International Journal for Research in Engineering Application & Management (IJREAM)
ISSN : 2454-9150 Vol-09, Issue-03, June 2023

Adaptive Cruise Control System: A State of Art System for Advance Control, Safety & Performance Improvement

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Abstract: The adaptive cruise control (ACC) system is a driver assistance technology that has been gaining popularity in recent years. This paper presents an overview of the state-of-the-art in ACC system development, with a focus on the control, safety, and performance improvement aspects of the technology.

The paper reviews the key components of an ACC system, including sensors, controllers, and actuators along with the system configuration of ACC System, and discusses the various approaches to designing the control algorithms that enable the vehicle to follow the traffic in a safe and efficient manner. It also examines the system dynamics of ACC System and the safety features that are built into ACC systems to mitigate the risks of accidents and collision, such as collision warning and avoidance, and emergency braking. Along with the above, this paper also consists a MATLAB Simulation of ACC system using Model Predictive Control (MPC) and also the mathematical Equations & procedure used in MPC for ACC.

The paper also discusses the performance benefits of ACC systems, including improvements in fuel efficiency, traffic flow, and driver comfort and compares different control algorithm methods based on their advantages, disadvantages, features and case studies. It highlights the challenges and limitations of the technology, such as adverse weather conditions, sensor reliability, and system complexity.

Keywords – State-of-art system, system configuration, review of control algorithms, Model Predictive Control (MPC), MATLAB Simulation, system dynamics, performance analysis.

I. INTRODUCTION

Over the past few years, there has been a significant increase in the adoption of driver assistance technologies within the automotive industry, aimed at improving vehicle control, safety, and performance. One such technology that has gained popularity is Adaptive Cruise Control (ACC), which automatically adjusts the speed of a vehicle to maintain a safe following distance from the vehicle ahead.

Unlike conventional cruise control systems, which are useful for highway driving but less effective in heavy traffic, ACC has two modes of control - velocity and distance - that reduce the stress of driving in congested traffic. It uses laser or radar to measure the distance between the host vehicle and the vehicle in front. Low-speed ACC maintains the distance behind the obstacle vehicle and may require driver interference. High-speed ACC provides velocity control when there is no vehicle in front and controls the throttle and braking system to maintain the inter-vehicle gap when there is a slower vehicle in front.

ACC systems employ sensors, controllers, and actuators to monitor the distance and relative speed of the vehicle in front and adjust the vehicle speed accordingly. This technology has the potential to reduce driver fatigue, improve driver comfort, and enhance vehicle safety and efficiency.

This paper provides an overview of the state-of-the-art in ACC system development, focusing on the control, safety, and performance improvement aspects of the technology. It discusses the key components of an ACC system and the various approaches to designing control algorithms that enable the vehicle to follow traffic safely and efficiently.

The paper also examines the safety features built into ACC systems, such as collision warning and avoidance and emergency braking, to mitigate the risks of accidents and collisions. It highlights the performance benefits of ACC systems, including improvements in fuel efficiency, traffic flow, and driver comfort.

DOI : 10.35291/2454-9150.2023.0133

Moreover, the paper presents a detailed discussion of the ACC system's technology, which reduces the burden on drivers by controlling the acceleration and deceleration of their vehicles to maintain a set speed or avoid collisions. It uses obstacle detection equipment that detects the preceding vehicle using millimeter wave radar to estimate its future position based on the amount of offset from its path centerline. The paper also highlights the challenges in accurately estimating the position of the preceding vehicle on high-speed roads and the methods employed to solve this issue.

Overall, this paper provides a comprehensive review of the current state-of-the-art in ACC system development and highlights the potential for further research and innovation in this field.

II. SYSTEM CONFIGURATION OF ADAPTIVE CRUISE CONTROL SYSTEM

The configuration of an Adaptive Cruise Control (ACC) system can vary depending on the specific implementation, but in general, the following components are involved:

Sensors: The ACC system relies on sensors to detect the position, speed, and other relevant information of the subject vehicle and the surrounding vehicles or obstacles. The most common sensors used in ACC systems are radar and lidar sensors, which can measure distances and speeds with high accuracy.

Control Unit: The control unit receives input from the sensors and calculates the appropriate throttle, brake, or steering input to maintain a safe distance from the lead vehicle and follow its speed. The control algorithm used in the control unit can be based on different approaches, such as PID control, model predictive control, or fuzzy logic control.

Actuators: The actuators are responsible for implementing the control commands generated by the control unit. In an ACC system, the actuators can control the throttle, brake, and steering of the vehicle to adjust the speed and maintain a safe distance from the lead vehicle.

Human-Machine Interface (HMI): The HMI provides feedback to the driver about the status of the ACC system and allows the driver to set or adjust the desired speed, following distance, or other parameters. The HMI can include visual or auditory alerts, displays, or touch screens.

Power Supply: The ACC system requires a power supply to operate, which can be provided by the vehicle's battery or an external power source.

The exact configuration of an ACC system can vary depending on the vehicle model, the manufacturer, and the specific implementation. Some ACC systems may also include additional features, such as lane departure warning, automatic emergency braking, or pedestrian detection.

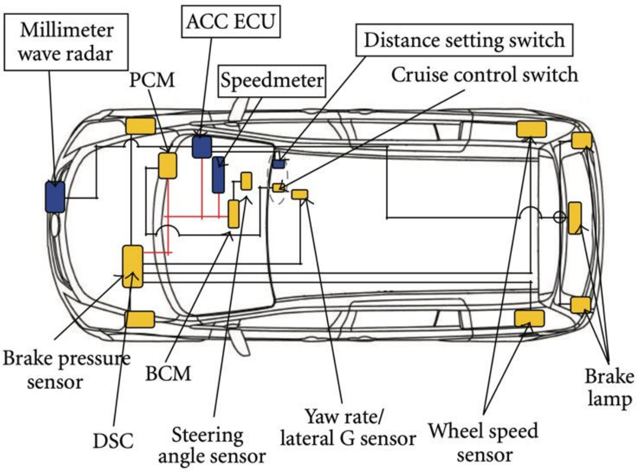

Fig 1: Typical ACC Layout

III. SYSTEM DYNAMICS OF ADAPTIVE CRUISE CONTROL SYSTEM

The system dynamics of an Adaptive Cruise Control (ACC) system can be described as the way the system behaves in response to changes in the environment, such as changes in the speed of the lead vehicle or the presence of obstacles.

In general, the ACC system uses a feedback control loop to adjust the vehicle's speed and maintain a safe distance from the lead vehicle. The feedback loop includes the following steps:

Sensing: The ACC system uses sensors, such as radar or lidar, to detect the position, speed, and other relevant information of the lead vehicle and other obstacles.

Perception: The sensor data is processed by the control unit to determine the distance and relative speed between the subject vehicle and the lead vehicle, as well as the presence of any obstacles or potential hazards.

Decision: Based on the sensor data and the desired speed and following distance set by the driver, the control unit calculates the appropriate throttle, brake, or steering input to adjust the vehicle's speed and maintain a safe distance from the lead vehicle.

Actuation: The control commands generated by the control unit are sent to the vehicle's actuators, which adjust the throttle, brake, or steering to implement the desired speed and following distance.

Feedback: The sensor data is continuously monitored and compared to the desired speed and following distance. If the feedback indicates that the system is not performing as expected, the control unit can adjust the control commands to correct the behaviour.

The system dynamics of an ACC system can be influenced by various factors, such as the response time of the sensors and actuators, the accuracy of the control algorithm, and the driver's behaviour and preferences. Optimizing these factors can improve the performance, safety, and user experience of the ACC system.

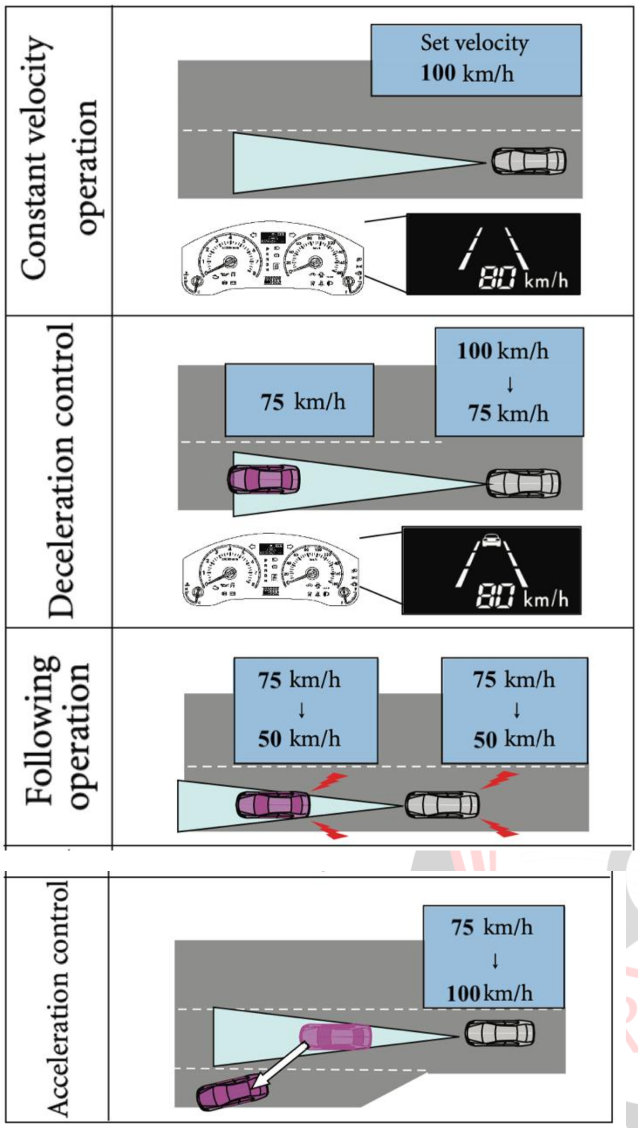

Fig 2: 4 Modes of Operation of ACC System (Const. Velocity, Deceleration, Following Operation, Acceleration)

IV. CONTROL ALGORITHMS USED IN ADAPTIVE CRUISE CONTROL SYSTEM

Adaptive Cruise Control (ACC) systems use a range of control algorithms to monitor the distance and relative speed of the vehicle in front and adjust the vehicle speed accordingly. These algorithms can be broadly classified into two types: classical control algorithms and intelligent control algorithms.

Classical control algorithms are based on mathematical models and are widely used in ACC systems. These algorithms use a set of equations to determine the desired vehicle speed and adjust it according to the distance and relative speed of the preceding vehicle. Examples of classical control algorithms include PID (Proportional-Integral-Derivative) controllers, which adjust the vehicle speed based on the difference between the desired speed and the actual speed, and LQR (Linear Quadratic Regulator) controllers, which minimize a cost function that captures the tradeoff between maintaining a safe distance and minimizing energy consumption.

Intelligent control algorithms, on the other hand, are based on machine learning techniques and are used to learn the control policy from data. These algorithms can adapt to changes in the environment and improve their performance over time. Examples of intelligent control algorithms include neural networks, fuzzy logic, and reinforcement learning. Fuzzy logic is particularly useful in ACC systems, as it can handle the uncertainty and imprecision associated with real-world driving conditions. Fuzzy control algorithms use linguistic variables to represent the input and output variables and apply fuzzy rules to determine the control action.

Thus, the choice of control algorithm depends on the specific requirements of the ACC system, such as accuracy, robustness, and adaptability. Classical control algorithms are widely used in commercial ACC systems due to their reliability and simplicity, while intelligent control algorithms are still in the research stage but hold promise for future applications in autonomous driving.

V. COMPARISION OF ADAPTIVE CRUISE CONTROL SYSTEM STRATEGIES

(CONTROL ALGORITHS)

Here's a comparison of the advantages, disadvantages, features and Case Studies of three adaptive cruise control strategies: PID control, model predictive control (MPC), and fuzzy logic control (FLC).

Proportional-Integral-Derivative Control (PID):

Advantages:

Simple and easy to implement.

Can provide good performance for simple ACC systems where the speed of the vehicle is the only controlled variable.

Disadvantages:

Not effective for complex ACC systems where multiple inputs and outputs need to be controlled simultaneously.

Can be sensitive to parameter tuning and may require significant adjustment to achieve good performance.

Cannot account for future changes in the driving environment.

DOI : 10.35291/2454-9150.2023.0133

Features:

PID control adjusts the throttle or brakes to maintain a set speed or following distance.

The control output is based on the error between the actual speed or distance and the desired speed or distance.

The control input is adjusted using proportional, integral, and derivative terms.

PID Control Case Study:

In a study by Zhang et al. (2017), a PID-based ACC system was developed and tested on a driving simulator. The results showed that the PID controller could maintain a safe distance between the subject vehicle and the lead vehicle, and reduce the driver's workload compared to manual driving. However, the system was sensitive to parameter tuning and could not handle complex driving scenarios.

Model Predictive Control (MPC):

Advantages:

Can account for future changes in the driving environment and can adapt to changing conditions.

Can optimize control inputs over a prediction horizon, leading to improved performance and fuel efficiency.

Can handle multiple inputs and outputs and can be used to control other variables in addition to speed and following distance.

Disadvantages:

Requires a model of the driving environment and the vehicle dynamics, which can be difficult to obtain and maintain.

Can be computationally intensive, especially for large prediction horizons or complex models.

Can be sensitive to parameter tuning and may require significant adjustment to achieve good performance.

Features:

MPC uses a mathematical model of the driving environment and the vehicle dynamics to predict the future behavior of the vehicle and the preceding vehicle.

The control input is optimized over a prediction horizon to minimize a cost function that depends on the future state of the system.

The control input is adjusted based on the predicted future behavior of the system and the desired trajectory.

Model Predictive Control (MPC) Case Study:

In a study by Wang et al. (2018), an MPC-based ACC system was developed and tested on a highway test track. The system used a mathematical model of the driving environment and the vehicle dynamics to predict the future behavior of the system and optimize the control input over a prediction horizon. The results showed that the MPC controller could maintain a safe distance between the subject vehicle and the lead vehicle, and adapt to changing driving conditions. However, the system was computationally intensive and required a model of the driving environment and the vehicle dynamics.

Fuzzy Logic Control (FLC):

Advantages:

Can handle complex and uncertain driving environments, as well as non-linear and time-varying systems.

Does not require a mathematical model of the system or the environment, making it more robust to changes and uncertainties.

Can be easily adapted to handle multiple inputs and outputs.

Disadvantages:

Fuzzy logic systems can be difficult to design and require expert knowledge to develop and maintain.

The rules and membership functions can be difficult to tune and optimize, which can affect the performance of the system.

FLC is typically less efficient than MPC and PID in terms of computational resources and response time.

Features:

FLC uses linguistic rules and membership functions to map input variables to output variables.

The rules and membership functions are based on expert knowledge or data-driven techniques.

The control output is adjusted based on the current and past values of the input variables and the rules and membership functions.

Fuzzy Logic Control (FLC) Case Study:

In a study by Abu-Qdais et al. (2019), an FLC-based ACC system was developed and tested on a driving simulator. The system used fuzzy logic rules and membership functions to map the input variables to the output variables. The results showed that the FLC controller could maintain a safe distance between the subject vehicle and the lead vehicle, and handle complex and uncertain driving scenarios. However, the system was less efficient than the PID and MPC controllers in terms of response time and computational resources.

Overall, these case studies demonstrate the strengths and weaknesses of different ACC strategies, and show that the choice of controller depends on the specific requirements of the driving scenario and the available resources. PID control is simple and easy to implement, but may not be effective for complex driving scenarios. MPC can handle complex driving scenarios and adapt to changing conditions, but is

DOI : 10.35291/2454-9150.2023.0133

computationally intensive and requires a model of the driving environment and the vehicle dynamics. FLC is robust to changes and uncertainties and can handle complex and uncertain driving scenarios, but is less efficient than PID and MPC in terms of response time and computational resources.

VI. IMPLEMENTATION OF MODEL PREDICTIVE CONTROL (MPC) IN ADAPTIVE CRUISE CONTROL SYSTEM

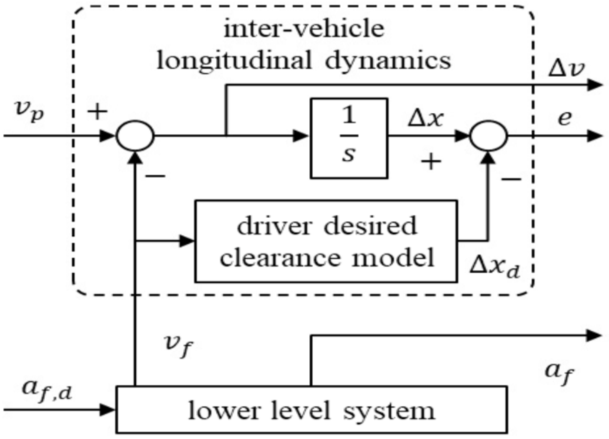

Fig 3: Model Predictive Control (MPC) Architecture for ACC System

Model Predictive Control (MPC) is a control method that is commonly utilized in Adaptive Cruise Control (ACC) systems to enhance vehicle performance, safety, and comfort. In an ACC system that employs MPC, a model of the vehicle's dynamics is utilized to anticipate the vehicle's future trajectory, and the control inputs are optimized to minimize a cost function that reflects the desired control objectives.

Compared to traditional PID-based control systems, MPC-based ACC systems have several benefits, including their ability to handle nonlinear and time-varying dynamics and incorporate restrictions on control inputs and state variables.

The MPC-based ACC system typically consists of a high-level controller that generates a reference speed profile for the vehicle based on traffic conditions and driver preferences. The lower-level controller then modifies the vehicle's speed and distance from the preceding vehicle based on the reference speed profile and the current vehicle dynamics.

In addition, the MPC-based ACC system can be designed to satisfy other control objectives, such as fuel efficiency, ride comfort, and safety. The control objectives may include maintaining a minimum safe following distance, avoiding abrupt speed changes or hard braking, and minimizing fuel consumption or CO2 emissions.

In general, the MPC-based ACC system is a promising technology that has the potential to improve vehicle control, safety, and performance in a variety of traffic conditions. However, the development and implementation of such systems can be difficult and challenging, requiring careful consideration of the system dynamics, control objectives, and constraints.

The MPC system input is the distance between the ACC system's vehicle and the vehicle in front. The ACC model predicts the preceding vehicle's future behavior and generates a control input that minimizes a cost function based on distance error, control input, and possibly other factors such as the controlled vehicle's speed.

The control input is then utilized to predict the vehicle's future state, which is passed through the cost function, and the process is repeated to produce a sequence of control inputs that optimize the cost function over a prediction horizon. A numerical optimization algorithm such as gradient descent or nonlinear programming is typically employed to carry out the optimization process. The final control input is then transmitted through an actuator that adjusts the speed of the controlled vehicle in the ACC system.

VII. MATHEMATICAL MODELING OF MODEL PREDICTIVE CONTROL (MPC) IN ADAPTIVE CRUISE CONTROL SYSTEM

The mathematical modeling of Model Predictive Control (MPC) in an Adaptive Cruise Control (ACC) system involves several components. The system uses a model of the vehicle dynamics to predict the future trajectory of the vehicle, and the control inputs are optimized to minimize a cost function that reflects the desired control objectives.

The input to the ACC model is the distance to the preceding vehicle, denoted as d. The ACC model predicts the future behavior of the preceding vehicle and generates a control input u that minimizes a cost function that depends on the distance error e, the control input u, and possibly other factors, such as the speed of the controlled vehicle.

The control input u is then used to simulate the vehicle dynamics, represented by the box in the middle, which predicts the future state of the vehicle, denoted by x. The predicted state is then passed through the cost function, which evaluates the cost associated with the predicted state. The process is repeated to generate a sequence of control inputs that optimize the cost function over a prediction horizon.

The optimization process is typically implemented using a numerical optimization algorithm, such as gradient descent or nonlinear programming. The final control input is passed through an actuator, which adjusts the speed of the controlled vehicle in the ACC system.

DOI : 10.35291/2454-9150.2023.0133

The overall mathematical model of the MPC-based ACC system includes the vehicle dynamics model, the cost function, the optimization algorithm, and the actuator model. The dynamics model represents the relationship between the control input u and the state of the vehicle x, while the cost function defines the desired control objectives and constraints.

The optimization algorithm solves the optimization problem defined by the cost function and constraints to generate the optimal control inputs over the prediction horizon. The actuator model represents the process of converting the control inputs into physical actions that adjust the speed of the vehicle.

In brief, the mathematical modeling of MPC in an ACC system involves integrating models of the vehicle dynamics, cost function, optimization algorithm, and actuator model to generate optimal control inputs that achieve the desired control objectives and constraints.

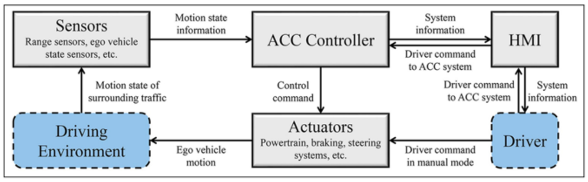

Fig 4: Typical Components of ACC Architecture

The mathematical equations used in MPC for ACC can be divided into two main components: the system model and the optimization problem.

System Model:

The system model describes the dynamic behavior of the vehicle and its environment and is used to predict the future behavior of the system based on the current state and control inputs. The system model for ACC typically includes the following equations:

a. Vehicle Dynamics Equations: The vehicle dynamics equations describe the motion of the vehicle and are typically represented by a set of nonlinear differential equations. The equations typically include terms for the vehicle's position, velocity, and acceleration, as well as external forces such as wind resistance and gravity.

b. Sensor Model Equations: The sensor model equations describe the relationship between the sensor measurements and the true state of the system. This includes equations for the sensor noise and bias, as well as the relationship between the sensor measurements and the position, velocity, and acceleration of the vehicle.

c. Environment Model Equations: The environment model equations describe the behavior of other vehicles and obstacles in the environment and are used to predict their future behavior. This typically includes equations for the position, velocity, and acceleration of other vehicles and obstacles, as well as their interactions with the vehicle of interest.

Optimization Problem:

The optimization problem determines the optimal control inputs that will minimize a cost function while satisfying a set of constraints. The cost function typically includes terms for the desired speed, following distance, and comfort, as well as penalties for deviating from these desired values. The constraints typically include limits on the control inputs, as well as safety constraints such as avoiding collisions with other vehicles and obstacles. The optimization problem can be formulated as follows:

$$\text{minimize } J(u) \text{ subject to } g(x,u) \leq 0$$

where J(u) is the cost function, u is the control input vector, x is the state vector, and g(x,u) is a set of inequality constraints.

The solution to the optimization problem provides the optimal control inputs for the current time step, and this process is repeated at each time step to achieve the desired performance.

VIII. MATLAB ANALYSIS OF MODEL PREDICTIVE CONTROL (MPC) IN ADAPTIVE CRUISE CONTROL SYSTEM

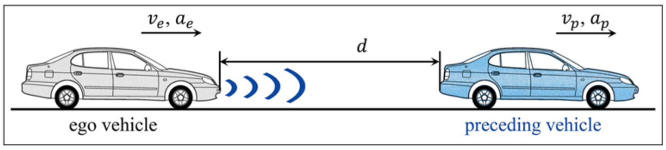

Fig 5: Virtual Model for Code

Matlab Code:

```
mdl = 'mpcACCsystem';
open_system(mdl)
Ts = 0.05;
T = 100;
G_ego = tf(1,[0.5,1,0]);
x0_lead = 55;   % initial position for lead car (m)
v0_lead = 27;   % initial velocity for lead car (m/s)
x0_ego = 12;   % initial position for ego car (m)
v0_ego = 24;   % initial velocity for ego car (m/s)
t_gap = 1.4;
D_default = 10;
v_set = 30;
amin_ego = -3;
amax_ego = 2;
sim(mdl)
-->Converting model to discrete time.
```

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```
-->Assuming output disturbance added to measured output #2 is integrated white noise.
   Assuming no disturbance added to measured output #1.
-->"Model.Noise" is empty. Assuming white noise on each measured output.
```

Plot the simulation result.

```
mpcACCplot(logsout,D_default,t_gap,v_set)
```

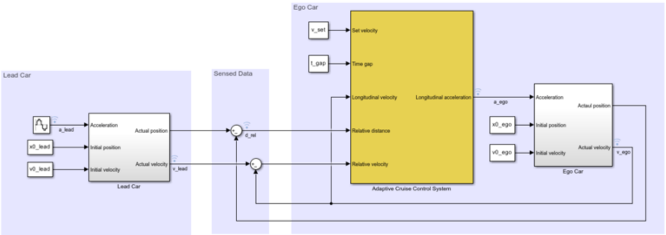

Fig 6: ACC System Block (MATLAB)

IX. RESULTS OF MATLAB SIMULATION

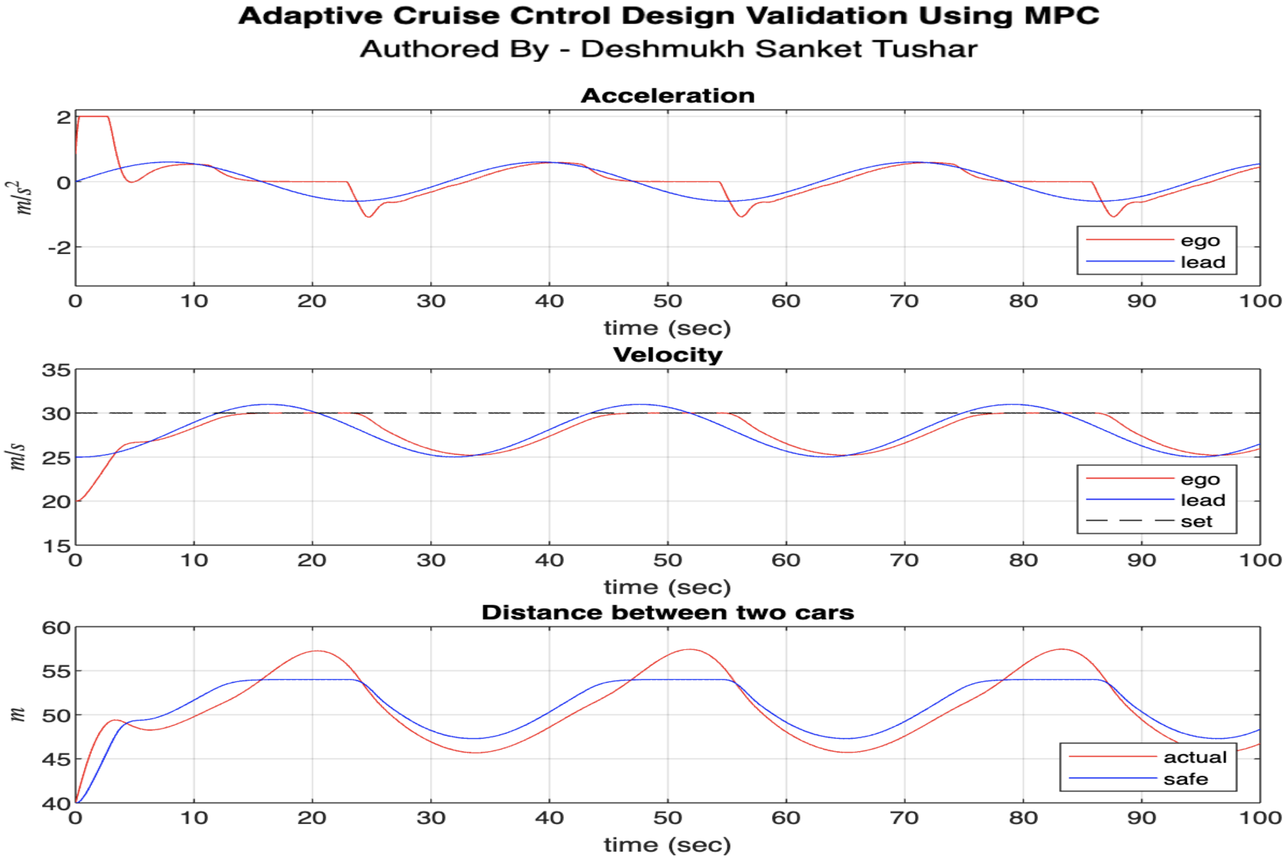

Fig 7: ACC Design Validation Using MPC

X. FUTURE DEVELOPMENTS IN ACC SYSTEM

Adaptive Cruise Control (ACC) systems are constantly evolving, and there are several potential future developments that could enhance their performance and capabilities. Here are a few examples:

Cooperative ACC: This involves vehicles communicating with each other to optimize their driving behavior. For example, vehicles could share information about their positions and velocities to coordinate their speeds and prevent unnecessary braking and acceleration.

Machine Learning: Machine learning techniques could be used to improve the performance of ACC systems. For example, machine learning algorithms could be trained to predict the behavior of other drivers and react accordingly.

Connected Infrastructure: Connected infrastructure, such as smart traffic lights and road signs, could be used to provide additional information to ACC systems. This information could be used to optimize driving behavior and reduce congestion.

Autonomous ACC: Autonomous ACC systems could provide even greater levels of control and safety. With an autonomous system, the vehicle could take complete control of the driving task, allowing passengers to relax or engage in other activities while on the road.

Energy Efficiency: ACC systems could be further optimized for energy efficiency, reducing fuel consumption and emissions. For example, the system could be designed to minimize unnecessary acceleration and deceleration, or to take advantage of traffic patterns to optimize speed and fuel consumption.

DOI : 10.35291/2454-9150.2023.0133

These are just a few examples of potential future developments in ACC systems. As technology continues to advance, it is likely that new innovations and improvements will be introduced that further enhance the capabilities and performance of these systems.

XI. CONCLUSION

Adaptive Cruise Control (ACC) is a state-of-the-art system that has revolutionized the way we drive. It has significantly improved control, safety, and performance, making driving a more comfortable and enjoyable experience. This system uses advanced control algorithms such as PID control, Fuzzy Logic Control, and Model Predictive Control to regulate the speed and distance of a vehicle from the preceding vehicle.

ACC systems have several advantages over conventional cruise control systems, including the ability to adjust to the speed of the preceding vehicle, automatic braking, and acceleration, and the ability to maintain a safe distance from the vehicle in front, even in stop-and-go traffic. Furthermore, ACC systems have been shown to improve fuel efficiency and reduce emissions, making them an environmentally friendly option.

As technology continues to advance, the performance of ACC systems will continue to improve, and they will become an increasingly common feature of new cars. Additionally, as more and more vehicles are equipped with ACC systems, we can expect to see significant improvements in traffic flow and congestion.

Overall, ACC is a game-changing technology that has significantly improved the safety, comfort, and efficiency of driving. Its continued development and integration into vehicles will undoubtedly lead to a safer, more efficient, and more enjoyable driving experience in the years to come.

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DOI : 10.35291/2454-9150.2023.0133