{\text{cfv},i} - a_{\text{cfv},i}) + \tilde{a}_{\text{sv}1} - a_{\text{sv}1} + \sum_{j=1}^{N_{\text{tfv}}} (\tilde{a}_{\text{tfv},j} - a_{\text{tfv},j}) \right] \tag{2}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\text{cfv}}, 0 \le \| x_{\text{sv}1} - x_{\text{cfv},i} \| \le L_w; \\ &\forall j = 1, 2, \ldots, N_{\text{tfv}}; 0 \le \| x_{\text{sv}1} - x_{\text{tfv},j} \| \le L_w \end{aligned} \tag{3}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\text{cfv}}, 0 \le \| x_{\text{sv}2} - x_{\text{cfv},i} \| \le L_w; \\ &\forall j = 1, 2, \ldots, N_{\text{tsv}}, 0 \le \| x_{\text{sv}2} - x_{\text{tfv},j} \| \le L_w \end{aligned} \tag{4}$$

where U represents the overall utility of the subject vehicle if it performs a lane change. The subscripts 'sv' and 'fv' represent the subject vehicle and following vehicle, respectively. The subscripts 'c' and 't' represent vehicles on the current lane and target lane, respectively. $a_i$and $\tilde{a}_i$ are the accelerations at before and after a lane change, respectively. The politeness factor p is a weight coefficient, denoting the total advantages or disadvantages (acceleration gain or loss) of the followers within a communication range on the current and target lane, weighted with p. x presents the current position of a vehicle. $\|\cdot\|$presents the Euclidean norm. L_w is the communication range of V2V. The communication range is set at 300 m, as suggested by previous studies, which is also widely adopted and recognised in previous studies [20–22]. Note that, for other communication ranges, the proposed lane change strategy can work in the same way.

For a decision which is to change lane, the incentive and safety criteria should be satisfied. The satisfied criteria are shown as follows:

$$U_{\text{sv}11}, U_{\text{sv}21} \ge \Delta a_{\text{th}} \tag{5}$$

$$a_{\text{sv}1}, a_{\text{sv}2}, a_{\text{cfv},i}, a_{\text{tfv},j} \ge -b_{\text{safe}} \tag{6}$$

where a switching threshold Δa_{th}denotes the permissiveness threshold of a lane change. A safety criterion b_{safe} guarantees that the deceleration of the subject vehicle and new followers cannot exceed a given safe limit after a lane change.

Game type 2: The subject vehicle and immediate current leader have a different gap on target lane for game type 2. The payoffs of the decision set are calculated according to the following equations:

$$U_{\text{sv}11} = \tilde{a}_{\text{sv}1} - a_{\text{sv}1} + p \cdot \left[\sum_{i=1}^{N_{\text{cfv}}} (\tilde{a}_{\text{cfv},i} - a_{\text{cfv},i}) + \sum_{j=1}^{N_{\text{tfv}}} (\tilde{a}_{\text{tfv},j} - a_{\text{tfv},j}) \right] \tag{7}$$

$$U_{\text{sv}21} = \tilde{a}_{\text{sv}2} - a_{\text{sv}2} + p \cdot \left[\sum_{i=1}^{N_{\text{cfv}}} (\tilde{a}_{\text{cfv},i} - a_{\text{cfv},i}) + \tilde{a}_{\text{sv}1} - a_{\text{sv}1} + \sum_{j=1}^{N_{\text{tfv}}} (\tilde{a}_{\text{tfv},j} - a_{\text{tfv},j}) \right], i \ne \text{sv}1 \tag{8}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\text{cfv}}, 0 \le \| x_{\text{sv}1} - x_{\text{cfv},i} \| \le L_w; \\ &\forall j = 1, 2, \ldots, N_{\text{tfv}}; 0 \le \| x_{\text{sv}1} - x_{\text{tfv},j} \| \le L_w \end{aligned} \tag{9}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\text{cfv}}, 0 \le \| x_{\text{sv}2} - x_{\text{cfv},i} \| \le L_w; \\ &\forall j = 1, 2, \ldots, N_{\text{tsv}}, 0 \le \| x_{\text{sv}2} - x_{\text{tfv},j} \| \le L_w \end{aligned} \tag{10}$$

$$U_{\text{sv}11}, U_{\text{sv}21} \ge \Delta a_{\text{th}} \tag{11}$$

$$a_{\text{sv}1}, a_{\text{sv}2}, a_{\text{cfv},i}, a_{\text{tfv},j} \ge -b_{\text{safe}} \tag{12}$$

Game type 3: Two subject vehicles have a switched target lane. Consequently, the payoff of the subject vehicle will not consider the effect of another subject vehicle. The payoffs are calculated as shown below:

$$U_{\text{sv}11} = \tilde{a}_{\text{sv}1} - a_{\text{sv}1} + p \cdot \left[\sum_{i=1}^{N_{\text{cfv}}} (\tilde{a}_{\text{cfv},i} - a_{\text{cfv},i}) + \sum_{j=1}^{N_{\text{tfv}}} (\tilde{a}_{\text{tfv},j} - a_{\text{tfv},j}) \right] \tag{13}$$

$$U_{\text{sv}21} = \tilde{a}_{\text{sv}2} - a_{\text{sv}2} + p \cdot \left[\sum_{i=1}^{N_{\text{cfv}}} (\tilde{a}_{\text{cfv},i} - a_{\text{cfv},i}) + \sum_{j=1}^{N_{\text{tfv}}} (\tilde{a}_{\text{tfv},j} - a_{\text{tfv},j}) \right] \tag{14}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\text{cfv}}, 0 \le \| x_{\text{sv}1} - x_{\text{cfv},i} \| \le L_w; \\ &\forall j = 1, 2, \ldots, N_{\text{tfv}}, 0 \le \| x_{\text{sv}1} - x_{\text{tfv},j} \| \le L_w \end{aligned} \tag{15}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\text{cfv}}, 0 \le \| x_{\text{sv}2} - x_{\text{cfv},i} \| \le L; \\ &\forall j = 1, 2, \ldots, N_{\text{tsv}}, 0 \le \| x_{\text{tsv}2} - x_{\text{tfv},j} \| \le L \end{aligned} \tag{16}$$

$$U_{\text{sv}11}, U_{\text{sv}21} \ge \Delta a_{\text{th}} \tag{17}$$

$$a_{\text{sv}1}, a_{\text{sv}2}, a_{\text{cfv},i}, a_{\text{tfv},j} \ge -b_{\text{safe}} \tag{18}$$

2.3.2 Payoff function for decision set (LC, NLC): In this scenario, the decision set means that the subject vehicle 1 makes a decision of discretionary lane change, and the decision of the subject vehicle 2 (current leader or putative leader/follower) is no lane change. The payoff is set to be a large negative number to penalise the decision if the criteria of the lane change are not satisfied. The payoffs of the decision set are calculated as follows:

$$U_{\text{sv}11} = \tilde{a}_{\text{sv}1} - a_{\text{sv}1} + p \cdot \left[\sum_{i=1}^{N_{\text{cfv}}} (\tilde{a}_{\text{cfv},i} - a_{\text{cfv},i}) + \sum_{j=1}^{N_{\text{tfv}}} (\tilde{a}_{\text{tfv},j} - a_{\text{tfv},j}) \right] \tag{19}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\text{cfv}}, 0 \le \| x_{\text{sv}1} - x_{\text{cfv},i} \| \le L_w; \\ &\forall j = 1, 2, \ldots, N_{\text{tfv}}, 0 \le \| x_{\text{sv}1} - x_{\text{tfv},j} \| \le L_w \end{aligned} \tag{20}$$

$$U_{\text{sv}11} \ge \Delta a_{\text{th}} \tag{21}$$

$$a_{\text{sv}1}, a_{\text{cfv},i}, a_{\text{tfv},j} \ge -b_{\text{safe}} \tag{22}$$

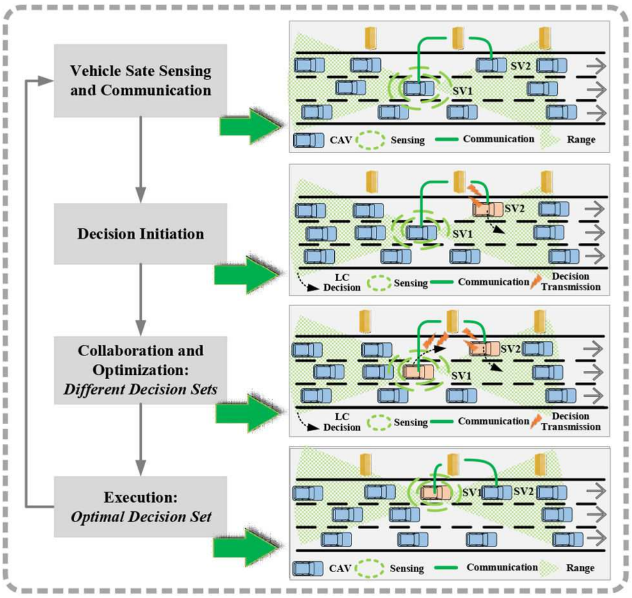


Fig. 4 *Schematic diagram of an implementation of the strategy*

2.3.3 Payoff function for decision set (NLC, LC): The decision set is that the decision of subject vehicle 1 is to no lane change, and the subject vehicle 2 decides to perform a lane change. As shown above, the payoff of the decision set is shown as follows:

$$U_{\mathrm{sv21}} = \tilde{a}_{\mathrm{sv2}} - a_{\mathrm{sv2}} + p \cdot \left[\sum_{i=2}^{N_{\mathrm{cfv}}} (\tilde{a}_{\mathrm{cfv},i} - a_{\mathrm{cfv},i}) + \tilde{a}_{\mathrm{sv1}} - a_{\mathrm{sv1}} + \sum_{j=1}^{N_{\mathrm{tfv}}} (\tilde{a}_{\mathrm{tfv},j} - a_{\mathrm{tfv},j}) \right] \tag{23}$$

$$\begin{aligned} &\forall i = 1, 2, \ldots, N_{\mathrm{cfv}}, 0 \le \| x_{\mathrm{sv2}} - x_{\mathrm{cfv},j} \| \le L_w; \\ &\forall j = 1, 2, \ldots, N_{\mathrm{tsv}}, 0 \le \| x_{\mathrm{sv2}} - x_{\mathrm{tfv},j} \| \le L_w \end{aligned} \tag{24}$$

$$U_{\mathrm{sv21}} \ge \Delta a_{\mathrm{th}} \tag{25}$$

$$a_{\mathrm{sv2}}, a_{\mathrm{cfv},i}, a_{\mathrm{tfv},j} \ge -b_{\mathrm{safe}} \tag{26}$$

2.3.4 Payoff function for decision set (NLC, NLC): The decision set indicates that both two subject vehicles decide to not perform a lane change. The payoff is set to be a large negative number while the criteria of the lane change are not satisfied.

2.4 Optimal decision set for players

For a given game, the Nash equilibrium proposed by Nash (1950) is used to find the optimal action set for both players. The Nash equilibrium is a solution set where neither player has a motivation to change their own action, as no player can have any rewards to gain by a change individually. In other words, each player will choose the optimal action set to maximise their own payoff. In a two-player decision game, both player 1 and player 2 have two pure decisions, respectively: $S_1 = \{a_1,\ a_2\}$ or $S_2 = \{b_1,\ b_2\}$. The utility functions U_1 and U_2 are the payoffs for two players, respectively, when the players choose a set of decisions. Nash equilibrium defines the pure decision, which is specified as follows:

$$U_1(a*, b*) \ge U_1(a, b*), \forall a \in S_1 \tag{27}$$

$$U_2(a*, b*) \ge U_2(a*, b), \forall a \in S_2 \tag{28}$$

where a* and b* represents the equilibrium decision for player 1 and player 2, respectively. Note that a pure strategy is assumed to provide a complete definition of how a player will play a game in our study.

3 Simulation platform for CAVs

In practice, a field experiment conducted to evaluate the proposed lane change strategy is difficult because the strategy may increase the crash risk to drivers. The traffic simulation technique, which is regarded as an acceptable surrogate method, is used to evaluate the proposed strategy. To characterise the car following and lane change behaviours, microscopic models were widely used in previous studies, such as the IDM [23–26] and MOBIL [27, 28]. Our study requires precise vehicular control, and thus the simulation platform for CAVs needs to be built based on the microscopic models.

CAVs can perceive state information (relative distance/speed) of an immediate leader and exchange the state information with surrounding vehicles via V2V communication. It is not available to use conventional models with those new concepts of CAVs for a CAV analysis in previous studies [22]. Moreover, the modified IDM [29] and MOBIL are used to simulate the communication effects with the weighted state information of surrounding vehicles. Considering the features of inter-communications between vehicles, a simulation platform of a CAV environment was built based on the modified IDM and MOBIL, as indicated by the previous studies [27, 30]. It can better simulate the effects of advanced connection and automation technologies on the car following and lane changing manoeuvres of CAVs. More details on the microscopic models of the simulation platform are mentioned in the previous study [27].

Note that the vehicle dynamics and constraints in the car-following model are both simplified to ease the simulation in our study. There are vehicle dynamics-based models in the literature works that can more accurately model the car following behaviours as realistically as possible [31]. However, these models are complicated in mathematical representations and the scalability of the model needs to be further explored in a new environment. Moreover, the state-of-art IDM can also be used to reproduce the car following behaviours. The model can be easier to be implemented but does not consider the mechanical characteristics of vehicles. Therefore, it is significant to find the optimal balance between complexity and simplicity for the application of car-following models. In a CAV environment, the IDM can be extended to consider the exchanged state information of the surrounding vehicles into the calculation of acceleration [29], to better simulate the effects of intercommunication between vehicles. Moreover, the model in our study does not consider vehicle dynamics for the simplification, which is referential to previous studies [25, 26, 30, 31].

3.1 Simulation framework

In the simulation platform, the modified IDM is used to determine the acceleration of each vehicle. The modified MOBIL model can model the decision-making process of a discretionary lane change. All the vehicles are CAVs in our study, which can execute multi-functions of sensing, decision, control and communication etc. The motion state information of CAVs can be updated, by considering the state information of the surrounding vehicles within a communication range (i.e. relative position, position, and decision information). Note that the main purpose of the study is to propose a new lane-change strategy. The impacts of data packet loss and transmission delay are not considered in our current simulation analysis [10, 30].

The proposed strategy becomes effective while a vehicle makes a decision of discretionary lane change based on the surrounding state information, as shown in Fig. 4. When a CAV generates a discretionary lane change decision, the decision system of vehicles will search whether there exist other decisions of discretionary lane change among the surrounding vehicles. A game-theoretical approach in the proposed strategy is used to model the decision interactions between the vehicles, while the other decisions are received within the communication range. The proposed strategy can calculate the payoffs of different decision sets and find the optimal decision set for participating vehicles. The decision information (lane change or no lane change) can be transmitted to the two vehicles via V2V communication. Vehicles equipped with

Table 2 Default parameter settings

Parameter	Symbol	Value
desired time gap	t_d	1.2 s
maximum acceleration	a_{max}	1.4 m/s^2
comfortable deceleration	a_{min}	2.0 m/s^2
free flow acceleration	δ	4
length of vehicle	L	4.0 m
minimum distance	s_0	2.0 m
desired speed	v_{des}	[17, 33 m/s]
communication range	L_W	300 m
threshold of the lane change	a_{th}	0.1
politeness factor	p	1.5
safety criterion	b_{safe}	−2.09 m/s^2

an on-board display can receive instructions from the vehicles' decision system to which the vehicle should react. Note that our study assumes the vehicle is in full control instruction of acceleration and lane change, which can be achieved under the CAV environment. After a lane change, vehicles maintain travelling on current lane for a short period before initiating a new lane change. The execution process of discretionary lane change is not considered into the study for the simplification.

3.2 Evaluation metrics

A set of metrics were considered to evaluate the game theory-based lane change strategy. An optimal strategy should consider improvements in various aspects, such as traffic operation, safety and oscillations. Therefore, the total travel delay, surrogate safety measurements, and the number of waves are considered, which are shown as follows:

3.2.1 Total travel delay: Total travel delay in a network is the main indicator to assess the system operational efficiency [32]. The total travel delay is calculated as follows:

$$\mathrm{TTD} = \sum_{i=1}^{N} \left(\mathrm{TTT}_i - \mathrm{TTT}_i^{\mathrm{desired}}\right) \tag{29}$$

where TTT_i and $\mathrm{TTT}_i^{\mathrm{desired}}$ is the time and expected time spent on freeways for the vehicle i and N denotes the total number of vehicles generated in the system during the simulation period.

3.2.2 Surrogate safety measurement: In our study, surrogate safety measurements are used to evaluate safety effects, due to direct safety measurements (i.e. crash count) are difficult in practice. The time-to-collision (TTC) notion was first introduced (Hayward, 1972) [33] and has widely been applied in the previous studies [34, 35].

Based on the TTC, two advanced measures are developed to assess the risks associated with the vehicle movements near oscillations, which correspond to the time exposed time-to-collision (TET) and the modified time-integrated time-to-collision (TIT) [35]. Particularly, TET is a sum over the simulation period T that a driver approaches a front vehicle with a TTC value below a critical threshold. A lower TET value indicates a safer situation. TIT calculates the entity of the TTC lower than the threshold. A larger TIT indicates a more dangerous condition

$$\mathrm{TTC}_i(t) = \begin{cases} \dfrac{x_{i-1}(t) - x_i(t) - L}{v_i(t) - v_{i-1}(t)}, & \text{if } v_i(t) > v_{i-1}(t) \\ \infty, & \text{if } v_i(t) \le v_{i-1}(t) \end{cases} \tag{30}$$

$$\mathrm{TET}(t) = \sum_{i=1}^{N} \gamma_t \Delta t, \gamma_t = \begin{cases} 1, & \forall 0 < \mathrm{TTC}_i(t) \le \mathrm{TTC}_{\mathrm{threshold}} \\ 0, & \text{else} \end{cases} \tag{31}$$

$$\mathrm{TET} = \sum_{t=1}^{T} \mathrm{TET}(t) \tag{32}$$

$$\mathrm{TIT}(t) = \sum_{i=1}^{N} \left(\frac{1}{\mathrm{TTC}_i(t)} - \frac{1}{\mathrm{TTC}_{\mathrm{thres}}}\right) \Delta t, \forall 0 < \mathrm{TTC}_i(t) \le \mathrm{TTC}_{\mathrm{thres}} \tag{33}$$

$$\mathrm{TIT} = \sum_{t=1}^{T} \mathrm{TIT}(t) \tag{34}$$

where L is the length of predecessor vehicle, t is time, T is simulation period, Δt is simulation time step, i is vehicle ID, N is the number of vehicles, and $\mathrm{TTC}_{\mathrm{thres}}$ is the threshold of TTC which is set to be 2 s adopted in previous studies [26].

3.2.3 Number of waves: In our study, one wave number is counted when the speed of a vehicle is <1 m/s. A new wave can be counted only after 10 s from the immediate last time that the speed is <1 m/s, as adopted in the previous studies [27, 36]. Moreover, the total number of waves for all vehicles in the system can be calculated by accumulating the wave number of each vehicle. It is regarded as the overall metric and used to evaluate the magnitude of traffic oscillations.

4 Experiment design

In this section, a lane change strategy was to make the decision of discretionary lane change independently using the modified IDM and MOBIL in the previous study, which is regarded as the baseline strategy. We can compare the proposed game theory-based lane change strategy with the baseline strategy to validate the effectiveness of coordinated decision optimisation of the discretionary lane change. Moreover, the two strategies are compared with various aspects under two traffic flow conditions in the following section.

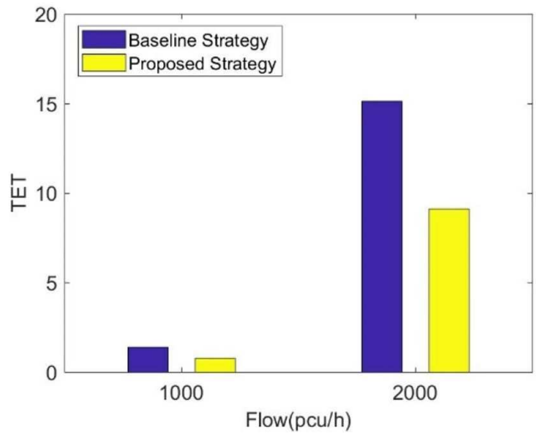
A hypothetical three-lane freeway segment is considered in our simulation analysis. Each simulation test lasts 300 s and the time step is 0.1 s. The simulation includes the two classes of vehicles to emerge the different driving characteristics and then trigger the incentives of a discretionary lane change. The first type is the faster vehicle, which has a higher desired speed. The average speed of faster vehicles is 28 m/s, and the interval of speed is from 23 to 33 m/s. Another type is the slower vehicle with an average speed of 20 m/s, and the speed is ranging from 17 to 23 m/s. The initialised speed of all vehicles was set to be 17 m/s for all scenarios. Moreover, the composition of the vehicle in the system contains 80% faster vehicle and 20% slower vehicle. In total 300 of the vehicles are initialised on freeway segments. The gap between every two consecutive vehicles was set depending on the traffic demand. The traffic demand was set at 1000 and 2000 pcu/h to generate different traffic states. The simulation results are averaged to reduce the impact of randomness for the ten times tests. For the CAVs, six parameters were needed to be determined in the modified IDM, which were the time gap, desired speed, minimum distance, maximum acceleration, free flow acceleration, and comfortable deceleration. In the modified MOBIL model, we require to determine four parameters, including the communication range, threshold of the lane change, safety criterion, and politeness factor. Due to the lack of empirical data, these parameters were set the same with previous studies. More details on parameter settings are shown in Table 2, according to the previous studies [17, 21, 23–26].

5 Evaluation results

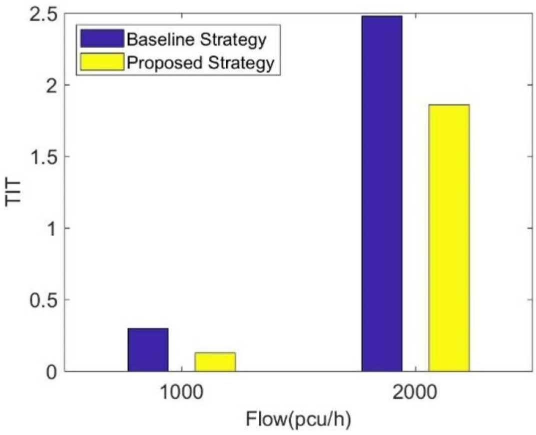
The experiment results between the two lane change strategies are shown under two traffic flow conditions in the following parts.

Table 3 Comparisons of total delay between two strategies

	Small flow, h	Large flow, h
baseline strategy	3.95	5.73
proposed strategy	3.94	5.54
reduction, %	0.26	3.30



a



b

Fig. 5 *Safety effects between different lane change strategies*
(a) TET, ***(b)*** TIT

5.1 Impacts on total travel delay

The results of total travel delay between different lane change strategies are illustrated in Table 3.

The proposed strategy has a smaller travel delay than the baseline strategy under the traffic flow conditions of 2000 and 1000 pcu/h. The reductions in total travel delay are 3.3% and 0.26% for the two conditions, respectively. Consequently, it is found that the proposed strategy can improve traffic operation compared to the baseline strategy. It is due to the fact that the proposed strategy can collaborate and optimise the decisions of discretionary lane change between CAVs using the game-theoretical approach, to find the optimal decision set compared with the individual decisions made in baseline strategy. Furthermore, the two strategies have better improvements in traffic operation under the large flow condition than the small flow condition, due to the sufficient gaps for the small flow condition are helpful in reducing the travel delay and cannot highlight the benefits with the implementations of the proposed strategy.

5.2 Impacts on traffic safety

The impacts of different lane change strategies on traffic safety are shown in Fig. 5. We can observe that the reductions in TET/TIT values are ranging from 25.0% to 39.6% and 43.8% to 54.2% under the large and small traffic flow conditions, respectively. It indicates that the proposed strategy using a game theoretical approach can effectively improve traffic safety compared to the baseline strategy based on the smaller TET/TIT values. This is because the game theory-based lane change strategy can collaboratively optimise the decisions between vehicles to effectively reduce the collision risks arising from the lane change. Moreover, the proposed strategy under the smaller flow condition has a significant effect on improving traffic safety than the baseline strategy under larger flow condition with the larger reductions in TET/TIT. It indicates that the discretionary lane change can increase the collision risks while the original gap is smaller under large flow condition.

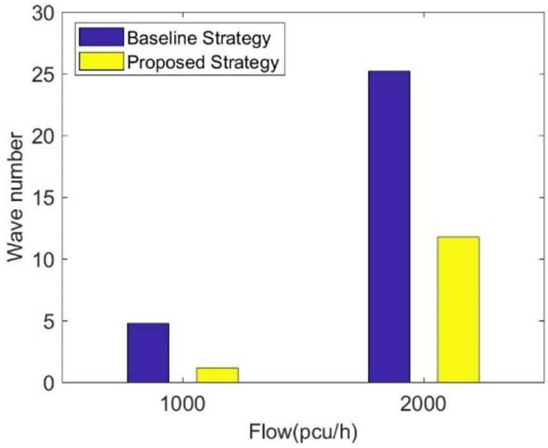


Fig. 6 *Wav number between different lane change strategies*

5.3 Impacts on traffic oscillations

The results of the wavenumber between different strategies are shown in Fig. 6 under the traffic conditions of 2000 and 1000 pcu/h. Particularly, it is found that the implementation of the proposed strategy reduces the number of waves by 53.2 and 75.0% compared with the baseline strategy under the larger and smaller flow, respectively. This indicates that the proposed strategy can effectively reduce the oscillatory effects arising from discretionary lane change under the two flow conditions. It is mainly due to that the traffic oscillations (stop-and-go waves) can be significantly mitigated by the optimisation of the coordinated decision in the proposed strategy with a game-theoretical approach.

6 Conclusions

The study proposes a game theory-based lane change strategy for the coordinated decision-making problems of discretionary lane change between CAVs on freeway segments. The interactions of discretionary lane change decision between two CAVs are considered into the decision games. Three types of decision games are defined in our study. The payoff functions of decision game are formulated by acceleration utility subject to the criteria of a lane change, considering the effects of state information of surrounding vehicles. The Nash equilibrium is used to find the optimal decision set for participating vehicles. Based on a simulation platform of a CAV environment built using the modified IDM and MOBIL, various metrics are employed to evaluate the proposed lane change strategy, including total travel delay, surrogate safety measurements and wave number.

Moreover, several important results are summarised. First, the study provides an appropriate approach to characterise the interactions of lane change decision between CAVs via V2V communication based on the game theory. The proposed strategy can be feasible to solve a coordinated decision problem between multiple CAVs and regarded as a supplement for discretionary lane change of CAVs. Moreover, the state information of the surrounding vehicles is considered to formulate the payoff function for a lane change decision to better simulate the effects of intercommunication in a CAV environment. Furthermore, the proposed game theory-based lane change strategy can improve traffic performances compared to the baseline strategy from various aspects, by collaborating and optimising decisions of discretionary lane change between the CAVs. The improvements in traffic operation, safety and oscillations for the proposed strategy are ranging from 0.26 to 3.30%, 25.0 to 54.2%, and 53.2 to 75.0% compared to baseline strategy under the two traffic flow conditions, respectively.

In our current study, the payoffs of the proposed strategy only considered the effect of acceleration utility. On freeway segments a discretionary lane change accompanied by multi-factor, the payoff calculation needs to be modified in the current lane change strategy using a game-theoretical approach. The coordinated decision of discretionary lane change between multiple vehicles for various game types will be considered into our future research. More action alternatives (deceleration or acceleration) and a mixed game-theoretical approach will also be used to characterise the discretionary lane change in a CAV environment. Furthermore, we can integrate mandatory lane change into our proposed strategy to better characterise traffic dynamics on freeways.

7 Acknowledgments

This study is jointly supported by the National Key R&D Program in China (Grant No. 2018YFB1600600), the MOE (Ministry of Education in China) Project of Humanities and Social Sciences (Grant No. 20YJAZH083), and the National Natural Science Foundation of China (Grant No. 51878161), and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (Grant No. KYCX18_0136).

8 References

[1] Ge, J. I., Gábor, O.: 'Dynamics of connected vehicle systems with delayed acceleration feedback', *Transp. Res. C, Emerg. Technol.*, 2014, **46**, pp. 46–64

[2] Wang, M., Daamen, W., Hoogendoorn, S. P., *et al.*: 'Rolling horizon control framework for driver assistance systems. Part II: cooperative sensing and cooperative control', *Transp. Res. Part C, Emerg. Technol.*, 2014b, **40**, pp. 290–311

[3] Talebpour, A., Mahmassani, H.S.: 'Influence of connected and autonomous vehicles on traffic flow stability and throughput', *Transp. Res. C, Emerg. Technol.*, 2016, **71**, pp. 143–163

[4] Shladover, S. E.: 'Connected and automated vehicle systems: Introduction and overview', *J. Intell. Transp. Syst.*, 2018, **22**, (3), pp. 190–200

[5] Ding, J., Peng, H., Zhang, Y., *et al.*: 'Penetration effect of connected and automated vehicles on cooperative on-ramp merging', *IET Intell. Transp. Syst.*, 2019, **2019**, pp. 14, (1), pp. 56–64

[6] Yao, Z., Jiang, Y., Zhao, B., *et al.*: 'A dynamic optimization method for adaptive signal control in a connected vehicle environment', *J. Intell. Transp. Syst.*, 2020, **24**, (2), pp. 184–200

[7] Zheng, Y., Zhang, Y., Ran, B., *et al.*: 'Cooperative control strategies to stabilize the freeway mixed traffic stability and improve traffic throughput in an intelligent roadside system environment', *IET Intell. Transp. Syst.*, 2020, **14**, (9), pp. 1108–1115

[8] Yao, Z., Shen, L., Liu, R., *et al.*: 'A dynamic predictive traffic signal control framework in a cross-sectional vehicle infrastructure integration environment', *IEEE Trans. Intell. Transp. Syst.*, 2019, **21**, (4), pp. 1455–1466

[9] Zheng, Z.: 'Recent developments and research needs in modeling lane changing', *Transp. Res. B, Methodol.*, 2014, **60**, pp. 16–32

[10] Wang, M., Hoogendoorn, S. P., Daamen, W., *et al.*: 'Game theoretic approach for predictive lane-changing and car-following control', *Transp. Res. C, Emerg. Technol.*, 2015, **58**, pp. 73–92

[11] Lee, S., Ngoduy, D., Keyvan-Ekbatani, M.: 'Integrated deep learning and stochastic car-following model for traffic dynamics on multi-lane freeways', *Transp. Res. C, Emerg. Technol.*, 2019, **106**, pp. 360–377

[12] Jin, H., Duan, C., Liu, Y., *et al.*: 'Gauss mixture hidden Markov model to characterise and model discretionary lane-change behaviours for autonomous vehicles', *IET Intell. Transp. Syst.*, 2020, **14**, (5), pp. 401–411

[13] Arbis, D., Dixit, V.: 'Game theoretic model for lane changing: incorporating conflict risks', *Accident Anal. Prev.*, 2019, **125**, pp. 158–164

[14] Scheel, O., Nagaraja, N. S, Schwarz, L., *et al.*: 'Attention-based lane change prediction'. Int. Conf. on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 8655–8661

[15] Kita, H., Tanimoto, K., Fukuyama, K.: 'A game theoretic analysis of merging-giveway interaction: a joint estimation model'. Transportation and Traffic Theory in the 21st Century: Proc. 15th Int. Symp. on Transportation and Traffic Theory, Adelaide, Australia, July 2002, pp. 16–18

[16] Liu, H. X., Xin, W., Adam, Z., *et al.*: '*A game theoretical approach for modelling merging and yielding behaviour at freeway on-ramp sections*' (Elsevier, London, 2007), pp. 197–211

[17] Kang, K., Rakha, H. A.: 'Game theoretical approach to model decision making for merging maneuvers at freeway On-ramps', *Transp. Res. Rec., J. Transp. Res. Board*, 2017, **2623**, pp. 19–28

[18] Kim, C., Langari, R.: 'Game theory based autonomous vehicles operation', *Int. J. Veh. Des.*, 2014, **65**, (4), pp. 360–383

[19] Zhou, M., Qu, X., Jin, S.: 'On the impact of cooperative autonomous vehicles in improving freeway merging: a modified intelligent driver model-based approach', *IEEE Trans. Intell. Transp. Syst.*, 2016, **18**, (6), pp. 1422–1428

[20] Meng, F., Su, J., Liu, C., *et al.*: 'Dynamic decision making in lane change: game theory with receding horizon'. 2016 UKACC 11th Int. Conf. on Control (CONTROL), Belfast, UK, 2016, pp. 1–6

[21] Talebpour, A., Mahmassani, H. S., Hamdar, S. H.: 'Modeling lane-changing behavior in a connected environment: A game theory approach', *Transp. Res. C, Emerg. Technol.*, 2015, **59**, pp. 216–232

[22] Scarinci, R., Hegyi, A., Heydecker, B.: 'Definition of a merging assistant strategy using intelligent vehicles', *Transp. Res. C, Emerg. Technol.*, 2017, **82**, pp. 161–179

[23] Kesting, A., Treiber, M., Helbing, D.: 'Adaptive cruise control design for active congestion avoidance', *Transp. Res. C, Emerg. Technol.*, 2008, **16**, (6), pp. 668–683

[24] Khondaker, B., Kattan, L.: 'Variable speed limit: A microscopic analysis in a connected vehicle environment', *Transp. Res. C, Emerg. Technol.*, 2015, **58**, pp. 146–159

[25] Milanés, V., Shladover, S. E.: 'Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data', *Transp. Res. C, Emerg. Technol.*, 2014, **48**, pp. 285–300

[26] Li, Y., Li, Z., Wang, H., *et al.*: 'Evaluating the safety impact of adaptive cruise control in traffic oscillations on freeways', *Accident Anal. Prev.*, 2017, **104**, pp. 137–145

[27] Zheng, Y., Ran, B., Qu, X., *et al.*: 'Cooperative lane changing strategies to improve traffic operation and safety nearby freeway off-ramps in a connected and automated vehicles environment', *IEEE Trans. Intell. Transp. Syst.*, 2019, **21**, (11), pp. 4605–4614

[28] Monteil, J., Nantes, A., Billot, R., *et al.*: 'Microscopic cooperative traffic flow: calibration and simulation based on a next generation simulation dataset', *IET Intell. Transp. Syst.*, 2014, **8**, (6), pp. 519–525

[29] Monteil, J. R., Billot, J., Armetta, F., *et al.*: 'Cooperative highway traffic: multiagent modeling and robustness assessment of local perturbations', *Transp. Res. Rec.*, 2013, **2391**, (1), pp. 1–10

[30] Guériau, M., Billot, R., El Faouzi, N. E., *et al.*: 'How to assess the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies', *Transp. Res. C, Emerg. Technol.*, 2016, **67**, pp. 266–279

[31] Fadhloun, K., Rakha, H.: 'A novel vehicle dynamics and human behavior car-following model: model development and preliminary testing', *Int. J. Transp. Sci. Technol.*, 2020, **9**, (1), pp. 14–28

[32] Goñi-Ros, B., Schakel, W.J., Papacharalampous, A.E., *et al.*: 'Using advanced adaptive cruise control systems to reduce congestion at sags: an evaluation based on microscopic traffic simulation', *Transp. Res. C, Emerg. Technol.*, 2019, **102**, pp. 411–426

[33] Hayward, J.: '*Near miss determination through use of a scale of danger*' (Highway Research Board, Washington D.C., USA, 1972)

[34] Li, Z., Ahn, S., Chung, K., *et al.*: 'Surrogate safety measure for evaluating rear-end collision risk related to kinematic waves near freeway recurrent bottlenecks', *Accident Anal. Prev.*, 2014, **64**, pp. 52–61

[35] Rahman, M., Abdel-Aty, M.: 'Longitudinal safety evaluation of connected vehicles' platooning on expressways', *Accident Anal. Prev.*, 2018, **117**, pp. 381–391

[36] He, Z., Zheng, L., Song, L., *et al.*: 'A jam-absorption driving strategy for mitigating traffic oscillations', *IEEE Trans. Intell. Transp. Syst.*, 2016, **18**, (4), pp. 802–813