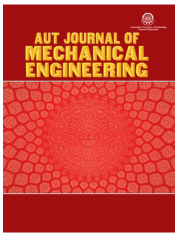

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A New Adaptive Cruise Control Strategy Considering Road Conditions

Mohammad Foroutan Moharrami, Mohsen Mohammadi*

School of Mechanical Engineering, Shiraz University, Shiraz, Iran

ABSTRACT: This abstract serves as a concise yet comprehensive overview of this research's contributions, highlighting its significance in advancing Adaptive Cruise Control technology and autonomous vehicles. The provided paper introduces an innovative approach to Adaptive Cruise Control systems, emphasizing safety, comfort, and efficiency. Also, the proposed Adaptive Cruise Control model surpasses traditional longitudinal velocity control by integrating lateral motion and surface condition considerations. The proposed control strategy uses a new tail-following approach with the implementation of a new throttle valve controller which results in a smoother deceleration with an average of 40 percent decrease in maximum deceleration value while following other vehicles. Also, the implementation of brakes is minimized to lower the overall energy waste in vehicle motion. The proposed Adaptive Cruise Control can regulate braking force and tail-following distance based on road surface material and circumstances. This action enhances safety while driving on various roads and weather conditions. One of the innovative sections in this study is the integration of lateral motion with Adaptive Cruise Control. This approach helps the vehicle to stay laterally stable by limiting the lateral acceleration of the vehicle. The research signifies a notable advancement in Adaptive Cruise Control technology, establishing a connection between vehicle dynamics and adaptive control algorithms.

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1- Introduction

Priority of safety, efficiency, and comfort turns the Advanced Driver-Assistance System (ADAS) into one of the current hotspots of the automotive industry. ADAS technologies have the potential to prevent over 20,000 deaths per year or about 62% of total traffic deaths. Cruise control systems, lane-keeping assist, and pedestrian automatic braking are among the most known driver-assistance systems.

Adaptive Cruise Control (ACC), which is the mature model of the conventional Cruise Control is a system that controls the vehicle speed respective to the road conditions[1]. In the absence of any kind of obstacles like other vehicles and pedestrians, the vehicle control section utilizes the powertrain to reach a pre-defined speed that is set by the driver. Throughout time various sensors, radars, and cameras observe the range of vehicle motion[2]. At any instant that an obstacle is recognized on the vehicle path line, the ACC processing unit calculates the relative motion between the main car and the obstacle so that in the case of need, there will be further actions; namely engaging the brakes, changing the throttle opening valve, and changing the gear so that the safe journey is obtained for passengers[3].

In the last couple of decades, a great amount of effort has been put into expanding ACC and solving safety issues[4]. These researches were conducted in different sections; trying to come up with a more accurate dynamics model[5], high-precision sensors and radars[6], designing driving cycles[7], and driving strategies are just some examples of these studies.

However, the employment of ADAS technologies is not the same for all types of vehicles, there is a vivid trend among the Original Equipment Manufacturers (OEM) which tries to integrate certain types of driving-assistance systems[8]. For instance, the integration of lane-keeping assist[9] and ACC is a repeated example of this trend. Also, the growth in the popularity of Electric Vehicles (EVs) besides the spread of autonomy in the automotive industry made the whole process of integration even more immense[10].

Similar to most electronic parts of vehicles, there is a processing unit in the ACC system that is responsible for evaluating input data and motion planning. The calculations in this module are executed in real-time according to pre-compiled programs and codes while it can plan the most reasonable vehicle movement state and send it to the execution control module[11]. The algorithms behind the ACC have been modified continuously over time[12]. The latest versions of ACC are capable of operating at speeds less than 30 km/h through the Stop & Go function [13], detecting cutting in and out vehicles in traffic [14], and responding to other vehicles' situations via V2V communication[15].

*Corresponding author's email: Mohsen_mohammadi@shirazu.ac.ir

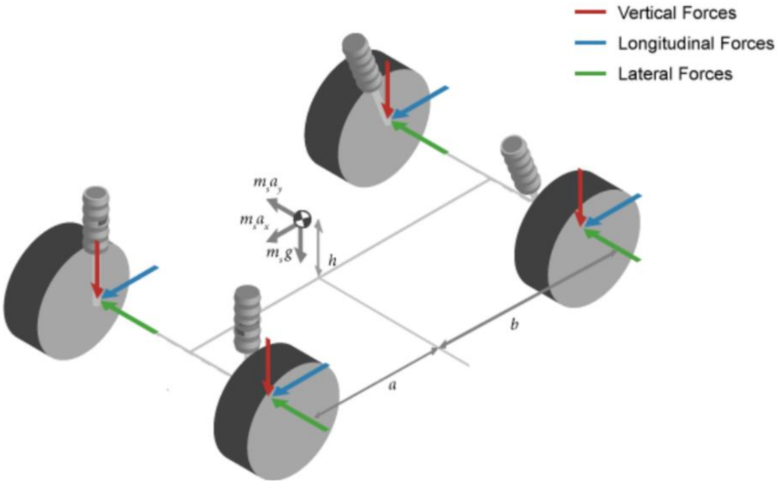

Fig. 1. Three degrees of freedom, dual track vehicle dynamic model

The main goal of ACC is to control vehicle longitudinal movement, although while studying various driving scenarios, it is not obscure that vehicle lateral motion is also responsible for passengers' satisfaction and comfort[16]. On the other hand, it is barely seen that road circumstances and climate effects are considered in the ACC. In the cases where ACC is employed parallel to other safety systems like the Electronic Stability Program (ESP) or Traction Control, the absence of road and weather considerations is compensated. However, due to financial aspects on the low-end side of the automotive market, it rarely happens to see all these high-tech features, utilized together. Based on the reasons above, considering both safety and comfort, it seems to be inevitable to enter other parameters than only longitudinal properties to the study and control of vehicle motion at high speeds.

In this paper, the proposed control algorithm for the Adaptive Cruise Control system can increase the quality and comfort of the ride alongside its main capability, controlling the vehicle velocity relative to the environment. Based on various studies on vehicle dynamics, it is found that acceleration is an important factor in maintaining comfort for passengers since acceleration and jerks are both responsible for a comfortable ride. Relatively, in this study, the strategy to minimize the average acceleration and also the maximum acceleration applied to the vehicle is followed. This module limits the vehicle speed not only by the obstacles that are identified by the sets of sensors and cameras but also respective to the lateral acceleration. Also, extra caution was involved for various road surface conditions.

The main novelties of this research are introducing a new approaching method for tail-following scenarios in a traffic flow which will increase the comfort and overall fuel efficiency, including surface condition and material in maneuverings since the road material, temperature, and circumstances will affect acceleration, braking, and turning of the vehicle, and lastly, introducing a new augmentation to the ACC system which control the lateral motion of the vehicle and will not allow the vehicle to surpass certain limits to maintain safety and comfort for the passengers.

The remainder of this paper is organized as follows: Section 2, modeling; Section 3, control unit; Section 4, Optimization, Section 5, Validation and Results, and Section 6, Conclusion.

2- Modeling

The purpose of this paper is to design a new control scheme for Adaptive Cruise Control. For a thorough study of this scheme, a research model is employed. This model consists of two vehicles, the host vehicle which is connected to the ACC module and includes a more comprehensive structure, and the front vehicle to counter-act to the host vehicle. In the following, the details of the model are illustrated.

Vehicle Body: parameters like motion degrees of freedom and the number of inputs and outputs of the problem determine the most appropriate framework to work on. In this research, the intention to study the longitudinal and lateral motion of the vehicle makes vehicle body with 3 degrees of freedom, the most appropriate dynamic model[17]. Also, for a higher level of precision, the dual-track model was implemented so the lateral and cornering motions happen to be in a more accurate form. (Fig. 1)

The Vehicle Body 3DOF block implements a rigid two-axle vehicle body model to calculate longitudinal, lateral, and yaw motion. The block accounts for body mass and aerodynamic drag between the axles due to acceleration and steering [17].

The steering dynamic of a four-wheel vehicle also needs to be discussed. In order to understand the steering dynamics,

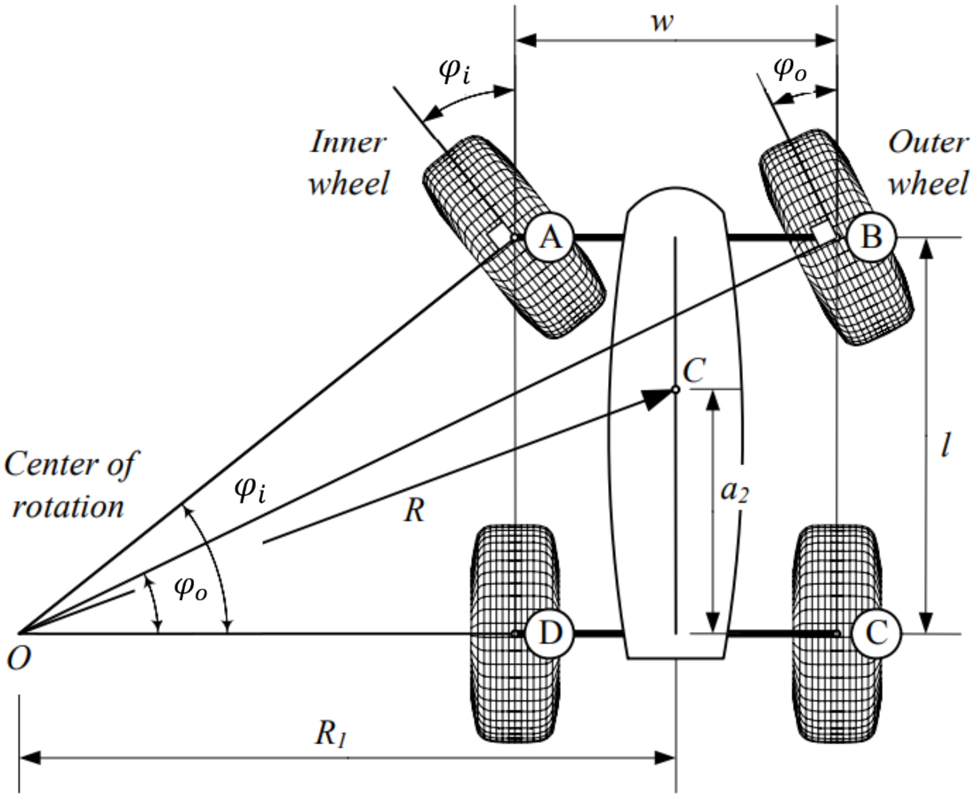

Fig. 2. A front-wheel-steering vehicle and the Ackerman condition.

the Ackerman condition is expressed by;

$$\cot\varphi_0 - \cot\varphi_i = \frac{\omega}{l} \tag{1}$$

where, φ_i is the steering angle of the inner wheel, and φ_o is the steering angle of the outer wheel. The inner and outer wheels are defined based on the turning center O.

$$R = \sqrt{a_2^2 + l^2 \cot^2\varphi} \tag{2}$$

$$\cot\varphi = \frac{\cot\varphi_0 + \cot\varphi_i}{2} \tag{3}$$

The mass center of a steered vehicle will turn on a circle with radius R, where φ is the cot-average of the inner and outer steer angles. The angle φ is the equivalent steer angle of a bicycle having the same wheelbase *l* and radius of rotation R. (Fig. 2)

Powertrain and steering: In order to accelerate or decelerate properly in time of need, the powertrain, driveline, and hydraulic brake system are designed and implemented separately. The exerted force by the brake system on the wheels is calculated from Eqs. (4) and (5) [18];

$$F_{Brake} = \mu F_{Normal} \tag{4}$$

$$\mu = \mu_0 - a\ln(1+bv) + cT \tag{5}$$

where μ is the coefficient of friction, T represents temperature, and v is the sliding velocity. μ_0 is the initial or reference coefficient of friction, which could be the value under standard conditions. a is a constant that scales the effect of the logarithmic term on the overall coefficient of friction. b is a constant that scales the velocity v and c is a material constant. Also, a rack and pinion mechanism is implemented as the steering mechanism.

Table 1. Vehicle body mechanical properties (Audi RS7)

Parameter	Symbol	Value
Mass (kg)	M	2065
distance from CG to front axle (m)	z	1.79
distance from CG to rear axle (m)	x	1.94
CG height above ground (m)	c	0.24
Frontal area (m2)	A	2.13
Drag coefficient	C	0.3
Air density (kg/m3)	ρ	1.18
Rolling resistance coefficient	f	0.015
Tire rolling radius (m)	R	0.33
Tire pressure (kpa)	P	250
Yaw polar inertia (kgm2)	I	1803

Tires: Tires are one of the most important components of dynamics simulation and they are the only parts of the vehicle in touch with the road surface. The importance of an accurate simulation in this paper arises from the point where various surface materials, dry and wet asphalt, and ice, are examined in the ACC test. Magic formula tires are the best-fit model which obeys the following equation [19].

$$F_y = D\sin(C\arctan(B\alpha - E(B\alpha - (\arctan(B\alpha))))) \quad (6)$$

In the equation above, F_y is the lateral tire force, α is the slip angle in radians, B is the shape factor, C is the stiffness factor, D is the peak lateral force, and E is the curvature factor.

In the case that ACC decides to gain speed, the throttle controller will open the throttle respective to the required acceleration. Analyzing the demanded force for this process can be calculated as follows:

$$am = F - F_D - F_R - F_{ext} \quad (7)$$

$$F_R = mgf_{Rolling} \quad (8)$$

$$F_D = \frac{1}{2} C_{Drag} A\rho v^2 \quad (9)$$

Where a is the expected acceleration, m is the vehicle mass, F is the driving force, F_D is the drag force exerted on the vehicle, F_R is the tire rolling resistance, and F_{ext} is the extra forces that may be applied to the vehicle. Also, $f_{Rolling}$ represents the coefficient of rolling friction. Table 1 demonstrates the two vehicles' body mechanical properties, host and front vehicles. This model is based on the exterior specifications of Audi RS7.

3- Control Unit

The inception of novelty in this study is rooted in its innovative and versatile control strategy. Accordingly, in the first place, the novelties of this study are outlined. Alongside the conventional capabilities of an ACC system, there are 3 main sections augmented to the system.

Firstly, in most proposed algorithms for ACC, it can be seen that the controller has mainly two phases for gaining and losing speed; changing the throttle valve opening and braking. However, in this research, a third transitional phase is developed which occurs before the stated stages. In this phase, the controller changes the throttle valve opening magnitude from further distances. This third stage will help to improve the comfort of passengers by extending deceleration time especially when the front vehicle tries to accelerate which happens repeatedly in traffic flow.

Secondly, the proposed controller observes the lateral acceleration to maintain lateral stability (safety) and comfort for the passengers. It is obvious that vehicles cannot turn at high speeds and if so, there is discomfort for passengers and danger of roll-over for the vehicle, however, none of the conventional ACCs controls the lateral motion of the vehicle. Respectively, in this study, the ACC takes control of the lateral motion as well. There is a limited lateral acceleration defined for the ACC controller to not allow the vehicle to surpass this amount. If the vehicle reaches this amount, brakes will be activated to reach the safe amount. (Fig. 3)

Finally, it is not obscure that vehicle dynamics are affected by the road condition. It is for this reason that there

Fig. 3. Schematic of ACC control algorithm

are different regulations for driving in various weathers and roads. One of many actions that the proposed ACC does is observing road surface conditions. The designed controller uses the data from surface material and consequently, employs different safety distances for braking and tail-following actions. For instance, the tail-following distance on icy roads is greater than on dry road conditions.

The proposed ACC control algorithm is divided into 4 different levels; acceleration, throttle control, throttle closure, and braking. The margin between these four operations is obtained by optimization of various driving styles' examples. In the following paragraphs, each level is discussed more accurately:

Level 1: If there are no obstacles or vehicles in the sensor range or the preceding vehicles have a higher speed than the host vehicle, then a pre-set velocity from the driver will be the target velocity for the ACC system and it controls the throttle for the requested speed.

Level 2: Sometimes it happens to see that the vehicle detection system recognizes a vehicle on the road, but factors like relative velocity and distance make it unnecessary to brake or fully close the throttle. In these cases, a PID controller is utilized to minimize the difference between the two vehicles' speeds. Through this action, the host vehicle still applies the accelerator, although the rate of gaining speed seems to be smoother.

Level 3: In the case that a vehicle or an obstacle with a velocity lower than the pre-set velocity is recognized in the zone, the controller will fully cut the input torque to the wheels, which means the complete closure of the throttle, to decrease the speed. In this scenario, on a flat road, the main forces exerted on the vehicle are drag and rolling resistance forces, consequently, the rate of deceleration is concise.

Level 4: If the distance between the host and the leading vehicle reaches the emergency distance, the braking system will be activated. According to the experts, the amount of maximum safe deceleration for a normal driver is approximately 0.47 of gravitational acceleration and ACC must not employ more force while braking.

The consideration of the lateral forces and acceleration and noticing the surface circumstances are among other innovations of this research. According to previous studies, for a safe journey in a normal daily vehicle, there should be a limit for lateral acceleration for vehicle stability[20]. Due to differences in mechanical characteristics of each vehicle and road, there is no exact number to set the border of safety on that, although the majority of studies show that the maximum safe amount of lateral acceleration is about 80 to 90 percent of gravitational acceleration.

Due to the lack of an exact amount for the lateral acceleration limit, an optimization method was employed to reach the best possible amount for the lateral acceleration controlling unit. In this part, various driving scenarios were designed. In each state, parameters like velocity, steering angle, and turning period were altered. Finally, the optimum amounts of lateral acceleration for throttle and braking control were found.

In respect of the previous results, there is a section in the ACC controller that measures the lateral acceleration rapidly. In the first step, if the lateral acceleration passes a certain amount, which was optimized as illustrated, the throttle will be closed. This action will lead to smooth deceleration which will caused by all types of friction. However, because of any possible reason, for instance; increasing the steering angle from the driver, the lateral acceleration soars to more than the optimum lateral acceleration for braking initiation, and the brakes will kick in. It is worth mentioning that while these amounts are still in the safe zone for the vehicle, there must not be a harsh level of braking since an intense deceleration will deteriorate the comfort of the passengers.

Although the Adaptive Cruise Control system's main target is to control the longitudinal velocity of the vehicle, it is crucial to consider other aspects as well. Efficiency and Comfort are among these goals. It is logical to state that the rate of deceleration or acceleration has a direct relation with the comfort of passengers. On the other hand, in most braking systems, all the momentum that is taken from the vehicle while braking is transferred to heat, so in other words, using the brakes will be against efficiency. According to the statement above, in this research, it is tried to optimize comfort, efficiency, and safety relatively.

An important consideration in the topic of most ADAS technologies is the detection system. This system is made of various sensors, radars, lidars, and cameras which have to work accurately all the time. There is an important limit in the performance of these components; namely the range.

In the automotive industry applications, normally the maximum covering range for obstacle detection systems is

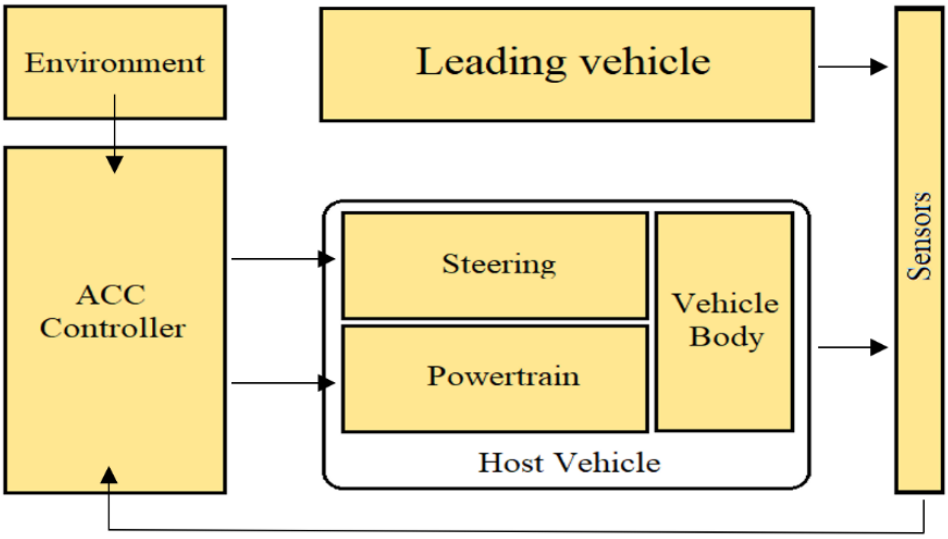

Fig. 4. A schematic of how vehicle components operate

about 250 meters. According to this matter, the ACC model proposed in this research is based on the limitations of all components, including all kinds of sensors and cameras. As it is demonstrated in Fig. 4, all the subsystems of the vehicle that were explained previously, have to work in a loop to perform the programmed orders from the controller.

Also, in Fig. 5 a schematic procedure of the decision-making algorithm in ACC controller is shown. The three major sections of this model are designed to work independently. In every time step that the ACC is switched on, the material circumstances are checked, whether the road is dry, wet, or icy. Also, the coefficient of friction and respectively maximum force able to be used in brake calipers are calculated. The other two sections, lateral motion and longitudinal motion control are demonstrated as well. It has to be mentioned that this flowchart is just a simplified procedure to understand the whole algorithm behind ACC, otherwise, the whole system has many complicated sections which are not shown in the picture.

4- Optimization

The purpose of this research is to design an ACC control strategy that provides safety, comfort, and efficiency at the same time. Acceleration and brake power, brake usage distance, and the relative distance of the vehicles in which the throttle enters the control mode are the parameters that are optimized.

One of the most important factors in designing systems is how they perform in terms of interaction with humans. The same stands true for ACC, the controlling method must avoid sudden changes in acceleration or deceleration. In other words, jerk, the amount of deceleration has to be minimized. The other crucial parameter which has to be minimized is the brake usage. In normal cars where regenerative braking systems are not widely employed, using brakes will cause a loss in kinetic energy of the vehicle so minimizing the usage of this parameter will help the vehicle to reach the optimum performance. As the third item, the best distance to start controlling the accelerator pedal is derived. This item will provide ACC with the highest velocity for the vehicle, which is safe and comfortable, simultaneously. Starting to decelerate in long distances will cause losing time and the same in short distances will endanger safety. Finally, Eq. (10) is the relationship that is optimized according to the priorities via MATLAB’s genetic algorithm. (Fig. 6)

$$f = c_1 \int^t (v(t))^2 dt + \frac{c_2}{\int^t |a(t)|\, dt} + \frac{c_3}{d(end) + \varepsilon} \quad (10)$$

5- Validation and Results

This section is divided into three different scenarios. The proposed ACC controller can operate in these scenarios interchangeably. The first scenario is designed to examine the conventional responsibility of ACC which means controlling the vehicle velocity according to the leading vehicle. In the second scenario, the effect of lateral acceleration is included and so the steering mechanism is utilized as well. Finally, in the third and last part, various surface materials were employed for the road surface and so the practicality of the ACC model is tested for various road conditions.

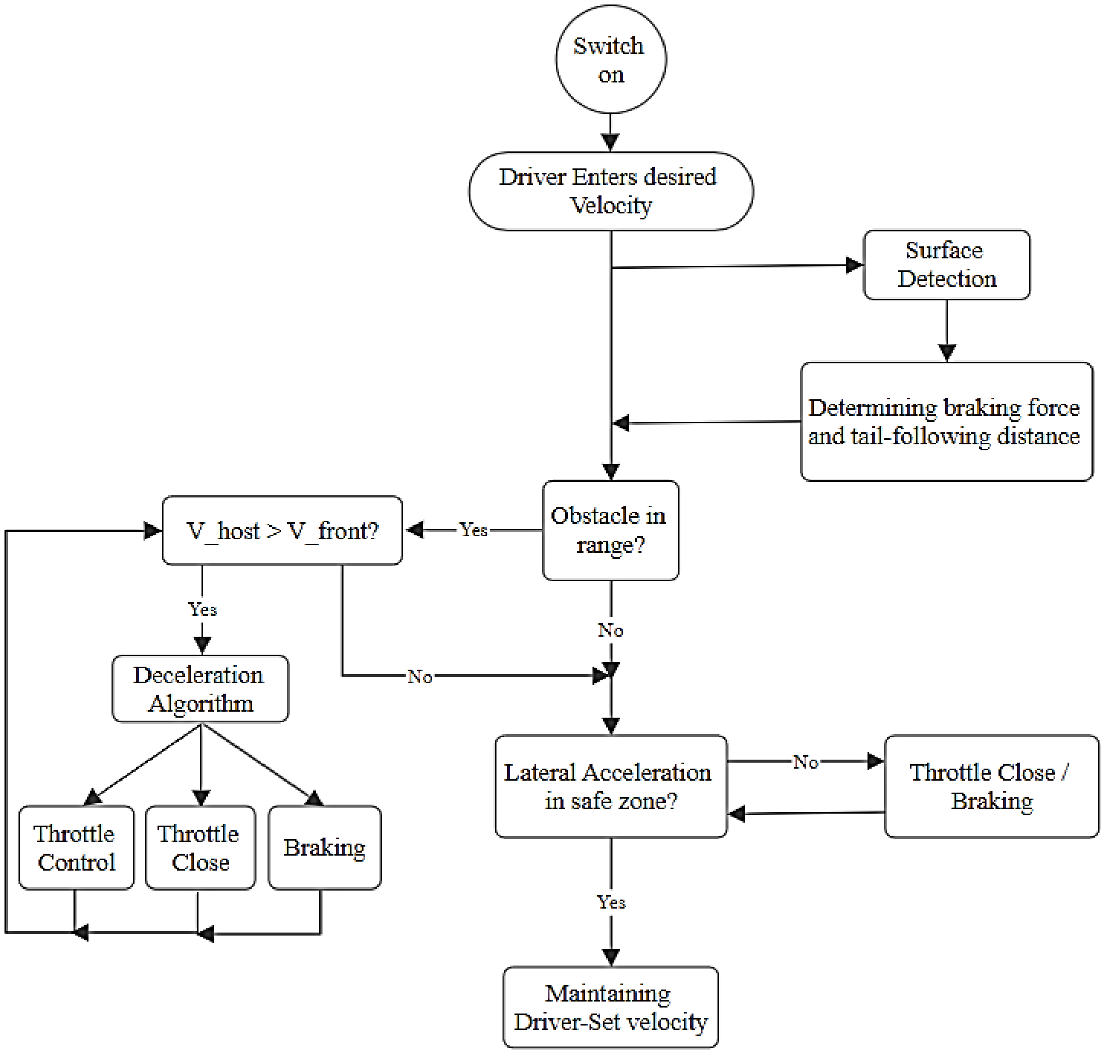

Fig. 5. A schematic flowchart for the proposed control algorithm

In this study, a conventional ACC model for validation is utilized. This model benefits from an optimized Model Predictive Control (MPC) method[21]. However, since the segments about lateral acceleration and surface condition are the innovation of this study, it is not possible to validate the new control algorithm with the MPC type.

Scenario 1: Since it is intended to test the performance of the ACC while reaching a certain level of traffic, two vehicle models are positioned on a straight road. While the host vehicle has to be located behind the leading vehicle, the initial distance between the two cars is set at 100 meters. Also, the initial velocity for the host vehicles is 20 meters per second, and for the front vehicle, it is set at about 30 meters per second. In Figures 7 and 8, the relative distance of the two vehicles and the acceleration of each vehicle are shown.

In the plots, it is clear that the approaching phase for both models was successful. However, it can be seen that the MPC model reaches the target more aggressively and with a higher average acceleration amount. However, the proposed ACC model shortens the distance between the host and the ego vehicle more smoothly. This action led to the lower amount of average acceleration which is obvious in Figure 8 and consequently, this lower amount of acceleration will result in a more comfortable experience for the passengers. Also, it is possible to see the extra stage of deceleration from the acceleration plot. For the first 9 seconds, the throttle controller is actuated. For the following 16 seconds, from 9 to 25 seconds, the throttle valve is completely closed, and finally, for the next 4 seconds the brakes are engaged.

Scenario 2: To analyze the performance of the ACC controller while cornering, the vehicle model is located on various road curves. Due to the limits, it is not possible to cover all the simulations in this article but a demonstration of the ACC reaction is shown in Fig. 9.

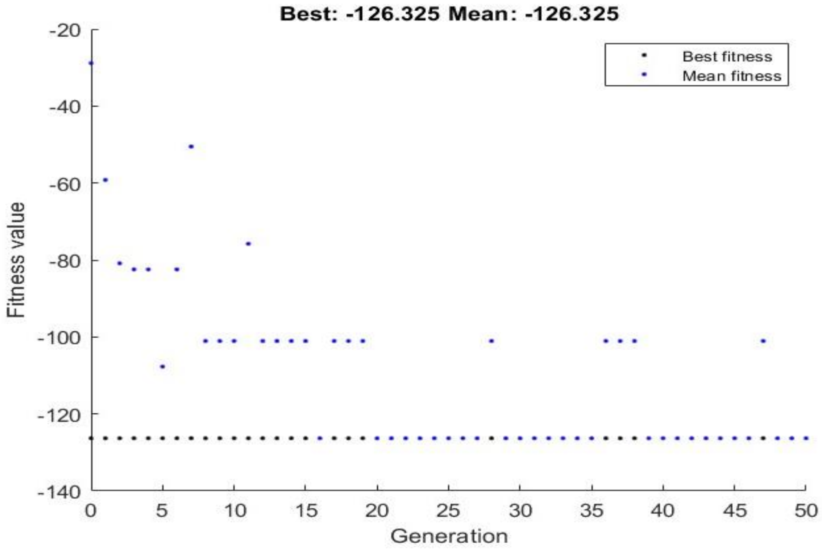

Fig. 6. The genetic algorithm results

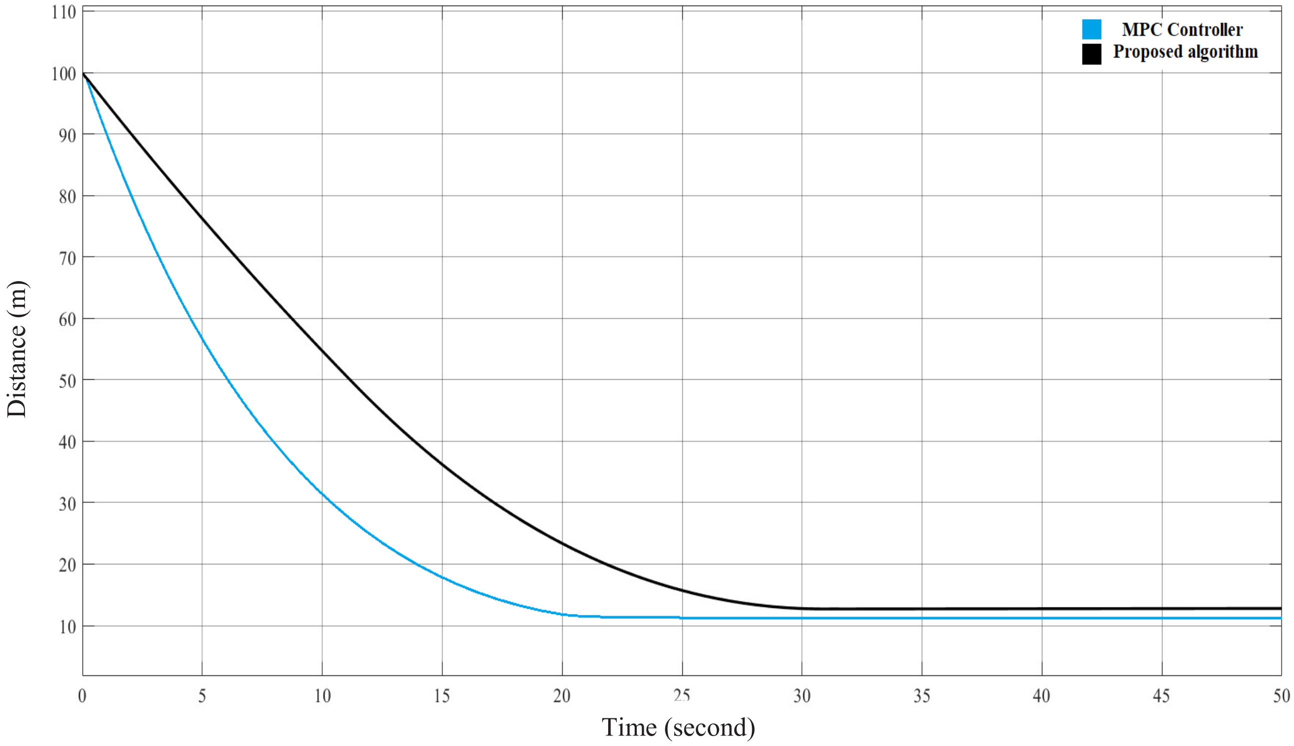

Fig. 7. Relative distance for two types of control method

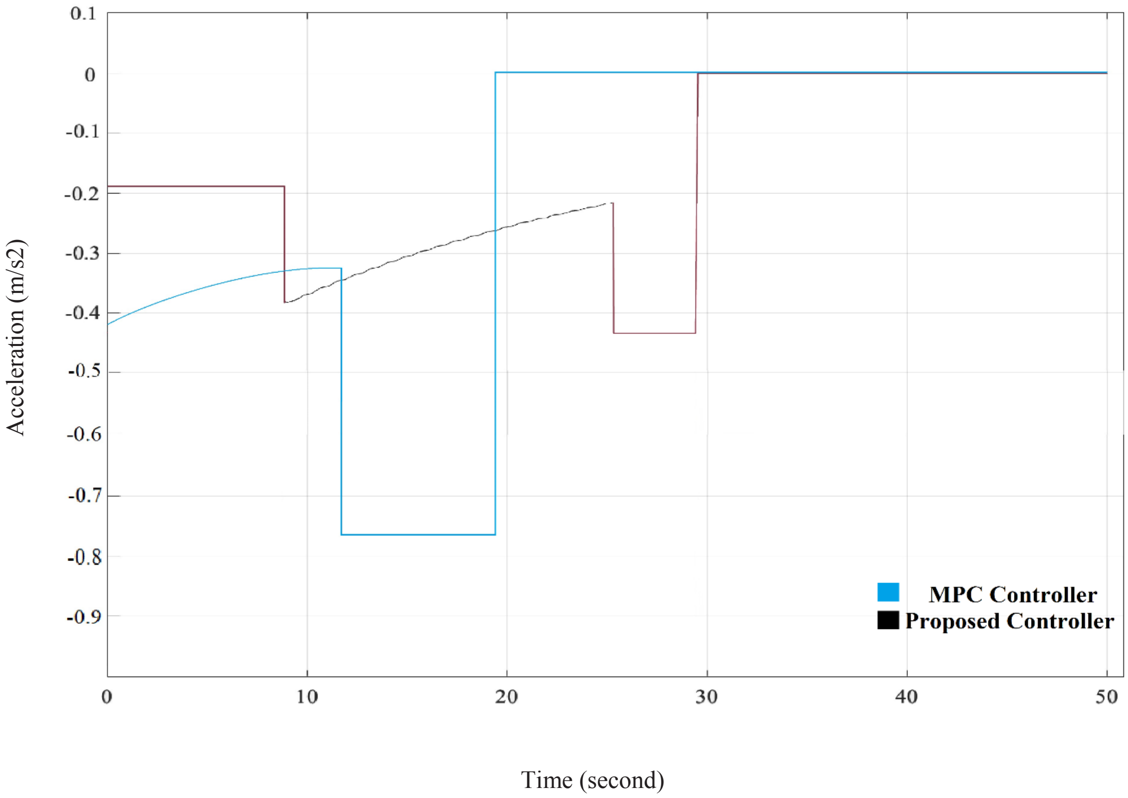

Fig. 8. Acceleration of the host vehicle in MPC controller and the proposed controller

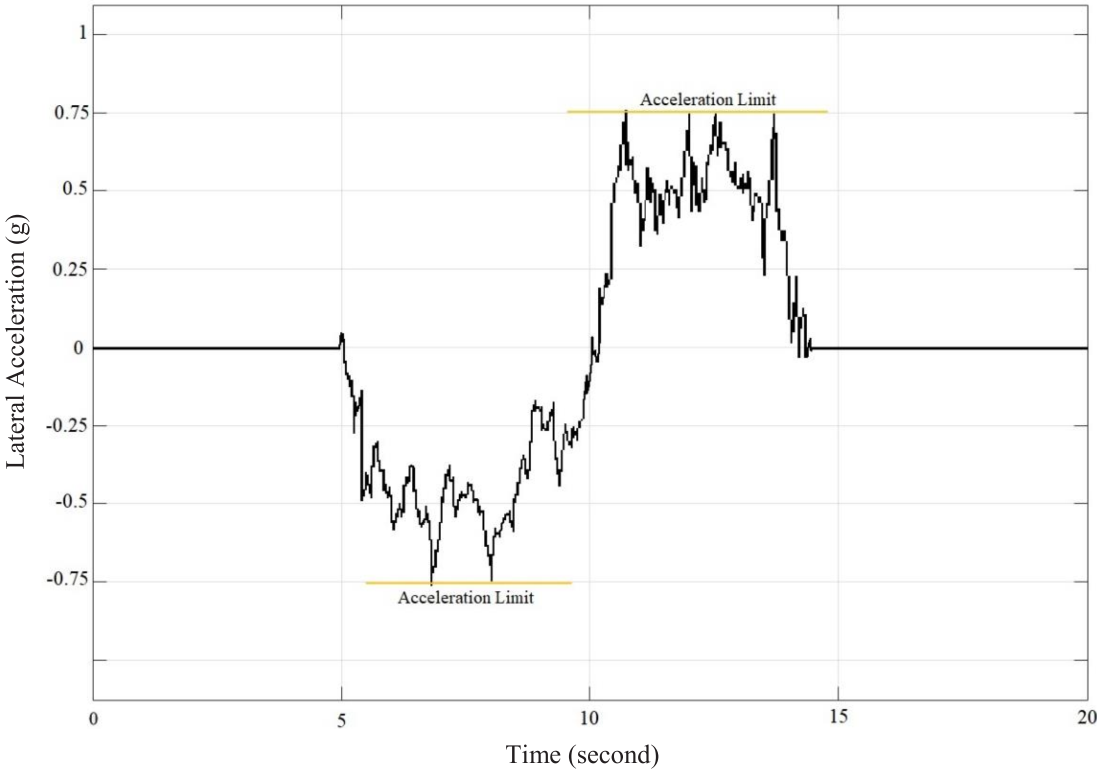

Fig. 9. host vehicle lateral acceleration

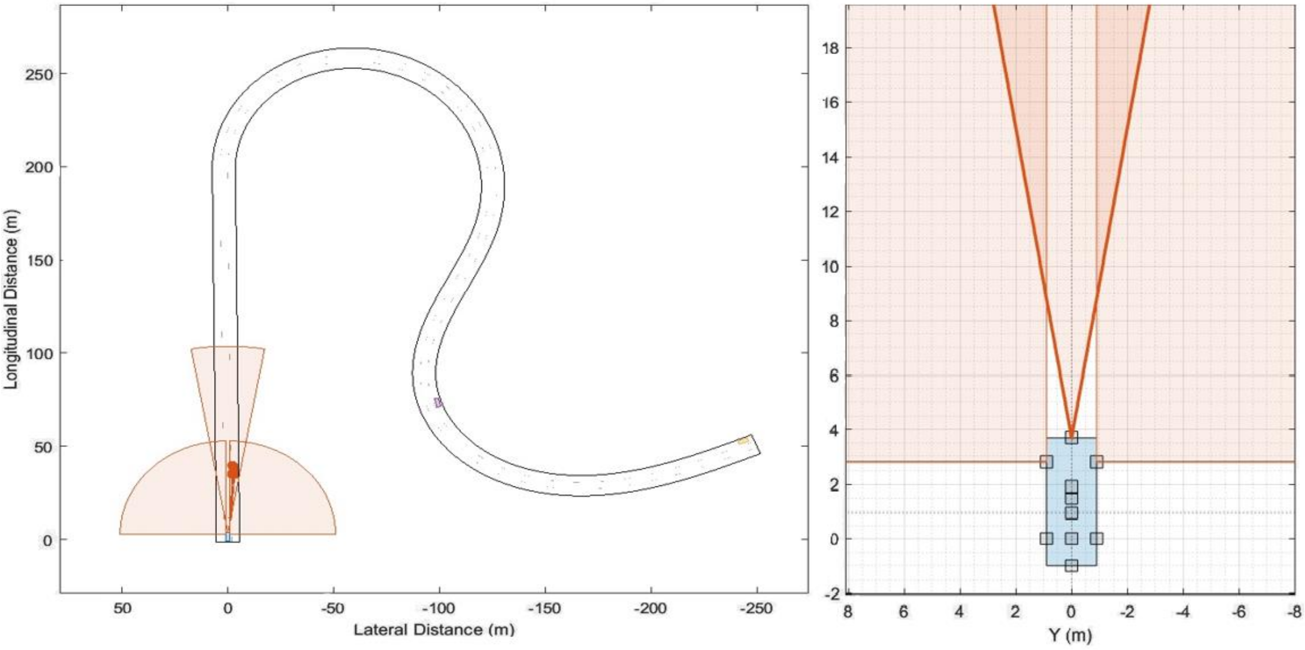

Fig. 10. Designation of road and sensor formation

Designing the roads and sensor formation were done in *Driving Scenario Designer/ MATLAB* [Fig. 10]. In various studies, the maximum safe acceleration for a normal passenger vehicle is about 0.8 to 0.9 of gravitational acceleration. Accordingly, the limit of lateral acceleration in this research is set at about 0.75 of gravitational acceleration. If the vehicles try to surpass this, the throttle will be closed simultaneously and also the brakes will be engaged.

In Fig. 9, it is seen that the control strategy operates at the limits perfectly. In this test, the steering wheel is turned by 15 degrees for 5 seconds on two sides, each by 5 seconds.

Scenario 3: The final section is devoted to the examination of the ACC controller respective to the road surface. While driving in colder seasons of the year it happens frequently that the asphalt surface turns to ice. The proposed model has to be able to react proportionally to each surface. The logic behind this program is to increase the tail-following distance from the leading vehicle and also, start decelerating sooner than dry road state. (Fig. 10)

In the following simulation, two separate states have been tested. The reaction of the system is proportional to each condition and these simulations are chosen as an example. In the first one, the surface material is assumed to be dry asphalt and the second state is simulated on an icy road. According to various data sources, it is reasonable to assume that black ice has a friction coefficient of 0.2. On the other hand, the friction coefficient is assumed to be 0.75 for dry asphalt. For both states, the initial distance is set at 500 meters.

Figures 11 and 12 illustrate how the Adaptive Cruise Control strategy reacts perfectly to various surface materials. It is clear that on an icy road, the tail-following distance increases about three times, from 5 meters in slow-flowing traffic to 15 meters in the same traffic condition. Also, the initiation of deceleration happens sooner. The throttle initiates about 2 seconds faster and the brakes kick in 3 seconds sooner.

Conclusion

In conclusion, our research has introduced a groundbreaking approach to adaptive cruise control, revolutionizing the way vehicles respond to diverse road conditions. By incorporating lateral acceleration and surface condition considerations alongside traditional velocity control. This model ensures a superior driving experience that prioritizes safety, comfort, and efficiency in unison. The comprehensive and dynamic control mechanism allows us to lower the average acceleration applied to the passengers by 40 percent average which is promising.

The successful integration of these factors not only enhances driving safety and passenger comfort but also contributes to overall driving efficiency. The usage of brakes in a normal driving scenario is minimized to 50 percent on average. Also on various road surfaces, the safe tail-following distance is optimized. For instance, this amount is tripled for black ice surfaces in comparison to dry asphalt.

Future research in this area could explore further refinements to the ACC model, considering additional environmental factors, such as inclement weather conditions and varying traffic densities. Additionally, investigating the implementation of machine learning algorithms for real-time

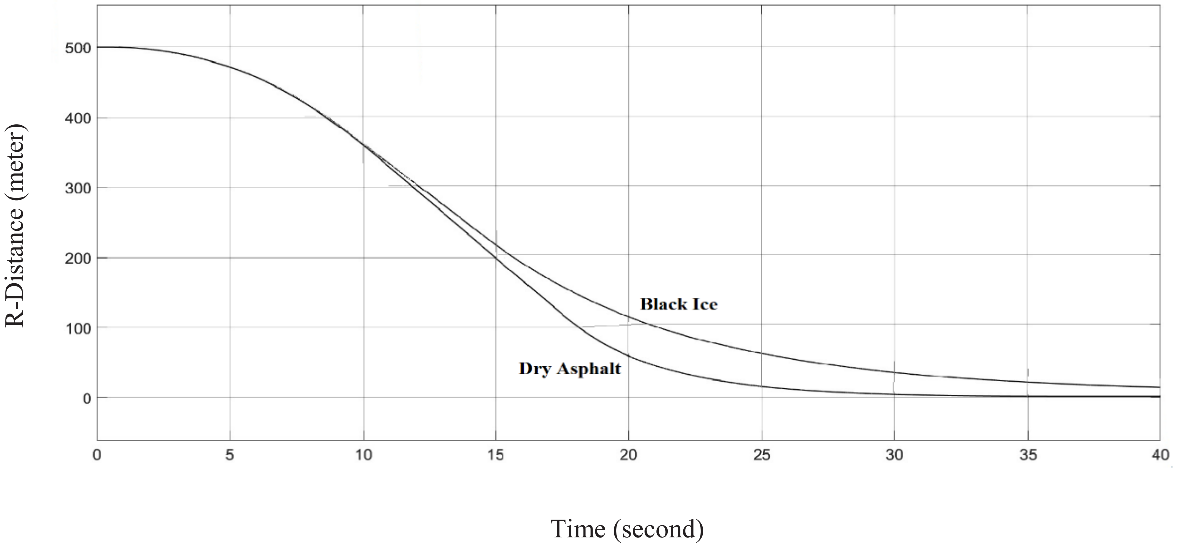

Fig. 11. Relative distance between vehicles for black ice and dry asphalt surface

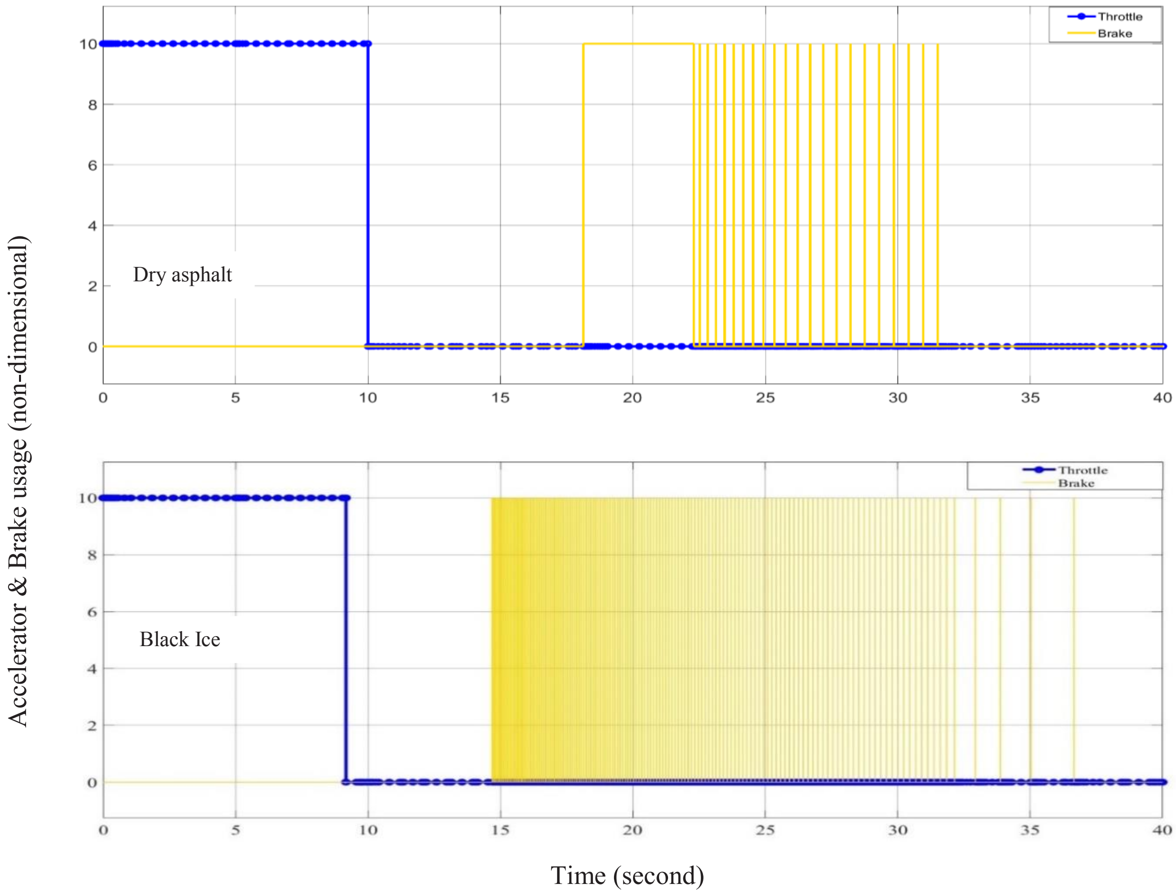

Fig. 12. Brake and throttle actuation for dry and icy asphalt surface

adaptation and predictive analysis could open new avenues for enhancing the efficiency and responsiveness of ACC systems. Moreover, exploring the integration of vehicle-to-vehicle communication protocols could foster collaborative driving environments, further improving the overall safety and efficiency of road transportation.

In summary, our work signifies a milestone in ACC technology, providing a robust foundation for continued exploration and innovation. By addressing the complexities of real-world driving scenarios, it is paved the way for a future where adaptive cruise control systems not only respond to changing conditions but also actively contribute to shaping the future of transportation**.**

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