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Data Based Parameter Setting Method For Adaptive Cruise Control

JIE CHEN, GUIZHEN YU, (Member, IEEE), AND XUESHU YAN
School of Transportation Science and Engineering, Beihang University, Beijing 100191, China

Corresponding author: Jie Chen (cj1234cj@sina.com)

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ABSTRACT Recent years, advanced driver assistance system (ADAS) has been highly developed and widely used. Among various ADAS techniques adaptive cruise control (ACC) is the fundamental of longitudinal control. The tradeoffs among safety, comfort and traffic efficiency are the main issue in ACC design process. In this study, large amount of road tests was carried out to explore the circumstance characteristics in ACC usages scenarios. Based on statistical analysis of road test data, a method for ACC safety performance evaluation is proposed. Furthermore, the effects of parameters such as following distance, jerk limit and time delay to ACC safety performance are discussed. Finally, a way of ACC parameter designing is developed, this method can obtain best comfort and traffic efficiency after safety request is guaranteed. In this study, regulations and realistic constrains of production vehicles are considered. Different from theoretical simulation, production-oriented ACC system is restricted in maximum deceleration, maximum braking jerk, detection latency, actuation latency, calculation capacity etc. For this reason, all the analysis is based on statistical results and requests from actual products, no computationally expensive optimal method is implemented. The proposed method may not get optimal results in theoretical simulation but is very instructive in production-oriented ACC system design.

INDEX TERMS Adaptive cruise control, parameter setting, safety performance.

I. INTRODUCTION

Advanced driver assistance system is considered as a series of effective functions which can help driver drive safer and easier [1]–[3]. Recent years research topics come out of ADAS are becoming more and more popular. These studies have covered environment perception [4], [5], path planning [6]–[8], driving decision [9], [10], artificial intelligent autonomous vehicle [11]–[13], intelligent connected vehicles [14]–[16] etc. First used on Mitsubishi production cars [13] ACC has now been widely accepted as a basic function in ADAS [18]–[20]. As ACC can reduce the driving workload and provide safe and comfortable experience in most daily driving scenarios [21], [22]. ACC uses camera or radar as sensor to collect information about other vehicles. ACC controller sends control signals to engine management system (EMS) and electronic stability control (ESC) system to accelerate and decelerate. With ACC controlling the vehicle, driver doesn't need to step on gas pedal or brake pedal unless some boundary events beyond ACC's control limit happen. ACC needs driver to take over vehicle control in situations like hazardous events, stationary front vehicle, traffic light stop line, bad weather and daylight condition. Related to these situations, capability of handling hazardous events is one of the most concerned performance. As a driving assistance system, ACC cannot ensure one hundred percent safety [23]. The control safety boundary of ACC is a mainly concerned characteristic to both car manufacturers and car users [24]. From another point of view, comfort performance and traffic efficiency are two most important performance indexes of ACC. A safe but not comfortable ACC system is meaningless because no driver would choose to use it. The parameter setting of ACC to make a good balance among safety, comfort and traffic efficiency is a significant problem in ACC system design. In ACC system, there are several parameters which are closely related to the performance mentioned above. First one is steady state car following distance, following distance for short. The control target in car following case is to keep host vehicle running at the same speed with target vehicle and to keep the distance between two vehicles equals following distance. Apparently following distance increases with vehicle speed, to better explain

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following distance, another concept called time headway is introduced. Time headway, also called time gap, is defined as the distance between host vehicle and the target vehicle divided by host vehicle's velocity.

$$HW = Dist/Vx \tag{1}$$

A regular approach for following distance design is constant time headway (CTH), following distance equals vehicle speed multiplied by time headway. Many researchers suggest nonlinear time headway varies with vehicle speed [25]. Larger headway means larger brake distance in case the target vehicle brakes. On the other hand, larger headway may cause more cut in events from adjacent lanes, which would decrease traffic efficiency and decrease the safety level. Another parameter is jerk limit of deceleration decreasing. Jerk limit is calculated as the derivation of longitudinal acceleration. Larger jerk limit means faster establishing brake pressure in hazard situations, while passengers are very sensitive to large jerks [26], it would decrease the comfort performance. Besides the time delay of sensors, brake system and control algorithm would also impact ACC safety performance. Though we cannot adjust the delay time during control design process, these time delay should be concerned in the process of component selection of the vehicle.

To the best of our knowledge, most of the studies in topic of ACC focuses on algorithm of platoon cruise and distance control [27]–[30], only a few studies discussed the parameter setting problem. Wang *et al.* [31] analyzed NGSim dataset statistically and gave a suggestion about headway setting. The target of this study is to design a headway similar to human driver and get good traffic efficiency performance, safety performance was not discussed. Michail *et al.* [32] set up a series of experiments to test time delay and time headway of production ACC systems and human drivers. Some meaningful test results were shown in this paper but no further analysis was made. Wang and Rajamani [33] studied the relationship between time headway and traffic flow stability. It is proved that constant time headway would cause instability in traffic flow. Safety performance was not discussed in this paper. Liu and Dianhai [34] studied the minimum time headway to ensure car following safety. While the study is based on theoretical constant deceleration brake and constant time headway, no realistic limitation was considered. John [35] developed a model-based algorithm to ensure safety in ACC scenario. In his study, a following distance curve was designed combining driver's habit and constant time headway theory. While the hypothesis that time delay is 300ms is much smaller than general value, the deceleration amplitude limitation was also not considered.

As introduced before, a lot of research has been done to find better control algorithm and improve the platoon and following performance. However, there are few studies focus on how to guarantee safety performance and make a good tradeoff with comfort and traffic efficiency. Apart from this, studies about how to tune algorithm parameters to get required performance are also hard to find. The main contribution of this work is giving a thorough study of these topics from engineering perspective, which is of engineering guiding significance. We first study the safety related road data and find out the quantitative relationship between algorithm parameters and ACC safety performance. We innovatively proposed a data based parameter setting method which is implementable and performance guaranteed. Using this method, safety requirement for ACC can be fulfilled and good balance between safety performance and other performance index can be obtained. It is also a way to evaluate the performance of an ACC system.

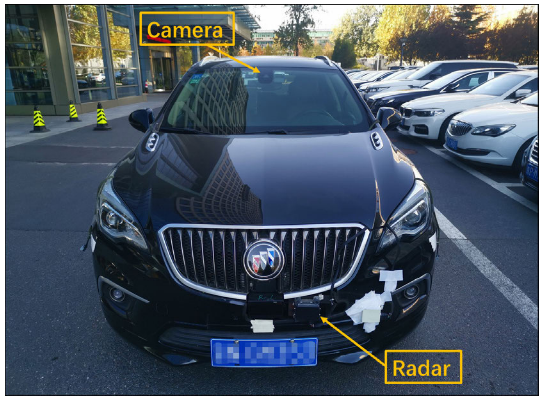


FIGURE 1. Test car and sensors for data collection.

In this research, first we collected large amount of real road test data for statistical analysis. Then we studied the characteristics of circumstance in ACC usage scenario including the probability of target hard brake and target cut in. By simulation test we determined the control boundary in theory and under different parameter settings. Using the statistic result of road test data, we proposed a data driven method of ACC parameter setting.

The remainder of this paper is organized as follows. Section 2 introduces the data collection method and instruments. Section 3 discusses the method and results of data analysis. Section 4 gives the statistical safety boundary and theory safety boundary. Safety performance evaluation based on safety boundary is discussed. Section 5 introduces the proposed ACC parameter setting method. Section 6 makes a conclusion of this work.

II. DATA COLLECTION

As we all know, different from active safety function like electronic stability control(ESC) or autonomous emergency braking(AEB), ACC is a system aims at improving driving comfort instead of ensuring one hundred percent driving safety. To decide to what extent should the ACC system ensure the driving safety, we have to know how dangerous the driving situation would be in the ACC usage scenarios.

To get original data of ACC usage scenarios, we set up several road tests on all kinds of roads in China. A camera sensor with EyeQ3 chip [36] is equipped behind the windshield of the test car, a millimeter-wave radar is mounted at the head of the test car. Ten test cars were set out and each ran a test of about 7500km. One of the test cars is shown in Fig.1

FIGURE 2. **Test routes for data collection.**

The camera and radar can detect up to 10 objects in the field of vision, including trucks, buses, cars, motor cycles, bicycles and pedestrians. For each detected object, sensors can output longitudinal distance, relative speed, longitudinal acceleration, lateral distance and lateral velocity. Lane information can also be detected by the camera. The data collection system is embedded with a production target selection fusion algorithm for ACC, so the car following information can also be decided. Host car information are collected from the CAN bus. Both sensor signals and host car signals are synchronized and processed by a self-designed onboard controller and saved on hard disk.

Test roads covered most kinds of public roads in China, including highway road, urban road, national road, provincial road, country road and other corner case roads. One of the test routes are shown in Fig.2.

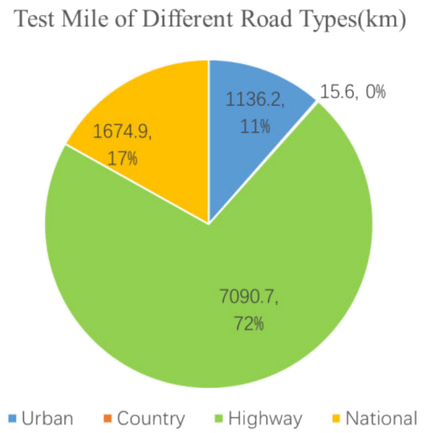
To best represent true probability of all kinds of ambient, weather and road types are all considered in the data collection process. The test mileage distribution on each dimension are shown in Fig.3.

III. DATA ANALYSIS

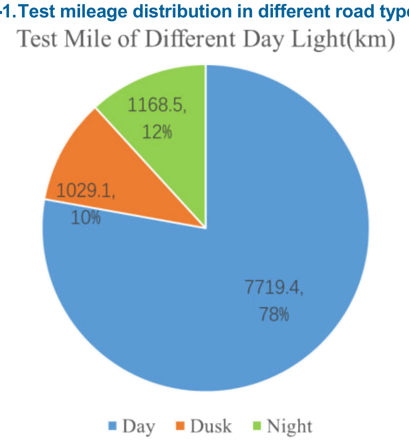
A. EVENT FILTERING

To pick up test data related to ACC safety performance, we focus on two typical scenarios. First scenario is called target brake scenario, in which target vehicle suddenly brakes during a steady car following process. We call the second cut in scenario, in which a target vehicle suddenly changes to the host lane while host car is cruising at a fixed speed. Most of the hazardous occasions can be classified in above two scenarios. The principle of event capture is introduced as below.

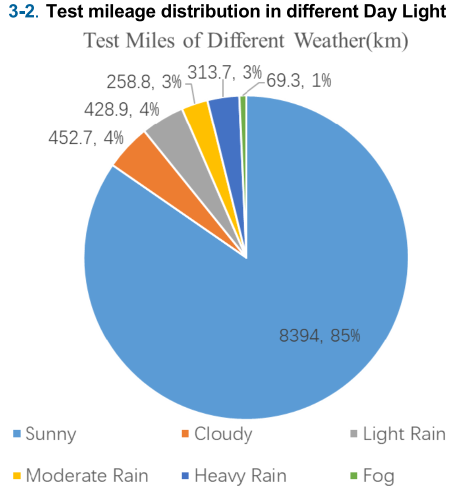
According to Chinese traffic regulation [37], in rear collision accident, the rear car should be responsible for all the results. Traffic regulation requires every car keep enough braking distance with front car. In addition, it is hard for drivers to observe speed and distance of following cars when they need brake. So during braking, deceleration amplitude is mainly decided by front objects. On this premise, the brake maneuver would not be different whether or not it is followed by other cars. All the brake maneuver detected by camera could happen on an ACC's CIPV target vehicle. We choose slices of data in which object's max deceleration is lower than -0.5m/s^2. A brake event begins at the point acceleration value decreases from positive to negative ends at the point acceleration value increases from negative to positive.



3-1. Test mileage distribution in different road types



3-2. Test mileage distribution in different Day Light



3-3. Test mileage distribution in different weather

FIGURE 3. **Test mileage distribution in different scenes.**

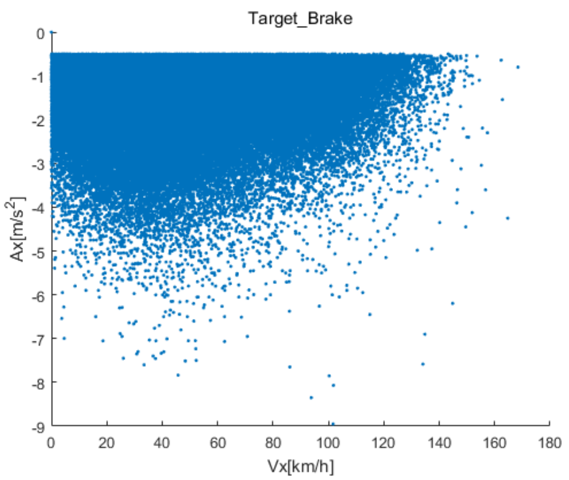


FIGURE 4. data distribution of target brake events.

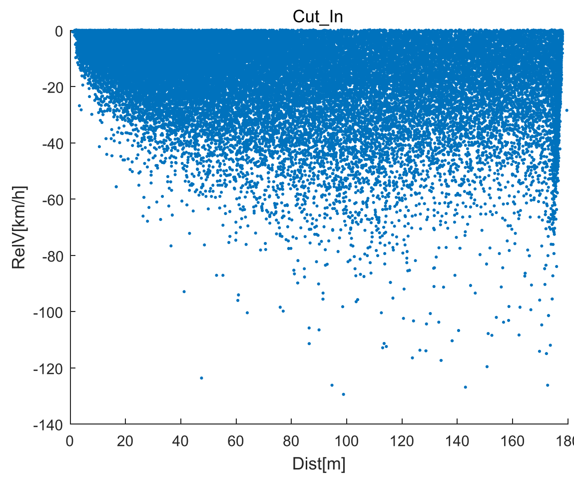


FIGURE 5. data distribution of cut in events.

Chinese traffic regulation states that drivers should keep enough distance to rear vehicle when changing lane. In lane change collision accident, the lane change vehicle should be responsible for all the results. In addition, the following car is not able to know when the merging car would cut in. So during lane changing, drivers usually take full observation of rear objects. On this premise, effective cut in event only occurs when there is a lane change vehicle and a following vehicle on the target lane. Limited by the capability of the camera, we only selected slices of data in which test vehicle was cut in by a lower speed neighbor lane vehicle. Another kind of scenario in which a low speed target vehicle was not detected at first and was detected afterwards is also considered as a cut in event. The reason is that in this scenario CIPV is shifted from a high speed vehicle or nothing to a low speed vehicle, which is quite similar to what happened in cut in case.

B. DATA DISTRIBUTION

According to the event filtering principles in part A, we selected 403635 slices of target brake event data. In target brake event, two key parameters determine the degree of hazardous, one is speed of two vehicles before brake, the other is maximum deceleration of the target vehicle. Higher speed means larger distance between two vehicles and longer braking process. Larger deceleration apparently leads to rear crash more easily. The scatter plot on Vx-Ax phase plane is shown in Fig.4

From Fig.4 we can see, at particular speed, number of brake events decreases as amplitude of deceleration increases. In about 99.1% of all brake events, amplitude of deceleration is smaller than 5m/s^2. At higher vehicle speed drivers prefer to brake more slightly, while at a speed below 40km/h driver sometimes brake hard. This is because in urban road, drivers prefer to start fast and brake hard to keep short distance from front car, this would prevent being cut in and increase traffic efficiency.

Among all test data, we selected 80401 slices of cut in event data. In cut in event, two key parameters determine the degree of hazardous. One is relative velocity between host vehicle and cut in vehicle, the other one is cut in distance between two vehicles. Larger relative velocity and smaller cut in distance leads to more hazardous situation. Fig.5 shows the distribution of cut in events on RelV-Dist phase plane. From Fig.5 we can see, cut in distance increases with relative speed. The leftmost data point stands for cut in with distance of about 3m, this often happens during traffic jam, adjacent lane vehicle may make a very close cut in to change lane. The bottom data point stands for cut in with relative speed of about −120km/h. This case often happens on highway when the target vehicle starts up in emergency lane and merges into host vehicle's lane.

IV. SAFETY BOUNDARY CALCULATION

A. STATISTIC SAFETY BOUNDARY

From the distribution of test data, we can get percentage form of safety boundary. This safety boundary is a meaningful guidance for ACC parameter design.

1) TARGET BRAKE SAFETY BOUNDARY

Due to 120km/h speed limit in Chinese traffic regulation, data with speed higher than 130km/h are relatively few, those data are not considered here. We segment vehicle speed range from 0km/h to 130km/h by 5km/h, and then segment deceleration range from 0m/s^2 to −10m/s^2 by 0.2m/s^2. Finally, we get a 26*50 table, each target brake event falls into one grid in this table. In each row of this table, vehicle runs at almost same speed. If we set a percentage value x, we can find a grid in nth row stands for speed Vn and deceleration Axn set that the number ratio of events whose deceleration amplitude smaller than |Axn| in this row is x%. For different x, we can get different Vx-Ax curves stands for the x percent safety boundary in target brake scenario. Fig.6 shows several safe boundaries derived from test data.

The target brake safety boundary shows the most critical situation ACC should handle at different car following speed. The deceleration threshold is nonlinearly monotonous with percentage value. We can find that the distance between 99.9% and 99% is much larger than that

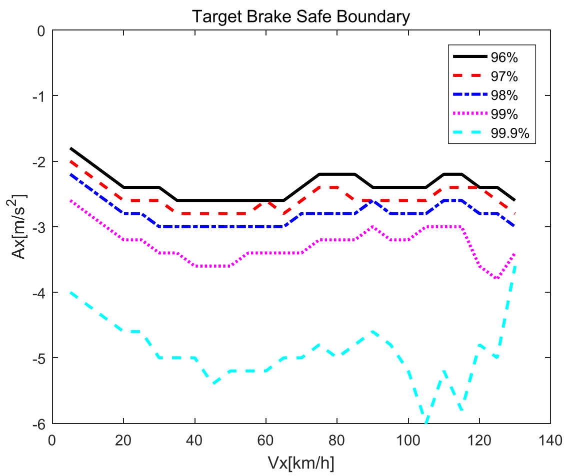


FIGURE 6. Target Brake Safety Boundary.

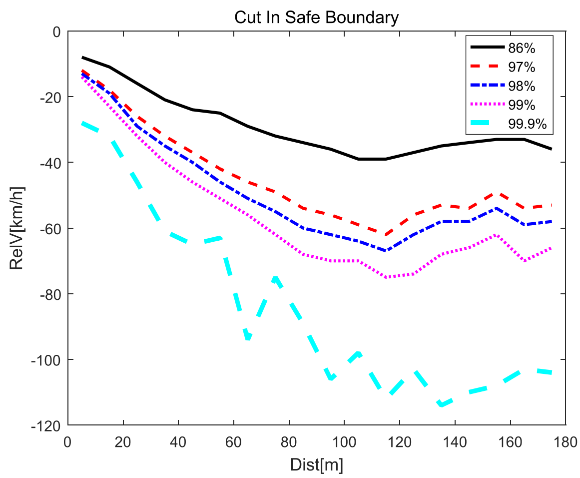


FIGURE 7. Cut In Safety Boundary.

between 98% and 99%. To reach 99.9% safe, ACC must handle the situation that target vehicle takes a −6m/s^2 brake during 110km/h car following. This is very hard for most ACC system, because the brake system usually doesn't support brake request stronger than −5m/s^2 due to ISO regulation restriction [38]. On the other hand, 99% safety boundary is relatively easy to reach.

2) CUT IN SAFETY BOUNDARY

Similarly, we segment relative distance range from 0m to 180m by 10m, and then segment relative speed range from 0km/h to 130km/h by 1km/h. Finally, we get an 18*130 table, each cut in event falls into one grid in this table. In each row of this table, vehicle cut in at almost same distance. If we set a percentage value x, we can find a grid in nth row stands for speed Dn and relative speed RelVn set that the number ratio of events whose relative speed amplitude smaller than |RelVn| in this row is x%. For different x, we can get different Dist-RelV curves stands for the x percent safety boundary in cut in scenario. Fig.7 shows several safe boundaries derived from test data.

The cut in safety boundary shows the most critical situation ACC should handle at different cut in distance. The relative

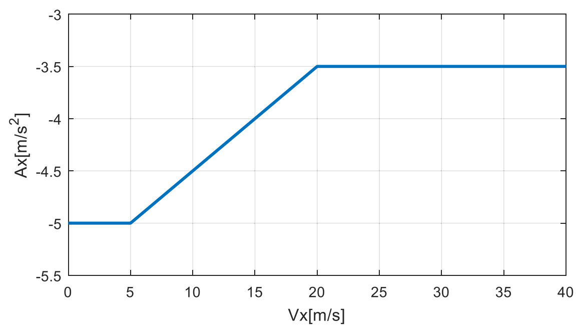


FIGURE 8. Deceleration limit in ISO22179.

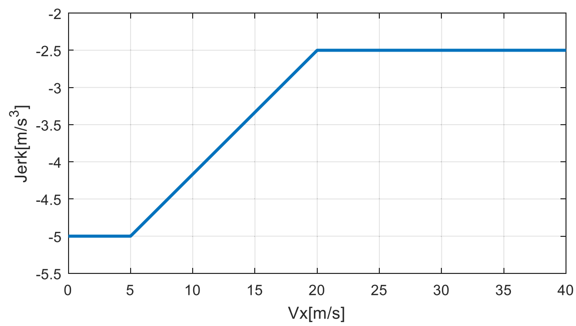


FIGURE 9. Deceleration Jerk limit in ISO22179.

speed threshold is nonlinearly monotonous with percentage value. We can find that the distance between 99.9% and 99% is much larger than that between 98% and 99%. To reach 99.9% safe, ACC must handle some critical situation like cutting in at relative speed of −94km/h and distance of 65m. Due to the maximum deceleration limit of ACC system, collision avoidance is very hard in these situations. Similarly, safety boundary below 99% is much more regular and easy to reach.

B. THERORETICAL SAFETY BOUNDARY

To decide a reasonable safety target of ACC system, we discuss the theoretical safety boundary ACC can reach under ISO regulation.

There are two main regulations related to ACC in ISO, one is ISO22179 for full speed range ACC and the other one is ISO 15622 for ACC used at speed higher than 30km/h. Here we use ISO22179 as a reference. In ISO22179 the maximum deceleration value and the maximum deceleration jerk value is limited as Fig.8 and Fig.9 show.

Under this restriction, we can calculate the theoretical safety of ACC system, the simulation method is as follows.

1) TARGET BRAKE CASE

To calculate theoretical target brake safety boundary, we must first set a headway curve. As mentioned in part 1, headway curve determines car following distance at different speed. In this part we choose the simplest form of headway curve, which is constant value at whole speed range. According to ISO22179, first level time headway must be greater than 1s, and a headway value between 1.5s to 2.2s must be set. Here we set four levels of time headway 1s, 1.5s, 2.1s and 2.5s.

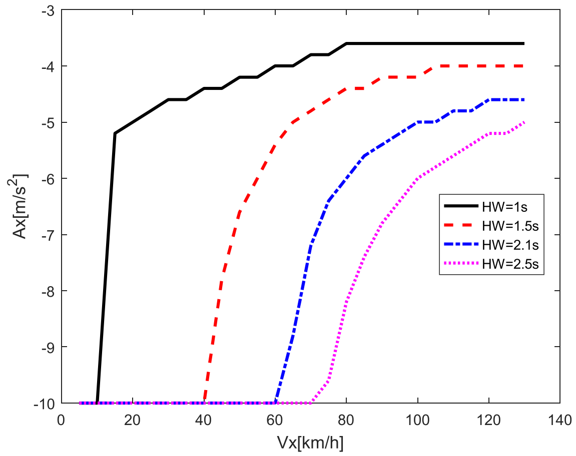


FIGURE 10. **Theoretical safe boundaries in target brake case.**

For each grid [Vx_i, Ax_j] in above mentioned 26*50 Vx-Ax table we run a simulation to check if ACC can avoid collision in this situation. At the beginning of the simulation, host vehicle and target vehicle both run at speed of Vx_i. The distance between these two vehicles is Vx_i*HW, HW is the set headway value. At time 0s, target vehicle brakes at jerk value of -10m/s^3 and the final deceleration value is Ax_j. After target vehicle starts to brake, it would take a time delay of τ for host vehicle to begin decelerating. The delay time consists of several part. From engineering experiences, we can find that sensor detection delay varies from 100ms to 800ms; algorithm filter delay varies from 200ms to 400ms; algorithm confirm delay varies from 100ms to 200ms; brake system delay varies from 400ms to1000ms. In this part we set total delay time as 800ms, this value is smaller than most product ACC systems. In this way, we can find out the best safety performance possible in reality. After delay time, host vehicle decelerates as fast as Fig.8 and Fig.9 allow. The simulation continues until collision happens or both vehicles stop. In each row, we find out the maximum deceleration ACC can avoid collision and get a Vx-Ax curve which is theoretical safety boundary. Fig.10 shows four theoretical safe boundaries under four different headway settings.

From Fig.10 we can find out that safe boundaries are larger at low speed than high speed, the main reason is that braking distance is proportional to square of speed while car following distance is proportional to speed, so as speed increase target brake event becomes more dangerous.

2) CUT IN CASE

In cut in simulation, we run two simulations for each grid [Dist_i, RelV_j] in above mentioned 18*130 table to check if ACC can avoid collision. The difference between two simulations is host vehicle speed. First simulation is called high speed cut in case, at the beginning of the simulation, host vehicle runs at fixed speed of 130km/h. The other one is called low speed cut in case, at the beginning of the simulation, host vehicle runs at fixed speed –RelV_i km/h. At time 0s, target vehicle cut in the host lane at the point Dist_i m away from host vehicle and the relative speed between two vehicles is RelV_i km/h. It means in high speed cut in case target vehicle cut in at speed of (130 + RelV) km/h, in low speed cut in case target vehicle cut in at speed of 0km/h. After time delay of τ, host vehicle begin to brake as fast as Fig.8 and Fig.9 allow. The simulation continues until collision happens or host vehicle's speed is lower than target vehicle's speed. Fig.11 shows the theoretical safety boundary in cut in case.

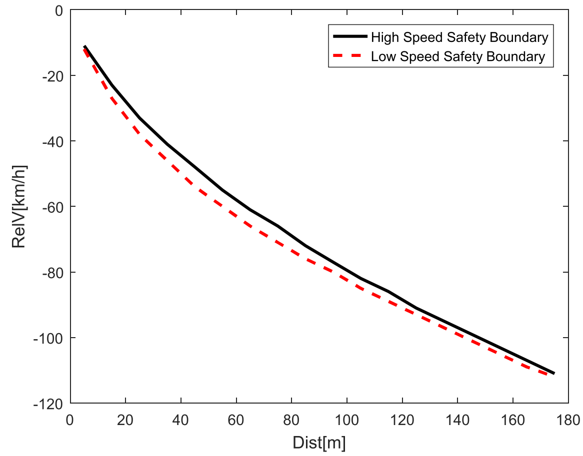


FIGURE 11. **Theoretical safety boundaries in cut in case.**

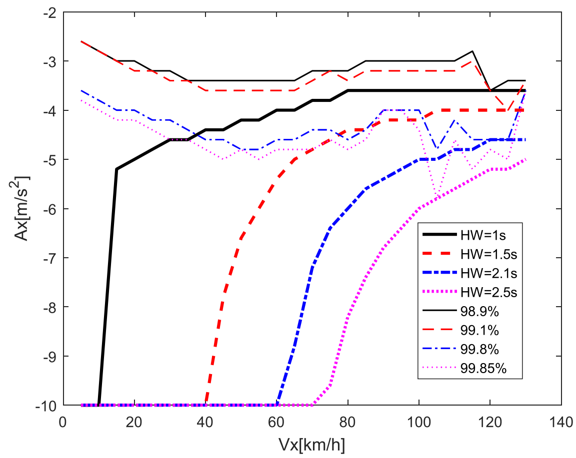


FIGURE 12. **Relationship between theoretical safe boundaries and statistical safety boundary in target brake case.**

The shape of the safety boundary is similar to the envelope of scatter points in Fig.5. Note that camera's detection range limit is about 180m, which means when relative speed exceeds -110km/h, it is impossible to avoid collision only by ACC decelerating. Two safety boundaries in Fig.11 are slightly different, it is because jerk limit and allowed deceleration amplitude are different in different speed range. In low speed range, stronger deceleration and larger deceleration rate are allowed.

3) SAFETY BOUNDARY COVERING RATE

By carefully tuning the percentage in statistic safety boundary we can find out the maximum percentage ACC system can cover in real traffic circumstances. Fig.12 shows the

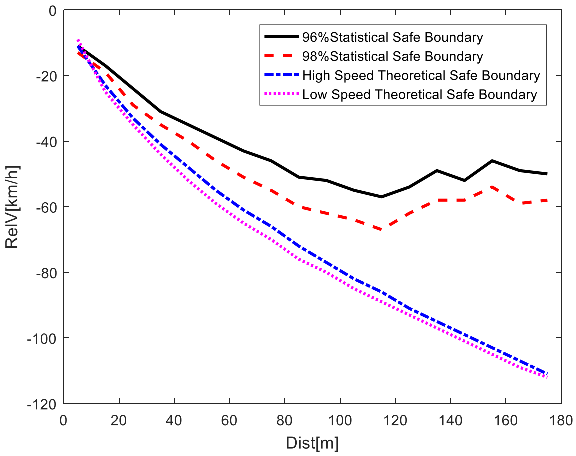


FIGURE 13. Relationship between theoretical safe boundaries and statistical safety boundary in cut in case.

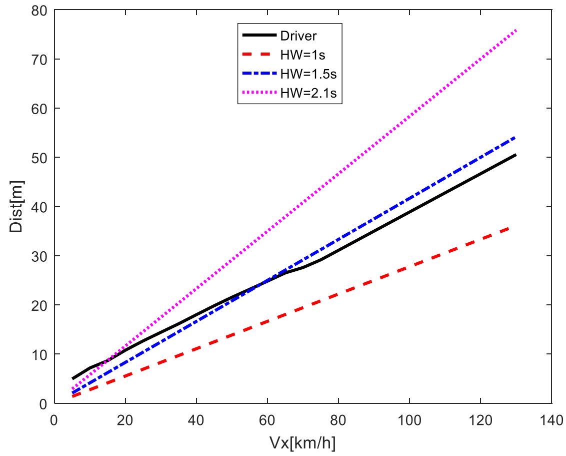


FIGURE 14. Following distance of human driver and constant headway design.

relationship between theoretical safety boundary and statistic safety boundary in target brake case.

It can be found that four theoretical safe boundaries can respectively cover 98.9%, 99.1%, 99.8%, 99.85% target brake cases. For each headway level, theoretical safety boundary is much larger than statistical boundary in low speed range, while in high speed range, two curves get close. This means constant headway setting would not lead to same safety level among different speed ranges. To get similar safety level among all speed ranges, time headway should be increased with speed. We can also find that, at high speed section, when time headway increases from 2.1s to 2.5s, the coverage only increases by 0.05%.

Fig.13 shows the relationship between theoretical safety boundary and statistic safety boundary in cut in case.

Fig.13 shows that the theoretical safety boundary can cover 99.1% cut in cases above 20km/h, but it can only cover 96% cases in full speed range. This is because at low speed range, drivers tend to frequently make very close cut in. At current level of technology, production cameras used in ACC system have a limited horizon field of vision of about 100°. Before a cut in vehicle entering the 100° field of vision, camera cannot see it. Another reason is that ACC camera needs to see most part of a vehicle to confirm it is a vehicle. This would cause detection time delay. In addition, to prevent false detection, camera usually confirm a target vehicle after it touches lane marker or enters host vehicle's path. This would also cause some time delay. All this technical limits would cause braking too late in a very close cut in scenario. When vehicle speed is higher than 80km/h, distance between two boundaries become larger, main reason is drivers seldom make close cut in when there is a much higher speed vehicle behind.

V. ACC PARAMETERS SETTING

ACC system with good safety performance would decrease take over request to driver, enhance users' confidence and increase the drivers' willing to use it. On the other hand, over conservative safety strategy would cause too large following distance, frequent braking, and too heavy braking, both comfort and traffic efficiency would decrease. Considering these, we discuss ACC parameters design method in this part.

A. FOLLOWING DISTANCE

ACC system usually offers 3 to 7 levels of following distances for users to choose. Referring to ISO22179, corresponding time headways usually vary from 1s to 3.6s. As discussed above, constant time headway is not a very good design, study in [39] also support this conclusion. On the other hand, constant time headway also doesn't fit human driver's driving habit. Drivers would keep a minimum distance about 2m to front vehicle no matter how slowly the vehicle is moving. When driving at high speed, drivers would decrease the time headway [40]. One reason is there are few low speed targets on highway, another reason is short distance can prevent cutting in and increase traffic efficiency. Besides, human driver can proceed deceleration up to −10m/s^2, they can also steer to avoid collision, there is no need to keep too large following distance. In Wang's study [31], authors give the statistic drivers' following distance from dataset of NGSim, Fig.14 shows the following distance of this study and constant time headway.

We can see that statistical driver's following distance is close to distance curve of constant time headway 1.5s. When driving faster than 60km/h, driver's time headway is lower than 1.5s, when driving slower than 60km/h, driver's time headway is high than 1.5s. At speed 5km/h, driver's time headway is about 4.2s. To let ACC drive more similar to human driver, we first modify constant headway curve as follows.

1) Define driver headway curve as HW = f(Vx)
2) For headway level HWi = Xs, HWi = f(Vx)/1.5*X

Then we get following distance for headway 1s, 1.5s, 2.1s, 2.5s as Fig.15 shows.

Using new following distance curve, we can get new safety boundary as Fig.16 shows.

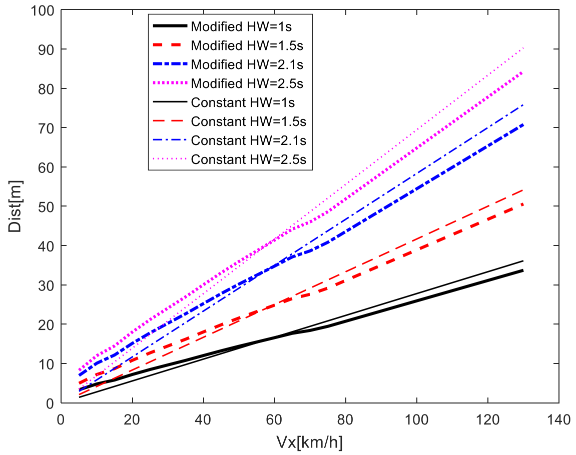


FIGURE 15. Modified following distance curve.

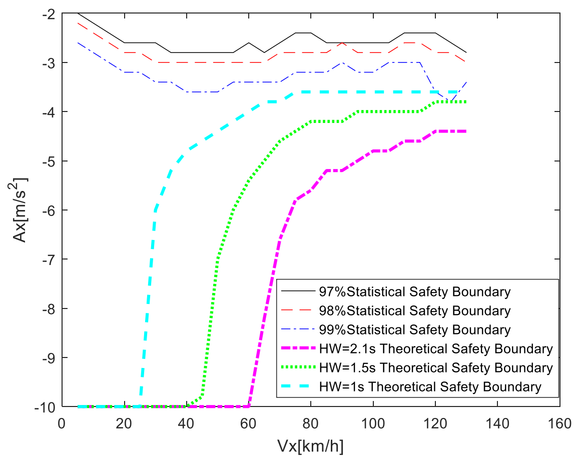


FIGURE 16. Safety boundary after headway curve modified.

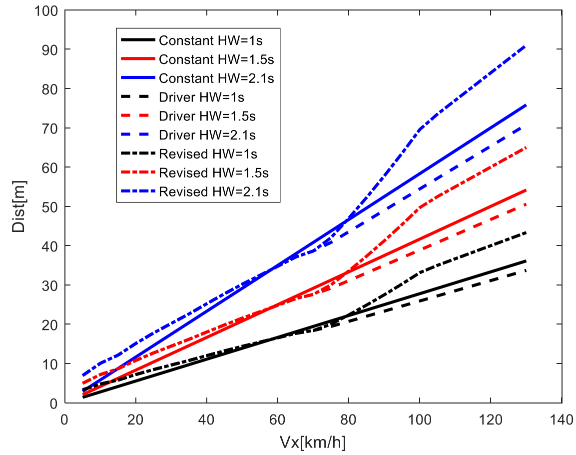


FIGURE 17. Further revised following distance.

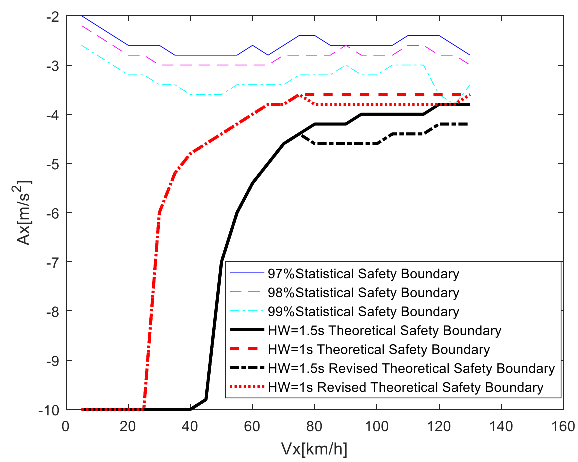


FIGURE 18. Safety boundary with revised headway.

The first level time headway decides the safety boundary of ACC system. If the safety performance request is 99%, from Fig.16 we can see the first headway level should be larger than 1.5s. If the minimum level time headway of 1.5s is acceptable, this group of headway curves would be appropriate. If a smaller headway value must be set, like 1s, then the headway curve should be further revised.

To improve safety performance in high speed range, we slightly increase high speed following distance. Revised following distance curves are shown in Fig.17.

The corresponding revised safety boundary is shown in Fig.18. As we can see, first level headway now can fulfill 99% safety performance request. Note that the delay time and jerk limit are both set in the best case, if actual delay time is larger or jerk limit is stricter than ISO22179, safety performance would deteriorate.

Following distance design process can be concluded as following steps:

1) Determine system delay time, deceleration jerk limit, first level time headway and percentage coverage requirement of target brake case.
2) Use following distance shown in Fig.15 to simulate and get safety boundary of first level time headway.
3) Calculate statistical safety boundary of the required coverage rate from test data in Fig.4. Compare these two safety boundaries, if simulated boundary lies below statistical safety boundary and there are no intersections, then the safety request is fulfilled. Otherwise, find the speed of intersections, slightly increase the corresponding point in headway curve
4) Run the simulation again. Repeat this tuning process until the safety request if fulfilled.

B. JERK LIMIT

Jerk limit is another important parameter in ACC control algorithm. Large jerk limit allows fast deceleration in hazardous situation but would cause uncomfortableness to users. Human are more sensitive to deceleration rate than deceleration amplitude, large deceleration rate would make users feel unsmooth and frightened, it would also cause carsickness. ACC designer usually prefer a slow but large deceleration than a fast but small deceleration. If the vehicle is equipped with ESC system as brake actuator, larger deceleration rate would also cause uncomfortable noise more easily. ESC use motor and pump to fill wheel cylinder with brake oil, large difference between requested deceleration and real

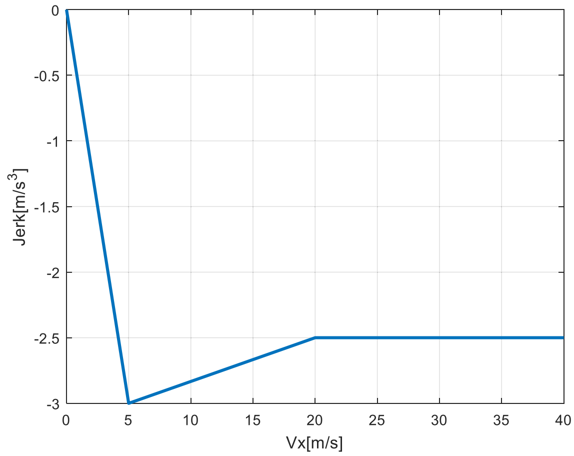


FIGURE 19. **Modified deceleration jerk limit.**

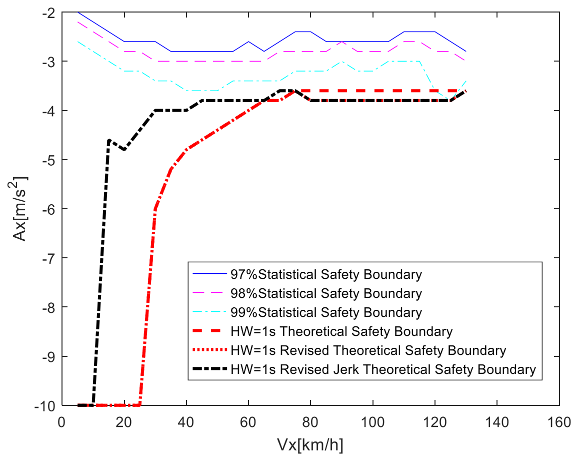


FIGURE 20. **Safety boundary with revised jerk limit in target brake case.**

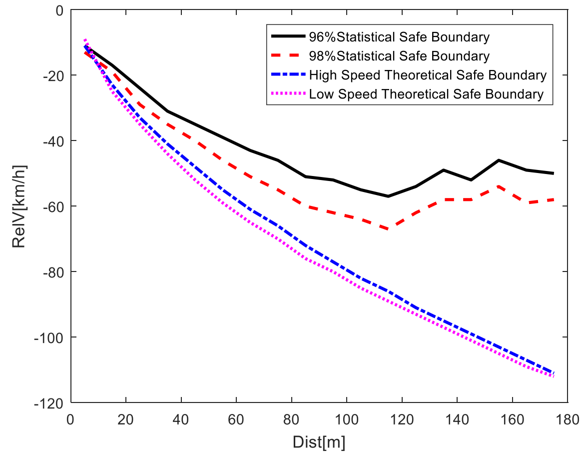


FIGURE 21. **Safety boundary with revised jerk limit in cut in case.**

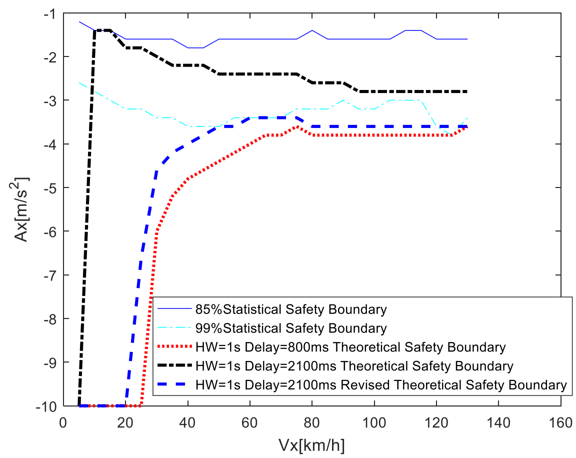


FIGURE 22. **Safety boundary under different delay time in target brake case.**

deceleration would make ESC motor rotate fast and make more noise.

From the simulation results in time headway design part we can see that in low speed range safety boundary is far beyond the request. It is possible to decrease the jerk limit in low speed range to get better comfort. We still assume the safety request to be 99% and first level time headway is 1s. Jerk limit is revised as Fig.19 shows.

The new safety boundary is shown in Fig.20.

To make sure the cut in case does not deteriorate, cut in case simulation should also be checked, Fig.21 shows that cut in case safety boundary remains.

Jerk limit design process can be concluded as follows.

1) Determine system delay time, following distance, first level time headway and percentage coverage requirement of target brake case.
2) Use jerk limit in Fig.9 to simulate and get safety boundary of first level time headway.
3) Calculate statistical safety boundary of the required coverage rate from test data in Fig.4. Compare these two safety boundaries, find out the speed point where two safety boundaries have large distance. Then slightly decrease the jerk limit of these point and ensure two safety boundaries don't get too close. At last, make sure cut in case safety boundary meet the safety request.
4) Run the simulation again. Repeat this tuning process until the safety request if fulfilled.

C. DELAY TIME REQUEST

Delay time would greatly affect safety performance of ACC system. Although delay time cannot be tuned during design process, it is meaningful to make clear how much delay is acceptable, it would help the designer choose proper sensors and brake actuators.

As mentioned before, delay time consists of sensor delay, algorithm confirm delay, brake system delay etc. From the typical delay time data mentioned in part IV.B. it is easy to calculate that total delay varies from 800ms to 2100ms.

Using revised headway curve in Fig.17 and jerk limit in Fig.9, we can get safety boundaries with different time delay as shown in Fig.22 and Fig.23. As we can see, delay time has evident effect to safety boundary. With delay time of 2100ms, coverage rate of target brake case decreases from

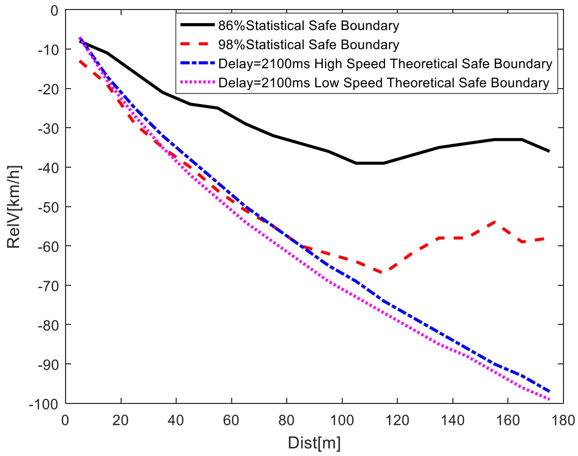


FIGURE 23. Safety boundary with large delay time in cut in case.

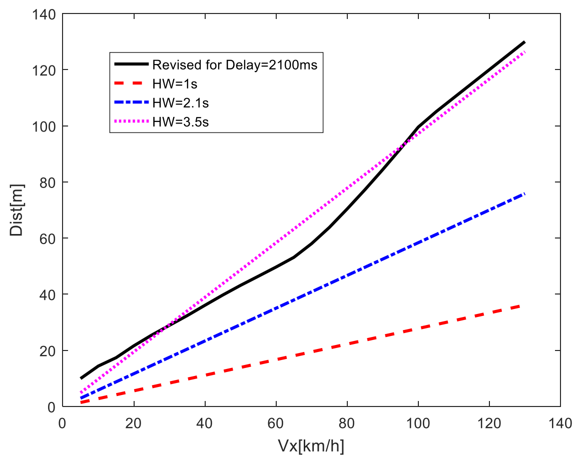


FIGURE 24. Revised following distance curve for delay = 2100ms.

99% to 85%, coverage rate of cut in case decreases from 96% to 86%. To compensate the effect caused by large delay time, time headway curve is revised according to Part A in this section. The revised safety boundary is shown in Fig.22. From Fig.24 we can find that the revised first level time headway curve is close to constant time headway 3.5s. This is not acceptable for too large following distance, and also not compatible to ISO22179's requirement of at least one time headway between 1.5s to 2.2s. So it is important to raise the delay time requirement for sensors and brake system before ACC designing.

VI. CONCLUSION

ACC is a system aims to partially substitute driver. Hazardous situation during using ACC comes from the interaction with other drivers. For this reason, the parameter design of ACC should consider both human driver's driving habit and statistical driving action data. Large amount of test was carried out in this paper to collect driving action data. Based on these data, driving behavior characteristics on Chinese public roads was analyzed. The main contributions of this work are the following four points:

1. A data based parameter designing method is proposed. This method not only provides step by step guidance but also gives a way to evaluate an ACC system's safety performance in designing process.
2. Using this method, we analyzed several key parameters in ACC algorithm. First one is steady state following distance. This parameter is designed based on driver database. After point by point adjusting we found that high speed range following distance usually needs to be enlarged due to limited safety margin.
3. Second key parameter is deceleration jerk limit. Similar design process can be carried out. After checking required safety boundary, points on jerk limit curve which have large safety margin can be shrunk to get better comfort performance. We found that in low speed range, jerk limit can usually be tuned down due to large safety margin.
4. Last parameter we investigated is delay time. Large time delay can severely deteriorate safety performance. Using the proposed method, we can make proper request for sensors and actuators at the beginning of development and lower the risk of unacceptable system performance.

Further study on this topic may explore more complex scenarios besides target brake and cut in cases. Driving habits in different countries and regions may be different, road test data outside China mainland would also be meaningful to this study. Another important topic about ACC safety is human in the loop dimension. The changing stage between human control and ACC control has complex and significant influence on ACC safety performance. Meaningful research could be carried out on this topic.

For ADAS system, statistical data analysis is a useful method to improve algorithm design. When ADAS system cannot ensure optimal performance, statistical results can give real data based performance index. Based on the data we collect, several further researches can be done. First is study of different driving behavior in different environments like weather, road type, day light etc. ACC parameters can be tuned automatically according to environment conditions. This paper mainly focuses on the parameter setting related to safety performance, other aspects like comfort and traffic efficiency can also be improved by statistical study. Another interesting study field is driving behavior or driver model. To drive like an experienced driver may not be an optimal but could be a second-best solution for ADAS system. An experienced driver model can be extracted from the database which can guide ACC parameter design.

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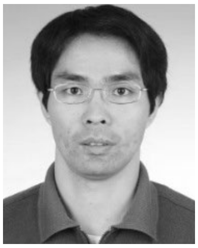
JIE CHEN received the B.S. and Ph.D. degrees in automotive engineering and mechanical engineering from Tsinghua University, Beijing, China, in 2011 and 2017, respectively. He is currently a Postdoctoral Researcher at the School of Transportation Science and Engineering, Beihang University, Beijing. His current research interests include intelligent vehicle and vehicle dynamics control.



GUIZHEN YU (Member, IEEE) received the Ph.D. degree from Jilin University, China, in 2003. He is currently a Professor with the School of Transportation Science and Engineering, Beihang University, Beijing, China. His research interests include intelligent vehicle and urban traffic operations. He is a member of the IEEE ITS Society.

XUESHU YAN received the B.S. and Ph.D. degrees in instruments science and technology from Tsinghua University, Beijing, China, in 2012 and 2017, respectively. He is currently a Postdoctoral Researcher at the School of Transportation Science and Engineering, Beihang University, Beijing. His current research interests include perception, positioning, and sensor fusion.