Title
Safety analysis of the eco-approach and departure application at a signalized corridor

Journal
Tsinghua Science and Technology, 23(2)

ISSN
1007-0214

Authors
Li, Weixia
Wu, Guoyuan
Zhang, Yi
et al.

Publication Date
2018-04-01

DOI
10.26599/TST.2018.9010061

Peer reviewed

Safety analysis of the eco-approach and departure application at a signalized corridor

Article *in* Tsinghua Science & Technology · April 2018

DOI: 10.26599/TST.2018.9010061

Weixia Li
Tsinghua University

Guoyuan Wu
University of California, Riverside

Matthew J. Barth
University of California, Riverside

TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 05/09 pp157–171
DOI: 10.26599 / TST.2018.9010061
Volume 23, Number 2, April 2018

Safety Analysis of the Eco-Approach and Departure Application at a Signalized Corridor

Weixia Li, Guoyuan Wu*, Yi Zhang, and Matthew J. Barth

Abstract: Various intelligent transportation systems and strategies for reducing vehicle fuel consumption and emissions have been developed. Energy and emissions could be reduced with the compromise of travel time in some environment-focused Connected Vehicle (CV) applications, which highlighted performance measures in terms of mobility and sustainability. Nevertheless, few studies have focused on safety assessment of such CV applications. In this study, a CV-based eco-driving application, namely, Eco-Approach and Departure (EAD), is selected as an example. A microscopic safety analysis tool, Surrogate Safety Assessment Model (SSAM), is utilized to assess the safety influence of EAD application in multiple scenarios. Further analysis is performed from two perspectives: (1) application users, i.e., EAD-equipped vehicles versus unequipped vehicles; and (2) traffic operators, i.e., overall traffic performance with and without the introduction of EAD. For each perspective, conflict statistics (e.g., frequency, time-to-collision distribution), overall and by type, are analyzed. Results indicate EAD is beneficial in improving the safety performance of equipped vehicles. The influence of EAD on overall traffic is scenario dependent, and a high penetration rate shows positive effects on network-wide safety benefits for most scenarios.

Key words: Eco-Approach and Departure (EAD); Surrogate Safety Assessment Model (SSAM); safety analysis; conflict type; Time-To-Collision (TTC)

1 Introduction

Transportation activities contribute to a large amount of energy consumption and emissions. According to the U.S. Department of Energy, transportation sector was responsible for 27.6% of the total energy consumption of the country in 2014[1]. The U.S. Environmental Protection Agency (USEPA) claimed that about 27% of U.S. Green-House Gas (GHG) emissions in 2013 were generated from traffic activities[2]. China Vehicle Emission Control Annual Report 2015 estimated that vehicles contributed more than 45 million tons of pollutants (including more than 6 million NOx, around 0.6 million PM, 4 million HC, and 34 million CO) in China in 2014[3]. The above problems have aroused awareness to mitigate energy and environment pressure caused by transportation activities. Great efforts have been devoted to research of environment-friendly intelligent transportation systems. Various eco-driving strategies have demonstrated significant benefits in reducing vehicle fuel consumption and emissions. Eco-driving means smarter and fuel-efficient driving and represents a new driving culture that makes best use of advanced vehicle technologies while improving road safety. Basically speaking, strategies

• Weixia Li and Yi Zhang are with the Department of Automation, Tsinghua University, Beijing 100084, China. E-mail: wx-li11@mails.tsinghua.edu.cn; zhyi@mail.tsinghua.edu.cn.
• Guoyuan Wu and Matthew J. Barth are with Bourns College of Engineering–Center for Environmental Research and Technology (CE-CERT), University of California, Riverside, CA 92507, USA. E-mail: gywu@cert.ucr.edu; barth@ece.ucr.edu.
* To whom correspondence should be addressed.
Manuscript received: 2016-12-10; revised: 2017-02-26; accepted: 2016-03-07

deployed in typical eco-driving assistance systems can be divided into three categories[4]: (1) pre-trip advice, such as eco-friendly navigation[5]; (2) in-trip support, e.g., infrastructure-based or in-vehicle advanced driving assistance[6]; and (3) post-trip feedback. Most studies have proven the effectiveness of different strategies. For example, an eco-driving study in Europe showed 5% to 15% fuel economy improvement[7]; moreover, Eco-Approach and Departure (EAD), an on-board driving assistant tool designed and evaluated in both simulation and field test, shows approximately 12% fuel savings and 14% CO_2 emission reduction for a single vehicle[8,9]. For a hypothetical 11-signalized intersection corridor, the indirect network fuel savings vary from 1% to 8% depending on the penetration rate of EAD-equipped vehicles, traffic congestion level, and signal timing plans[10]. However, most previous studies focused on the environmental influence of the application, and only few works conducted mobility performance analysis. To our best knowledge, no study has evaluated the safety performance of such environment-focused applications.

Safety along with mobility and environmental sustainability represents the cornerstone for evaluating the performance of transportation systems. Given that the driving behavior may be affected by eco-driving applications, safety performance is very likely to be affected. Therefore, a holistic assessment approach should be applied to investigate the safety impact of eco-driving applications and their effect on mobility and the environment. Unlike mobility and environmental sustainability analysis, safety analysis usually involves information from at least two vehicles. In addition, the following issues in traditional safety analyses complicate the assessment of the safety performance of ITS strategies: (1) traditional safety analyses heavily depend on actual crash or accident data, thereby requiring long-term observation and collection; (2) for nascent technologies, which have not been well implemented in field, traditional safety analysis methods are unsuitable due to the lack of real world crash data. Therefore, methods using surrogate metrics from the microscopic view to estimate safety performance have gained increasing research interest. The Surrogate Safety Assessment Model (SSAM) has been proposed and become a prevalent tool in microscopic safety analysis. Some field validation studies demonstrate that surrogate safety estimates are effective in reflecting real world crash statistics[11,12].

In this study, EAD application is selected as an example to carry out comprehensive safety performance analysis and complement the dearth of safety analysis on eco-driving applications. Safety performance of EAD application of both individual vehicle and overall traffic was systematically analyzed. Various scenarios, differentiated by application penetration rates, traffic demands, and a novel parameter signal coordination state, were tested to comprehensively evaluate the safety impacts of the application. An innovative method was then proposed and implemented to evaluate application safety impacts from potential conflicts, both type-based and severity-based (in terms of time-to-collision). This research will not only present the safety impact of EAD application but also provide systematic methodology of safety assessment for other environment-focused intelligent transportation strategies. Findings from this paper, along with previous studies on mobility and environmental sustainability, will provide a holistic insight into the performance of EAD application.

The rest of the paper is outlined as follows. Section 2 describes the methodology of the entire study and introduces the EAD algorithm, safety analysis tool, and the research framework. Section 3 presents the simulation setup and research scenarios. Section 4 discusses the safety analysis results for EAD-equipped vehicles in comparison with unequipped vehicles and overall traffic from the perspectives of conflict type and Time-To-Collision (TTC) of the conflict. Section 5 summarizes major conclusions on the safety performance of the EAD application.

2 Methodology

2.1 EAD

EAD is a velocity trajectory planning application aiming at reducing energy consumption and emissions when vehicles approach and depart from signalized intersections[8−10]. By making use of connected vehicles technology, Signal Phase and Timing information (SPaT) is broadcasted to EAD-equipped vehicles within Dedicated Short-Range Communication (DSRC) through Infrastructure to Vehicle (I2V) communication. Based on current velocity, location, and SPaT information, velocity profile with mild acceleration/deceleration is calculated to make sure the vehicle passes through the intersection in the most environment-friendly way. The basic idea of the EAD application is to reduce unnecessary stop-and-go and idling maneuvers, which are believed to be great contributors to vehicle energy consumption and emissions.

To avoid sharp accelerations and decelerations, the family of piece-wise trigonometric functions is selected as

$$v=\begin{cases} v_h - v_d \cdot \cos(st), & t \in [0, \frac{\pi}{2s}); \\ v_h - v_d \cdot \frac{s}{a} \cdot \cos a(t-\frac{\pi}{2s}+\frac{\pi}{2a}), & t \in [\frac{\pi}{2s}, \frac{\pi}{2s}+\frac{\pi}{2a}); \\ v_h + v_d \cdot \frac{s}{a}, & t \in [\frac{\pi}{2s}+\frac{\pi}{2a}, \frac{d}{v_h}) \end{cases} \tag{1}$$

the velocity profile for equipped vehicles to accelerate or decelerate to the target velocities. The selected velocity profile is presented in Eq. (1), where v_h stands for the maximum target velocity of the vehicle when it passes through the intersection on green traffic light; v_d is the difference between current velocity and v_h; s and a are two control parameters to satisfy some endogenous constraints, such as maximum power, maximum acceleration, or jerk. The control logic of EAD reveals the calculation process for the target velocity interval and is depicted in Fig. 1 (please refer to Ref. [9] for more details).

2.2 SSAM

The SSAM is a software application designed to evaluate the safety performance of traffic facilities, roadway designs, and operational strategies[13]. In contrast to traditional safety analysis that is based on historical crash data, SSAM can assess safety without waiting for the actual crash(es) to occur. The model can also be used for safety analysis before the strategies are implemented in real world. Instead of using actual crash data, the concept of conflict is adopted to indicate the risk of collision. In SSAM, a conflict is defined as an observable situation where two or more road users approach each other in space and time to such an extent that a risk of collision exists if their movements remain unchanged. The model validation results demonstrate that conflict data obtained from SSAM are highly correlated with real world crash data, and the relationship between the two parameters could be described with Eq. (2)[13]. Therefore, conflicts can be used

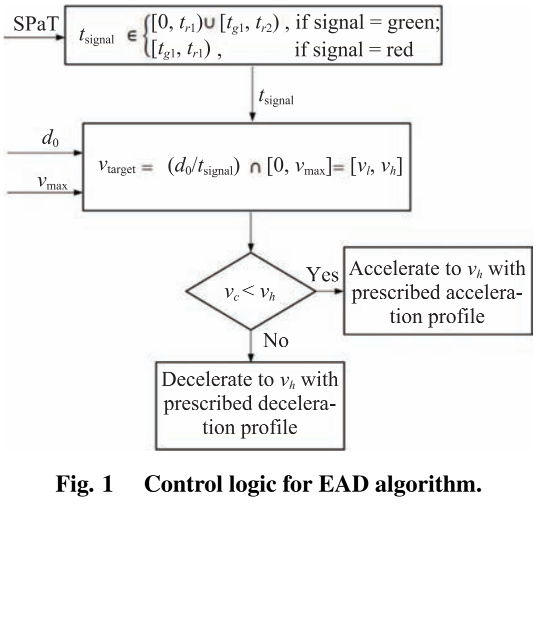


Fig. 1 Control logic for EAD algorithm.

to effectively analyze traffic safety performance.

$$\frac{\text{Crashes}}{\text{Year}} = 0.119 \times \left(\frac{\text{Conflicts}}{\text{Hour}}\right)^{1.419} \tag{2}$$

Another favorable feature of conducting safety analysis through SSAM is its compatibility with several microscopic traffic simulation software applications, including Paramics, VISSIM, TEXAS, and AMSUN. SSAM can output conflict information by processing .trj files, which are generated by these traffic simulation tools. Several surrogate safety measures between each vehicle pair are calculated in SSAM to identify potential conflicts, and two of these measures are key parameters used in conflict recognition, i.e., (1) minimum TTC, which is the minimum time to collision value estimated based on the current location, speed, and future trajectory of two vehicles at a given instant; (2) Post-Encroachment Time (PET), which is the time interval between when the first vehicle last occupied a position and the time when the second vehicle subsequently arrived at the same position. TTC and PET are calculated using Eqs. (3) and (4)[14], where $X_{i-1,t}$ and $X_{i,t}$ stand for the positions of the preceding and following vehicle, respectively; $L_{i-1,t}$ denotes the length of the preceding vehicle; $V_{i,t}$ and $V_{i-1,t}$ represent the velocities of the following and preceding vehicle; $D_{i,t}$ is the distance between the projected collision point and vehicle i; and t_1 and t_2 are the times when two vehicles last appear at the specified location. Default values of 1.5 and 5 seconds are utilized with respect to TTC and PET in SSAM; these values are selected based on the agreement in the safety community stating that conflicts with TTC values larger than the above threshold are not severe enough in traditional conflict study.

$$\text{TTC}_{i,t} = \begin{cases} \frac{(X_{i-1,t}-X_{i,t})-L_{i-1,t}}{V_{i,t}-V_{i-1,t}}, & \text{for vehicles} \\ & \text{travel in same direction;} \\ \frac{D_{i,t}}{V_{i,t}}, & \text{for vehicles} \\ & \text{travel in different direction} \end{cases} \tag{3}$$

$$\text{PET} = t_2 - t_1 \tag{4}$$

Although all vehicle pairs with TTC values less than the preset threshold are identified as conflicts, they may be differentiated in terms of conflict type and conflict severity. In SSAM, all conflicts are classified into three different types based on the conflict angle, i.e., crossing conflict (larger than 85), lane change conflict (30 to 85), and rear end conflict (smaller than 30). In addition, the severity of a conflict may vary when the TTC value falls into different sub-intervals between 0 and 1.5 s. Typically, three different intervals, i.e., [0, 0.5), [0.5, 1), and [1, 1.5), are utilized in SSAM to address the conflict severity levels. The interval with smaller upper and lower bounds corresponds to higher conflict severity (in the sense of time to collision). Conflict analysis in terms of conflict type and TTC interval is recommended for comprehensive safety performance evaluation.

2.3 Research approach

Several software tools are utilized for safety analysis of the EAD application. Safety evaluation is conducted through the previously introduced SSAM, and the EAD algorithm is implemented with microscopic traffic simulation software Paramics and MOtor Vehicle Emission Simulator (MOVES). Data are analyzed through MATLAB. The diagram of the interactions among the above-mentioned software tools is illustrated in Fig. 2. In EAD algorithm implementation, two APIs are developed for environment-friendly speed trajectory planning and energy/emission calculating. The first API interacts with Paramics in real time to obtain vehicle position, speed, signal information, and traffic condition and calculates the recommended speed in the next time step for Paramics. The second API takes the energy consumption/emissions rates in MOVES, which is a state-of-the-art emission simulator developed by the U.S. Environmental Protection Agency (EPA), as inputs and calculates real time energy consumption/emission rates according to vehicle type and speed trajectory information from Paramics. The .trj file is generated as the input for SSAM when each simulation run is completed. Finally, conflict files including conflict vehicles, TTC value, and conflict type information are exported from SSAM for safety analysis in MATLAB. This research takes EAD as an example to evaluate safety performance, but the methodology is also suitable for other environment-focused applications. The framework (Fig. 2) can be applied to other similar applications by simply replacing the EAD algorithm, MOVES energy consumption/emission rate, EAD API, and API for energy/emission calculation with corresponding modules for the target applications.

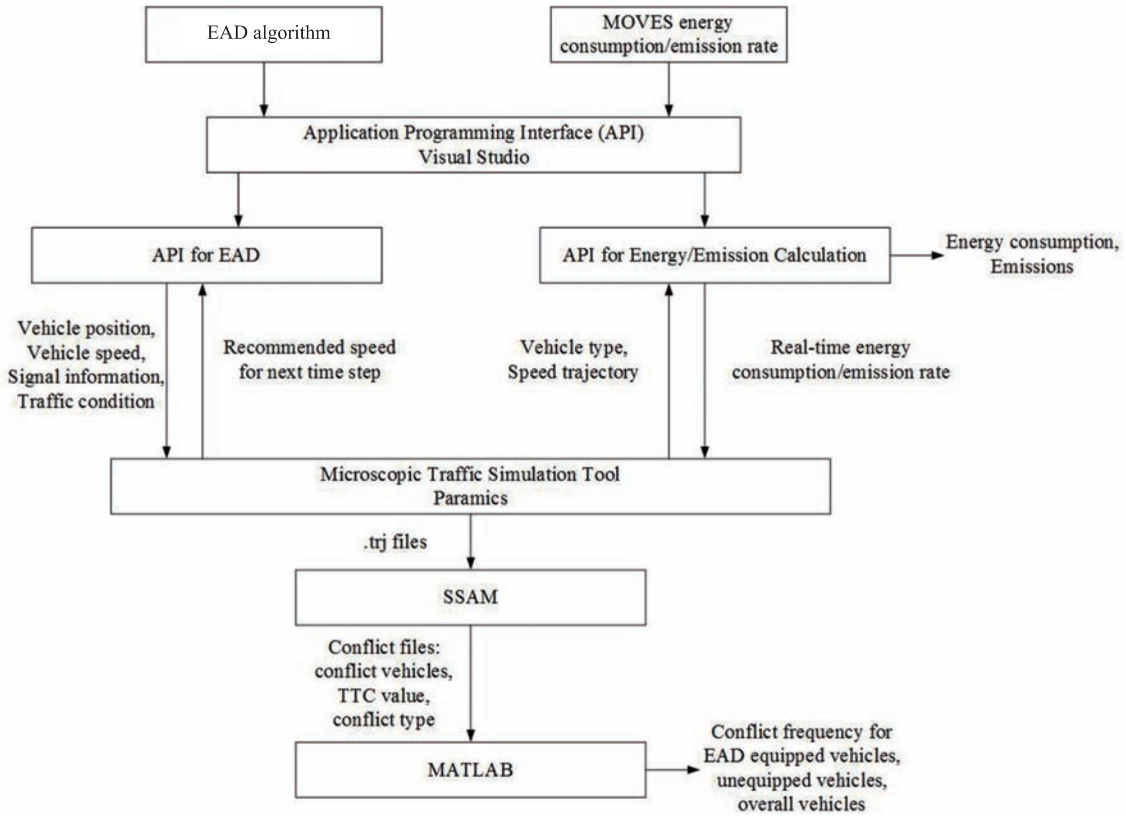


Fig. 2 Research approach for EAD safety evaluation.

3 Simulation Setup

3.1 Road network

In this study, a real world road network with three intersections is coded in Paramics. The road network is a segment of El Camino Real in Northern California (referred to as ECR-3), a major north-south arterial connecting San Francisco and San Jose, as illustrated in Fig. 3a. In this road network, each direction has three lanes, and the speed limit is 40 mph. The spacing between intersections varies from 200 m to 500 m. The detailed map of ECR-3 and its screenshot in Paramics are presented in Figs. 3b and 3c. The vehicle demands and their OD patterns have been calibrated according to traffic data collected in typical weekday mornings between 7:15 a.m. and 9:00 a.m. in the summer of 2005 to well reflect the influence of EAD on real world traffic condition[15]. The calibrated traffic is composed of 98.8% regular cars and 1.2% buses.

3.2 Scenarios

Various scenarios have been studied to evaluate the effects of EAD under different traffic situations. The parameters used to differentiate the scenarios include congestion level, signal coordination state, and penetration rates of EAD-equipped vehicles. Congestion level is quantified by the Volume-to-Capacity (V/C) ratio. Three V/C values of 0.38, 0.77, and 1.00 are selected to represent low, medium, and high demands, with which traffic states change from free flow to congestion. The total numbers of simulated vehicles are approximately 1500, 3000, and 4000 for the above-mentioned V/C values. For signal coordination state, two signal configuration strategies are compared, i.e., uncoordinated and coordinated signals. The uncoordinated signal is set according to the parameters of the actual traffic signal system in the road network in July 2005. The green bands of the original signals in the three intersections for the northbound and southbound are depicted in Figs. 4a and 4b. The original signals are not completely coordinated, and the green band is relatively narrow. Retiming is carried out to enlarge the green band by adjusting the signal offsets only (cycle length and phase duration remain the same) to enable most vehicles to pass through the intersections along the corridor without experiencing too many interruptions from the signals. The coordinated signals in both directions are presented in Figs. 4c and 4d.

In addition to different congestion levels and signal configuration strategies, several market penetration rates (0%, 20%, 50%, 80%, and 100%) of EAD-equipped vehicles (the ratio of equipped vehicles to overall traffic) are compared. All scenarios to be studied are summarized in Table 1.

3.3 Number of simulation runs

Multiple runs are required to acquire statistically

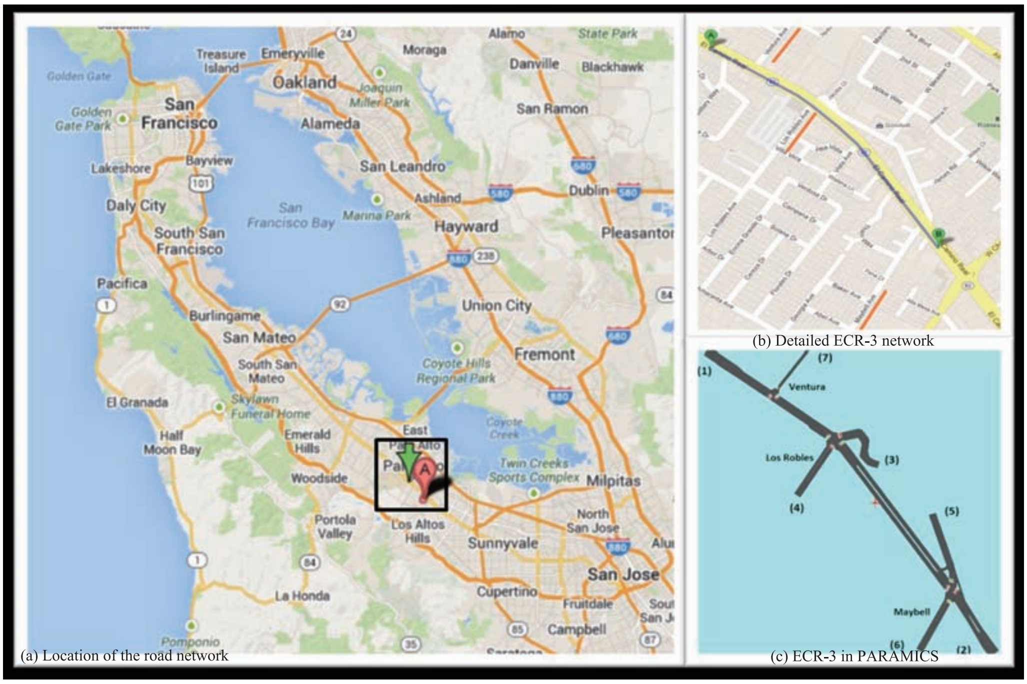
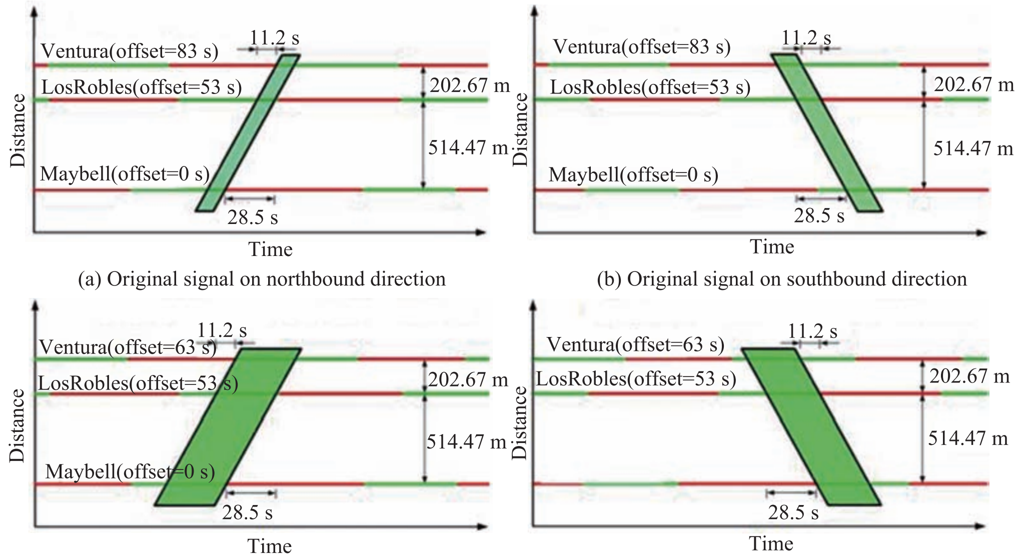


Fig. 3 ECR-3 road network in Google map and Paramics.



(c) Coordinated signal on northbound direction (d) Coordinated signal on southbound direction

Fig. 4 Green bands of uncoordinated and coordinated signals (Cycle Length=130 s, Speed Limit=18.06 m/s).

Table 1 Research scenarios for EAD safety analysis.

Scenario index	Signal coordination	V/C	Penetration rate (%)
1	Uncoordinated	1	0, 20, 50, 80, 100
2	Uncoordinated	0.77	0, 20, 50, 80, 100
3	Uncoordinated	0.38	0, 20, 50, 80, 100
4	Coordinated	1	0, 20, 50, 80, 100
5	Coordinated	0.77	0, 20, 50, 80, 100
6	Coordinated	0.38	0, 20, 50, 80, 100

significant results because of the stochastic features of microscopic traffic simulation software. The number of runs is determined by Eq. (5), where μ and δ stand for the mean and standard deviation of energy consumption based on the completed simulations; ε is the allowable error specified as a fraction of μ; $t_{\alpha/2}$ denotes the critical value of t-distribution at the significance level α; and N is the required number of simulation runs. In this simulation, the significance level is set as 0.05, and ε is set as 2%. For each run, a different seed is selected as the starting number for the random number generator, which ensures the simulation randomness in Paramics. The simulation will be completed when the calculated N is no more than the number of completed runs. Results show that nine runs should be performed for each scenario under each penetration rate level (Table 1). Therefore, the total number of simulation runs for the whole research is $9 \times 6 \times 5 = 270$.

$$N = \left(t_{\alpha/2} \cdot \frac{\delta}{\mu\varepsilon} \right)^2 \tag{5}$$

4 Simulation Results

Safety analysis is conducted from two perspectives, i.e., (1) user's perspective, where the safety performance of EAD-equipped vehicles is compared with that of unequipped ones; (2) operator's perspective, where the safety of overall traffic is analyzed. For both perspectives, analysis is carried out in terms of conflict type and TTC interval. The safety performance of the baseline (i.e., penetration rate of EAD-equipped vehicles is 0%) in all scenarios are analyzed first for comparison. Safety comparisons are then conducted in three aspects, i.e., general safety performance (in terms of conflict frequency), type-based safety performance (conflicts differentiated by type), and severity-based safety performance (conflicts differentiated by time-to-collision). For each aspect, the comparison is carried out from two perspectives, i.e., application users (EAD-equipped vehicles versus unequipped vehicles) and traffic operators (overall traffic in EAD-equipped scenarios versus baseline scenarios).

4.1 Safety analysis for baselines

For baselines in all six scenarios, the conflict frequency per vehicle calculated according to conflict information exported from SSAM is depicted in Fig. 5. The figure shows an obvious upward trend of conflict frequency when the traffic demand increases for both uncoordinated and coordinated scenarios. For scenarios with uncoordinated signals, the conflict frequency increases by 59% and 100%, respectively, for medium and high traffic demand

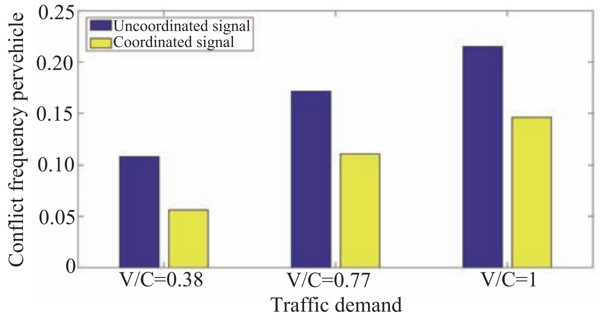


Fig. 5 Conflict frequency statistics in the baseline scenarios.

compared with the low demand. The corresponding increases are approximately 96% and 160%, respectively, for scenarios with coordinated signals. In addition, scenarios with coordinated signals exhibit better safety performance than those with uncoordinated signals. The conflict frequency reductions are up to 47.7%, 35.7%, and 32.1% corresponding to low, medium, and high traffic demands. These results demonstrate that coordinated signals are beneficial in improving traffic safety and are sensitive to changes in network parameters, such as traffic demand.

4.2 General safety analysis for eco-approach and departure application

As aforementioned in the definition of conflict, two vehicles are involved in each conflict and can be identified by two parameters, namely, FirstVID and SecondVID. FirstVID (SecondVID) is defined as the vehicle identification number of the first (second) vehicle. Definitions for these two vehicles have pointed out that the first vehicle is the one that arrives at the conflict point first, and the second vehicle subsequently arrives at the same location. In this case, the second vehicle should be responsible for the conflict for most of the time. The vehicles in the study are classified into two types, i.e., EAD-equipped and unequipped vehicles, and the conflicts are accordingly sorted as equipped and unequipped based on the type of the second vehicle. When the second vehicle in the conflict is an EAD-equipped vehicle, the conflict will be defined as an equipped conflict; otherwise, it is an unequipped conflict. In this part, general safety analyses for equipped versus unequipped vehicles and overall traffic are conducted without differentiating conflict type or TTC interval. The detailed results are presented as follows.

4.2.1 General safety comparison for EAD equipped versus unequipped vehicles

According to conflict information exported from SSAM and the equipped vehicle information from Paramics, comparative results of conflict frequency (normalized by vehicle number, conflict count per vehicle) for equipped and unequipped vehicles in six scenarios are illustrated in Fig. 6. The conflict frequencies for both equipped and unequipped vehicles increase with increasing traffic demand. Similar to the baseline scenarios, the numbers of equipped and equipped and unequipped conflicts in uncoordinated scenarios are higher than those in coordinated scenarios. In the sense of individual vehicle safety, EAD-equipped vehicles exhibit better safety performance, i.e., lower conflict frequencies, compared with unequipped vehicles in all six scenarios for all penetration rates.

Figure 7 presents the reductions of the average conflict frequency per vehicle for equipped and unequipped vehicles. For both uncoordinated and coordinated signals,

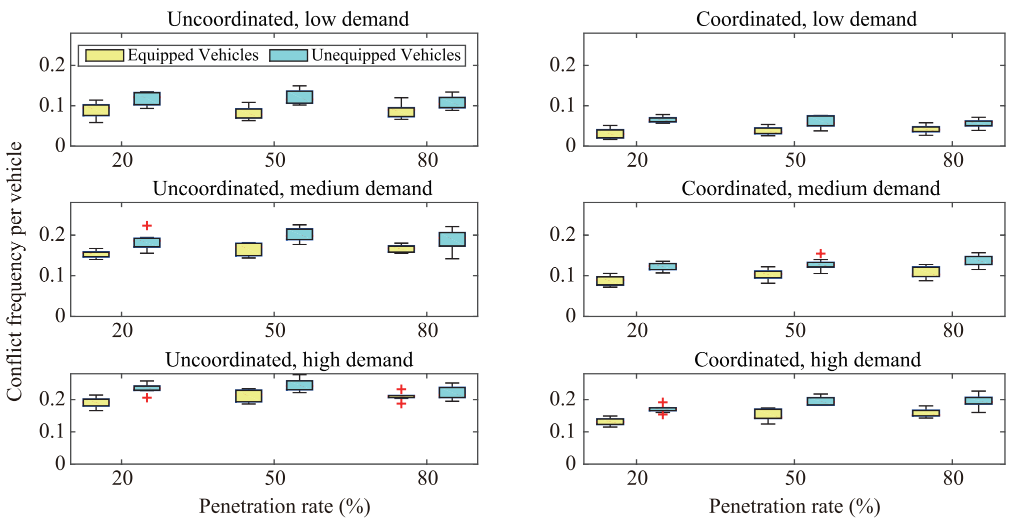


Fig. 6 Distributions of conflict frequency for equipped vs. unequipped vehicles.

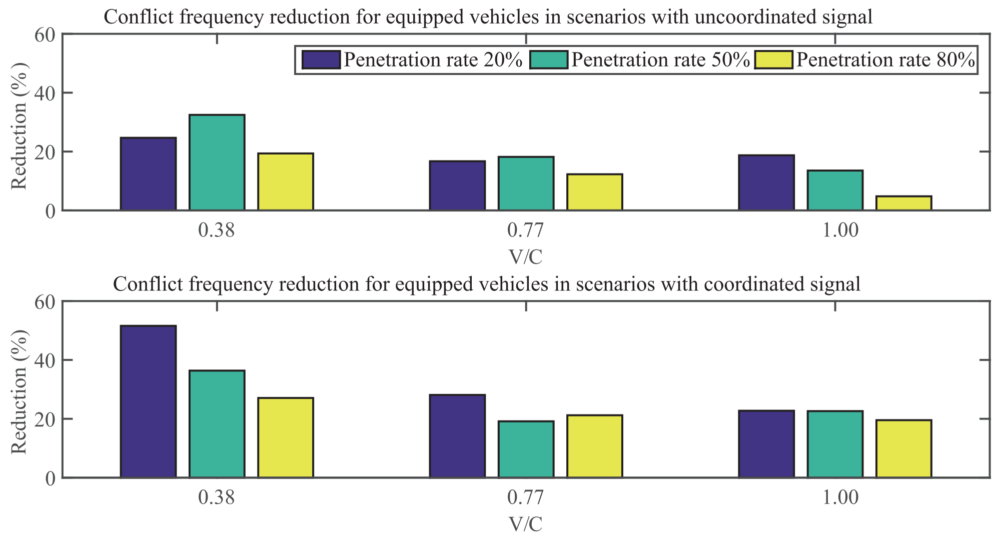


Fig. 7 Reductions of average conflict frequency for equipped vehicles.

EAD demonstrates the most benefit when the traffic demand is low, and the conflict frequency can be reduced by as much as 32% and 51%, respectively. In addition, equipped vehicles have much less conflicts than unequipped vehicles in scenarios with coordinated signals. With respect to penetration rate, medium penetration rate (50%) presents more safety benefits for equipped vehicles in most scenarios with uncoordinated signals (except for the high traffic demand scenario); meanwhile, low penetration rate (20%) proves to be more beneficial for equipped vehicles in all coordinated signals. Although the safety benefits for equipped vehicles are scenario dependent, EAD is beneficial in reducing vehicle conflict frequency for equipped vehicles compared with that for unequipped ones.

4.2.2 General safety comparison for overall traffic

The distributions of conflict frequency in six scenarios with different penetration rates are illustrated in Fig. 8. The overall traffic conflict increases in all scenarios when the penetration rate is lower (20%) than the corresponding baselines (PR = 0%) in terms of median conflict frequency. This finding indicates that a low penetration rate is not favorable for the safety of overall traffic. One possible reason might be that a small portion of equipped vehicles will work as disturbance to the overall traffic, and the induced driving behavior may cause chaos for other unequipped vehicles. When the penetration rate increases from 0% to 100%, the conflict frequency increases at first and then decreases for almost all scenarios (except for the scenario with coordinated signal and high traffic demand). A high penetration rate is required for conflict frequency to start decreasing when the traffic demand increases. High conflict frequencies are observed in the uncoordinated scenarios compared with the coordinated ones, consistent

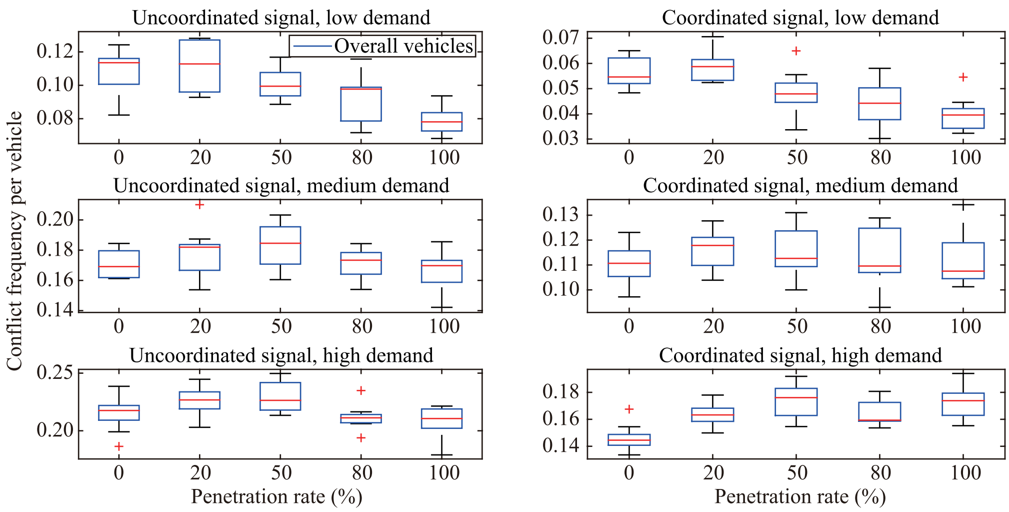


Fig. 8 Distributions of conflict frequency for overall traffic.

with the safety performances of the baselines. Hence, coordinated signals with a large green band are beneficial in reducing conflict frequency for both individual vehicle and overall traffic.

The increases in the average conflict frequency for overall traffic in EAD-equipped scenarios compared with the corresponding baselines are presented in Fig. 9. EAD is propitious to overall traffic safety (with negative conflict frequency increase) when the traffic demand is low (V/C=0.38) and penetration rate is relatively high (larger than 20%). Conflict frequency reductions can be up to 27% and 29%, respectively, for uncoordinated and coordinated scenarios. However, when the traffic demand increases to medium or high level, EAD shows negative influence on overall traffic safety for coordinated scenarios; for uncoordinated scenarios, only minor benefits are witnessed when the penetration rate is high (80% and 100%). The possible reason is that vehicle spacing decreases in high traffic demand level, and only high penetration rate can make equipped vehicles the majority of overall traffic. Under this circumstance, traffic flow will be better regulated and less variable when the minority unequipped vehicles follow the driving behavior of the equipped vehicles. Nevertheless, the impact of EAD on overall traffic safety for coordinated scenarios is still negative even if the penetration rate is 100%. One hypothesis is that the so-called coordination may depend on driving behavior. In other words, the calibrated corridor is coordinated in favor of unequipped vehicles but not necessarily for equipped vehicles. Some compound effects (interaction between vehicles) may possibly occur as the traffic demand increases. Therefore, positive safety impacts on overall traffic can be expected when the penetration rate of EAD-equipped vehicles is high. For overall traffic safety, EAD does not exhibit satisfactory results for coordinated scenarios, except when the traffic demand is low (in the sense of average conflict frequency).

4.3 Conflict type based safety analysis for eco-approach and departure application

As introduced in Section 2, conflicts can be classified into three types according to conflict angle. In this study, the typical distribution patterns of conflict frequency by type for equipped vehicles, unequipped vehicles, and overall traffic are depicted in Fig. 10 (taking the scenario with uncoordinated signals and medium traffic demand as an example). For both equipped versus unequipped (Fig. 10a) and overall conflicts (Fig. 10b), the crossing conflict (conflict angle $> 85°$) takes up the minimum portion, and the rear end conflict (conflict angle $< 30°$) contributes to the majority. The safety impacts of EAD on equipped vehicles and overall traffic in terms of conflict types are assessed in the following parts.

4.3.1 Conflict type based safety comparison for EAD equipped versus unequipped vehicles

Previous analysis indicates that EAD-equipped vehicles have smaller conflict frequencies than unequipped ones. Further details on the conflict frequency reductions by types are presented in Fig. 11. The results reveal the great benefits in reducing crossing and lane change conflicts for equipped vehicles. For crossing conflicts, frequency reductions for equipped vehicles compared with unequipped vehicles vary from 57% to 82% depending on penetration rates and traffic demands for scenarios with uncoordinated signals; meanwhile, the corresponding

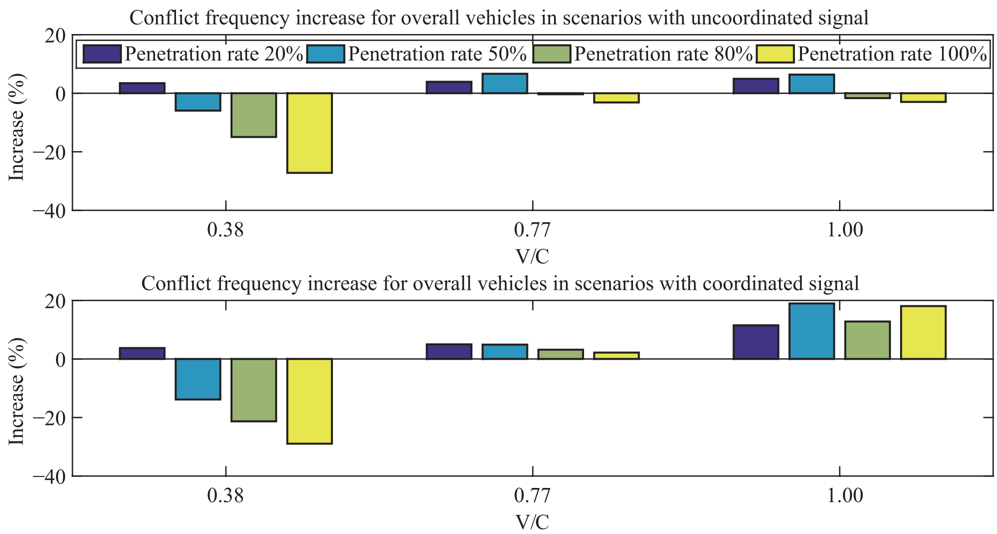


Fig. 9 Reductions of average conflict frequency for overall vehicles.

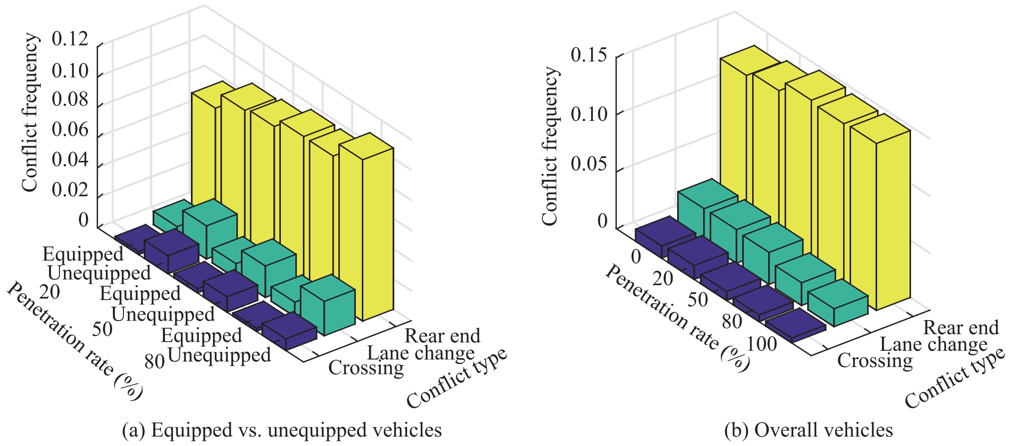


Fig. 10 Conflict type distributions for equipped vehicles, unequipped vehicles, and overall traffic (scenario with uncoordinated signals and medium traffic demand).

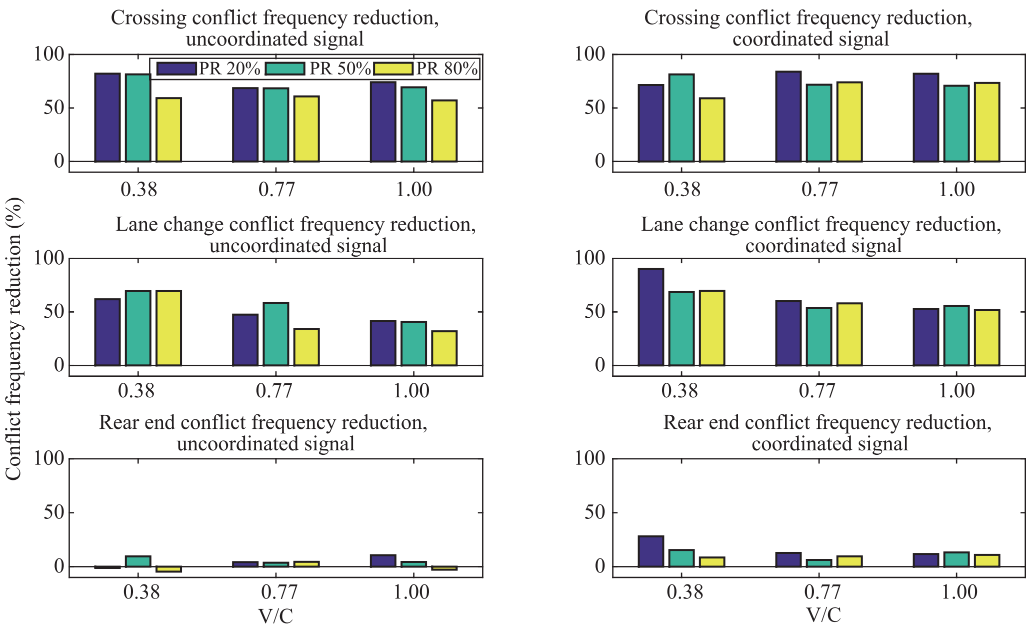


Fig. 11 Reductions of conflict frequency for equipped vehicles in terms of conflict type.

range for coordinated scenarios is 59% to 84%. For lane change conflicts, the conflict frequencies of equipped vehicles are 32% to 69% (for uncoordinated scenarios), which is 52% to 90% (for coordinated scenarios) lower than those of unequipped vehicles. Although EAD has shown extreme superiority in reducing crossing and lane change conflicts, few advantages are witnessed for rear end conflicts. On the contrary, minor disadvantages might be observed in few circumstances. Specifically, the rear end conflict frequency reductions for equipped vehicles range from 4% to 11% for uncoordinated scenarios and from 6% to 28% for coordinated scenarios. Minor increases of approximately 1%, 5%, and 3% are obtained when the penetration rates are 20%, 80% in light traffic level, and 80% in heavy traffic level for uncoordinated scenarios. Therefore, EAD is beneficial in reducing conflict frequencies (especially for crossing and lane change conflicts) of individual vehicles. Although some negative effects may be observed for uncoordinated scenarios, the increases in the conflict frequency are significant less compared with those in crossing and lane change conflicts.

4.3.2 Conflict type based safety comparison for overall traffic

For the overall traffic, the reductions of conflict frequency by type (compared with baselines) are shown in Fig. 12. Similar to the reductions for equipped vehicles, almost all EAD-equipped scenarios show less crossing and lane change conflicts. The general patterns of conflict frequency reductions for crossing and lane change conflicts can be summarized as: (1) conflict frequency reductions decrease when the traffic demand increases; and (2) high penetration rates will result in more reductions in conflict frequency. However, EAD has shown negative influence on reducing rear end conflicts for almost all scenarios. According to subfigures in the bottom of Fig. 12, EAD may increase the rear end conflict frequencies of overall vehicles by 4% to 12% and by 4% to 39% for uncoordinated and coordinated scenarios, respectively. Considering its mechanism, the possible reasons for EAD to be unfavorable to overall traffic safety can be summarized as follows. When equipped vehicles are recommended to accelerate to pass through the intersection on green phase, equipped vehicles may become more aggressive, resulting in less spacing between the EAD-equipped vehicle and the preceding vehicle; this phenomenon might contribute to rear end conflicts caused by the EAD-equipped vehicles. When equipped vehicles are recommended to decelerate to avoid hard break or long time idling at the intersection, the following unequipped vehicle might not be able to decelerate in time, leading to more rear end conflicts caused by the unequipped vehicle. In addition, given that rear end conflicts contribute to the majority of the total conflicts (depicted in Fig. 10), EAD shows negative influence on overall traffic safety in most scenarios despite of its positive effects on reducing crossing and lane changing conflicts.

4.4 TTC interval based safety analysis for eco-approach and departure application

TTC interval is highly related to conflict severity level, and conflicts with smaller TTCs are more likely to result in severer crashes. In this part, three TTC intervals, i.e., TTC1, TTC2, and TTC3, corresponding to TTC value within [0, 0.5), [0.5, 1), and [1, 1.5) are utilized to differentiate the severity levels for equipped, unequipped, and overall conflicts. The distributions of TTC intervals for equipped versus unequipped vehicles and the overall traffic under different scenarios are similar, as illustrated in Fig. 13 (taking the scenario with uncoordinated signal and medium traffic demand as an example). The figure exposits that conflicts with TTC1 account for the majority of total conflicts, whereas those with TTC2 contribute the minimum portion. Further conflict frequency comparisons for equipped versus unequipped vehicles and the overall traffic are presented in the following section.

4.4.1 TTC interval based safety comparison for EAD equipped versus unequipped vehicles

With regard to EAD-equipped and unequipped vehicles, the conflict frequency reductions for equipped vehicles in different scenarios are presented in Fig. 14. The conflict frequency reductions for equipped vehicles are quite significant for the most sever TTC level. Nevertheless, the reductions are less conspicuous for TTC2 and TTC3. Equipped vehicles even show higher conflict frequencies within TTC2 and TTC3 than unequipped vehicles in some

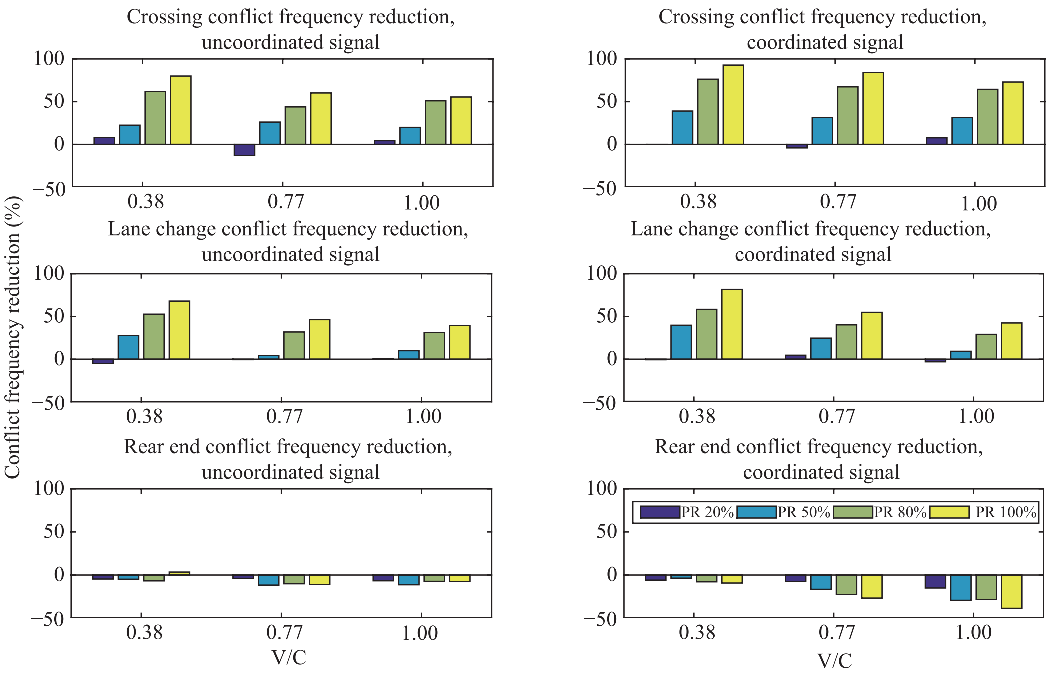


Fig. 12 Reductions of conflict frequency for overall traffic in terms of conflict type.

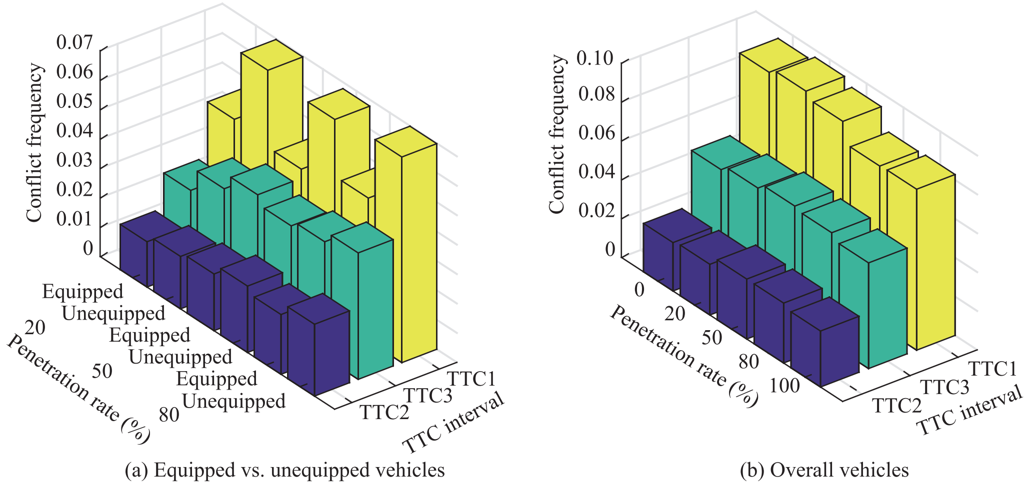


Fig. 13 TTC interval distributions for equipped vehicles, unequipped vehicles, and overall traffic (scenario with uncoordinated signals and medium traffic demand).

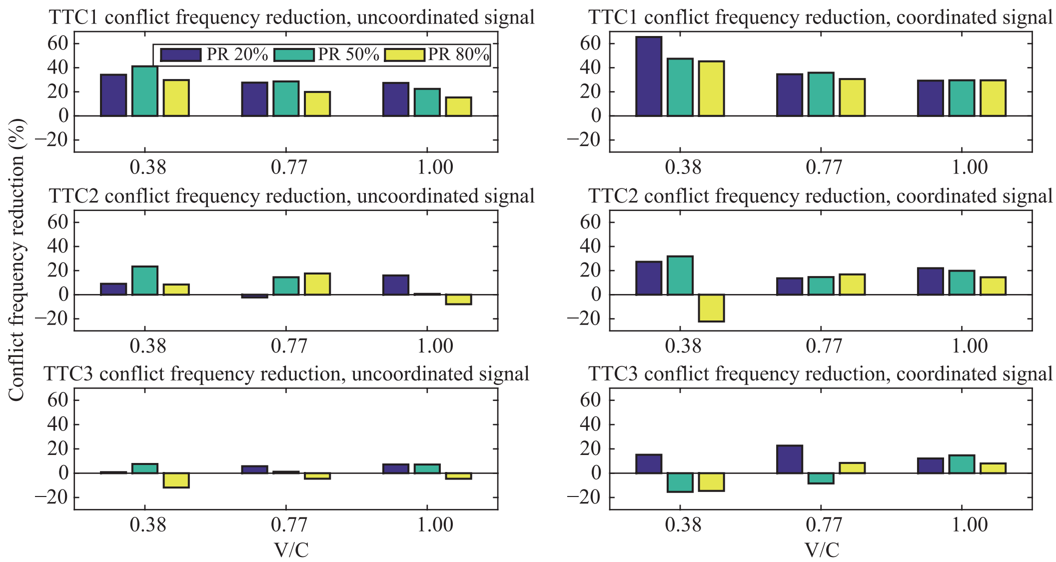


Fig. 14 Reductions of conflict frequency for equipped vehicles in terms of TTC intervals.

cases. Based on this finding and the analysis result that equipped vehicles may show high rear end conflict frequency, increased conflicts mainly correspond to low severity level (i.e., larger TTC interval). Notably, the same TTC thresholds for conflict identification are utilized for equipped and unequipped vehicles in this study. However, EAD-equipped vehicles are capable of obtaining speed information of the preceding vehicles due to the introduction of connected vehicle technology, which may pose the same safety level as unequipped vehicles under shorter TTC. This feature may further stand out the safety effects of EAD for equipped vehicles.

4.4.2 TTC interval based safety comparison for overall traffic

With regard to the safety performance of the overall traffic in terms of TTC intervals, the increases in conflict frequency in EAD applied scenarios compared with the corresponding baselines are shown in Fig. 15. EAD shows positive effects on reducing conflicts with the most sever TTC interval (i.e., negative increases in conflict frequencies with TTC1) except for the low penetration rate (20%) scenarios. In addition, for both uncoordinated and coordinated scenarios, higher penetration rates result in more reductions of conflict frequency with TTC1. However, EAD does increase conflict frequencies when the TTC interval is [0.5, 1) or [1, 1.5). Moreover, the increase is extremely significant especially for coordinated scenarios, where it reaches 47%. For uncoordinated scenarios, TTC2 conflict frequency increases vary from−1% to 25%, and TTC3 conflict frequency may increase by −30% to 11%. Interestingly, EAD is beneficial in reducing conflict

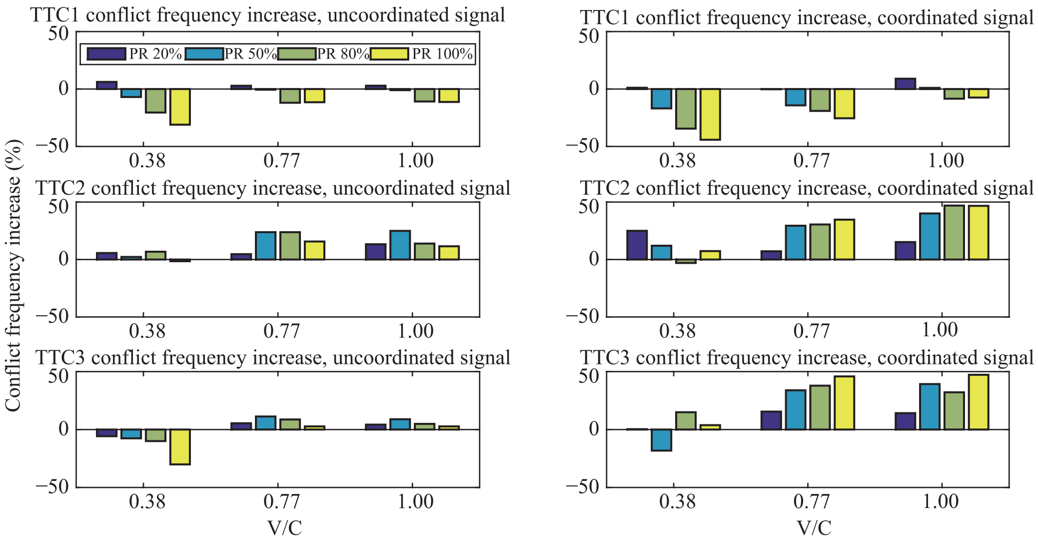


Fig. 15 Increases of conflict frequency for overall traffic in terms of TTC intervals.

frequencies when the TTC interval is [1, 1.5) under light traffic and uncoordinated conditions. Generally, EAD is advantageous to reduce conflicts with small TTC values while disadvantageous for conflicts within higher TTC intervals. For signal coordination, scenarios with coordinated signals might not be suitable for EAD because of negative influences on overall traffic safety for most scenarios. A high traffic demand is more likely to result in high conflict frequencies (or less conflict frequency reduction), which implies that EAD may show outstanding effects under light traffic situation. A high penetration rate is recommended to obtain more conflict reduction for uncoordinated scenarios.

5 Conclusion

This study proposes and implements a method for evaluating the safety performance of environmental sustainability-focused applications to address the research gap in the relevant field. The SSAM is adopted with microscopic simulation software (such as Paramics, VISSIM, etc.) to estimate potential conflicts of each individual vehicle. In addition, a generic safety evaluation scheme including three aspects, i.e., general safety comparison, type-based conflict comparison, and severity-based comparison, is developed from the perspectives of both application users and traffic operators. With the aforementioned methodology, the safety performance of eco-approach and departure application on equipped vehicles, unequipped vehicles, and overall traffic is carefully evaluated under various scenarios. The general safety performance, conflict type-based safety performance, and conflict TTC-based safety performance are compared between EAD-equipped vehicles versus unequipped vehicles (from drivers perspective) and the overall traffic versus the baseline with the penetration rate of 0% (from operators perspective).

For the comparison of equipped versus unequipped vehicles, the major findings include:

- EAD-equipped vehicles exhibit lower conflict frequencies than unequipped vehicles in all scenarios (with different traffic demands, signal coordination states, and EAD penetration rates). Equipped vehicles obtain great safety benefits from the EAD application, and the benefit is significant when the traffic demand is low.
- In terms of conflict type, EAD shows great advantages in reducing crossing and lane change conflicts, whereas minor disadvantages are obtained under rare circumstances in uncoordinated scenarios for reduction of rear end conflicts.
- With regard to TTC interval, EAD can reduce conflicts with small TTC values, although sometimes the conflict frequencies for large TTC values may increase slightly.

Notably, the same TTC thresholds are utilized in this study to identify potential conflicts for equipped and unequipped vehicles. The threshold for equipped vehicles might be further reduced due to the introduction of connected vehicle technology when they obtain the speed of preceding vehicles, thereby requiring less reaction time to decelerate. This finding may highlight the safety benefits for equipped vehicles because some conflicts within TTC3 (or TTC2) may be excluded for equipped vehicles.

For the comparison of the overall traffic in EAD applied scenarios versus baselines, the main conclusions can be summarized as follows:

• Safety benefits for the overall traffic can be barely observed except when the traffic demand is low (in the sense of conflict). Hence, EAD is not beneficial in improving overall traffic safety, especially when traffic signals are coordinated (which is might due to imperfect coordination resulted from the redefined driving behavior). Given that equipped vehicles usually show better safety performance than unequipped ones, the latter should be responsible for the safety degradation of the overall traffic.

• Further analyses on conflict type show that the crossing and lane change conflicts of the overall traffic for EAD applied scenarios are significantly less than those for the corresponding baselines. The increase in the overall conflicts is mainly contributed by rear end conflicts.

• EAD is proved to be favorable in reducing conflicts with smaller TTC values.

Although EAD may show negative effects on the overall traffic safety (especially for scenarios with coordinated signals), it can play a positive part in reducing crossing and lane change conflicts and conflicts with small TTC values, which may cause severe crashes. For uncoordinated scenarios (in which the traffic signal configurations are consistent with the real world), a high penetration rate (80% or more) may also provide benefits for the overall traffic. The findings from this study are expected to provide a holistic insight into the effectiveness of CAV (connected autonomous vehicles) applications for policy makers and/or traffic operators, which is critical for any decision making in real world deployment.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China (No. 616732333) and Beijing Municipal Science and Technology Program (No. D15110900280000).

References

[1] U.S. Department of Energy, Energy information administration, monthly energy review, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf, 2017.

[2] U.S. Environmental Protection Agency (USEPA), Inventory of U.S. greenhouse gas emissions and sinks: 1990-2013, https://www.epa.gov/sites/production/files/2015-09/documents/overview.pdf, 2015.

[3] Ministration of Environmental Protection of the Peoples Republic of China, China vehicle emission annual report, http://wfs.mep.gov.cn/dq/jdc/zh/201601/-P020160115523794855203.pdf, 2015.

[4] T. Hof, L. Conde, E. Garcia, A. Iviglia, S. Jamson, A. Jopson, F. Lai, N. Merat, J. Nyberg, and S. Rios, A state of the art review and user's expectations, Comission eco-Driver Project, 2012.

[5] K. Boriboonsomsin, M. J. Barth, W. H. Zhu, and A Vu, Eco-routing navigation system based on multisource historical and real-time traffic information, *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1694–1704, 2012.

[6] G. Y. Wu, K. Boriboonsomsin, W. B. Zhang, M. Li, and M. Barth, Energy and emission benefit comparison of stationary and in-vehicle advanced driving alert systems, *Transp. Res. Rec.: J. Transp. Res. Board*, vol. 2189, no. 1, pp. 98–106, 2010.

[7] T. Onoda, IEA policies-G8 recommendations and an afterwards, *Energy Policy*, vol. 37, no. 10, pp. 3823–3831, 2009.

[8] M. Barth, S. Mandava, K. Boriboonsomsin, and H. T. Xia, Dynamic ECO-driving for arterial corridors, in *Proc. 2011 IEEE Forum on Integrated and Sustainable Transportation Systems*, Vienna, Austria, 2011, pp. 182–188.

[9] H. T. Xia, K. Boriboonsomsin, F. Schweizer, A. Winckler, K. Zhou, W. B. Zhang, and M. Barth, Field operational testing of eco-approach technology at a fixed-time signalized intersection, in *Proc. 15th Int. IEEE Conf. Intelligent Transportation Systems*, Anchorage, AK, USA, 2012, pp. 188–193.

[10] H. T. Xia, K. Boriboonsomsin, and M. Barth, Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits, *J. Intell. Transp. Systems*, vol. 17, no. 1, pp. 31–41, 2013.

[11] C. Caliendo and M. Guida, Microsimulation approach for predicting crashes at unsignalized intersections using traffic conflicts, *J. Transp. Eng.*, vol. 138, no. 12, pp. 1453–1467, 2012.

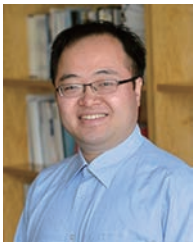
[12] F. Huang, P. Liu, H. Yu, and W. Wang, Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections, *Accid. Anal. Prev.*, vol. 50, pp. 1014–1024, 2013.

[13] Federal Highway Administration, Surrogate safety assessment model and validation: Final report, Publication No. FHWA-HRT-08-051, 2008.

[14] F. Cunto, Assessing safety performance of transportation systems using microscopic simulation, PhD dissertation, University of Waterloo, Waterloo, Canada, 2008.

[15] Y. F. Yin, H. X. Liu, J. A. Laval, X. Y. Lu, M. Li, J. Pilachowski, and W. B. Zhang, Development of an integrated microscopic traffic simulation and signal timing optimization tool, PATH Research Report UCB-ITS-PRR-2007-2, University of California, Berkeley, CA, USA, 2007.

Weixia Li received the BS degree in 2011 from Beijing Jiaotong University, China, and earned the PhD degree from Tsinghua University, China, in 2017. From 2015 to 2016, she conducted her research at the University of California, Riverside as a visiting research student. Dr. Li is now working as a Postdoctoral Researcher with Department of Automation in Tsinghua University. Her major research interests include intelligent transportation systems, mesoscopic energy/emissions modeling, eco-routing, eco-driving, and intelligent vehicle-infrastructure cooperative systems.



Guoyuan Wu received the BS degree in 2001 from Zhejiang University, China, and completed the MS degree in Tsinghua University, China, in 2004. Then, he earned Ph D degree from the University of California, Berkeley, USA, in 2010. Dr. Wu had been employed as a graduate student researcher at the California Partners for Advanced Transportation Technology (PATH) for over five years. Dr. Wu joined the Transportation Systems Research (TSR) group at CE-CERT as a Postdoctoral Researcher and now currently is an assistant research faculty of CE-CERT, and assistant adjunct professor of ECE Department at UCR. Dr. Wu is a member of the Institute of Transportation Engineers (ITE), Institute of Electrical and Electronics Engineers (IEEE), and Chinese Overseas Transportation Association (COTA). He is also a friend of several standing committees of Transportation Research Board (TRB), including the Traffic Signal Systems (AHB25), Managed Lanes (AHB35), and Transportation and Air Quality (ADC20). His research interests include intelligent transportation systems, electric vehicle technology, innovative connected vehicles technologies, and traffic simulation.

Yi Zhang received the BS degree in 1986 and MS degree in 1988 from Tsinghua University, China, and earned the PhD degree in 1995 from the University of Strathclyde in UK. He is a professor in control science and engineering at Tsinghua University with his current research interests focusing on intelligent transportation systems. Active research areas include intelligent vehicle-infrastructure cooperative systems, analysis of urban transportation systems, urban road network management, traffic data fusion and dissemination, and urban traffic control and management. His research fields also cover the advanced control theory and applications, advanced detection and measurement, and systems engineering, etc.

Matthew J. Barth received the BS degree from the University of Colorado, USA, in 1984, and MS and PhD degrees from the University of California, Santa Barbara, USA, in 1986 and 1990, respectively. Dr. Barth was also a member of the technical staff in the Advanced Technologies Division of General Research Corporation, Santa Barbara from 1985 to 1986. From 1986 to 1987, he conducted research at the University of Tokyo, Japan as a visiting research student. Upon completion of his PhD, Dr. Barth was a visiting researcher at Osaka University, Japan from 1989 to 1991. Dr. Barth joined the College of Engineering in 1991, conducting research in Electrical Engineering and at the Center for Environmental Research and Technology (CE-CERT). His research interests include intelligent rransportation systems, electric vehicle technology, innovative energy systems, vehicle activity analysis, aavigation, and advanced sensing and control.