Model in the Loop Optimization of Classic Cruise Control into Cooperative ACC

Mohamed Amine Tahiri[1*], *Aziz* Rachid[1], *Elhoussain* Saidi[1], and *Hicham* Bella[2]

[1]LSIB Laboratory, FST, Hassan II University of Casablanca, Mohammedia 28806, Morocco
[2]Mohammadia School of Engineering, Electrical Engineering Department, Mohammed V University, Rabat 10090, Morocco

Abstract. The introduction of Cruise Control revolutionized driving by maintaining a steady speed without constant accelerator adjustments. However, Cruise Control couldn't adapt to traffic conditions or maintain safe distances. Adaptive Cruise Control improved on this by using sensors to detect and adjust speed based on the car in front, adapting to traffic flow. Even with these technologies, the systems still struggle to manage the time interval during rapid changes in speed, which can lead to instability or even collisions. These problems are solved with Cooperative Adaptive Cruise Control by enabling communication between vehicles, to optimize speed and safety in real time. This paper presents a proof-of-concept design for longitudinal vehicle speed control following Model-in-the-Loop simulations. It aims to emphasize the shift from traditional cruise control to cooperative adaptive cruise control and exemplify the value and promises these strategies offer in modern vehicle systems.

1 Introduction

The automotive industry has witnessed significant advancements in recent years, highlighted by the rise of electric and hybrid vehicles, which have prompted a variety of research studies from improving testing methods to studying energy exchange strategies [1, 2]. However, alongside these advancements, the growing number of vehicles on the road has led to increased accidents and traffic congestion, posing significant challenges for circulation and transportation systems. Issues such as increasing accident rates, driver fatigue and distraction, along with energy-saving concerns, underscore the need for improved solutions [3, 4].

One of the most impactful future developments to address this issue is the emergence of advanced driver assistance systems (ADAS) and Vehicle-to-Everything (V2X) communication. ADAS, now commonly found in modern cars, use sensors to enhance safety and driving efficiency. Research literature has outlined various levels of automation (LOA) to help understand the changing role of humans in automated and autonomous driving systems [5, 6].

The initial driving assistance technology, known as Cruise Control (CC), was first introduced in the 1958 Chrysler Imperial [7]. Designed to maintain a steady speed set by the driver, it provided a basic level of convenience by reducing the need for continuous accelerator input, especially on long drives. However, despite its advantages, CC had significant limitations, particularly in adapting to changing traffic conditions. It was only capable of maintaining a constant speed and could not react to sudden slowdowns or road congestion. This inability to adjust to dynamic traffic environments raised safety concerns, as vehicles could fail to maintain a safe distance or contribute to disruptions in traffic flow. As traffic density grew and road networks expanded, these limitations underscored the need for more advanced driving assistance technologies capable of responding to real-time traffic dynamics. One significant improvement came with the introduction of Adaptive Cruise Control (ACC) [8].

ACC systems use sensors to continuously monitor the speed and distance of the vehicle ahead, automatically adjusting the speed to maintain a safe following distance. This capability significantly enhances safety and reduces driver fatigue, especially in stop-and-go traffic situations [9]. However, despite these improvements, ACC systems face challenges. Its reliance on maintaining a consistent time headway often struggled during sudden traffic speed changes, leading to shockwave effects that could result in rear-end collisions and destabilized traffic flow. To address these issues, the latest advancement in this domain is Cooperative Adaptive Cruise Control (CACC) [10].

CACC systems build on the capabilities of ACC by incorporating vehicle communication. This enables multiple vehicles to continuously exchange information about their speed, position, and acceleration, optimizing traffic flow and improving overall road safety [11, 12]. By reducing the time headway between vehicles, CACC achieves improved efficiency without compromising string stability, marking a significant advancement in intelligent transportation systems. Truck platooning, with minimized time gaps between vehicles, enhances transportation efficiency by reducing air drag and

* Corresponding author: medaminetahiri1@gmail.com

improving traffic flow. This strategic coordination among vehicles not only boosts fuel efficiency but also alleviates congestion, potentially revolutionizing contemporary transportation systems [13]. In the following chapters, we will delve into the various longitudinal control strategies, their goals, structure, and their control approaches. We will begin by presenting the vehicle model used in these simulations and understanding the key components and factors. Next, we will proceed to review the simulations conducted and the results obtained for each of the designed functions: CC, ACC, and CACC.
By analyzing these results, we aim to gain a deeper understanding of the applications and challenges associated with these functions. This examination of the obtained results will provide valuable insights into the effectiveness and performance of these functions in various driving scenarios, contributing to the ongoing advancements in intelligent transportation systems.

2 Vehicle overview and modeling

Creating a mathematical model of a car serves various purposes, such as predicting and analyzing its behavior, optimizing performance, and enabling simulation and testing without physical prototypes. To simplify the model, we focus on the main forces that influence the car's longitudinal motion, as shown in figure 1.

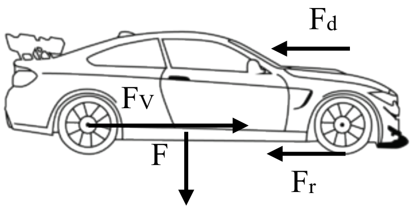

Fig. 1. Simplified dynamic vehicle model

2.1 Analysis of acting forces

We define the forces acting on the vehicle as shown in figure 1 :

- Aerodynamic Drag Force F_d:

$$F_d = \frac{1}{2}\rho C_d A(V - V_W)^2 \text{ linearized to } \rho C_d A(V - V_w) \quad (1)$$

where ρ is the air density, C_d is the drag coefficient, A is the cross-sectional area, V is the vehicle speed, and V_w is the wind velocity. This force increases with the square of the vehicle speed and affects the power required to maintain a certain speed.

- Rolling Resistance Force F_r:

$$F_r = f.m.g \quad (2)$$

where f is the rolling resistance coefficient, m is the mass of the vehicle, and g is the gravitational acceleration. This force is relatively constant at a given speed and contributes to the overall resistance the vehicle must overcome to maintain motion.

- Gravitational Force F_g:

If included, this would be $F_g = m.g.sin(\theta)$ (3)

Plant Mathematical Model

The system dynamics can be summarized as follows:

$$m.\frac{dV}{dt} = F_V - \rho.C_d.A.V_0\left(V - V_w\right) - f.m.g \quad (4)$$

Taking the Laplace transform:

$$m.S.V(S) = F_V(s) - \rho.C_d.A.V_0.V(s) + \rho.C_d.A.V_0.V_w(s) - \frac{f.m.g}{s} \quad (5)$$

Solving for V(s) in terms of F_V(s):

$$V(s)(m.s + \rho.C_d.A.V_0) = F_V(s) + \rho.C_d.A.V_0.V_w(s) - \frac{f.m.g}{s} \quad (6)$$

The transfer function from F_v(s) to V(s) :

$$G(s) = \frac{V(s)}{F_V(s)} = \frac{1}{m.s + \rho.C_d.A.V_0} \quad (7)$$

If we include the wind velocity V_w and rolling resistance force F_r :

$$V(s) = \frac{1}{m.s + \rho.C_d.A.V_0}\left(F_V(s) + \rho.C_d.A.V_0.V_w(s) - \frac{f.m.g}{s}\right) \quad (8)$$

Given the parameters P_i, we present them in the table I:

TABLE 1. SETTING WORD'S MARGINS

P_i	Value	Designation
m	1084 kg	Mass of the vehicle
ρ	1.2 kg/m³	Air density
C_d	0.3	Drag coefficient
A	2.24 m²	The frontal area of the vehicle
V_0	27.8 m/s (100kh)	Initial speed
f	0.0125	Rolling resistance coefficient
g	9.81 m/s²	Acceleration due to gravity

3 Conventional Cruise Control

3.1 Cruise Control Model

In this section, we utilize the Plant Model previously defined by equation (7). In the CC script, after running the model (figure 2), a prompt appears, requesting the user to input their desired speed in kilometers per hour (Kph). This input serves as the set speed for the vehicle. The value entered by the user is then stored in a variable for future use in the program. Additionally, to achieve optimal performance, the PID gain values can be obtained from the PID Tuner App, which assists in tuning the PID controller.

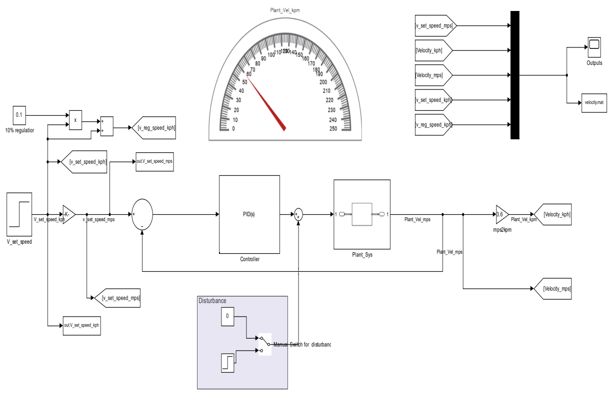

Fig. 2. Design of Conventional Cruise Control model

3.2 Simulation results

The light purple block represents the disturbance, which considers the weight of the plant as a function of the road incline angle (theta) as shown in equation 3. This disturbance factor is not considered in figure 3, which presents simulation results for a setpoint of 60 Km/h. However, in figure 4, we demonstrate a road disturbance of 2° at the 100 second mark, where we incorporate it into the system.

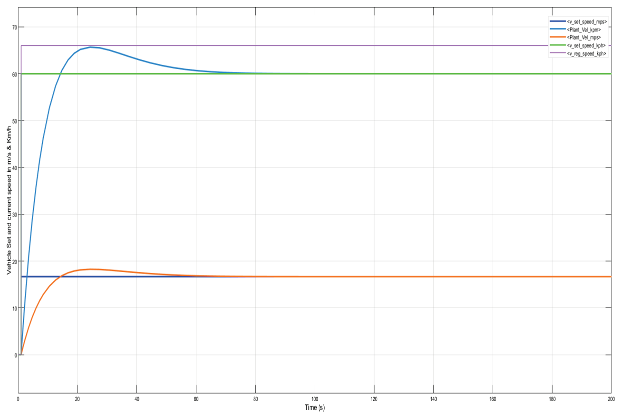

Fig. 3. Simulation results for CC System with a Setpoint of 60Km/h

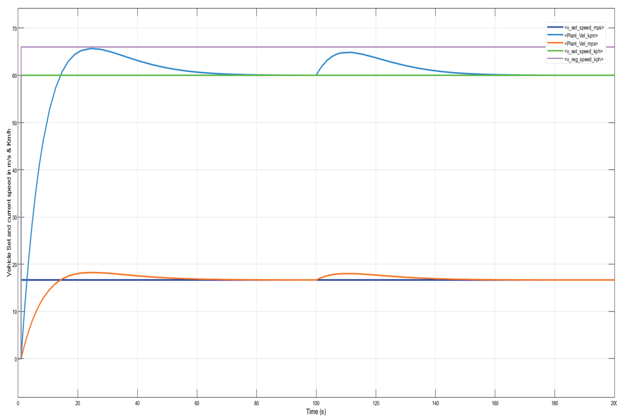

Fig. 4. Simulation Results for CC System with a Setpoint of 60 Km/h and incorporation of Road Disturbance step

The simulation shows that our cruise control system can effectively regulate vehicle speed, albeit with an initial overshoot and subsequent oscillations before stabilizing. However, these oscillations, as indicated in figure 3 and figure 4, remain within 10% of the regulated tolerance of speed cameras (Vreg_speed_kph), represented in purple [14]. This behavior is typical in control systems and indicates that the cruise control is functioning as intended. It successfully maintains the vehicle at the desired speed of 60 Km/h.

The problem with cruise control lies in its potential to create a false sense of safety, leading to driver complacency, especially in adverse weather conditions or during low-light situations such as night driving. When drivers overly rely on cruise control in these situations, they may become less attentive and fail to adapt to changing road conditions. This can be especially dangerous when sudden obstacles or reduced visibility arise. It is crucial for drivers to remain vigilant and actively involved in driving, even when using cruise control, especially in challenging meteorological conditions and during nighttime journeys. These factors have prompted the development of advanced cruise control systems ACC, which take into account these variables to enhance CC [15].

4 Adaptive Cruise Control

4.1 Cruise Control Model

Adaptive Cruise Control, when compared to classic cruise control, goes beyond merely maintaining speed. It utilizes perception sensors such as Long Range Radar and/or cameras to autonomously regulate the vehicle's speed and maintain a safe distance from other vehicles on the road. This ensures an efficient and secure driving experience. Figure 5 illustrates how ACC functions. [16].

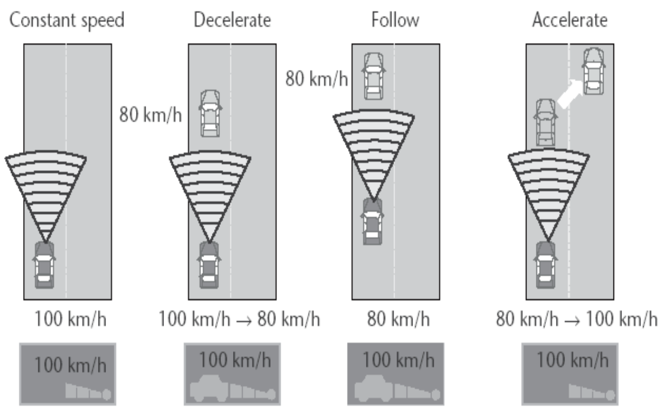

Fig. 5. Illustration of ACC Functionality [17]

The figure 6 represents the global block diagram of the designed ACC system. This system integrates the previous plant control architecture, which is shown in the central block simulating vehicle dynamics. The system's behavior is adjusted based on ACC commands and real-time conditions. The diagram shows various components and subcomponents, as well as input signals such as vehicle speed and data obtained from the "radar" block (figure 8). The ACC sub-block (figure 7) processes inputs to determine appropriate control actions and handles calculations necessary to maintain the desired speed and distance from the vehicle ahead. The plant adjusts the throttle and braking to maintain the desired speed and ensure safe distances from preceding vehicles. Feedback loops are used to continuously update the system for simulating dynamic adaptation to changing traffic conditions.

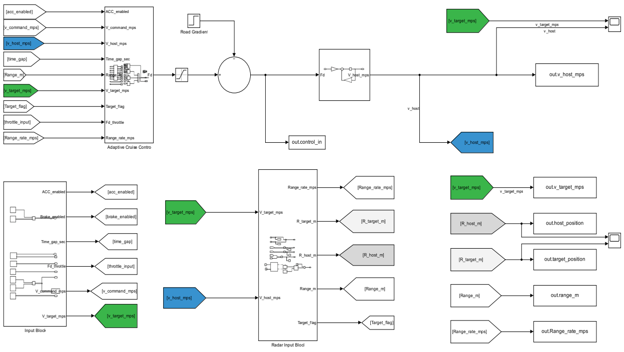

Fig. 6. Overall Model of Adaptive Cruise Control (ACC) System

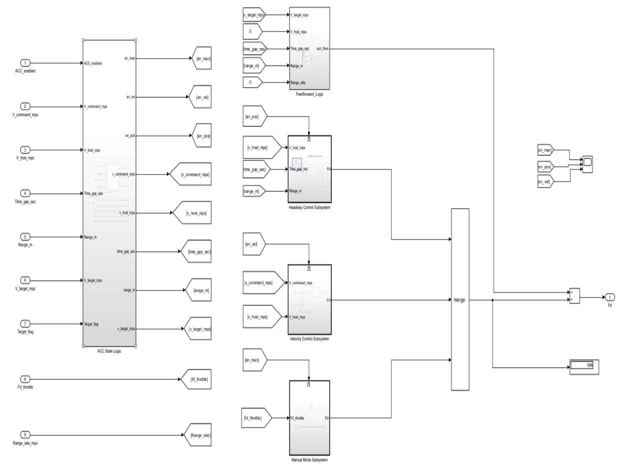

Fig. 7. Detailed Components of ACC Sub-Block

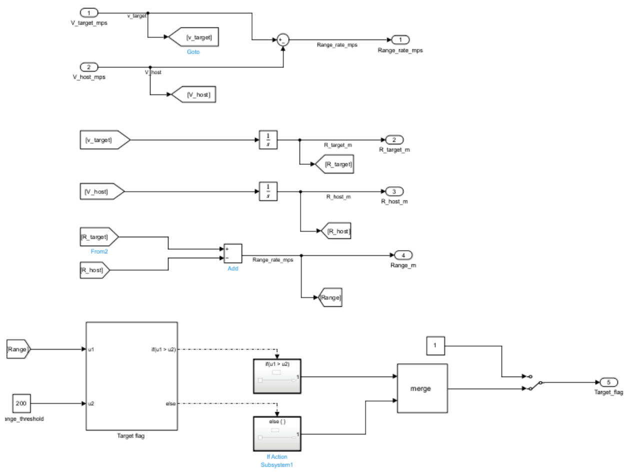

Fig. 8. Radar Input Processing Sub-Block in ACC System

4.2 Simulation results

In this section, we present the results of the ACC model simulation. The signal builder block allowed us to design a target vehicle speed change scenario. We set a target set point of approximately 100 km/h. Figures 9 and 10 present Scenarios 1 and 2, where we propose different scenarios for the target vehicle speed and evaluate the results. Figs. 11 and 13, respectively, present the target vehicle and ACC host vehicle positions over time for scenarios 1 and 2. Figs. 12 and 14 show their speeds, respectively. We can observe that the distance is maintained over time for every scenario.

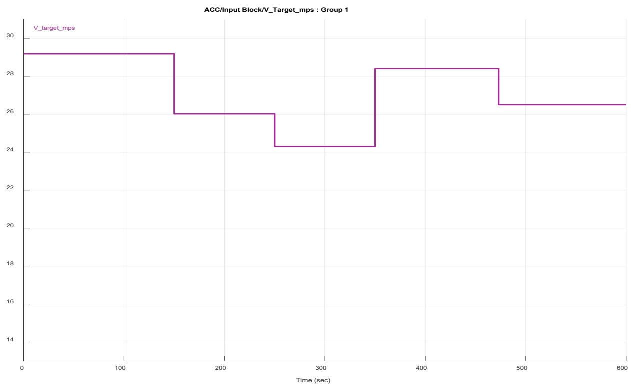

Fig. 9. Signal Builder Block for Scenario 1

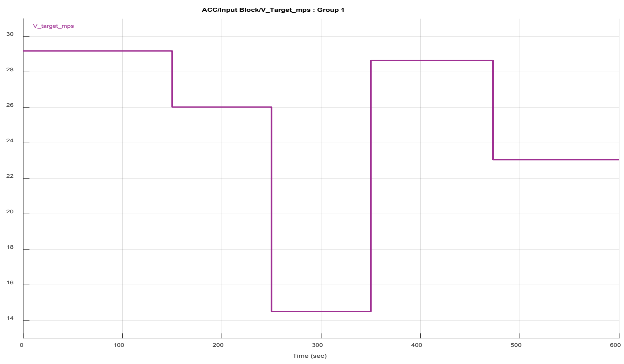

Fig. 10. Signal Builder Block for Scenario 2

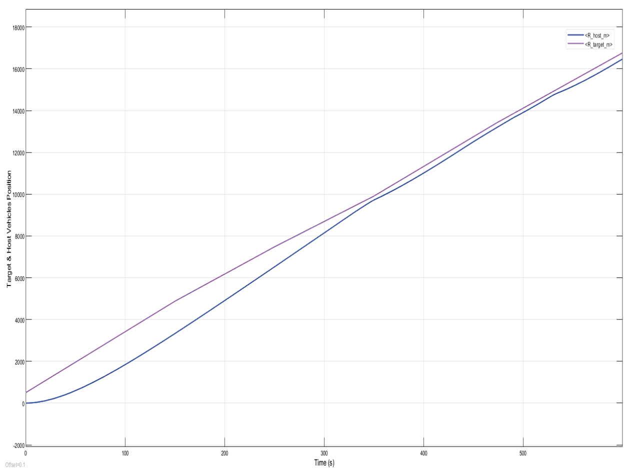

Fig. 11. Target & Host Vehicles Position over Time for Scenario 1

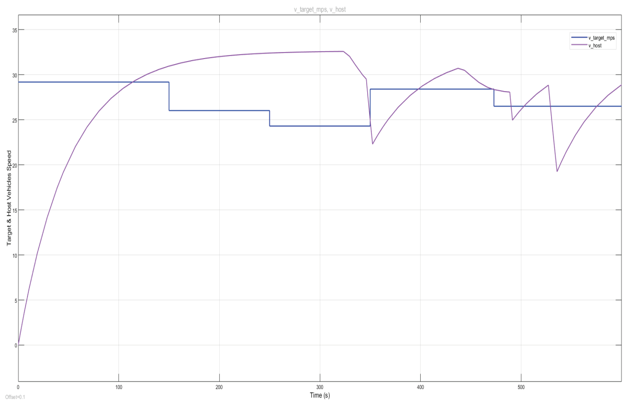

Fig. 12. Target & Host Vehicles Speed over Time for Scenario 1

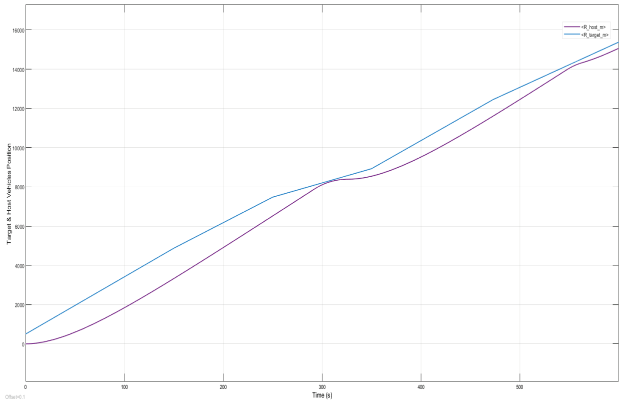

Fig. 13. Target & Host Vehicles Position over Time for Scenario 2

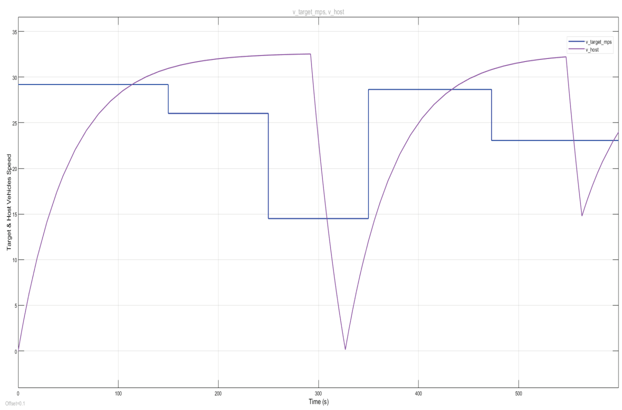

Fig. 14. Target & Host Vehicles speeds over Time for Scenario 2

From the results, we conclude that ACC offers significant advantages over traditional Cruise Control. IT not only maintains a set speed like CC but also adjusts the vehicle's speed to maintain a safe distance from the preceding vehicle. Despite the positive outcome observed in the designed system following strategy, figure 14 highlights that having vehicles with independent ACC systems may not result in a harmonious platoon formation. Thus, considering the implementation of CACC can significantly enhance control and coordination among the vehicles.

5 Adaptive Cruise Control

Cooperative Adaptive Cruise Control (CACC) is an advanced extension of Adaptive Cruise Control (ACC) that incorporates communication and cooperation among connected and automated vehicles (CAV). CACC enables coordinated maneuvers, such as platooning and merging, to optimize traffic flow and aerodynamic drag, save energy, and reduce pollutant emissions [18]. By closely following each other with minimal gaps, CACC-enabled vehicles can achieve aerodynamic drafting, which reduces air resistance and improves fuel efficiency. This, along with real-time data exchange and precise control, minimizes rear-end collisions and promotes smoother, more efficient driving. Overall, CACC represents a transformative technology that enhances safety, efficiency, and sustainability in transportation.

5.1 Information Sources and Topologies

The figure 15 illustrates a CACC system within vehicles labeled from 1 to n that communicate with each other to maintain safe distances and coordinated speeds. This inter-vehicle communication enables vehicles to react collectively to changes in speed and distance [19]. The system relies on continuous data exchange between vehicles, ensuring that each car can adjust its speed in response to the behavior of the others, leading to smoother and more efficient driving patterns.

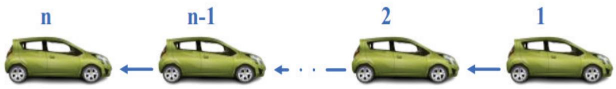

Fig. 15. System structure illustration of a CAV with CACC capabilities

5.2 Cooperative Adaptive Cruise Control Model

As discussed in earlier sections, both CC and ACC have their limitations in terms of string stability and harmonized platooning. To address these challenges, we propose a CACC model consisting of one leading vehicle and three following vehicles. Figure 16 presents this proposed CACC system, where the output of each vehicle serves as the input for the others. This system enables the sharing of position and acceleration information between the vehicles in the platoon, offering a potential solution to enhance string stability and achieve harmonized platooning, resulting in reduced air resistance, lowered gas emissions, and improved fuel efficiency.

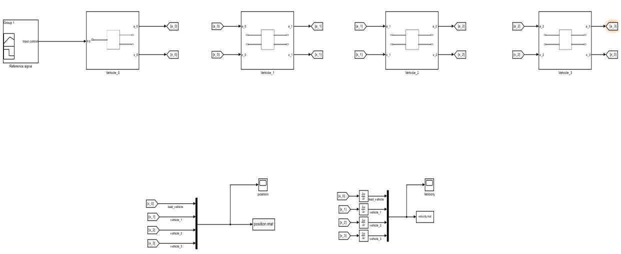

Fig. 16. Designed Model of a CACC System

5.3 Simulation results

The simulation results of the designed CACC system are presented in figure 18 and 19, figure 18 illustrates the positions of each of the three following vehicles compared to the position of the leader, while figure 19 shows the speeds of these following vehicles, highlighting how they adjust their velocities to maintain safe distances. The figure 17 below depicts the input command of the leader vehicle, ensuring safe and smooth operation within the convoy.

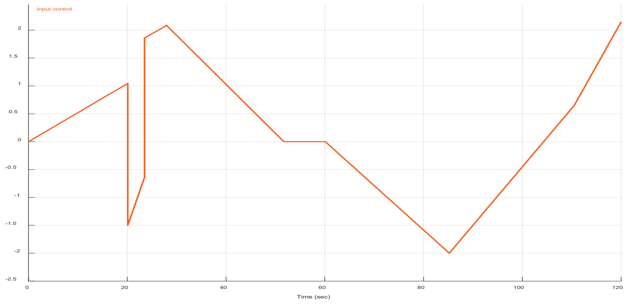

Fig. 17. Input command of the Leader Vehicle

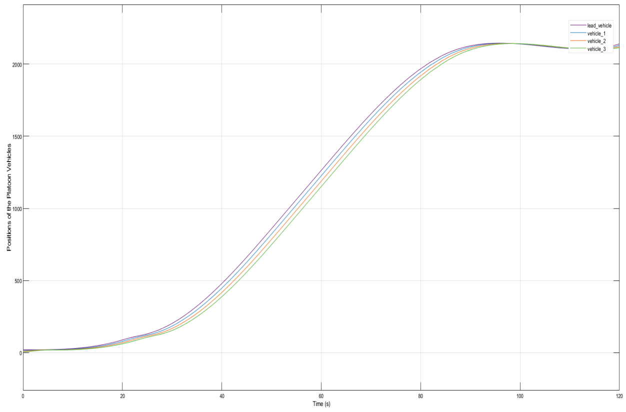

Fig. 18. Positions of the Platoon Vehicles

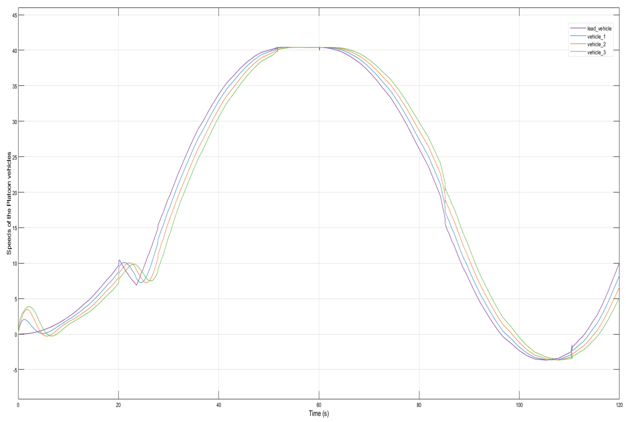

Fig. 19. Speeds of the Platoon Vehicles

Overall, we conclude that the CACC system effectively coordinates the movement and speed of the vehicles, ensuring a synchronized and efficient travel pattern.

6 Discussion

The transition from classic Cruise Control (CC) to Cooperative Adaptive Cruise Control (CACC) represents a substantial leap forward in vehicular control technology. This study highlighted the key differences between these systems: while CC maintains a constant speed, it falters in dynamic traffic conditions, ACC improves safety by adjusting speed based on the distance to the preceding vehicle but struggles with maintaining consistent headway during sudden speed changes. CACC, however, leverages real-time inter-vehicle communication to optimize traffic flow, improve road safety, and enhance fuel efficiency through coordinated platooning.

The simulation results underscore the limitations of CC and ACC, particularly in managing unpredictable traffic patterns. CACC stands out as a solution capable of synchronizing vehicle movements across a fleet, significantly reducing collision risks and promoting smoother traffic flow. This real-time communication between vehicles not only ensures a safer driving environment but also enables more efficient use of road infrastructure, which is crucial for addressing the increasing traffic congestion in modern urban areas. Beyond these immediate benefits, CACC's potential extends to a broader transformation of the transportation landscape. By enabling coordinated vehicle platooning, CACC can dramatically reduce fuel consumption and emissions, contributing to environmental sustainability. It also offers new opportunities for autonomous driving systems, where enhanced communication between vehicles will play a critical role in future smart cities and intelligent transportation systems.

7 Conclusion

In conclusion, the findings of this study reveal that CACC offers a scalable and effective solution to many of the challenges facing current traffic management systems. Future research should explore its integration with Vehicle-to-Infrastructure (V2I) technologies to enhance its effectiveness further. Additionally, implementing CACC across heterogeneous vehicle fleets and developing robust communication protocols will be essential to ensuring its reliability and widespread adoption. The ongoing development of CACC technology holds significant promise for revolutionizing the future of transportation and improving safety, efficiency, and sustainability in the automotive industry.

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