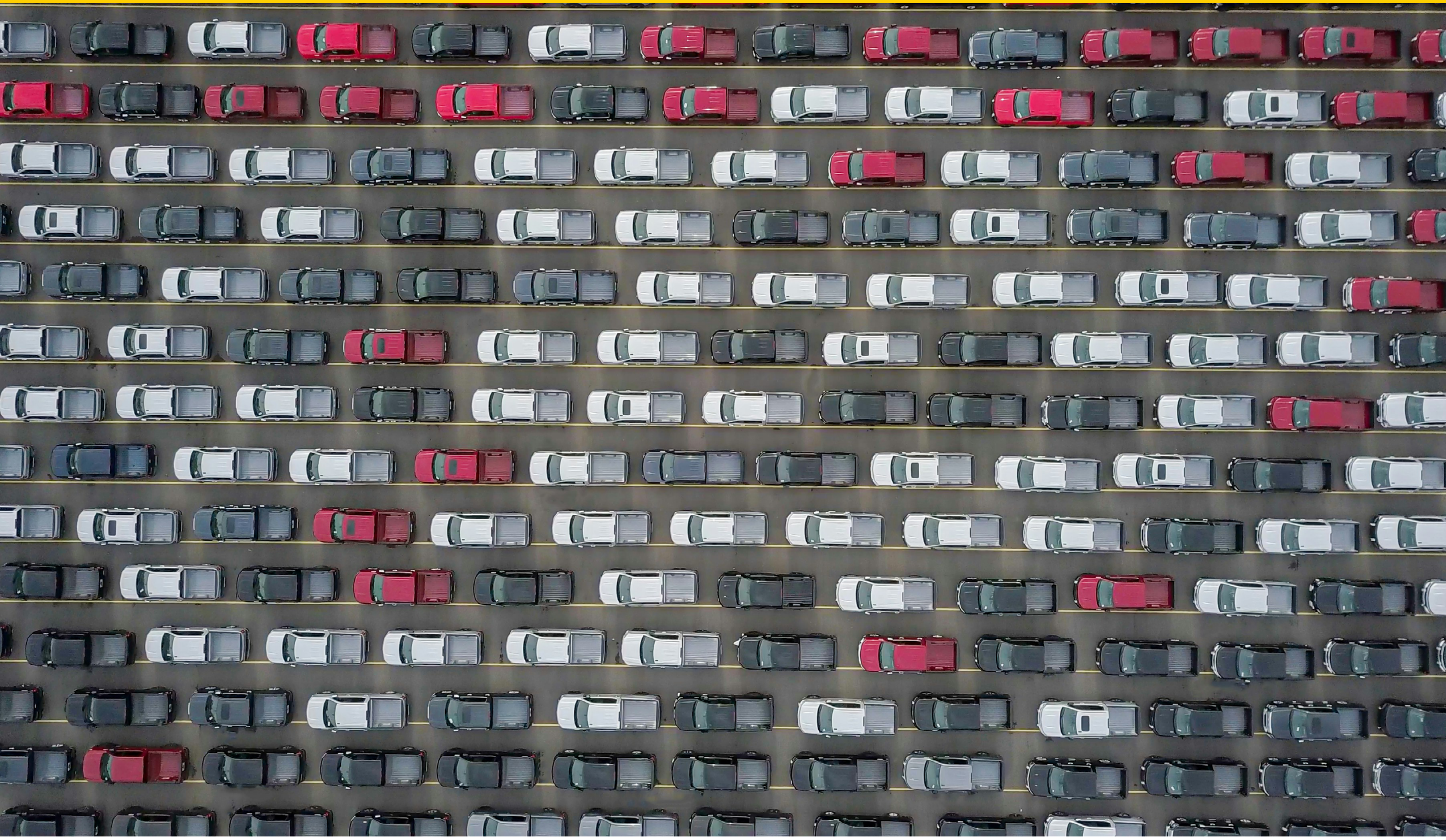
CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Final Report UA-CETran-2023-03
March 2024



Impact Analysis of Roadway Surface and Vehicle Conditions on Fleet Formation for Connected and Automated Vehicles

Dr. Ping Yi, PE
Tariq Alqubaysi

The University of Akron

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Report No.: UA-CETran-2023-03

August 2023

Project Start Date: 6-1-2021

Project End Date: July-30-2023

Impact Analysis of Roadway Surface and Vehicle Conditions on Fleet Formation for Connected and Automated Vehicles

by

Dr. Ping Yi, P.E.

The University of Akron

Tariq Alqubaysi, PhD Candidate

The University of Akron

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

DISCLAIMER

Funding for this research was provided by the Center for Connected and Automated Transportation under Grant No. 69A3551747105 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (OST-R), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Suggested APA Format Citation:

Contacts

For more information:

Dr. Ping Yi
Department of Civil Engineering
The University of Akron
Phone: 330-972-7294
Email: pyi@uakron.edu

CCAT
University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48152
uumtri-ccat@umich.edu
(734) 763-2498

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UA-CETran-2023-03	Leave blank – not used	Leave blank - not used

4. Title and Subtitle Impact Analysis of Roadway Surface and Vehicle Conditions on Fleet Formation for Connected and Automated Vehicles	**5. Report Date** August 31, 2023 **6. Performing Organization Code** Enter any/all unique numbers assigned to the performing organization, if applicable.
7. Author(s) Ping Yi, https://www.uakron.edu/engineering/CE/profile.dot?u=pyi ORCID: 0000-0003-3761-7162	**8. Performing Organization Report No.** **UA-CETran-2023-03**
9. Performing Organization Name and Address Center for Connected and Automated Transportation University of Michigan Transportation Research Institute 2901 Baxter Road, Ann Arbor, MI 48109 Department of Civil Engineering The University of Akron, Akron, Ohio 44325-3905	**10. Work Unit No.** **11. Contract or Grant No.** Contract No. 69A3551747105
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** DRAFT **14. Sponsoring Agency Code** OST-R

15. Supplementary Notes

Conducted under the U.S. DOT Office of the Assistant Secretary for Research and Technology's (OST-R) University Transportation Centers (UTC) program.

16. Abstract

Taking advantage of the rapid development of vehicle control and communication technologies, many studies have suggested that operating vehicles in platoons in the future would help improve the safety and efficiency of the transportation system.

Although vehicles in a platoon can share data from V2/V communication, a platoon model built on proper control laws is needed to keep the formation of the vehicle fleet and take the real advantage in platoon operations in an environment encompassing different pavement, roadway, and tire conditions. This research introduces a platoon model using a headway-based distance control policy to maintain stability and reduce errors in inter-vehicle spacing. After defining the stability condition and estimating the model parameters, simulation runs are carried out to show that the proposed model is able to keep a small inter-vehicle spacing, follow leader vehicle's speed, and adjust for changes in acceleration by all the vehicles in the platoon under the influence of vehicle characteristics and roadway frictions.

17. Key Words	18. Distribution Statement
Platoon operation, CAV Inter-vehicle spacing, control law, Stability analysis, Simulation	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	86	Leave blank – not used

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. Traffic Problems

Road transportation and traffic congestion have gained immense attention in the past decades amidst the development of cities as well as road networks. Of note, road transportation is an important aspect of an urban setting as it holds a significant socio-economic status in carrying out day-to-day activities (Olayode et al., 2020). This results in the increasing demand for better and improved transportation services and systems.

Over the years, the number of vehicles on the road have constantly increased, which leads to myriad problems in addition to traffic congestion, including environmental hazards, accidents, high level of energy consumption, high cost of infrastructural maintenance and land consumption for building roads (Abdul Jabbar et al., 2019). Among all the issues, traffic congestion is considered to be the primary concern as it not only causes disruption in movement but also leads to traffic delays, fuel and time wastage, and safety concerns.

Among the inevitable experiences in the highway system, traffic congestion and stop and go movements are largely due to the limitations of information access as well as the driving behaviors. The increasing need for mobility in the present time has resulted in significant changes in the transportation infrastructure and the development of more efficient and safer mobility systems. Among the key approaches in such changes is to combine communications with transportation management as an intelligent transportation system (ITS) to address many of the problems previously mentioned (Dimitrakopoulos and Demestichas, 2010; Zear, Singh, and Singh, 2016).

B. Intelligent Transportation Systems

Literature on intelligent transportation systems in recent years has given much attention to the automation of vehicles with much regard and importance to the infrastructure on which they operate. The first generation of urban automated cars and vehicles have been found to have limited sensory capabilities, being primarily confined to controlled environments with restricted interactions and low speeds (Berkeley, 2017). For these vehicles to provide complete transportation services, the development of specialized road markings, signal protected crossings, barriers, and curbs must be ensured to safely separate the automated vehicles from manual modes: pedestrians and bicyclists.

Vehicle intelligence refers to the application of mechatronics, sensors, and artificial intelligence (AI) technologies for the purpose of enhancing the performance of vehicles or making cars fully autonomous or driverless. The automation of driving tasks, such as obstacle avoidance, safe lane following, and traffic overtaking, are among some of the prominent functional benefits of an intelligent vehicle (Broggi et al., 2016).

C. Connected and Autonomous Vehicles

Connected and autonomous vehicles (CAVs) combine connectivity with automated driving technologies for the purpose of providing facilitation to humans in the task of driving or to completely replace humans in the driving process (Shladover, 2018). Connectivity in vehicles can be explained as the ability of the vehicle to share information with sources both within and outside of the vehicle. These sources can be other vehicles, road infrastructure systems, or any other connected source or network (Martinez-Diaz et al., 2021). This plays a crucial role in traffic management and safety along with addressing issues related to congestion, pollution, etc. The Society of Automotive Engineers International (SAE) has formulated five levels to explain the relativeness in the automation of vehicles. These levels begin from 0 (no automation) to 5 (full automation). A study revealed that replacing one manual vehicle with an autonomous vehicle can subtly moderate the speed of the human driven vehicle, which results in the better management of complex environments (Salter, 2022). Another study has found that with 100% penetration of autonomous vehicles in the traffic flow, 40% more vehicles can be accommodated without causing delays (Park et al., 2021).

1. CAV Platoons

With the help of communication and automated control technologies, it is possible to form vehicle platoons, in which vehicles can significantly enhance the capacity of highway system from the reduction in time headways among consecutive vehicles (Ghiasi A., 2018). CAV platoons can also assist in modifying driving behavior and controlling vehicle trajectories (Ma et al., 2016). The objective of control law is to regulate vehicle platoons, as spacing policy is the core of any platoon system that balances safety and efficiency and also plays a key role in fuel/energy consumption. There are two main types of control laws, the Time Headway Policy (THSP) and Constant Spacing Policy (CSP). With a proper control algorithm, spacing and speed oscillations can be dampened significantly and thereby reducing stop-and-go traffic.

D. Research Problems

Platooning is a part of the suite feature of connected and automated vehicles, which allows a group of vehicles to travel safely in the vicinity to each other and at high speeds. Each vehicle moving in a platoon can communicate with the other one, and a lead vehicle within a group controls the direction as well as the speed to which each car responds (Ali, Garcia and Martinet, 2013).

Vehicle platooning is an effective example of using wireless communication to facilitate a group of vehicles moving as a single unit with small time headways. This ultimately improves the highway capacity while enhancing travel safety through maintaining the traffic flow stability. Therefore, the first problem of this research is to devise a platooning control algorithm (i.e., a controller) for that purpose.

In addition, one of the key aspects in the formation of a vehicle platoon is the dependency against dynamic resistive forces. These forces come from the relevant factors, including vehicle dynamics, wheel dynamics, rolling resistance, aerodynamic drag, tire model, and brake/powertrain actuator dynamics during the stages of platoon modeling and control design (Hussein and Rakha 2022).

Subsequently, the second problem of this research project is to describe the string stability controller design enclosing complete vehicle dynamics under different vehicle conditions.

The external disturbances to the platoon operation should also be considered. The disturbances are from the road or other vehicles affecting a platoon, such as tire-pavement friction, vehicle mass, and roadway alignment. Also, aerodynamic resistance has been found to be a dominant environmental disturbance experienced by a platoon when travelling at a high speed. Still, the gravity force resulting from the roadway slope has been found to as the primary disturbance observed in vehicle platoon at a low speed (Kim, 2012).

Therefore, the third problem of this research is to analyze the performance of a vehicle platoon under the influence of various external disturbances.

E. Objectives of the Study

The main goal of this research is to analyze the longitudinal control and inter-vehicle distances in an autonomous vehicle platoon subject to disturbances .

With the intention of accomplishing the goal of this research project, the following objectives are considered:

- To develop/build a base control model for longitudinal inter-distances of vehicle platoons.
- To check the stability of the proposed model and calculate the spacing error function as well as its optimum parameters.
- To propose a theoretical algorithm that incorporates the vehicle dynamic characteristics in building the platoon model.
- To simulate the proposed algorithm under different vehicle conditions.
- To study how roadway and vehicle-based factors may impose disturbances to the platoon model.
- To investigate the performance of this platoon under the influence of disturbances (abnormal pavement conditions, braking system, and environmental factors, etc.).

II. LITERATURE REVIEW

The automated highway systems are assumed to have embedded prescribed highway lanes consisting of vehicles with complete automated brakes, steering, and throttles that can be controlled with a computer system. These new technologies can be equipped with adaptive cruise control (ACC), collaborative ACC (CACC) and a platooning system to allow vehicles to travel smoothly and reduce traffic congestion (Kim and Jerath, 2016). Van et al. (2003) propounded that the benefits of organizing the vehicles into platoons are common among small inter-vehicle distances. The reduction in inter-vehicle platoons can increase the traffic flow, reduce fuel consumption, and improve highway safety.

A. Platooning in Traffic

In transportation, platooning in traffic is the method of driving different vehicles together to increase the road capacity. The 2016 Highway Capacity Manual (HCM) articulated that platooning is important for traffic operations. It increases the flow rate when two or more vehicles form platoons. HCM defines platoons as a group of various vehicles that travel either voluntarily or involuntarily due to geometric, signal control, or other factors. Platooning occurs when a higher desired speed vehicle catches up with a slower speed, reducing the speed and urge to follow it to maintain the desired following distance. Traditionally, a platoon can also be referred to as vehicles that travel in a single lane with a specified distance from each other. However, contemporary studies use the term platoon to refer to autonomous vehicles while traveling on the highway. In platoons, vehicles are expected to travel with each other at generally the same speed by following the leader. Therefore, one of the important areas of research emerges, including autonomous highway platoons, where varied autonomous vehicles are restricted from each other in the form of platoons. A holistic setup of autonomous vehicles traveling together in a platoon is shown in Figure 1 below. The autonomous vehicles in the diagram are equipped with different onboard sensors, including sonar, radar, GPS, and others.

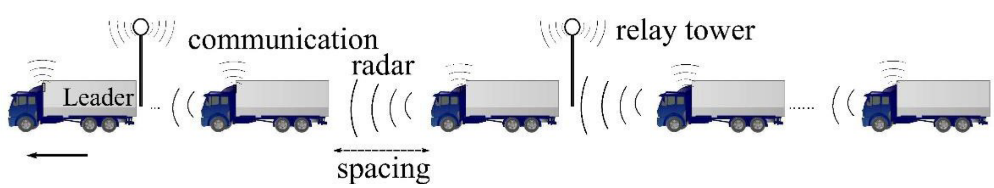


Figure 1 - Vehicle Platoon Set-up on Highway

Bhoopalam et al. (2017) articulated that traditionally platooning can be referred to as the way of reducing the air drag acting on the vehicles, fuel consumption, and others. However, the modernization of technology has led to much work on monitoring and controlling the platoon's vehicles, and advanced technology is revolutionizing the transportation industry in academia. Unfortunately, a gap exists in the literature related to other aspects of platooning, including truck platoons influence on other traffic, platoon formulation, and vehicle decision making in platoons for efficient traffic flow and other needs research. Therefore, the research aimed to fill some of these gaps.

Application of a platoon involves the vehicle driver's desired behavior that defines the distance between vehicles moving in the platoon. It is important to maintain stability in the platoon; thus, the concept of string stability is applicable. String stability requires information about distance error amplification along the platoon and shows the signs to avoid collisions. To understand platoons the following details are relevant.

1. Spacing Policy Types

Platoons follow distance-related policies that fall into different types. Current spacing guidelines can be divided into two main categories, including constant spacing and variable spacing (Swaroop and Huandra 1998). Interval policy attributes are summarized in the following subsections.

Constant Distance Policy: an ACC vehicle that uses Constant Distance Policy (CSP) will always maintain a constant distance to the vehicle ahead during ACC operation, regardless of the driving environment.

Variable Spacing Policy: Variable Spacing Policy treats the desired spacing as a function of ACC vehicle speed. The clearance policy can be classified into four main types according to the basic working mechanism. Time Clearance Based Clearance Policy, Traffic Stability Clearance Policy, Constant Factor of Safety Clearance Policy, and Human Driving Clearance Policy.

2. Evaluation Criteria for Spacing Policies

Evaluation of spacing policies in platoons is based on different criteria. Wu et al. (2020) described the following criteria used to assess the spacing policies.

- Individual vehicle stability must be guaranteed by the spacing policy and related control law.
- The selected spacing policy must have a companion, i.e., an ACC controller, to assure the string stability. The ACC vehicles' string stability in the platoon is a characteristic of the spacing errors emerging from the tail of the platoon as the divergence happens.
- The selected spacing policy must guarantee the traffic flow. The stability of traffic flow is interlinked with the particular spacing policy referred to as the macroscopic attribute of the traffic flow, which can be obtained through all vehicles following the specified spacing policy.
- The benefit of the spacing policy includes collision avoidance with the preceding vehicle due to unpredictable circumstances. This

particular criterion can impose comprehensive security constraints on spacing policy.

- The spacing policy must be comfortable for drivers and passengers. Discomfort can be avoided by maintaining similar driving patterns relevant to human driving behaviors.

B. Car Following Models

The car-following model is one of the favorable microscopic traffic models to describe vehicles' longitudinal interactions on the roadway (Zhang et al., 2021). A car-following model controls a simulated vehicular interactions with vehicles in front of the subject vehicle in the same lane, and a lane-changing model governs lane-changing decisions. In such a model, a driver's behavior is controlled by the preceding vehicle in the same lane (Olstam et al., 2004). Thus, the car following model defines how one vehicle is followed by another vehicle in uninterrupted traffic flow facilities. Different car following model theories have been developed to explain how a vehicle responds to the changes caused by the vehicle ahead.

The different theories of a car following models are based on the assumption that this model is the response to a stimulus. The foundation of any car following model is the response stimulus idea in which the following vehicle, vehicle B, responds to the stimulus provided by the front vehicle, denoted by A, as shown in Figure 2. Vehicles' longitudinal spacing is of huge importance and relevance to the level of service, safety, and capacity. A vehicle occupies the longitudinal space based on the physical dimensions of the vehicles and the distance between one and another.

To understand the car following models, Figure 2 provides a holistic overview of various notations used in car-following models. The figure is derived from Mathew (2009), which denoted the leader vehicle as n and the following vehicle as (n+1). The speed and location of the leader vehicle are denoted by v_{tn} and location by x_{tn}. In a similar context, the vehicle is expected to accelerate at the time period of t + ΔT, not solely t, and ΔT represents the time interval used by the driver to react to the changing circumstances. The difference between the follower and leader vehicle is then x_{tn} - x_{tn+1}.

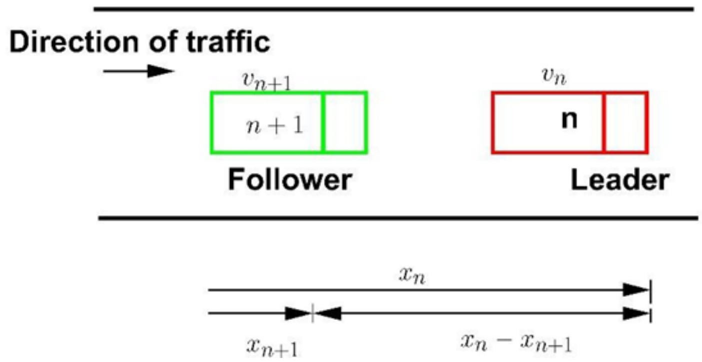


Figure 2 – Basic Assumptions of the Car Following Model Theory

As illustrated previously, car following theories describe the vehicle following condition in an uninterrupted flow. Different models have been formulated to show the driver's reaction to the changes in condition of the position of the leader vehicle. The different models include General Motors, Forbes, Pipe, and the Optimal velocity model, which are discussed below.

1. Pipe Model

The pipe model is based on the assumption that a good rule for following another vehicle is for the user to maintain a safe following distance between its vehicle and the vehicle in front. In the pipe car-following model, the minimum safe distance increases proportionally with speed. The drawback of this model is that at low speeds, the minimum vehicle-following distance proposed by the theory is significantly smaller than the corresponding field measurements (Mathew, 2009).

2. Forbes Model

The Forbes model takes into account the reaction time it takes for the following vehicle to slow down and perceive the need to brake. The time between the leader's back bumper and the follower's front bumper should be greater than or equal to the reaction time. The minimum lag is then the time it takes the lead vehicle to travel a distance equal to its length plus the reaction time (minimum lag). The shortcomings of this model are similar to those of the Pipe model. There is a big difference between high speed and the shortest distance (Mathew, 2009).

3. General Motors' Model

The most discussed model is the General Motors model relevant to the car following theories due to differences as explained by Mathew (2009), given below.

- Field data Agreement or Association; the simulation models show a good relation to the field data as discussed by the General Motors car-following model.

- Mathematical relation to the macroscopic model; Greenberg's logarithmic model related to velocity density mapping can be developed from General Motors model cars.

4. Optimal Velocity Model

As the name indicates, in the optimal velocity model, every driver tries to achieve an optimal velocity based on the distance with the preceding vehicle and differences in speed between the two vehicles. This model was an alternative approach explored in contemporary times in the car following models (Mathew, 2009).

C. Intelligent Vehicles

Automatically controlled vehicles are required to implement the Automated Highway System (AHS). Automobiles are becoming intelligent in the current time because of the increased use of electromechanical sub-systems, communication systems, sensors, actuators, and feedback control. Advancements in solid state electronics, computer technology, control systems, and sensors have revolutionized the production of vehicles. In the last two decades, intelligent transportation systems resources and technologies have gradually become available for field implementations. Among the different vehicle control systems developed, this research effort concentrates on the design of the two most basic control systems: longitudinal control and lateral control.

D. Autonomous Vehicles

Vehicles that can drive themselves are autonomous. Litman (2014) articulated that autonomous vehicles have various automated functions, including determining the vehicle position, reading road signals, tracking other vehicles, and more. That enables automated vehicles to be driven with or without human interaction. In other words, self-driving cars can be defined as driverless or robotic vehicles. They operate with programmed instructions enabling them to navigate streets, highways, and freeways as normal humans do. Such advanced technology is similar to the autopilot mode in which pilots engage airplanes while flying. While planes cannot take off and land on autopilot mode, autonomous vehicles can start the engine, maneuver to prescribed locations, and stop and turn off the engine. Many automobile manufacturers have produced autonomous vehicles and have carried out a series of test runs over 500,000 miles on major highways. A brief view of autonomous vehicles and their functions follows.

Autonomous vehicles can be programmed to avoid breaking traffic laws. They can also be instructed to optimize fuel consumption, ensure smooth traffic flows, and reduce emissions. Autonomous vehicles can deliver unlicensed travelers and goods to their destinations in a safer way while taking comparatively less time. It is right to say that autonomous vehicles can affirm the role of autonomous technology in the economy, society, and mobility.

5. Levels of Autonomous Vehicles

There are different technology levels of autonomous vehicles. According to different researchers, including Talebpour and Mahmassani (2016), Mahmassani (2016) and Bagloee et al. (2016), six different incremental levels of technology for automated vehicles have been defined by the U.S. National Highway Traffic Safety Administration. These levels are discussed below and shown in Figure 3:

No Automation (Level 0): This level refers to vehicles fully controlled by the driver, and the driver is the only decision-maker. According to Mahmassani (2016), in such vehicles, the commands and control, including braking, steering, motive power, and throttle, reside with the driver. The monitoring and execution of commands are considered the responsibility of the driver.

Function Specific Automation (Level 1): This is the automation level where at least one control function of the vehicle is automated. In this automation, as discussed by Bierstedt et al. (2014), the driver is assisted with a medium level of automation with braking or stability control. Electronic stability and Lane adjustment are the main highlights of this type of automation. Function-specific automation is already present in standard higher-end cars, and it is also known as a driver-assistant function.

Combined-Function Automation (Level 2): Combined-function automation is the type of automation consisting of at least two vehicle functions to work together and help the driver. The prominent capabilities include assistance in traffic jams; the vehicle would maintain lane position and speed in a congested environment. This automation aims to provide better convenience and overall safety while posing the least impact on mobility systems and traffic.

Restricted Self-Driving Automation (Level 3): At this level of automation, although the driver has control over the vehicle, vehicles can take control of safety-critical functions. However, the control is limited to certain traffic, roadway, and weather conditions. The driver can take over any time, provided that enough time is given. Although it is a handy feature, it comes with different problems. For instance, the driver does not check the performance of a self-driving vehicle, and sometimes, overreliance becomes an issue.

Complete Self-Driving Automation (Level 4): Caldwell (2016) discussed that complete self-driving automation refers to autonomous vehicles that do not require human interaction. In this type of automation, it is the responsibility of the vehicle to take care of entire driving functions. According to Yeomans

(2014), at this level the driver is only required to put in the destination; the self-driving vehicle will find the best possible route to reach that destination. Yet, this level of automation is subject to certain weather, traffic, and road conditions.

Automated Taxis (Level 5): At this level vehicles can travel in all conditions without any human intervention. The vehicles can fully communicate with each other, and based on communication, traffic congestion and accidents can be avoided.

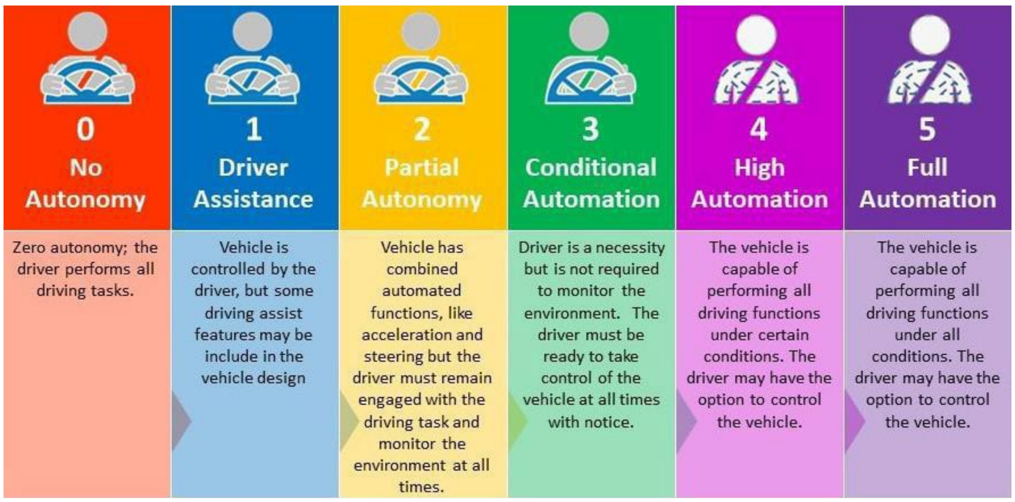


Figure 3 - Levels of Automation (Source: US National Highway Traffic Safety Administration)

Figure 4 shows in more detail, the definition of each automation level and Advanced Driver Assistance Systems (ADAS). Figures 5, 6 and 7 show a picture of the automation vehicle, a roadway coverage of the driving test, and the sensor installation on an autonomous vehicle, respectively. Table 1 shows the sensor applications in support of the automated functions.

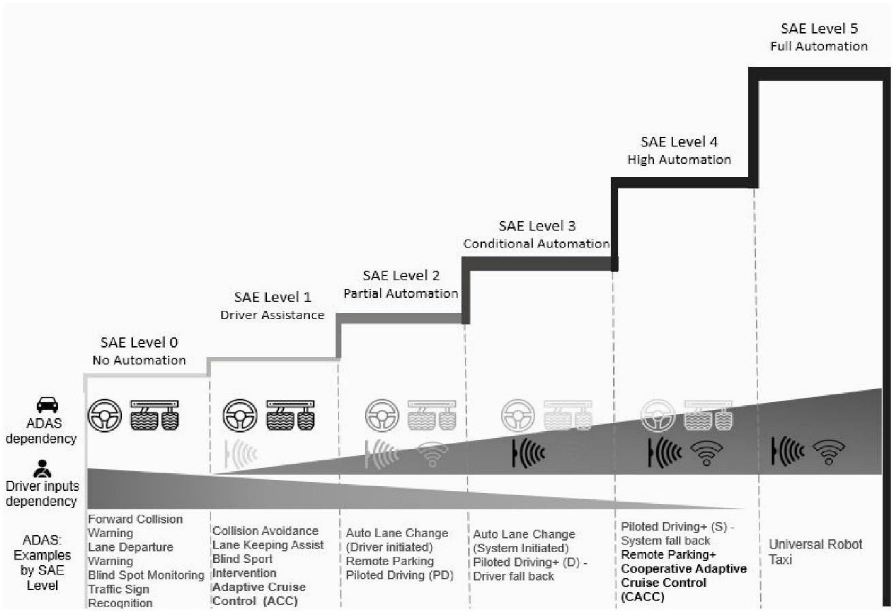


Figure 4 - Society of Automotive Engineers (SAE) Automation Levels (Source: SAE, 2018)

Figure 5 – Picture of Autonomous Vehicle

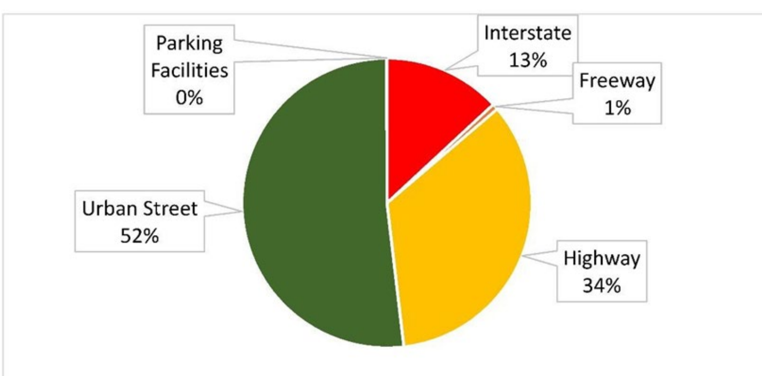


Figure 6 – Land Coverage of Autonomous Vehicle Testing

Table 1 – Sensor Applications by Autonomous Vehicles

	Lane Change Assistance	Lane Departure Warning	Automatic park	Pre-crash collision mitigation systems	Obstacle and Collision Warning and Avoidance	Platooning	ACC
Radar	√	√	√	√	√		√
Lidar	√	√	√	√	√		√
Infrared Camera						√	
Vision	√	√		√		√	√

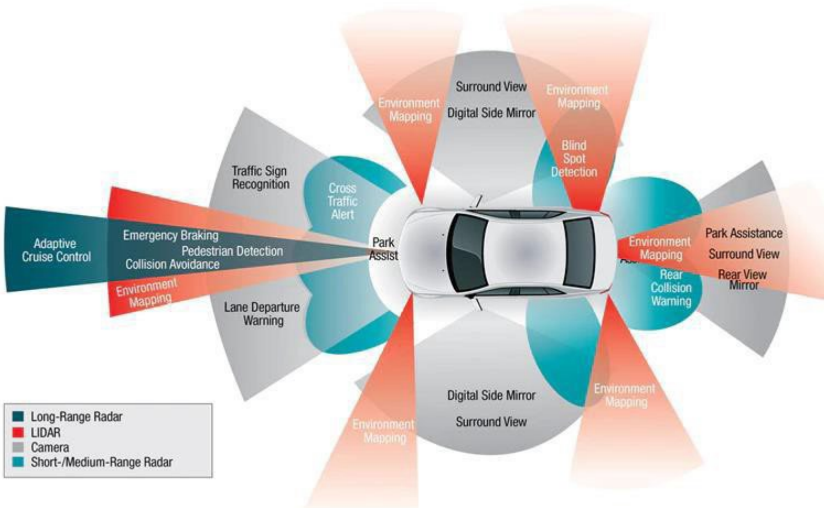


Figure 5 – Sensor Installations on an Autonomous Vehicle

E. Control of Autonomous Vehicle Platoons

All operations in cooperative driving can be divided into basic operations: split, merge, follow, and lane change. The design of the control architecture for autonomous vehicles in AHS should aim for more flexible autonomous vehicle platooning, such as smooth merging and lane changes to achieve both safety and efficiency.

1. Control Mechanism

The technical configuration described in the previous section leaves the question of how all these technologies work together to drive a car without the need for a human driver. Campbell et al. (2010) summarized his 2007 DARPA (Defense Advanced Research Projects Agency) Urban Challenge (DUC) experience, in which most participants divided the control mechanism into different subsystems, as shown in Figure 8.

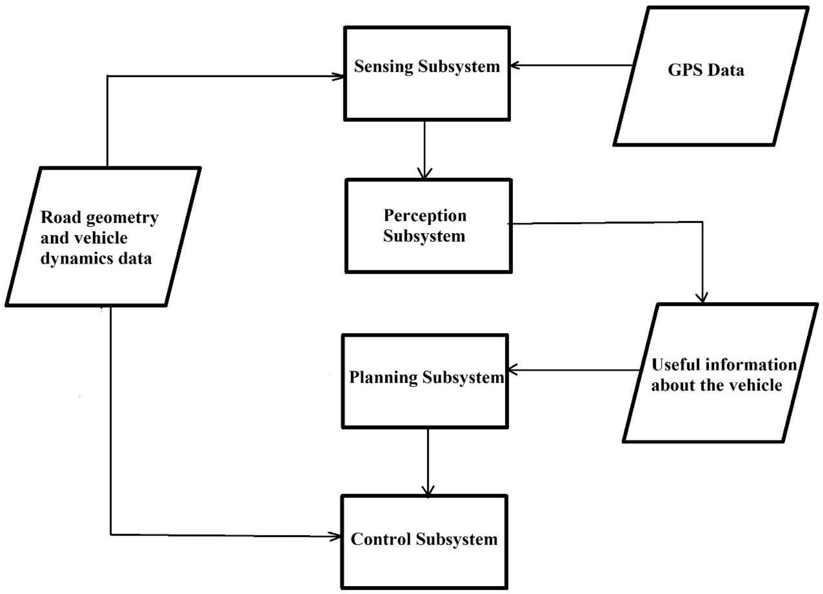


Figure 6 – Subsystems in Control Mechanism

2. Type of Platoon Controllers

Platoons may be operated by two main types of controllers. Longitudinal guidance, which takes over distance control without regard to steering, and lateral guidance, which controls the steering of the vehicle to maintain trajectory.

a. Longitudinal Control

Longitudinal guidance and lateral guidance are two rudimentary functions of vehicle automation. In general, the longitudinal control of subsystems is designed to be layered with lower and upper-level controllers, as shown in Figure 7. High-level controllers determine the desired acceleration or speed of the vehicle being controlled, and low-level controllers determine the throttle and brake commands needed to track the required speed and acceleration (Zhou and Peng, 2005).

Lower-level control

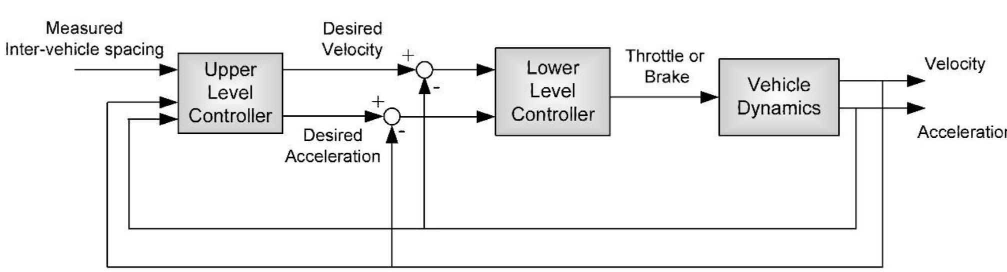


Figure 7 - Two-Level Structure for Longitudinal Control

Uncertainties and nonlinearities in longitudinal vehicle dynamics are the greatest challenges in designing throttle and brake controllers. Research has been conducted at various levels for decades by researchers and automakers. During the 1970s and 1980s, several studies were conducted on the design of control systems for vehicle engines and braking systems. Since then, several first-generation engine control systems have emerged, and some have resulted in great success in braking system control, such as Antilock Braking System (ABS), which has gained wide acceptance in the automotive industry (Cho and Hedrick, 1989).

Upper-level control

A higher-level controller determines the required acceleration or velocity for the controlled vehicle. The main design tasks for the higher-level controller include designing distance policies and associated control algorithms. A distance guideline represents the desired distance that the autonomous vehicle will attempt to maintain in relation to the vehicle ahead. Generally, the desired distance rule refers to the function of vehicle speed as well as a constant distance or other functions like the relative speed between the controlled vehicle and the vehicle ahead. Of significance, it has a crucial role to play in a longitudinal control system of vehicles. This is because it poses a significant impact on traffic capacity and vehicle safety. Furthermore, clearance policies and associated control algorithms can be assessed in terms of traffic flow stability, chain stability, and capacity of traffic flow (Swaroop and Rajagopal 1999).

b. Lateral Control

Lane departure is one of the leading reasons behind fatalities, killing more than 25,000 people each year and accounting for nearly 60% of all fatalities on US highways. It has also been found that the average accident rate on curves is about three times higher than on straight sections (AASHTO, 2008). In addition, vehicle lateral control systems offer a potential solution to address steering problems of vehicle and obtain road centerlines through a road-based reference system and other onboard sensors. Afterwards, it generates steering commands to steer the vehicle into an adjacent lane and have the vehicle on the desired path. A design requirement for lateral vehicle control must ensure a small lateral error and a small relative yaw angle and simultaneously maintain ride comfort under various conditions.

c. Integrated Longitudinal and Lateral Control

For fully automated vehicles on automated highways, consideration should be given to combining longitudinal and lateral guidance. There are two types of binding methods: separate and combined. In the decoupled method, coupling effects between longitudinal and lateral dynamics are ignored, and the designed longitudinal and lateral controllers are completely independent. Hence, global control is easily achieved by linking two separate controllers. The combined method no longer ignores the combined effect between the two movements. Therefore, a coupling regulator can be considered, though it is more complex than treating them separately.

F. Disturbances

The formation of a platoon fleet can be seriously affected by disturbances. Even though the radar and video systems manage some disturbances, there are other disturbances that need to be controlled by the adaptive cruise control (ACC). These disturbances have been separated into two groups; external disturbances caused by different road and traffic situations and internal disturbances due to the vehicles.

1. Internal Disturbances

Internal disturbances are disturbances in a vehicle and its components, such as the vehicle's control logic, brake system, or radar. Two possible types of disturbances have been identified: reaction time and noise. The ACC acts on the messages it receives, and any type of inaccuracy could cause reduced performance and safety for the vehicle.

2. External Disturbances

External disturbances are disturbances from the road, weather, or other vehicles affecting a platoon. The limitations and configurations of the ACC can cause certain traffic disturbances to be dangerous. Scenarios such as slip-road, braking and cut-in, or even topography can be understood and analyzed as disturbances.

3. Disturbance Combinations

In the real world, each disturbance is not isolated, occurring only by itself. Disturbances can affect the system in different combinations, exerting the system to extreme conditions. Disturbances in different combinations might amplify their isolated effects or cancel them out, affecting the robustness of the platoon.

G. Summary

This section has reviewed the background of autonomous vehicles technologies. It discussed platoon models under different spacing and speed control policies in order to achieve safety and stability. This research study focuses solely on platoon longitudinal control to build a car-following model and conduct an in-depth analysis on the model characteristics. The impact of disturbances to the model has also been studied to test the ability of the model to cope with changes in roadway and environmental factors.

III. RESEARCH METHODOLOGY

A. Introduction

Two critical factors must be considered in safe and efficient vehicle platoon operations. They are the minimum and maximum spacing between two successive vehicles. The performance and reliability of a longitudinal vehicle platoon relies on effectively managing disturbances to the system. In this study, these disturbances have been categorized into two groups: external disturbances resulting from diverse road and traffic conditions (including road conditions and environmental factors), and internal disturbances specific to the vehicle (such as tire condition and the braking system). The attainment of the stable platoon operation is achievable through the assurance of both individual vehicle stability and platoon string stability.

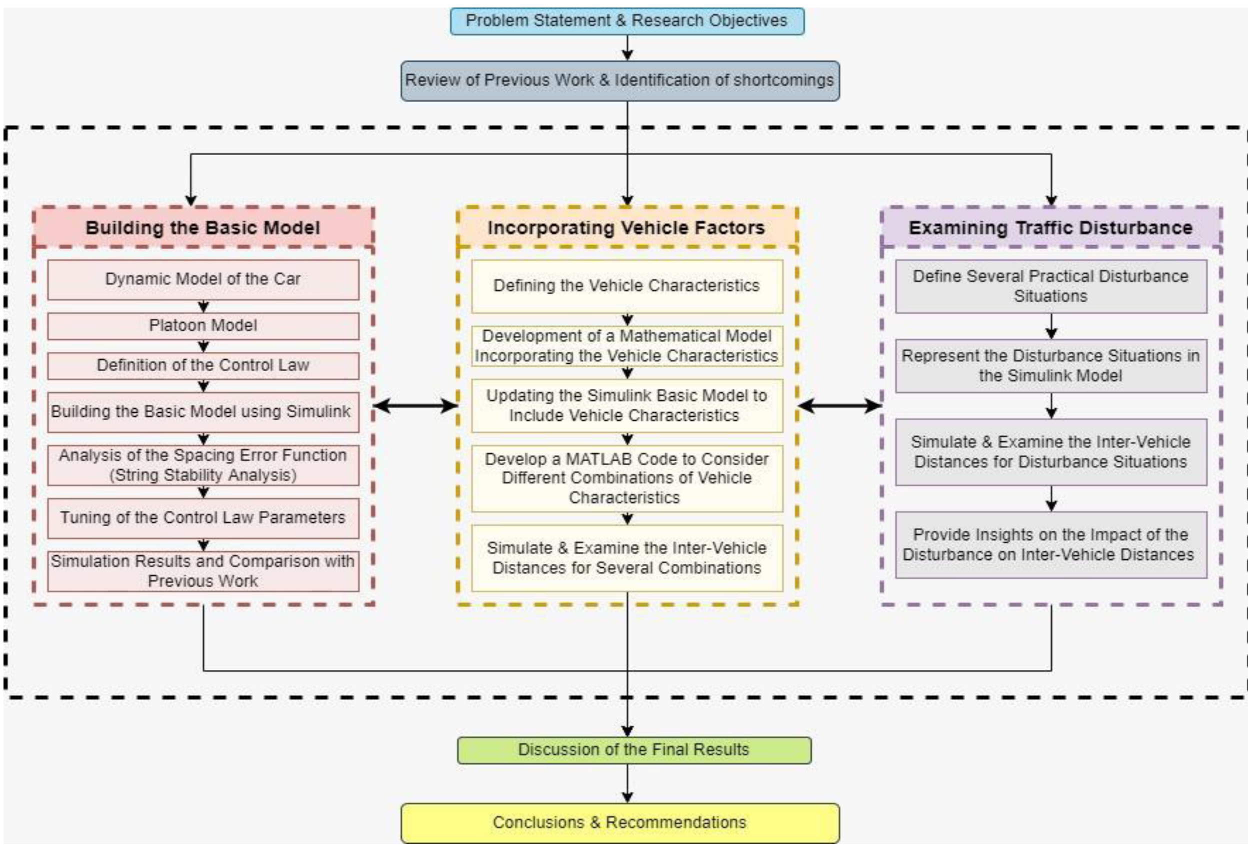


Figure 8 - Research Methodology

Figure 8 shows the research methodology of the current study. The methodology starts with problem identification and articulation of research objectives, which include building the basic model, incorporating vehicle dynamic factors, and examining traffic disturbances.

Concerning the basic model, this study builds the dynamic platoon model, illustrates the definition of control law, builds the basic model through the Simulink software, analyzes the spacing error function, tunes the control law parameters, and shows simulation results to compare with other studies.

Concerning incorporating vehicle dynamic factors, this study develops the mathematical model by considering specific vehicle characteristics, such as vehicle length, wheel space, and axle weight, and developing the MATLAB code to stimulate and examine the inter-vehicle distances within the platoon.

Concerning traffic disturbances, this study defines the different practical situations, where the internal and external disturbances may occur, and uses the Simulink program to simulate and examines potential unsafe conditions.

B. String Stability Analysis

A general definition of string stability is given in (Swaroop, 1997). If the initial states (position and velocity errors) are bounded and summable, then all states are bounded. Rajamani, (2006) gives sufficient conditions for chain stability. This research project will analyze string stability of the platoon in the base model as well as the dynamic model with the influence of disturbances.

C. Simulation Model Development

Longitudinal platoon control will be simulated in different travel speeds. The simulations are to be performed assuming straight roads in MATLAB and including small curvatures in Simulink. Modeling of various traffic scenarios due to disturbances by following the three-step logic shown in Figure 9.

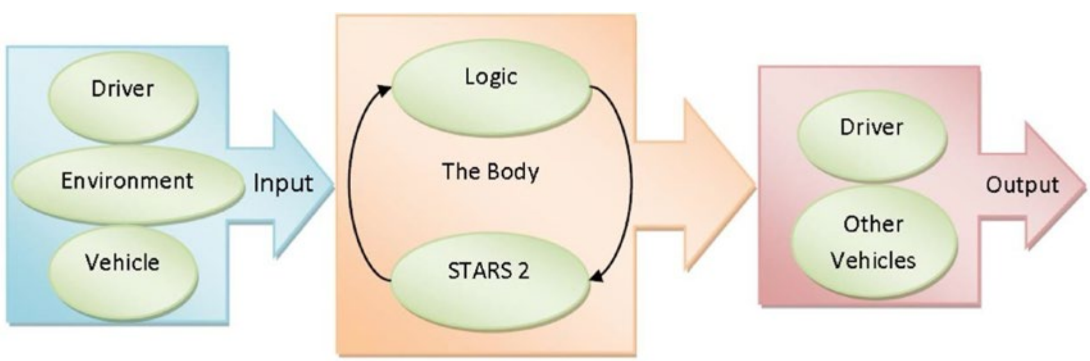


Figure 9 - Illustration of Modeling Process

IV. BUILDING THE BASIC MODEL

A. Introduction

This part of the research was conducted in several steps. The first step involves building a basic dynamic vehicle model, forming an efficient platooning model, and enabling the control law. Next, the string stability analysis analyzes the spacing error function, and the control law parameters are estimated. Finally, a simulation is conducted to demonstrate the effectiveness of the proposed model, making comparisons with other related work over model results.

B. Longitudinal Model for a Vehicle

The dynamic equation of a vehicle can be written according to Newton's law as follows:

$$\boldsymbol{m\ddot{x}} = \boldsymbol{F} - \boldsymbol{F_g} - \boldsymbol{F_{aero}} - \boldsymbol{F_{drag}} \tag{1}$$

The longitudinal model of the vehicle is formulated by Equation (1) to allow the following forces in the direction tangent to the ground to be balanced: the engine force, the three resistance forces F_R (the gravitational force F_g , aero-dynamical force F_{aero} , the mechanical drag force $\boldsymbol{F_{drag}}$), and the inertial force $m\ddot{x}$ (m is the mass of vehicle and $\ddot{x}$ is the vehicle acceleration). More details about these forces are discussed in detail in the next section. The form of equation can be simplified as follows:

$$\boldsymbol{m\,\ddot{x}} = \boldsymbol{F} - \boldsymbol{F_R} \tag{2}$$

The engine of the vehicle is modeled in the automobile industry, and its first-order system (Ali et al. 2013) is provided by Equation (3):

$$\dot{F} = -\boldsymbol{\tau\,F} + \boldsymbol{u} \tag{3}$$

where τ is the vehicle engine time constant, and u is the control input to the vehicle engine. Taking the derivative of Equation (2) and substituting it into Equation (3), the following linearized model is obtained:

$$\boldsymbol{u} = \boldsymbol{m\gamma} + \boldsymbol{\tau\,F} + \dot{F}_{\boldsymbol{R}} \tag{4}$$

where

$$\boldsymbol{\ddot{x}} = \boldsymbol{\gamma} \tag{5}$$

In the above model, γ is the new control input for the system, as it reflects the engine torque from the accelerator. To simplify the mathematical representation and aid the stability analysis to be conducted later, the Laplace transform is used on Equation (5), and the block diagram in Figure 10 is obtained.

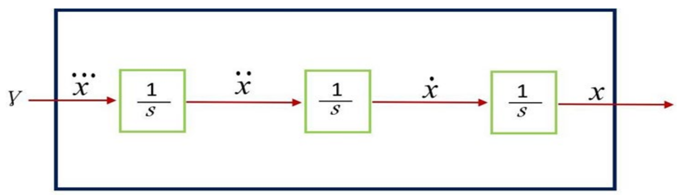


Figure 10 - Longitudinal Vehicle Model.

C. Platoon Model

A vehicle platoon is the combination of N vehicles, where the relative positions of the vehicles are given in Figure 11.

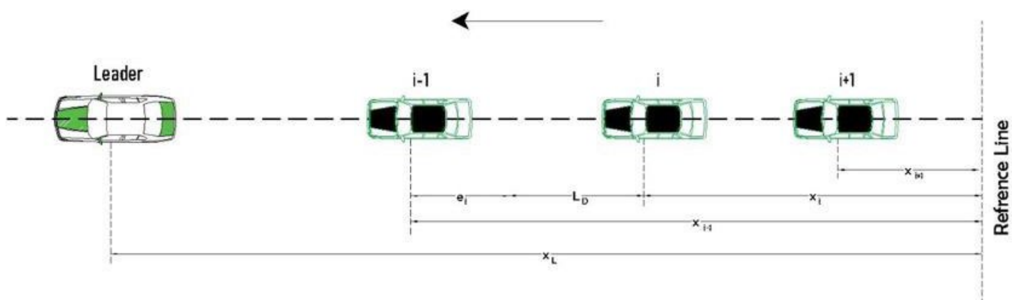


Figure 11 - Vehicle Platoon.

In this study, the following assumptions were made:

- The vehicles travel on a flat and straight road without obstacles.
- The longitudinal movement of each vehicle is considered.
- The leader vehicle sets the speed for the entire platoon.
- L_D is the desired inter-vehicle space between two successive vehicles.

The spacing error of the i^th vehicle ($\boldsymbol{e_i}$), assuming a point mass model for all vehicles, is defined as:

$$\boldsymbol{e_i} = \Delta \boldsymbol{X_i} - \boldsymbol{L_D} \tag{6}$$

where $\Delta \boldsymbol{X_i}$ represents the inter-vehicle spacing, $\Delta \boldsymbol{X_i} = \boldsymbol{x_{i-1}} - \boldsymbol{x_i}$.

The key aspect in forming a platoon system is the selection of the spacing policy, which refers to the desired steady state spacing between the two following vehicles. This plays an important role in terms of road capacity, fuel/energy consumption, safety, and other factors. There are two general types of spacing policies:

Constant Spacing Policy (CSP). In CSP, the controller will try to make $\boldsymbol{e_i} = 0$ so that the inter-vehicle distance equals the desired spacing, $\boldsymbol{L_D}$. CSP can provide high traffic capacity if a small $\boldsymbol{L_D}$ value is chosen; however, when linear controllers are used, it cannot guarantee string stability because the system is not able to capture and adjust for minor changes in vehicle spacing. CSP could also result in poor ride quality in addition to possible collisions. For improved operation, continuous inter-vehicle communication should be used in addition to the information provided by the onboard sensors (Wu et al., 2020).

Time Headway Spacing Policy (THSP). THSP is a variable spacing policy that employs time headway. It has been more commonly used for spacing control in both academia and at industry test tracks. By adding a time-based term while setting L_D as the minimum spacing for safety, the new spacing error $\boldsymbol{\delta_i}$ is given by:

$$\boldsymbol{\delta_i} = \boldsymbol{e_i} - \boldsymbol{h}\,\dot{\boldsymbol{x}} = \Delta\boldsymbol{x_i} - \boldsymbol{L_D} - \boldsymbol{h}\,\dot{\boldsymbol{x}} \tag{7}$$

Where $\boldsymbol{h}$ is the time headway and $\dot{\boldsymbol{x}}$ the vehicle speed. In this case, the controller aims to make $\boldsymbol{\delta_i} = \boldsymbol{0}$ so that $\Delta\boldsymbol{x_i} = L_D + \boldsymbol{h}\,\dot{\boldsymbol{x}}$. Accordingly, $\Delta\boldsymbol{x_i}$ will increase when the vehicle travels at high speed. To further help in maintaining the formation of the platoon and reduce the overshoot/undershoot problem in the spacing adjustment, a reference speed, V, is introduced so that a relative speed is used as in Equation (8). The reference speed is taken as the speed of the leader vehicle, which can be obtained through V2V or V2I communication. As shown in Equation (8), this modified THSP makes a time headway–based adjustment to control the magnitude of the error correction term according to the difference in speed between the leader vehicle and the following vehicle (Ali et al. 2013 & Wu et al., 2020). Since $\boldsymbol{V}$ is set by the leader vehicle, the speed difference helps increase the inter-vehicle spacing when a follower vehicle is traveling faster than the leader, and it reduces the spacing when the follower is traveling more slowly than the leader.

$$\boldsymbol{\delta_i} = \boldsymbol{e_i} - \boldsymbol{h}(\dot{\boldsymbol{x}} - \boldsymbol{V}) = \Delta\boldsymbol{x_i} - \boldsymbol{L_D} - \boldsymbol{h}\,(\dot{\boldsymbol{x}} - \boldsymbol{V}) \tag{8}$$

4. Control Law for a Vehicle Platoon

The control objective of a vehicle platoon is to maintain the inter-vehicle spacing while moving at the same speed as the leader vehicle. To achieve the control objective, it is necessary to ensure the string stability of the platoon so that the spacing error does not increase as it propagates through the platoon. Many controller schemes exist in industrial automation. The most commonly used are proportional, derivative, and integral controls and their combinations as proportional– integral–derivative (PID) controllers (Nise et al. 2004). In reference to Equation (5), the research problem can be modeled by using a PID controller to investigate the vehicular interactions in the fleet by using the following equation:

$$u_i = -C_a\ddot{x}_i + C_v\,\dot{e}_i + C_p\delta_i \quad (9)$$

where C_a, C_v, and C_p are the control law parameters that need to be estimated. The underlying principle in the parameter determination is to ensure safety by keeping the minimum inter-vehicle distance while reducing the spacing between vehicles to maintain the fleet formation and maintain its efficiency of operation.

D. Building the Basic Model using Simulink

The platoon Size (N) equals 10 vehicles including the leader in the example shown in Figure 12, where vehicle 10 is the leader. Velocity and inter-vehicle distance are the main parameters maintained in this model to perform the simulation.

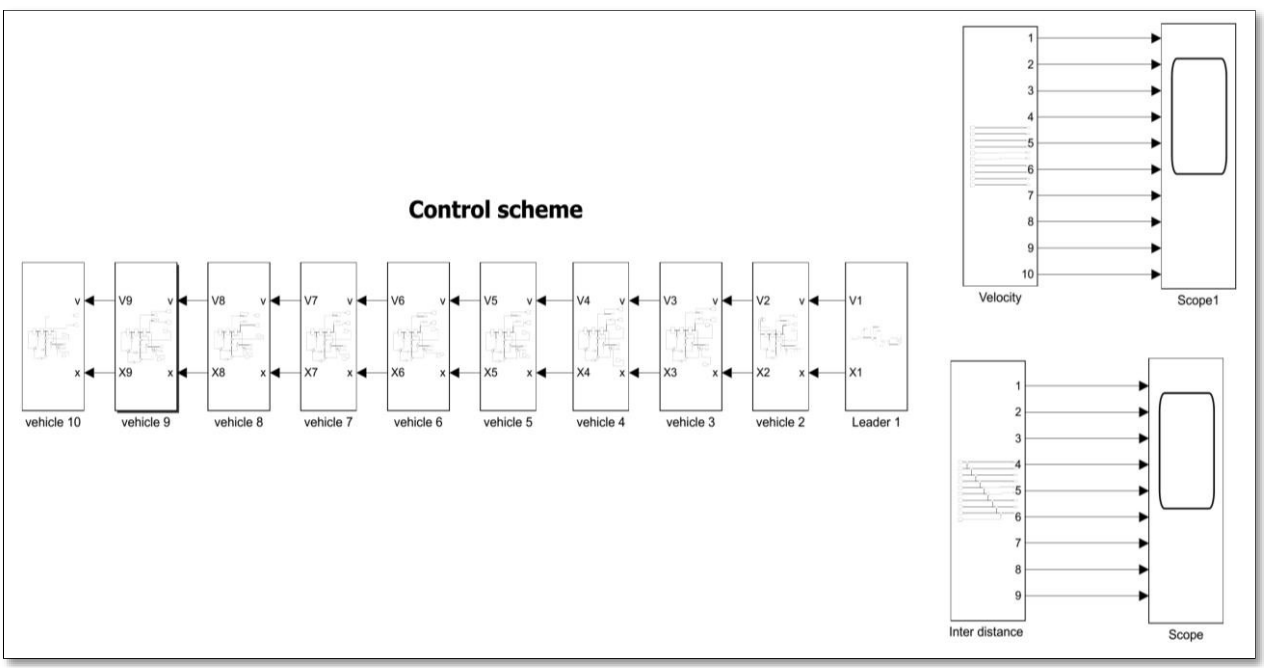


Figure 12 - Platoon Size (N) = 10 Vehicles Including the Leader.

1. i^{th} Vehicle Block

Figure 13 shows the control behavior of the i^{th} vehicle in the platoon. These parameters are altered later during simulation to determine the results.

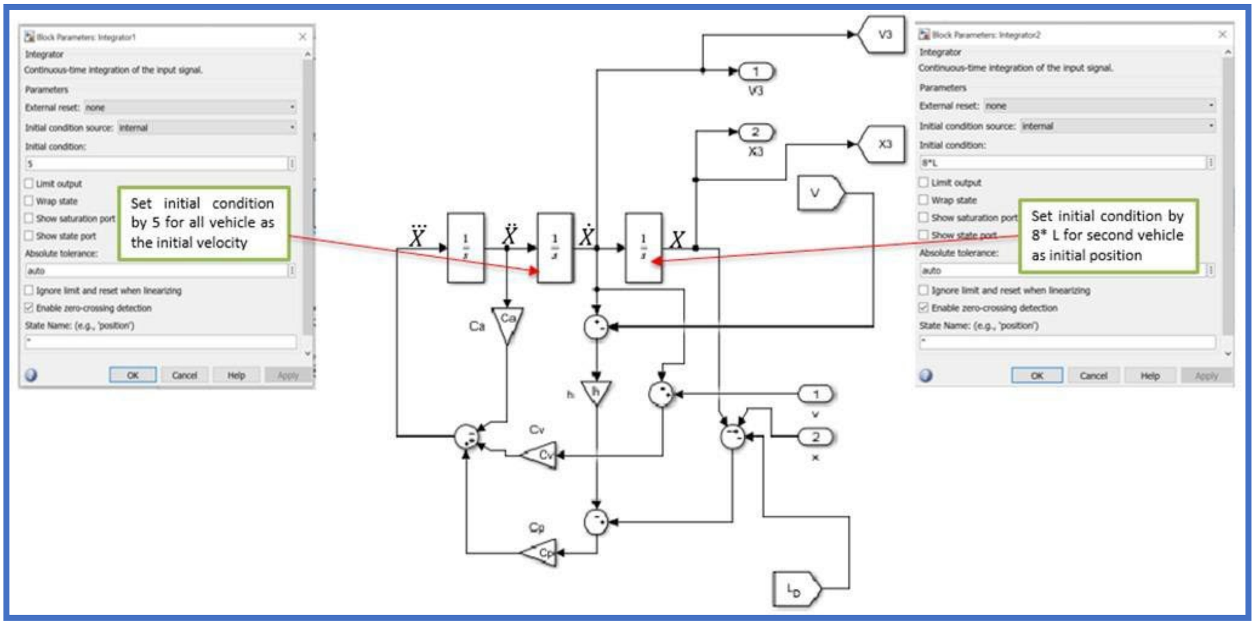


Figure 13 - Control Conditions of the i^{th} Vehicle.

2. Leader Block
In the speed profile, the speed of the platoon leader is changed several times to assess the transient response and to the platoon stability as shown in Figure 16.

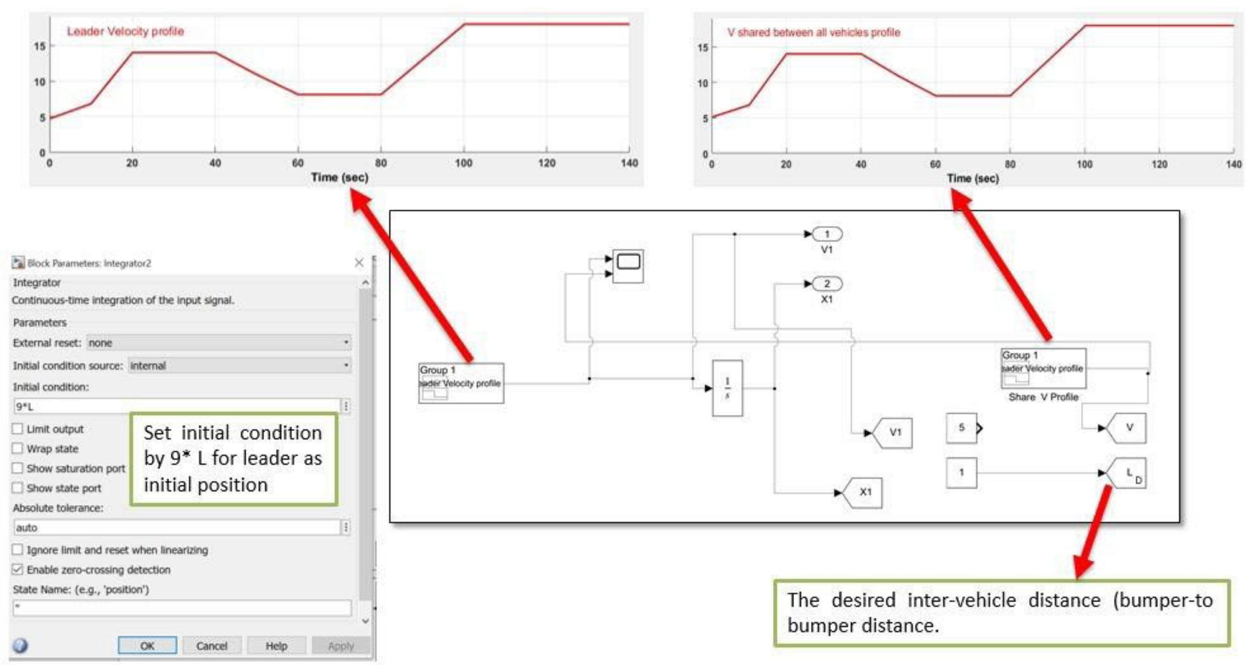


Figure 14 - Velocity Profile of Leader Vehicle.

3. Inter-Vehicle Distances Calculation Block

The Inter-Vehicle Distances Calculation Block $\Delta \boldsymbol{X_i} = \boldsymbol{x_{i-1}} - \boldsymbol{x_i}$ is shown in Figure 15 and 18, which calculate the real spacing and velocity between car number *i* and its predecessor, car number *i – 1*.

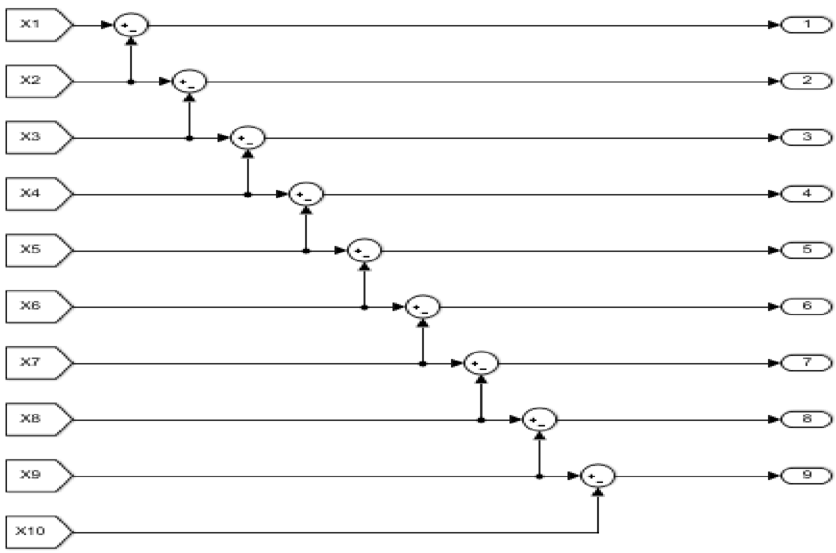


Figure 15 - Inter-Vehicle Distances Calculation Block.

Figure 16 - Velocity Calculation Block.

E. String Stability

One critical task of platoon control is to evaluate the errors of the inter-vehicle spacing and achieve string stability (Pueboobpaphan et al., 2011). The system automatically adjusts to help prevent the spacing errors from diverging as they propagate towards the back of the platoon. In a stable platoon, the spacing error would smoothly decrease along the platoon, as shown in Figure 17. To conduct the analysis, the spacing error transfer function $\boldsymbol{H_i}(\boldsymbol{s})$ must be first be obtained by considering the spacing policy and control law that is used to build the model.

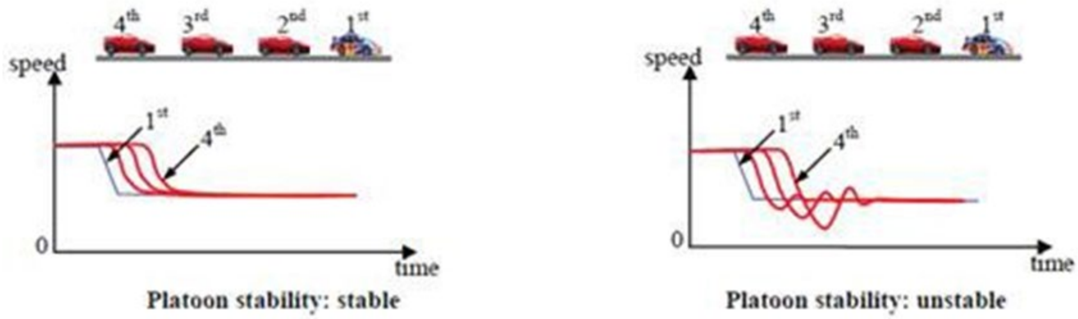


Figure 17 - Error Propagation and Platoon Stability (Source: Pueboobpaphan et al. 2011).

The spacing error propagation transfer function is defined by:

$$H_i(s) = \frac{e_i(s)}{e_{i-1}(s)} \tag{10}$$

To achieve string stability, the following condition must be satisfied:

$$||H_i(s)||_\infty \leq 1 \tag{11}$$

By substituting from Equations (5) and (9):

$$\ddot{x}_i = -C_a\,\ddot{x}_i + C_v\,\dot{e}_i + C_p[\,e_i - h(\,\dot{x}_i - V)] \tag{12}$$

Since

$$\ddot{e}_i = \ddot{x}_{i-1} - \ddot{x}_i \tag{13}$$

Then

$$\ddot{e}_i = -c_a\ddot{x}_{i\text{-}1} + c_v\dot{e}_{i-1} + c_p\,e_{i-1} - c_p h\,\dot{x}_{i\text{-}1} + c_p h\,v - [-c_a\ddot{x}_i + c_v\dot{e}_i + c_p e_i - c_p h\,\dot{x}_i + c_p h\,v] \tag{14}$$

or $$\ddot{e}_i + c_a\,\ddot{e}_i + \dot{e}_i[c_v + c_p\,h] + c_p\,e_i = c_v\dot{e}_{i-1} + c_p\,e_{i-1} \tag{15}$$

By applying Laplace transform, we can obtain:

$$S^3\,e_i(s) + ca\,S^2 e_i(s) + S\,e_i(s)\,[c_v + c_p h] + c_p e_i(s)$$

$$= c_v\,S\,e_{i-1}(s) + c_p\,e_{i-1}(s) \tag{16}$$

The spacing error propagation transfer function H(s) is obtained by:

$$H_i(s) = \frac{C_v S + C_p}{S^3 + C_a S^2 + (C_v + C_p h) S + C_p} \quad (17)$$

Stability Conditions

To verify the string stability, the condition in Equation (11) must be satisfied as follows:

$$H_i(s) = \frac{e_i(s)}{e_{i-1}(s)} \leq 1 \quad (18)$$

Substituting $S = i\omega$ in Equation (17),

$$H_i(i\omega) = \frac{C_v i\omega + C_p}{(i\omega)^3 + C_a(i\omega)^2 + (C_v + C_p h) i\omega + C_p} \quad (19)$$

$$i = \sqrt{-1} \qquad i^2 = -1 \quad i^3 = -i$$

$$H_i(i\omega) = \frac{C_p + C_v i\omega}{(C_p - C_a\omega^2) + ((C_v + C_p h)\omega - \omega 3) i} \quad (20)$$

and

$$||H_i(\omega)|| = \sqrt{\frac{Cp2 + Cv2\,\omega 2}{(Cp - Ca\omega 2)2 + ((Cv + Cph)\,\omega - \omega 3)2}} \quad (21)$$

For $||H_i(\omega)|| \leq 1$, the denominator must be greater than or equal to the numerator:

$$(C_p - C_a\omega^2)^2 + ((C_v + C_p h)\,\omega - \omega^3)^2 \geq C_p^2 + C_v^2\,\omega^2 \quad (22a)$$

$$C_p^2 + C_a^2\omega^4 - 2C_pC_a\omega^2 + (C_v + C_p h)^2\omega^2 + \omega^6 - 2\omega^4(C_v + C_p h) \geq C_p^2 + C_v^2\,\omega^2$$

$$C_p^2 + C_a^2\omega^4 - 2C_pC_a\omega^2 + (C_v^2 + C_p^2h^2 + 2C_vC_ph)\omega^2 + \omega^6 - 2\omega^4(C_v + C_p h) \geq C_p^2 + C_v^2\omega^2 \quad (22b)$$

To simplify, consider $C_v = \frac{C_a}{h}$

Then

$$\omega^6 + (C_a{}^2 - 2(\frac{Ca}{h} + C_p h))\ \omega^4 + (C_p{}^2 h^2 + 2C_p\ (\frac{Ca}{h}h - C_a))\ \omega^2 \geq 0 \tag{23a}$$

$$\omega^6 h + (C_a{}^2 h - 2(C_a + C_p h^2))\ \omega^4 + C_p{}^2 h^3 \omega^2 \geq 0 \tag{23b}$$

and the stability condition becomes:

$$hC_a{}^2 - 2C_a - 2C_p h^2 \geq 0 \tag{24}$$

The control parameters C_a, C_v, and C_p, together with h, must satisfy the stability conditions in Equation (24) to ensure that the system is stable. The parameter values for C_a, C_v, C_p, and h will be estimated, and the resultant stability checked.

F. Stability of the Transfer Function ($H_i(s)$) Poles and Transient Response Parameters

After obtaining the parameters of the String stability Transfer Function, it is important to check the performance of the Transfer Function (TF), considering obtained parameters, i.e., poles and zeros, as well as the transient response parameters. See Figure 18 and Figure 19.

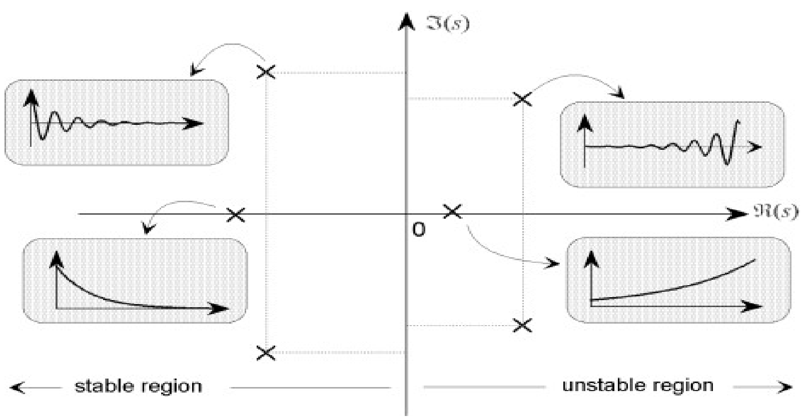


Figure 18 - Performance of the Transfer Function ($Hi(s)$).

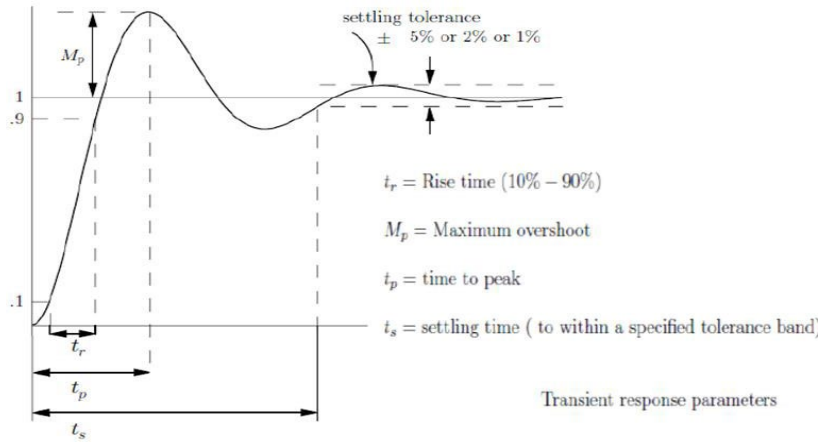


Figure 19 - Transient Response Parameters of the Transfer Function ($\boldsymbol{Hi(s)}$).

1. Estimation of Control Law Parameters

The stability condition in Equation (24) can be satisfied by tuning the control law parameters $\boldsymbol{C_a}$ (1/sec), $\boldsymbol{C_v}$(1/sec^2), $\boldsymbol{C_p}$(1/sec^3), and $\boldsymbol{h}$ (sec). In this study, we used the following steps to find the appropriate values for these parameters:

1) Generate random numbers for all parameters of the stability condition, as shown in Figure 20.
2) Calculate the outputs of the stability condition.
3) Rank the output from lowest to highest, as shown in Figure 21.
4) Remove the output values with a negative sign, as shown in Figure 22.
5) Find the values of the numerator and the denominator terms of the string stability transfer function for each parameter combination, as shown in Figure 23.

A2 =RANDBETWEEN(1,10)

	A	B	C	D	E
1	h	Ca	Cp	Cv	Stability Condition
2	4	3	7	0.75	-194
3	10	3	4	0.30	-716
4	6	3	7	0.50	-456
5	4	2	4	0.50	-116
6	5	5	1	1.00	65
7	6	4	1	0.67	16
8	1	9	2	9.00	59
9	4	3	3	0.75	-66

$$hC_a{}^2 - 2C_a - 2C_ph^2 \geq 0$$

Figure 20 - Using Random Numbers for Parameter Estimation.

h	Ca	Cp	Cv	Stability Condition
10	2	10	0.2	-1964
10	3	10	0.3	-1916
10	4	10	0.4	-1848
10	1	9	0.1	-1792
10	1	9	0.1	-1792
10	1	9	0.1	-1792
10	5	10	0.5	-1760
10	3	9	0.3	-1716

Figure 21 - Ranking of the Output from Lowest to Highest.

h	Ca	Cp	Cv	Stability Condition
1	4	4	4	0
2	4	3	2	0
2	5	5	2.5	0
1	3	1	3	1
1	4	3	4	2
3	3	1	1	3
3	3	1	1	3
4	6	4	1.5	4
4	6	4	1.5	4

Figure 22 - Parameters after Removing Negative Output

h	Ca	Cp	Cv	Stability Condition	num1	num2	dem1	dem2	dem3	dem4
1	4	4	4.00	0	4.00	4	1	4	8.00	4
2	5	5	2.50	0	2.50	5	1	5	12.50	5
2	5	5	2.50	0	2.50	5	1	5	12.50	5
2	5	5	2.50	0	2.50	5	1	5	12.50	5
1	3	1	3.00	1	3.00	1	1	3	4.00	1
1	4	3	4.00	2	4.00	3	1	4	7.00	3
3	3	1	1.00	3	1.00	1	1	3	4.00	1
3	3	1	1.00	3	1.00	1	1	3	4.00	1

$$H_i(s) = \frac{C_v\, S + C_p}{S^3 + C_a S^2 + (C_v + C_p h)\, S + C_p}$$

Figure 23 - Value of the Numerator and Denominator Terms

2. Stability of the Transfer Function ($\boldsymbol{H_i(s)}$)

After obtaining the parameter values in the string stability transfer function (TF), we need to check the performance of the TF based on the poles and zeros. The roots of the denominator (i.e., the poles) should be negative (located on the left-hand side of the S-Plane) to satisfy the stability of the system. Also, the transient performance of the system must be investigated to see how quickly it makes spacing adjustments, which includes the following two indicators:

- Rise time (t_r), which is considered as the time for the waveform to go from 10% of its final value to 90%.
- Settling Time (t_s), which is defined as the time for the response to reach and stay within 2% of its final value.

The stability of the system is verified by using one set of parameters that satisfies Equation (24). By substituting the control law parameters $\boldsymbol{h}$, $\boldsymbol{C_a}$, $\boldsymbol{C_v}$, and $\boldsymbol{C_p}$ with the parameter values ($\boldsymbol{h}$ = 1, $\boldsymbol{C_a}$ = 4, $\boldsymbol{C_v}$ = 4, and $\boldsymbol{C_p}$ = 4) in the transfer function in Equation (22) and the stability condition in Equation (17), we obtain

$$\boldsymbol{H_i(s)} = \frac{\mathbf{4\,S + 4}}{\mathbf{S^3 + 4S^2 + 8\,S + 4}} \qquad (25)$$

where the condition $\boldsymbol{hC_a^2 - 2C_a - 2C_ph^2 = 0}$. By calculating the zeros and poles of the transfer function, it was found that it has one zero (−1) and three poles (−1.6478 + 1.7214$\boldsymbol{i}$, −1.6478 − 1.7214 $\boldsymbol{i}$, and −0.7044 + 0.0000 $\boldsymbol{i}$).

The stability of the system has been verified by plotting the zeros and poles of the transfer functions obtained from Equation (25), as shown in Figure 24 through Figure 26. From this figure, we can see that all poles and zeros fall on the left-half plane so that the system is stable. Another way to verify the stability is by plotting the system's step response (Figure 25, 28,Figure 27), where it can be found that:

- The rise time t_r, the time for the waveform to go from 0.1 to 0.9 of its final value, is equal to 1.5 sec (for the proposed parameters), which outperforms (shorter than) some existing work reported in the literature.
- The settling time t_s, the time for the response to reach, and stay within, 2% of its final value, is equal to 4.4 sec, which is a much shorter than some of the reported values by other researchers for quick system settlement.

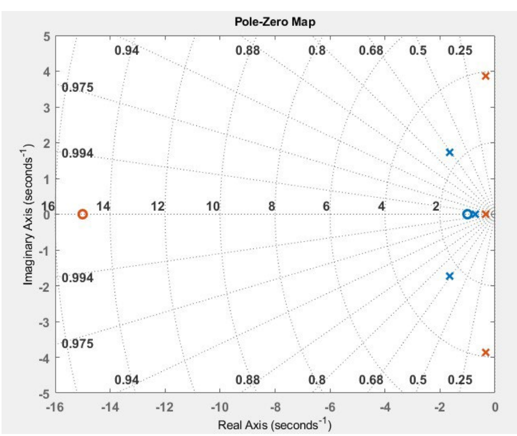


Figure 24 - Zeros-Poles plot of the Transfer Function for the Proposed Model

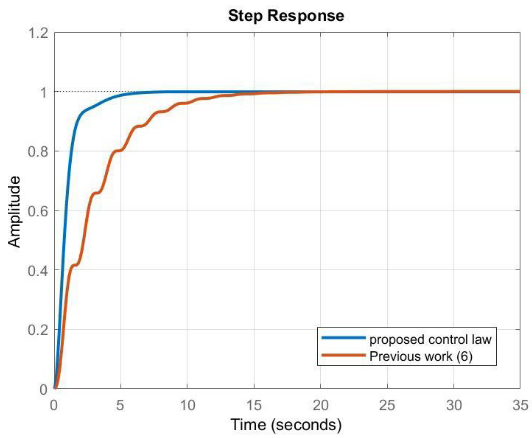


Figure 25 - The Step Response of the Transfer Function for the Proposed Model Compared with Reported Work.

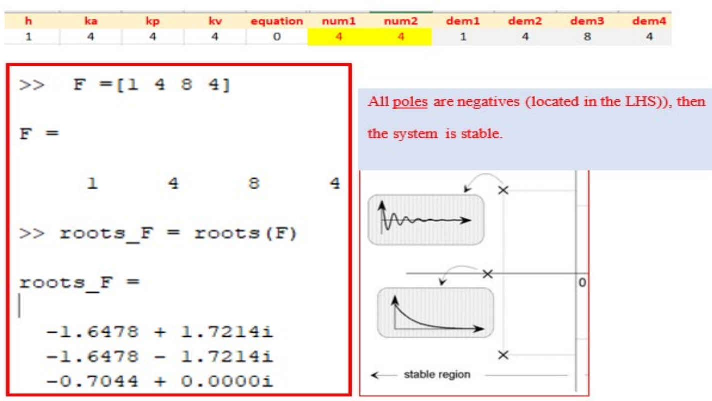


Figure 26 - Tuning of the Control Law Parameters.

h	ka	kp	kv	equation	num1	num2	dem1	dem2	dem3	dem4
1	4	4	4	0	4	4	1	4	8	4

```
sys =

         4 s + 4
  ---------------------
  s^3 + 4 s^2 + 8 s + 4

Continuous-time transfer function.


S =

  struct with fields:

        RiseTime: 1.5036
    SettlingTime: 4.4157
     SettlingMin: 0.9036
     SettlingMax: 0.9988
       Overshoot: 0
      Undershoot: 0
            Peak: 0.9988
        PeakTime: 8.3283
```

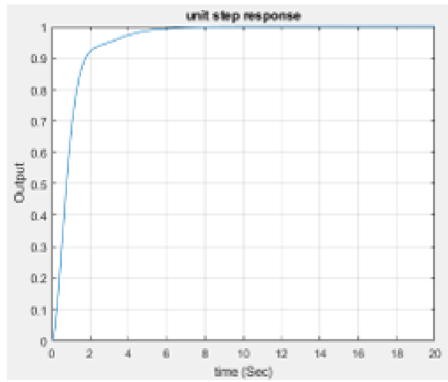
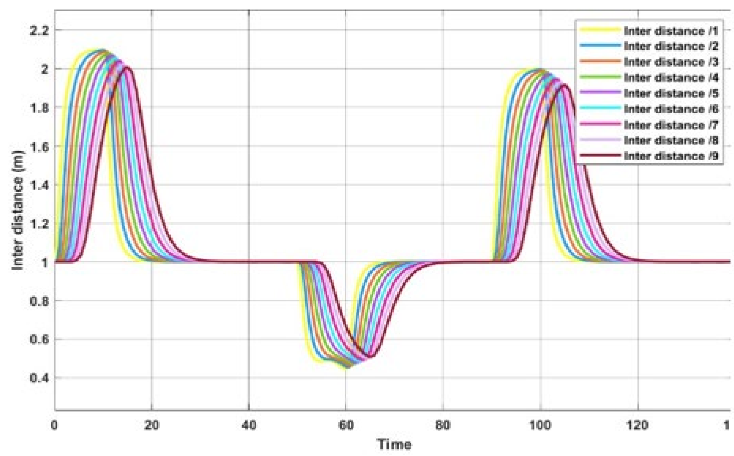


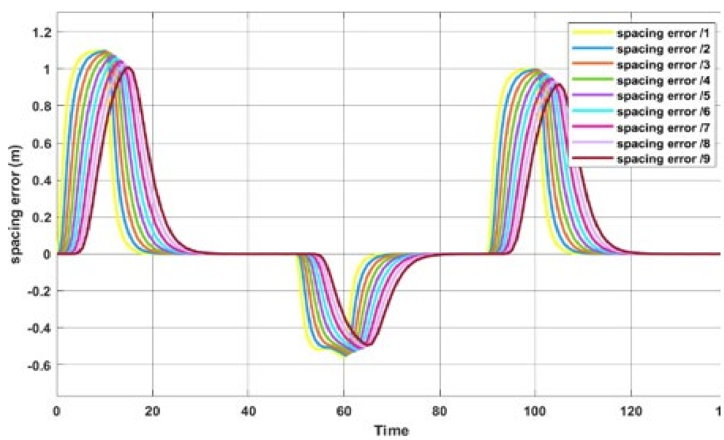
Figure 27 - Performance of the Control Function with Trial-and-Error Parameters.

G. Tuning of the Control Law Parameters and Simulation Results

In this section, the results obtained from the performed simulations are presented. The simulation work considered changes in inter-vehicle spacing, velocity, and acceleration as part of parameter tuning. It includes a comparison of the results when different minimum inter-vehicle distances and leader vehicle speeds are used. Figure 28 shows the change in inter-vehicle spacing when the minimum inter-vehicle distance ($\boldsymbol{L_D}$ = 1m) is used for all vehicles in the platoon. For example, the "Inter Distance /1" trajectory refers to the spacing change for the vehicle directly behind the leader vehicle as it tries to adjust to the leader's arbitrary position change. It can be seen from this figure that the spacing changes for all vehicles are smooth, and the response is fast. The platoon operation is stable, and the spacing errors converge within a small range (−0.58 to 1.05m). It can be noticed that the minimum spacing dropped below the $\boldsymbol{L_D}$, indicating that a larger $\boldsymbol{L_D}$ value may be used.



(a)



(b)

Figure 28 – (a) Inter-vehicle distances and (b) corresponding spacing error for the proposed model.

Next, when a speed profile for the leader vehicle is used, the corresponding speeds of the vehicles that follow are depicted in Figure 29 and Figure 30. It can be seen that the speed variations (overshoots and undershoots) are small, and the speed errors (i.e., the difference from the speed of the leader vehicle) dissipate after a short period of time.

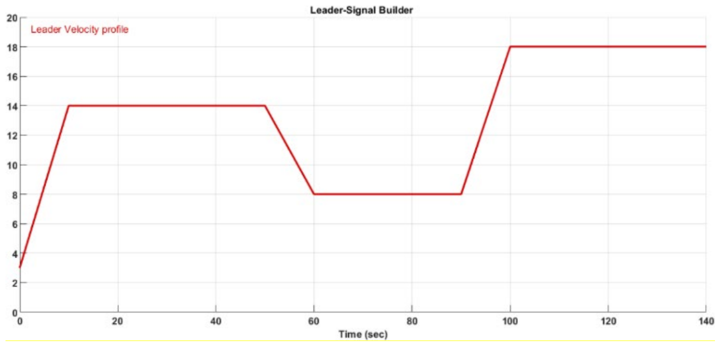


Figure 29 - Leader Velocity.

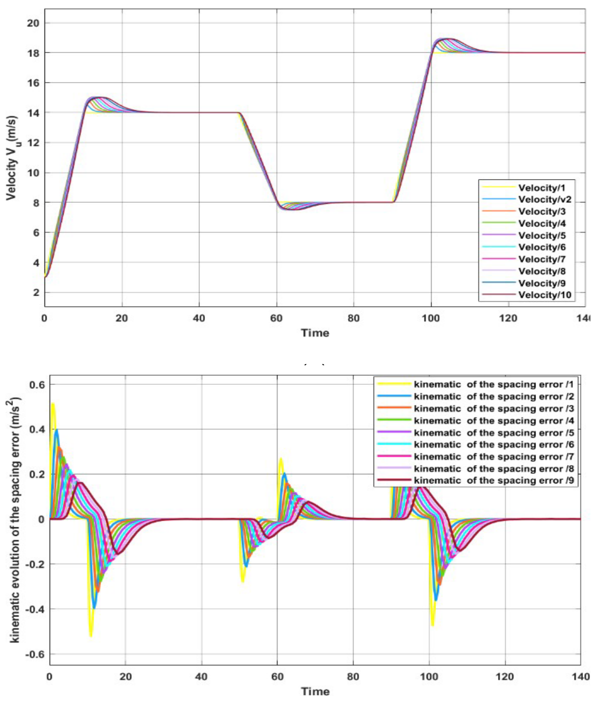
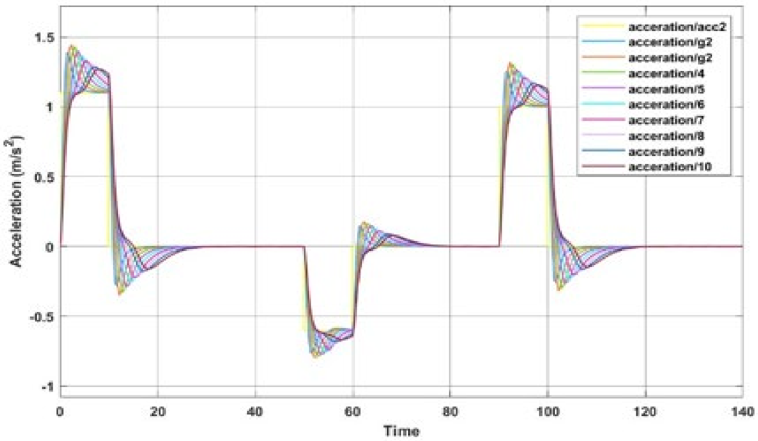
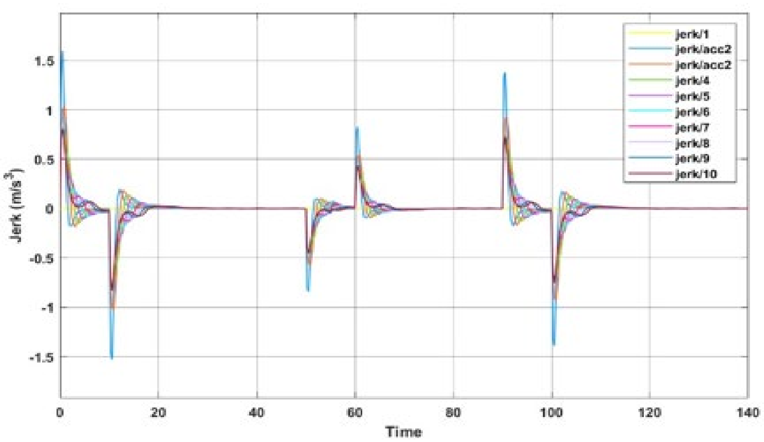


Figure 30 – (a) Follower velocities and (b) corresponding velocity error for the proposed model.

Figure 31 shows the variations in acceleration that were tracked for the following vehicles in comparison to that for the leader. For driving comfort, a set of established limits is used to control the magnitude of the acceleration jerks so that they will not exceed the comfort and economy constraint bound (Villagra et al. 2012). The results shown in the figure were found to conform to these standards.



(a)



(b)

Figure 31 - (a) The acceleration of the vehicles and (b) corresponding jerk for the proposed model.

The effect of using a target minimum inter-vehicle distance of 2 meters with different initial vehicle spacings in the platoon is further studied. The use of a different initial speed for the leader vehicle is also tested. Figure 32 and Figure 33 show the results when the initial inter-vehicle distance is set to 1 meter rather than 2m, and there seems to be very little difference between the two. The results for inter-vehicle spacing for different shared speeds of 0 and 5 m/sec are shown in Figure 34 and Figure 35, respectively. It can be observed from these figures that the platoon is able to maintain the formation even when the platoon moves at different shared speeds than the leader vehicle. It also shows that the inter-vehicle spacing is larger for a platoon at a lower shared speed. A comparison is also made with some previous work to depict consistency in spacing variations, as shown in Figure 38.

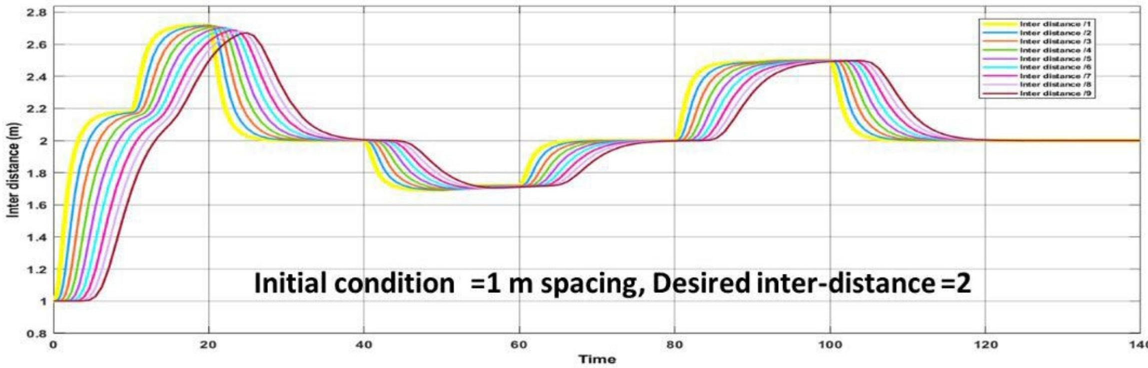


Figure 32 - Inter-Vehicle Distances (initial condition = 1 meter and desired inter-distance = 2m).

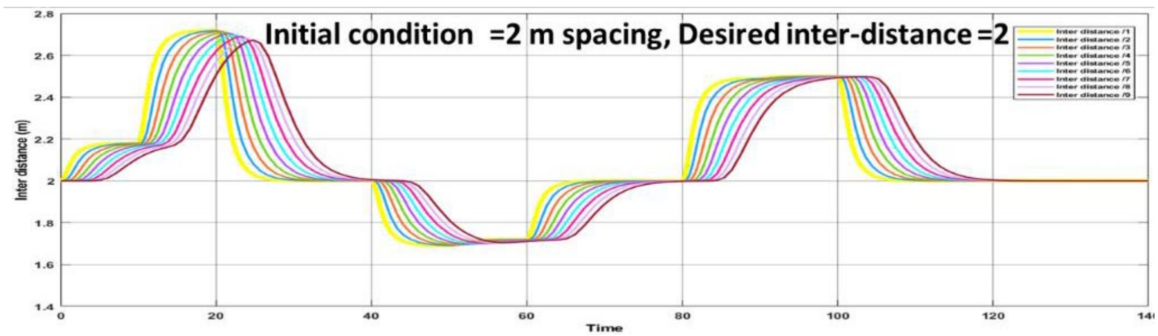


Figure 33 - Inter-Vehicle Distances (initial condition = 2 meters and desired inter-distance = 2m).

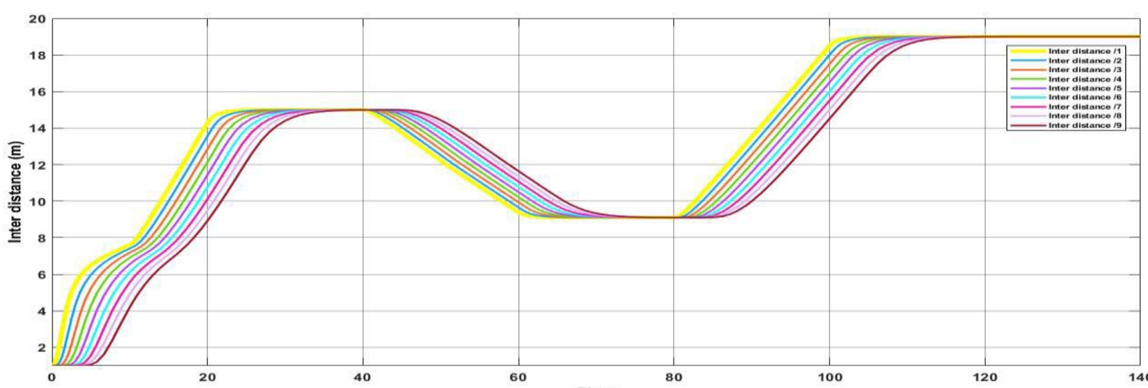


Figure 34 - Inter-Vehicle Distances (Shared Speed = 0m/sec).

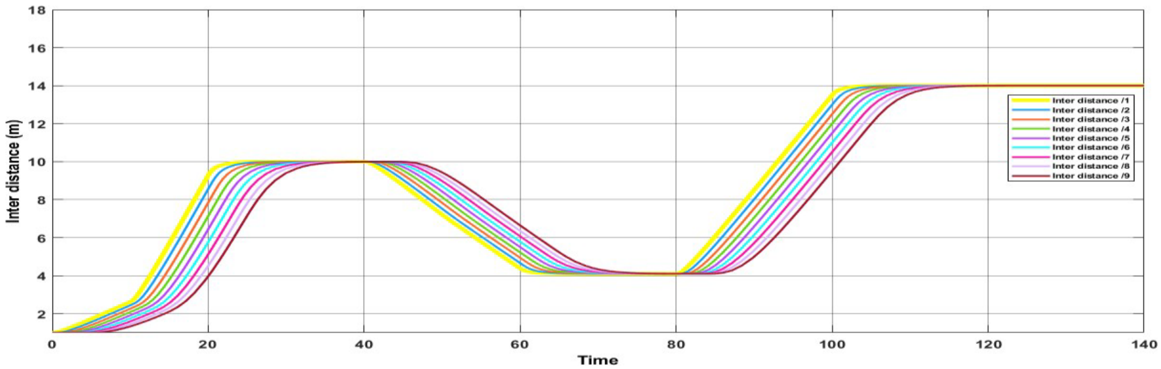


Figure 35 - Inter-Vehicle Distances (Shared Speed V = 5 m/sec).

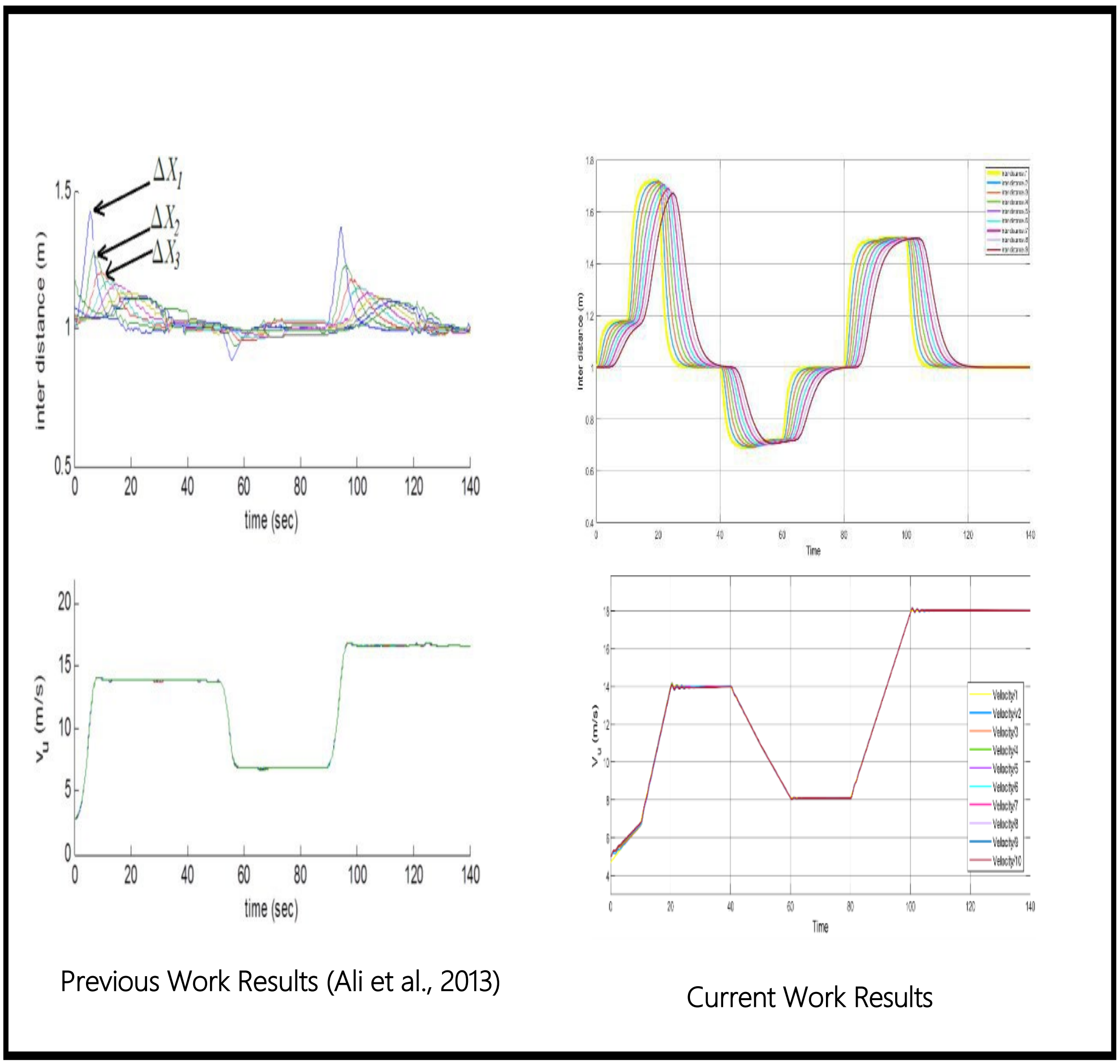


Figure 36 - Comparison with Other Work.

H. Summary

This section discussed the development and tests of the proposed platoon model for longitudinal control. The string stability of the control systems has been obtained, and the parameters used in the control law have been estimated to support its operation. The simulation results show that the proposed model can achieve the string stability condition while keeping the overshoots and undershoots in inter-vehicle spacing, speed, and acceleration under control with a small convergence time. Additionally, the proposed model has the flexibility to change the parameters such as the minimum inter-vehicle distance, initial position of vehicles in the platoon, and speed of the leader vehicle as well as the shared speed.

V. INCORPORATING VEHICLE LONGITUDINAL DYNAMICS IN THE PLATOON MODEL

A. Introduction

A plethora of research studies in this realm have considered the realization of string stable controllers for passenger car platoons by using kinematic vehicle models for controllers' design (Devika et al., 2020). As discussed in Section IV, in the basic model all platoon vehicles are assumed to be identical (i.e., have the same capabilities and vehicle characteristics). This may not be true in the real world. New parameters should be introduced (as an input) for each vehicle. The parameters may include surface friction, tire conditions, braking system, etc. It is inevitable to consider relevant key factors like dynamics of vehicle when it comes to dealing with realization of high speed of the vehicles in the platoon. More precisely, it must include rolling resistance, aerodynamic drag, brake/powertrain actuator, and wheel dynamics during control design and platoon modelling stages. These factors are highly significant. Therefore, this section discusses a modified algorithm that incorporates the vehicle dynamic characteristics in the platoon model.

B. Modeling of the Vehicle Dynamics

The initial step in designing the control system is to model the dynamics of vehicle. Vehicle system dynamics is usually a known complex system in which nonlinear parts such as clutch and tire, as well as tire-road friction coefficients, mass, etc. always exist. The different mechanical parts and the tire/road interface of the vehicle is most important because the modeling of vehicle dynamics is based on those forces.

In a series of tire design models, Pacejka (2006) combined them with vehicle models. This provided a practical understanding regarding the influence of tire on the behavior of vehicles. Other researchers Nikravesh and Gim suggested a detailed analysis using Finite Element Method on tire modeling (Gim 1990, Gim 1991a, Gim 1991b).

It is important to select a list containing mechanical parts including suspension geometry, tire, anti-roll bar, steering angle, etc. to attain the view of vehicle dynamics. Moreover, the list is very important for the accuracy and complexity of the expression of vehicle model. Commonly, it is essential to discover the concession between complexity and accuracy.

Researchers and automotive manufacturers have been followed in the modelling of vehicle dynamics at different levels. Researchers (Hingwe 1997, Nouvelière 2002, Day 1995 and Pham 1997) believe that the final purpose of implementation will define the accuracy and complexity of the vehicle model. Lowndes (1998) suggested that each element of a vehicle, including independent suspension, sprung mass, and wheels, should be considered in detail. In one of the most complex models there are 28 degrees of freedom to vary. Moreover, another complex model was

F_{rr}

employed that contains 18 degrees of freedom which involves the dynamics of tire suspensions system, rigid body dynamics, and tire dynamics (Addi 2005). Today, a model containing six degrees of freedom is accepted widely which has the capability to define the principal vehicle movements. These six key principal movements include three rotational motions about three axes (roll-pitch-yaw) and three translations along x, y and z-axes.

Since this study is focused on a longitudinal model, it will mainly considered wo key areas - longitudinal dynamics and powertrain dynamics. Moreover, the longitudinal dynamics are impacted by aerodynamic forces, rolling resistance forces, tire forces, and others. The powertrain dynamics include subsystems dynamics, e.g., torque converter, internal combustion engine, wheels, and transmission.

C. Vehicle Longitudinal Dynamics

1. Longitudinal Vehicle Forces

Figure 37 shows that a vehicle contains a large body which is not flexible and it moves along a inclined roadway. The forces in the wheel contact points are mixed with normal longitudinal forces on each axle. Other external forces include aerodynamic drag forces, rolling resistance forces, and gravitational forces act on the vehicle.

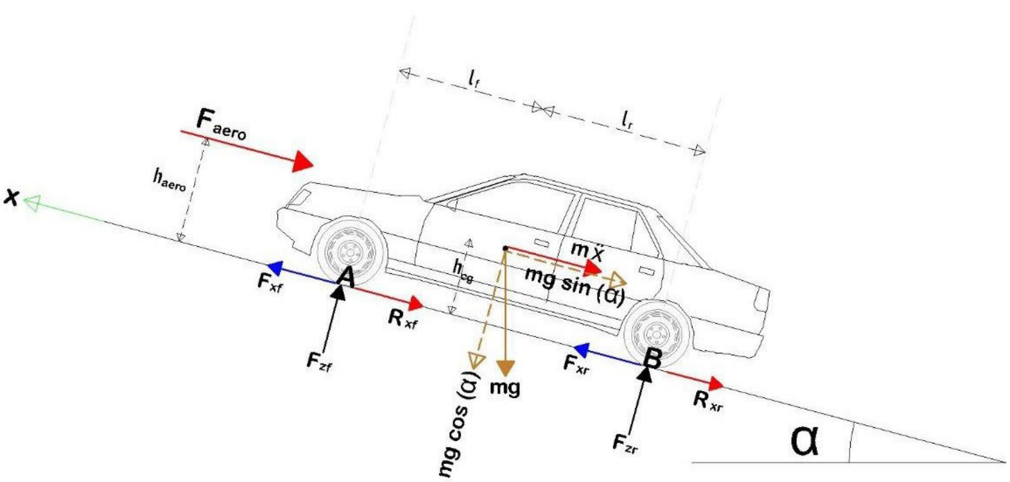


Figure 37 - Forces acting on a road vehicle.

Where:

F_{xf}	longitudinal tire force at the front tires.
F_{xr}	longitudinal tire force at the rear tires.
F_{aero}	longitudinal aerodynamic drag force.
F_{rf}	rolling resistance at the front tires.
F_{rr}	rolling resistance at the rear tires.

m mass of the vehicle.
$\ddot{x}$ vehicle acceleration.
g gravitational acceleration.
$\propto$ angle of inclination of the road.
h_{aero} height of aero force.
h_{cg} height of center of the vehicle.
F_{zf} normal force at the front tires.
F_{zr} normal force at the rear tires.
l_r length from center of the vehicle to the center of the rear wheels.
l_f length from center of the vehicle to the center of the front wheels.

The basic equation of vehicle motion is formed after the combination of the forces with the vehicle's longitudinal axis:

$$m\ddot{x} = F_{xf} + F_{xr} - F_{aero} - F_{rf} - F_{rr} - F_{grade} \quad (26)$$

Let F represent the sum of tractive effort carried by the rear and front tires (F_{xr} + F_{xf}) for exposition purposes and F_r represents the sum of rolling resistance (F_{rf} + F_{rr}). F_{grade} is the grade resistance which is equal to $mg\ sin\ \alpha$. This also can be written as follows:

$$F = m\ddot{x} + F_{aero} + F_r + F_{\mathrm{grade}} \quad (27)$$

The following subsection shows the basic equation of vehicle motion with the resistance terms in Equation (26), to direct the attention toward tractive effort F (F_{xf} and F_{xr}) for front and rear wheels to mitigate the resistance and/or to accelerate the vehicle.

2. Longitudinal Tire Force and Vehicle Wheel Dynamics

Front and rear wheels rotational dynamics (Devika et al., 2020) are provided through:

$$I_f\dot{\omega}_f = T_f - R_fF_f \quad (28)$$

$$I_r\dot{\omega}_r = T_r - R_rF_r \quad (29)$$

Where:

F_f and F_r represent the longitudinal traction forces produced based on the engine for front and rear wheels, (for ease, in the next sections we will mention the longitudinal traction forces without x; F_f instead of F_{xf} and so on).

I_f and I_r represent the moment of inertia of front and rear wheels,

R_f and R_r represent the tire radius for front and rear wheels,

T_f and T_r represent the transmitted torques to the front and rear wheels respectively, and

$\dot{\omega}_f$ and $\dot{\omega}_{f\mathrm{r}}$ represent the angular acceleration of front and rear wheels.

The below two equations are rearranged to get the longitudinal traction forces on the left- hand side:

$$F_f = \frac{1}{Rf}(T_f - I_f\dot{\omega}_f) \quad (30)$$

$$F_r = \frac{1}{Rr}(T_r - I_r\dot{\omega}_r) \quad (31)$$

The force of vehicles engine or any value that is a function of weight distribution of vehicle and the features pertaining to roadway surface-tire interface determine the wheel's longitudinal force. Irrespective of the force that the vehicle's engine makes available at the roadway surface, the idea beyond which additional force just results in the spinning of tires and does not mitigate resistance or accelerate the vehicle. Basic physics suggest the tractive longitudinal exertion pertaining to the roadway surface-tire interaction will be the normal force F_Z multiplied by the coefficient of road adhesion μ, so the equation will be:

$$F_{Longitudinal} = F_Z \times \mu \quad (32)$$

Where
$F_{Longitudinal}$ represents total traction longitudinal forces from wheels.
μ represents the coefficient of road adhesion.
The typical values the coefficient of road adhesion μ are provided in Table 2.

Table 2 - Typical Coefficients of Road Adhesion (μ) (Mannering et al., 2017).

Pavement	Coefficient of Road Adhesion (μ)
Good, dry	1
Good, wet	0.9
Poor, dry	0.8
Poor, wet	0.6
Packed snow or ice	0.25

The following equation can be written to restate the Equation (32):

$$F_f + F_r = F_{Zf}\,\mu_f + F_{Zr}\,\mu_r \quad (33)$$

Where:

F_f longitudinal force at the front tires,
F_r longitudinal force at the rear tires,
F_{Zf} normal force at the front tires,
F_{Zr} normal force at the rear tires,
μ_f coefficient of road adhesion at the front tires,
μ_r coefficient of road adhesion at the rear tires.

It is particularly important to inspect the normal forces on the front and rear wheels to ascertain the longitudinal tractive effort that the roadway surface-tire contact can support. Moment gathering and a force diagram is obtained for Figure 37 to describe what regulates this point of maximum tractive effort that what is the limiting value beyond which tire spinning begins.

In Figure 37, the normal force on the front wheels F_f is provided by adding the moments about point A:

$$F_{Zf} = (l_f + l_r) + F_{aero}h_{aero} + m\ddot{x}h_{cg} + mgh_{cg}\,sin(\propto) - mgl_r\,cos(\propto) = 0 \quad (34)$$

Consequently, the normal force on the front wheels will be equal:

$$F_{Zf} = \frac{mgl_r\,cos(\propto) - F_{aero}h_{aero} - m\ddot{x}h_{cg} - mgh_{cg}\,sin(\propto)}{(l_f + l_r)} \quad (35)$$

The normal force on the rear wheels F_r is provided by adding the moments about point B:

$$F_{Zr} = (l_f + l_r) - F_{aero}h_{aero} - m\ddot{x}h_{cg} - mgh_{cg}\sin(\propto) - mgl_f\cos(\propto) = 0$$ (36)

As a result, the normal force of the rear wheels will be equal:

$$F_{Zr} = \frac{mgl_f\cos(\propto) + F_{aero}h_{aero} + m\ddot{x}h_{cg} + mgh_{cg}\sin(\propto)}{(l_f + l_r)} \quad (37)$$

Where:

F_{Zf} normal force at the front tires,
F_{Zr} normal force at the rear tires,
F_{aero} equivalent longitudinal aerodynamic drag force,
m mass of the vehicle,
g gravitational acceleration,
$\propto$ angle of inclination of the road,
h_{aero} height of aero force,
h_{cg} height of center of the vehicle,
$\ddot{x}$ acceleration rate,
l_r length from center of the vehicle to the center of the rear wheels, and
l_f length from center of the vehicle to the center of the front wheels.

It is analyzed through the above equation that the acceleration of the vehicle affects the normal force distribution on the tires. There is a decrease in the normal load on the front tires and increase in the normal load of rear tires when the vehicle accelerates.

3. Resistance Factors

Usually, there are two sources of vehicle resistance that are divided into two types:

a. Aerodynamic Resistance

The performance of the vehicle can be affected by a resistive force called Aerodynamic Resistance. The proper aerodynamic design of the vehicle is important because this part of resistance becomes devastating at high speeds. Aerodynamic resistance evolves from many sources. The primary source comes from the turbulent flow of air surrounding the vehicle body which accounts for 85% of the total aerodynamic resistance. The shape of the vehicle creates this turbulence especially the rear part of vehicle which is also a major source of air turbulence. The friction of the air that passes through the vehicle contributes around 12% of total aerodynamic resistance at a much lesser extent. Lastly, the air flow that comes through the other parts such as radiators and air vents contribute a small 3% of the overall aerodynamic resistance.

The design of racing and sports cars is heavily based on aerodynamic efficiency. Recently, the need for more fuel efficiency and overall vehicle performance has given rise to more efficient aerodynamic designs in passenger cars. However, aerodynamic efficiency has a limited scope in pickup trucks and sports utility vehicles because of the cargo space.

According to these sources, the equation has been drawn to determine the Aerodynamic resistance is given below:

$$F_{aero} = \frac{1}{2} \rho C_d A_F (X)^2 \tag{38}$$

Where:

ρ represents the mass density of air,
C_d represents the aerodynamic drag coefficient,
A_F represents the frontal area of vehicle (projected area of the vehicle in the direction of travel), and
X Represents the longitudinal vehicle velocity.

For a clear picture of Aerodynamic resistance calculations, X is the vehicle's speed in comparison to the prevailing speed of wind. The exposition of concepts will be presented for the simplification and this research assumes the wind speed is equal to zero for all problems and derivations. Because aerodynamics resistance is in proportion to the square of vehicles' speed. Therefore, it is clear that the higher speed will increase the resistance.

Table 3 indicates both elevation and temperature form the air density. Equation (38) shows the connection between aerodynamic resistance and air. As the air becomes denser, there will be an increase in total aerodynamic resistance. The drag coefficient C_d includes the three aerodynamic resistance sources mentioned above. Empirical data measures the drag coefficients either from actual field tests or wind tunnel experiments where the vehicle is given permission to decelerate from a given speed with other sources of resistance including grade and rolling. A range of drag coefficients for different types of vehicles are given in Table 4.

A wide variety of drag coefficients are shown over time in Table 3. Lower drag coefficients are found among the vehicles with fuel efficiency. Sport cars having high performance, are likely to seek for low drag coefficients, but these cars can be designed to generate down force for performance braking and cornering which will affect the drag coefficients adversely. The upper ranges of drag coefficients in the Table 4 represent some larger vehicles such as pickup trucks and sport utility vehicles. Drag coefficients can also be impacted by the operating conditions. For instance, there will be an increase of 5% or more in drag coefficients when a small operational change occurs, such as opening a window. Moreover, there can be an increase of more than 25% when significant operational changes occur such as having the top down on a convertible automobile.

Table 3 - Typical Values of Air Density under Specified Atmospheric Conditions (Mannering et al., 2017).

Altitude (m)	Temperature (C)	Pressure (kPa)	Air density (kg/m^3)
0	15	101.4	1.2256
1500	9.7	84.4	1.0567
3000	-4.5	70.1	0.9096

Table 4 - Ranges of Drag Coefficients for Typical Road Vehicles (Mannering et al., 2017).

Vehicle Type	Drag coefficient (C_D)
Automobile	0.25-0.55
Bus	0.5-0.7
Tractor – Trailer	0.6-1.3
Motorcycle	0.27-1.8

Lastly, projected frontal area AF is approximated as the vehicle's height multiplied by its width. The frontal area for passenger cars usually ranges from 1m^2 to 2.5m^2 and frontal area is also an important factor considering the aerodynamic resistance.

b. Rolling Resistance

Rolling resistance is a type of resistance that is generally created by the tires of the cars and their inner mechanical fractions. The basis of the rolling resistance is the distortion of the tires, specifically when they pass through a road. Almost 90% force of the overall rolling resistance is required to overcome this distortion. However, the overall weight of the vehicles and the quality of the road material is one of the main determinants of rolling resistance. Taborek (1957) believes that solidity and diffusion account for almost 4% of the overall rolling resistance, specifically for the types of pavements and weight of the vehicles. Frictional motion on the road surface because of the slippage and presence of the airflow also affects the overall rolling resistance but only around 6% of the overall rolling resistance (Taborek 1957).

It has been seen that strong and hard pathways or roads provide a relatively lower level of rolling resistance, but on the other side, flexible pathways provide a higher level of rolling resistance. Similarly, the rolling resistance relies on the overall condition of the tire which not only includes the temperature but also includes the inflation pressure. A greater level of inflation of the tires reduces the overall rolling resistance, specifically on hard and solid surfaces, due to the reduction in friction. However, on the other side, flexible and soft surfaces lead to increased rolling resistance as shown in Figure 40. Furthermore, it is known that the temperature of the tire also creates additional flexibility in the tire's body, which consequently reduces the level of resistance and causes deformation of tires. Finally, the velocity of a vehicle has a significant impact on the deformation of the tire. A greater level of rolling resistance arises due to the higher speed of the vehicles, which not only creates additional flexibility in the tire but also leads to a greater level of vibration in the tire.

$$\mathrm{T}_r = F_{\mathrm{Z}} \Delta_X \quad (39)$$

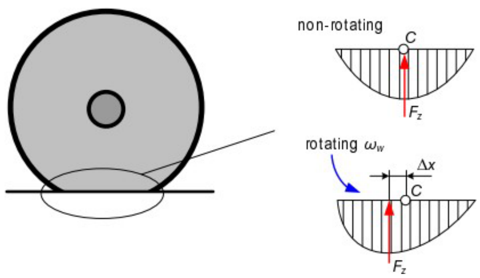


Figure 38 - Pressure distribution at a non-rotation and rotation tire.

Moreover, there are different determinants and factors which influence the overall rolling resistance. To simplify the estimation of the results, an approximation approach is used to determine the rolling resistance. It has been found that total rolling resistance can be approximated due to the friction term of the product and the overall weight of the vehicle. Hence, the rolling resistance force can be easily measured with the help of the following formula.

$$F_{\mathrm{r}} = F_{\mathrm{rf}} + F_{\mathrm{rr}} = f\ (F_{Z\mathrm{f}} + F_{Z\mathrm{r}}) \quad (40)$$

Here, in this case, F_{r} indicates the vehicle's rolling resistance force, and f indicates the coefficient of the rolling resistance. F_{rf} is the acting rolling resistance force on front tire rolling resistance, and F_{rr} is the rear tires acting rolling resistance force. $F_{Z\mathrm{f}}$ and $F_{Z\mathrm{r}}$ are the two normal acting forces on the rear and front tires of the vehicle.

The coefficient of the rolling resistance of roads vehicles can be measured with the help of the following formula.

$$f = 0.0236 + 0.4 \times 10{-}2 \times \dot{x}2 \qquad (41)$$

Here, in this case, $\dot{x}$ indicates the overall speed of the vehicle while f represents the co- efficient of the rolling resistance.

c. Grade Resistance

The weight of the vehicle causes the vehicle to lose speed when it moves in the upward direction and vice versa when it moves in the downward direction. The grade resistance can be calculated with the help of the following expression.

$$Fg = mg \sin \alpha \qquad (42)$$

Here, in this expression, m refers to the overall mass of a vehicle, α indicates the angle, which shows the level of the inclination of a pathway or road and lastly, g refers to the level of the gravitational acceleration against the vehicle or any other body.

D. Powertrain Dynamics

The performance of the vehicle plays a vital role in assessing the quality and importance of the new technologies of the vehicle on existing pathways, like the design of the guidelines on the roadways. The autonomous vehicle is one of the advanced technologies which is crucial for the evaluation of vehicle performance. It was discussed earlier that rear and front tires are the fundamental source of the force, which is known as the longitudinal force of the tire, and consequently lead to moving the vehicle. However, the findings of Rajamani (2012) suggest that these two forces are also directly linked with the slippage of the tires. It can be determined by knowing the variation between the velocity of the wheel and the real velocity of the axle. The following figure depicts the vehicle's powertrain system, which consists of the different small systems of the overall engine, final drives transmission, and conversion of the torque.

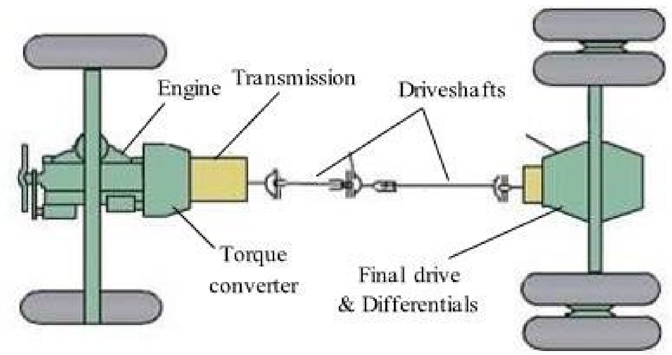


Figure 39 - Typical Vehicle Powertrain System.

Engine Model

The overall output of the engine is known as the torque of the engine. It is the non-linear operation and practices of the different components, including the mass charge of the cylinder, speed of the engine, the total load of the drivetrain and many more. How an engine works can also be understood from Figure 40.

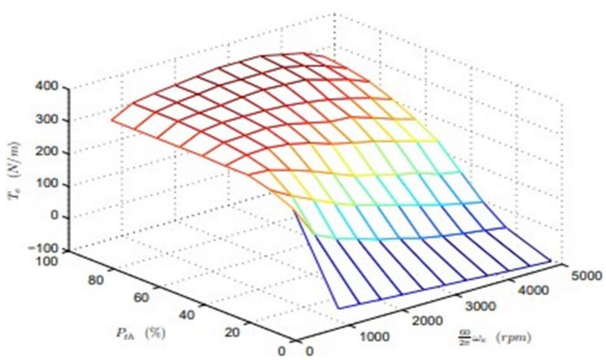


Figure 40 - An Example of an Engine Map.

Torque Converter

The Torque Converter refers to a fluid coupling device that is used to create the connection between the engine and transmission line. It is the combination of the three major constituents, including stators, pump, and turbine. There are different researchers who critically analyze the torque converter modeling (Kotwicki 1982, Assanis 2000, Cho 1989). From a generic point of view, this model of the torque can be illustrated with the help of the quasi-steady model and the experimental data.

Gearbox

The Gearbox, which is also known as transmission, assists the gear ratio in the process of adjustment with the help of gear shifting either automatically or manually. The engine is considered one of the most efficient regions of the vehicle as it allows the vehicle to move at a faster speed. The gear shift schedule decides the operating gear, which is influenced by the throttle opening and the velocity of the vehicle. The gear shift modeling is considered the main component in automatic gearbox modeling. Normally the Gearbox consists of fixed gears within the range of four or five. But based on the condition, it changes the gear automatically. The automatic system of the Gearbox works based on the pre-stored data or instruction, and it is also an automatic event-driven system.

Drive Shaft

The Drive Shaft is a mechanical part of the vehicle which is used for conducting the torque and also assisting in the rotation. Generally, in vehicles, the drive shaft helps to create a connection between different parts of a drive train, which are usually difficult to connect directly either due to the wider distance or the requirement of the movement.

Final Drive and Differential

The primary objective and operation of the final drive in the powertrain of a vehicle is to offer a continuous and extra reduction of the gear in the overall system of the transmission. There are generally two kinds of final drive reduction gears, specifically in the longitudinally mounted engine, including worm and bevel gear. Vehicles that are based on the transversely mounted engine consider this as a helical option. A differential is also part of the final drive unit which generally assists in transmitting the torque and rotation with the help of the three primary shafts: the two output and an input shaft. The input shaft is linked with the drive shaft, while the other two shafts assist in driving the wheels. Due to the presence of the differential, it becomes easier for wheels to drive at different wanted speeds with the provision of a similar velocity. The study of Zhao (2010) and Rajamani (2012) discussed this in more detail.

Braking System

The braking system of the vehicle is crucial in stopping the vehicle at a specified distance, protecting it from accidents and extenuating the system. Braking technology of automobiles is advancing rapidly. The advanced braking system of the cars is designed in such a way that facilitates and prevents locking, known as the antilock braking system. There are usually two main objectives of the antilock braking system. Firstly, it prevents the road friction from declining the slide values, and secondly, this system has the potential to increase the overall efficiency of the break. The study by Mannering et al. (2017) shows that the advanced technology of the antilock system of the brakes can help to detect the locked wheel and stop the application of the wheels if it is already locked and release this automatically.

It is shown (Kienhöfer 2006, Hedrick 1996) that, from a generic standpoint, the highest level of the automobile's braking force is in direct proportion to the value of the road friction coefficient and the total weight of the vehicle normal to the road surface. See Figure 41 for a diagram of a typical braking system.

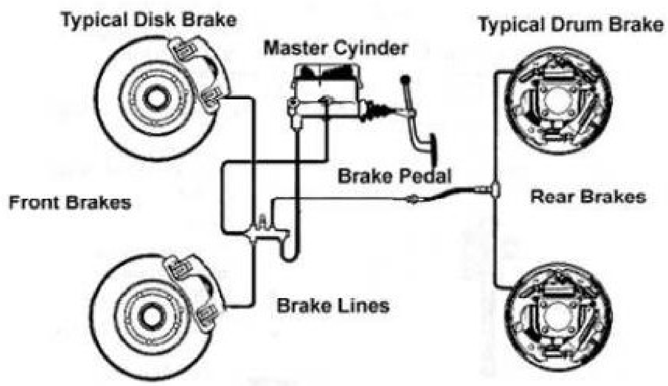


Figure 41 - Typical Braking System.

E. Longitudinal Model for Simulation

The fundamental aim of this part is to illustrate the longitudinal dynamic model of automobiles that is generally combined with the different forces discussed above. This model is designed specifically to check the impact of internal conditions and external conditions that affect the system, hence making variations in the results of the system. To perform the simulation, it is assumed that the vehicle is in a driving position on a straight roadway, and that the lateral motion of the vehicle does not have any significant correlation with the longitudinal movement, that is, $\delta = 0$. Accordingly, the longitudinal dynamic model is presented below.

$$m\ddot{x} = F_{xf} + F_{xr} - F_{aero} - F_{rf} - F_{rr} - F_{grade} \tag{43}$$

The different acted forces on the wheels and the body of the vehicles are shown in Figure 42.

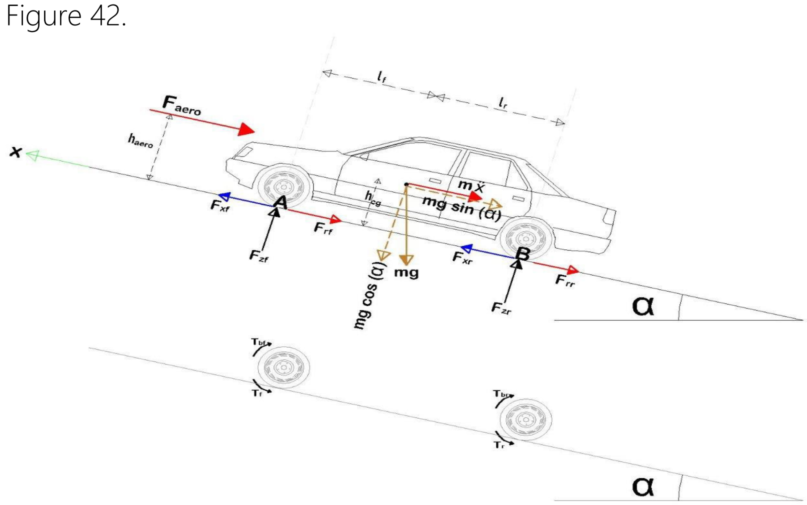


Figure 42 - The different forces acting on the body and wheels.

The figure shows that the resistive forces are acting against the direction of the movement of the car, which is causing a decelerating effect. These resistive forces include aerodynamic forces and a component of weight when the car is being driven on an inclined road. On the other hand, the engine produces a forward force to drive the car forward. Therefore, the net acceleration forward is a result of the net forward force that is exerted by the engine.

The following equation can assist in measuring the torque each wheel offers:

$$T_f = I_f\dot{\omega}_f + R_f F_f \quad (44)$$

$$T_r = I_r\dot{\omega}_r + R_r F_r \quad (45)$$

T_f and T_r refer to the transmitted torque, R_f and R_r are the radii of the wheel, I_f and I_r denote the inertia of the rare front tire, F_f and F_r Indicate the longitudinal traction force created through wheels, and lastly $\dot{\omega}_f$ **and** $\dot{\omega}_r$ indicate the angular acceleration.

Combining the above, the following equation is obtained:

$$m\ddot{x} = \frac{1}{R}\left[T_{f} + T_r - (T_{\mathrm{b}f} + T_{\mathrm{br}}) - (I_f\dot{\omega}_f + I_r\dot{\omega}_r)\right] - F_{\mathrm{r}} \quad (46)$$

The above equation can be beneficial in the case of the controller design. Here, $T_{\mathrm{b}f}$ and T_{br} indicate the braking torque and F_{r} is the overall rolling resistance force.

Generally, it is a common perception that wheels do not experience any type of slip. This perception is not based on a realistic point of view as, according to the findings of Zhao (2010), the slip is relatively small at the low acceleration place, and due to this, the slip of the tire may be ignored. Furthermore, the value of the $\dot{\omega}$ It can be found with the help of the following equation.

$$\dot{\omega}_f = \dot{\omega}_r = \ddot{x}/R \quad (47)$$

Hence, the brake torque ($T_{\mathrm{b}f}$,T_{br}) can be calculated by the following equation:

$$T_{\mathrm{b}} = T_{\mathrm{b}f} + T_{\mathrm{br}} = -m * DecRate * R - [(I_f\dot{\omega}_{fi} + I_r\dot{\omega}_{ri})] - R\ F_{\mathrm{r}} \quad (48)$$

Here, the $DecRate$ is the deceleration rate, R is the radius of the wheel, F_{r} is the rolling resistance, and $\dot{\omega}_{fi}$ **and** $\dot{\omega}_{ri}$ **are** the angular speed of the wheel.

The mass "m" of the vehicle remains the same throughout the system. The system cannot perform as a non-isolated system, as there is a significant need to develop this model while considering the internal and external conditions.

The rate of deceleration required is dependent on the situations, which can vary based on the speed of vehicle and urgency to stop. Deceleration is a result of the braking force which overcomes the forward force exerted by the engine on the wheels. Therefore, at high speeds, more powerful braking force may be required to stop the vehicle in a shorter time.

Previous studies found that the majority of drivers decelerate above 14.8 ft/s^2, specifically when there is an unexpected need for a brake. Almost 90% of drivers experience deceleration above 11.2 ft/s^2. These types of decelerations can easily be overcome by drivers. Due to this, 11.2 ft/s^2 is considered the deceleration threshold for quick stopping. In addition to this, the advanced braking system of the vehicles and availability of friction on the wet roadway surface consequently leads to an increase in deceleration, which also increases the efficiency of the overall braking system (AASHTO, 2018). This increase rate of deceleration is caused by the great braking force exerted by the driver. Such cases can cause road accidents as there are chances of the tire losing traction, causing the vehicle to slip. However, at lower speeds, the tire slip can be neglected as the braking force required is not high enough to cause the vehicle to slip.

Hence, the complete model is obtained below:

$$m\ddot{x} = \frac{1}{R}\left[T_f + T_r - (T_{\mathrm{b}f} + T_{\mathrm{br}}) - (I_f\dot{\omega}_f + I_r\dot{\omega}_r)\right] - F_{aero} - F_{rf} - F_{rr} - F_{grade} \qquad (49)$$

F. Updating the Simulink Basic Model to Include Vehicle Characteristics

The basic model can be produced by including the vehicular factors and characteristics and includes basic methods for driveline modelling. The engine and transmission frameworks for driveline model can be created through four gears, the clutch stress signals that can be more non-fiction and give results that can be incorporated in real world situations. The model has variables for limiting the blocks in order to convey information regarding creation, access and changes in workspace.

In order to develop the longitudinal dynamics platoon model, the equation of the controller to model is mentioned below:

$$m\ddot{x} = F - F_R \qquad (50)$$

$$m\ddot{x} = -\tau F + u - F_R \qquad (51)$$

Where:

$\ddot{x}$= acceleration of the vehicle
u = the control input of the vehicle engine
m = motor vehicle's mass
F = force produced by the engine

F_R = resistance forces.
τ = time constant of engine

Figure 43 shows all the forces in the Simulink model. This model is an equation- and diagram-based abstract and condensed description of a system. Understanding how to mathematically describe a system using Simulink model is made easier by the modelling principles using MATLAB. The Signal builder in the Simulink indicates the brake signals to engine and transmission regulating system. The driver input block needs to be opened to view the brake status in the simulation further. To model the system more appropriately, the engines and motor provide the torque and speed values as the characteristic of driveline model.

Figure 44 is a more focused on the dynamic forces. The mathematical relationships of all the dynamic forces are shown in the figure that can help visualize all the critical areas of influence. The dynamic forces acting on the system as the external component have a major influence on the results of the overall system.

The front wheel torque stands for the rotational force of wheels which can be measured in Newton-meter. Every vehicle and its wheels possess a different torque so it shall be installed with its own requirements. An average torque for holding the car tire could range from 108 to 122 Newton-meters. The front wheels' torque in this system is thus measured and analyzed as a separate entity.

The front wheel torque is visualized in Figure 45. The figure shows all the forces affecting the performance of the front wheels. Front wheel torque holds high importance as it can help vehicles perform more efficiently, especially in the case of front-wheel drive vehicles. Inefficient torque on the wheels can cause the vehicle to feel underpowered, leading to more fuel consumption and inefficient performance.

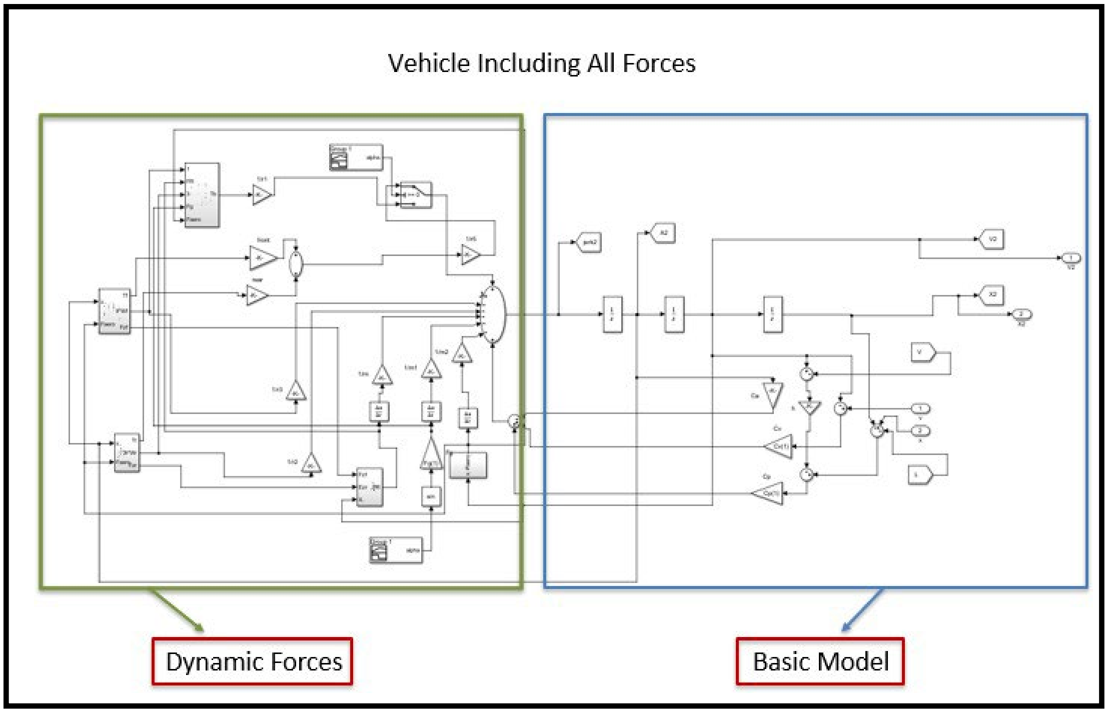


Figure 43 - The Simulink Model including all forces.

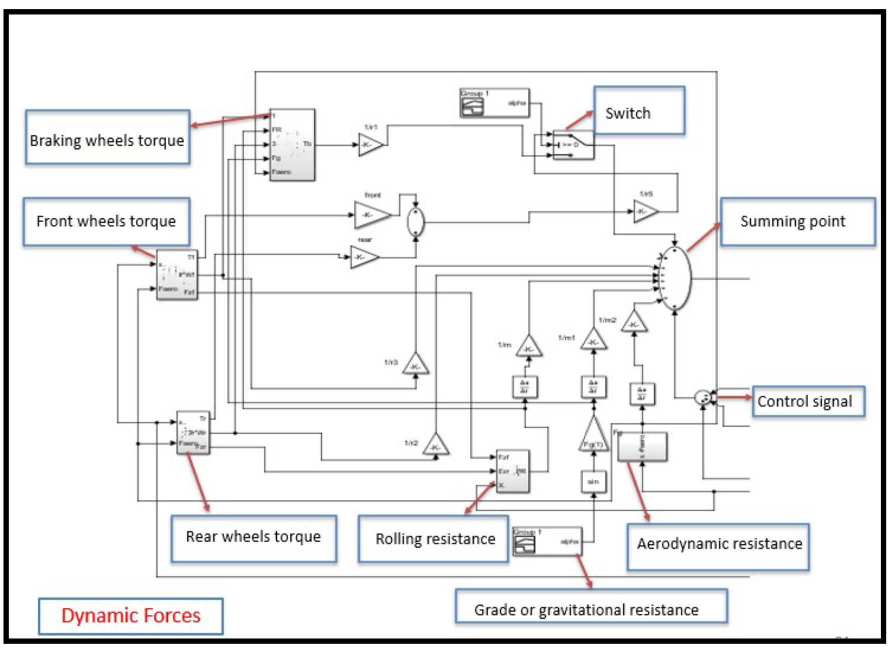


Figure 44 - The Dynamic Forces.

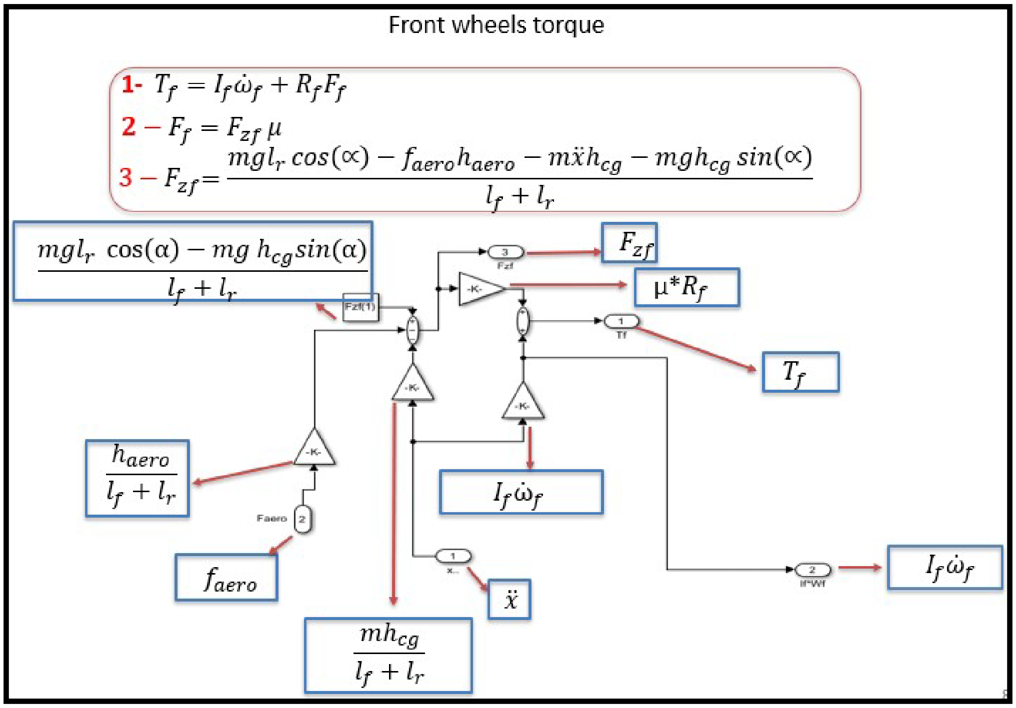


Figure 45 - Front Wheels torque block.

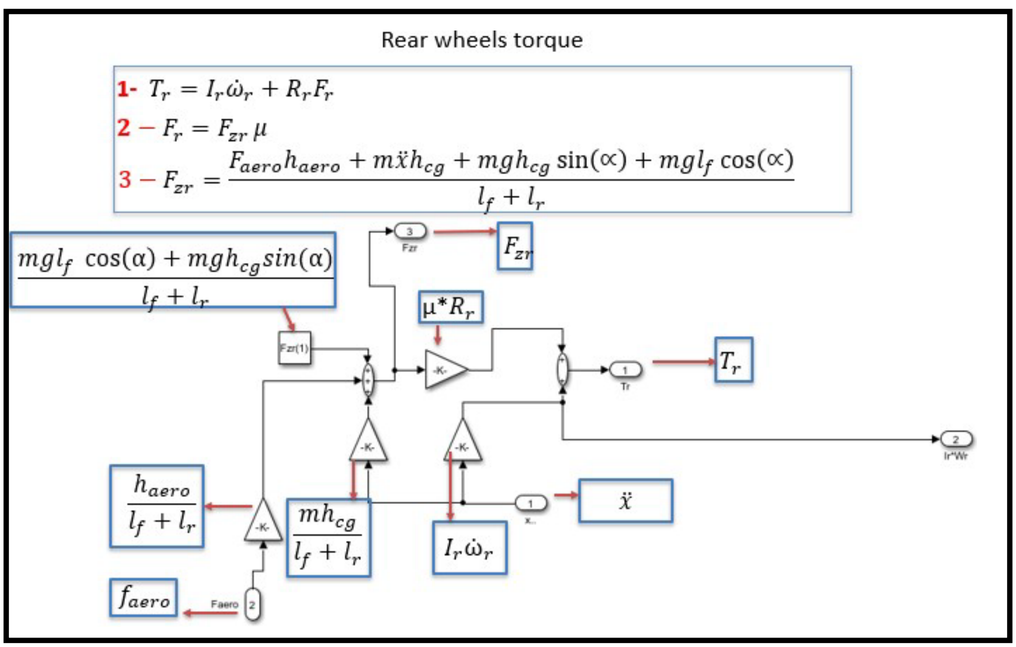


Figure 46 - Rear Wheels torque block.

Like front wheel, rear wheel torque is presented in Figure 48. It can be noted that the rear wheel almost has the same forces as those affecting the front wheels. Therefore, it is important that all wheels of the vehicle are torque efficient to enhance performance. The rear wheel torque of the vehicle is measured separately assigning the parameters for the equation.

Braking wheel torque or braking torque is the ability of braking system to stop a moving body (vehicle in this case). A frictional force is exerted by the braking pad creating torque on the axle. Torque is a form of force to stop a rotating body so it is measured in Newton, N. The maximum torque applied on a vehicle to stop it motion is 500 N for the vehicle moving at the speed of 88km/h while minimum torque is 200 N at the speed of 18km/h.

Figure 47 shows the braking wheel torque. It can be noted that a resistive force is added to the wheel due to braking, which causes the car to slow down. This resistive force is often greater than the forward force when the vehicle is braking.

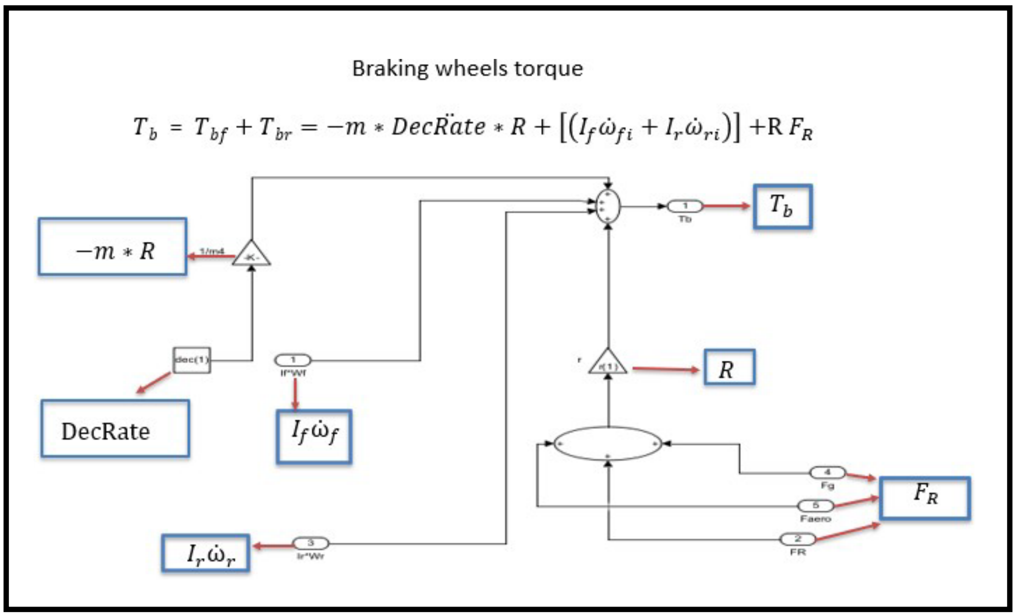


Figure 47 - Braking Wheels torque block.

The aerodynamics block shown in Figure 48 presents the forces caused by the movement of wind on the vehicle body. It is important to note that aerodynamic forces are resistive forces as they are opposite to the direction of the movement of the vehicle. The shape of the vehicle has a major influence on how strong the aerodynamic forces are. Also, these forces increase as the speed of the vehicle increases. Another factor that impacts the strength of aerodynamic forces is density of air. Therefore, all these factors cumulatively make an impact to create a resistance against the movement of the vehicle.

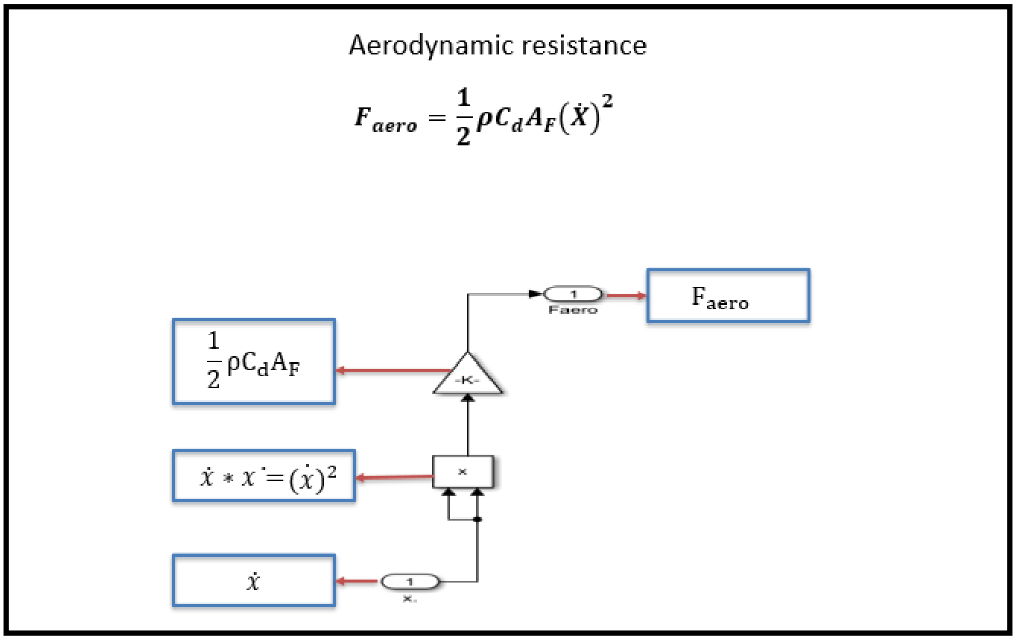


Figure 48 - Aerodynamic Resistance block.

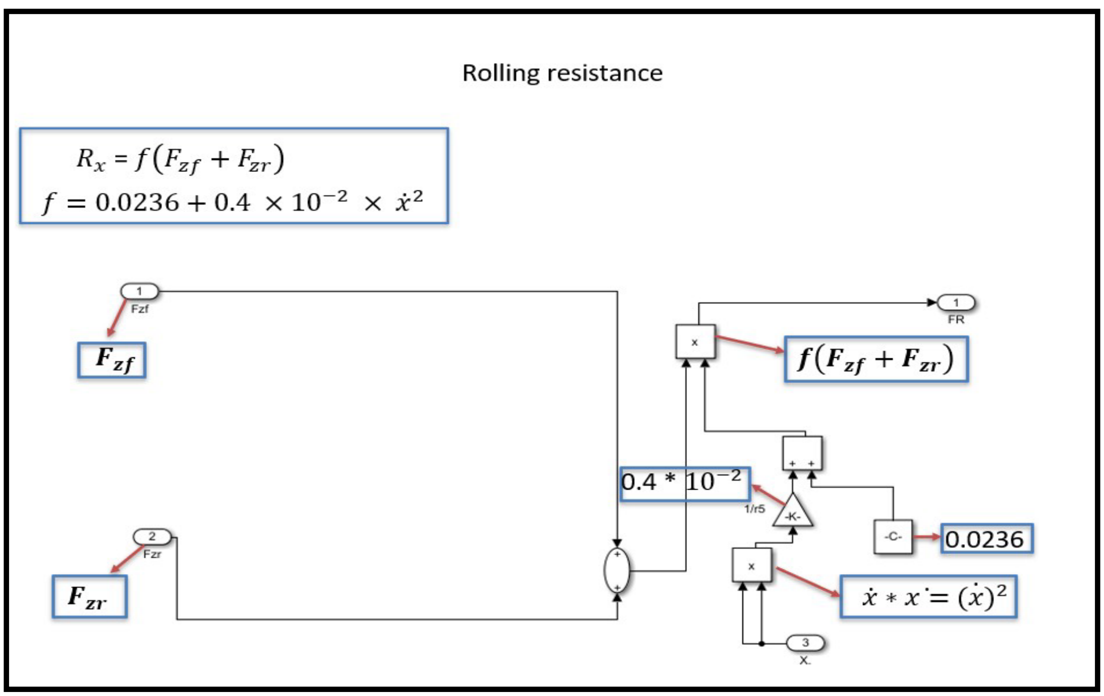


Figure 49 - Rolling Resistance block.

Rolling resistance consumes energy used in the system which cannot be recovered Rolling resistance produces an opposite force to the motion of a vehicle that also escalates the energy consumption of the vehicle. Thus, a rubber tire experiences a greater rolling resistance on a coarse road.

Rolling resistance is a critical factor for objects that roll on other surfaces. Therefore, rolling resistance is an important input for vehicle's performance as it can impact power required to move forward. Figure 50 shows the rolling resistance forces affecting the vehicle.

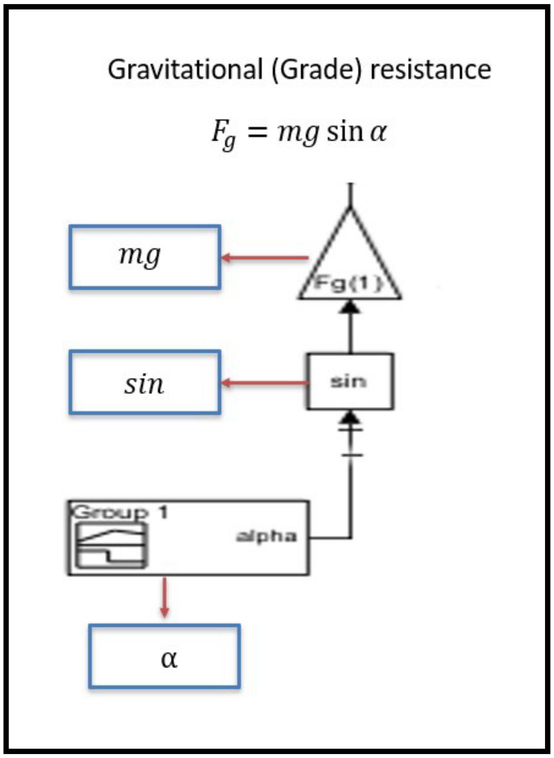


Figure 50 - Gravitational (Grade) Resistance block.

Gravity is another important factor that affects the movement of cars. Many roads have specific degrees of inclination, adding a component of the weight (gravity) that causes resistance for the vehicles to move forward. Figure 52 shows the gravitational resistance acted on the vehicle, where alpha is the degree of inclination. The sine ratio is used to calculate the component of gravity on inclined roads. Obviously, for roads where the degree of inclination will be zero, the gravitational resistance will also become zero.

```matlab
clc; clear all;
m = [1200 1200 1200 1200 1200 1200 1200 1200 1200 1200];
L = [1 1 1 1 1 1 1 1 1 1];
h=  [1 1 1 1 1 1 1 1 1 1];
Ca = [4 4 4 4 4 4 4 4 4 4];
Cv = [4 4 4 4 4 4 4 4 4 4];
Cp = [4 4 4 4 4 4 4 4 4 4];
r = [0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268];
g= 9.81 ;
t = [1/0.13 1/0.13 1/0.13 1/0.13 1/0.13 1/0.13 1/0.13 1/0.13 1/0.13 1/0.13];
p = [1.225 1.225 1.225 1.225 1.225 1.225 1.225 1.225 1.225 1.225];
Cd = [0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5];
Af = [1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4 1.4];
Faero = 0.5 .* p .* Cd .* Af;
Fg = m .* g;
lf = [1.02 1.02 1.02 1.02 1.02 1.02 1.02 1.02 1.02 1.02];
lr = [0.68 0.68 0.68 0.68 0.68 0.68 0.68 0.68 0.68 0.68];
a = [0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0];
haero = [0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7];
hcg = [0.35 0.35 0.35 0.35 0.35 0.35 0.35 0.35 0.35 0.35];
Fzr = (m .* g .* hcg .* sin(a) + m .* g .* lf .* cos(a))./(lf + lr); % m x.. h is remaining
Fzf = (m .* g .* lr .* cos(a) - m .* g .* hcg .* sin(a))./(lf + lr); % - m x.. h is remaining
Mu1 = [0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5];
Mu2 = [0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5];
mh = m .* hcg;
Rr = [0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268];
Rf = [0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268 0.268];
Wr = 1./Rr; % x.. is remaining
Wf = 1./Rf; % x.. is remaining
dec = [0 0 0 0 0 0 0 0 0 0];
If = [1 1 1 1 1 1 1 1 1 1];
Ir = [1 1 1 1 1 1 1 1 1 1];
front = [1 1 1 1 1 1 1 1 1 1];
rear =  [0 0 0 0 0 0 0 0 0 0];
```

Figure 51 - MATLAB Code for Different Combinations of Vehicle Characteristics.

G. Simulation Results

The simulation work of the platoon model has evaluated the following scenarios:

- Inter-vehicle distances with different vehicle types (four-wheel driving, rear wheel driving, front wheel driving), as shown in Figure 52 through Figure 54.
- Inter-vehicle distance for a combination of vehicles with different driving wheels, an example is shown in Figure 55.
- Inter-vehicle distances in the case of a road with upgrade or downgrade, as in Figure 56 and Figure 57.
- Inter-vehicle distances on an upgrade or downgrade road with a vehicle subject to braking for small interval of time, as in Figure 58 and Figure 59.
- Inter-vehicle distance in the case of braking taken by two different vehicles at different times, as in Figure 60.
- Inter-vehicle distance in the case of braking/deceleration mode for three different road friction coefficients, as in Figure 61 through Figure 63.

In the simulation runs, each vehicle was considered to have a mass of 1200kg in the case of front and rear wheel driving vehicles. For four-wheel drive vehicles, it was taken as 2000kg. In most cases, the simulation has been evaluated for the middle value of road friction coefficient (μ = 0.5) during driving. In case of braking mode (e.g., vehicle deceleration), the platoon has been evaluated for three levels of deceleration rates with road surfaces with three different tire-road friction coefficients (μ).

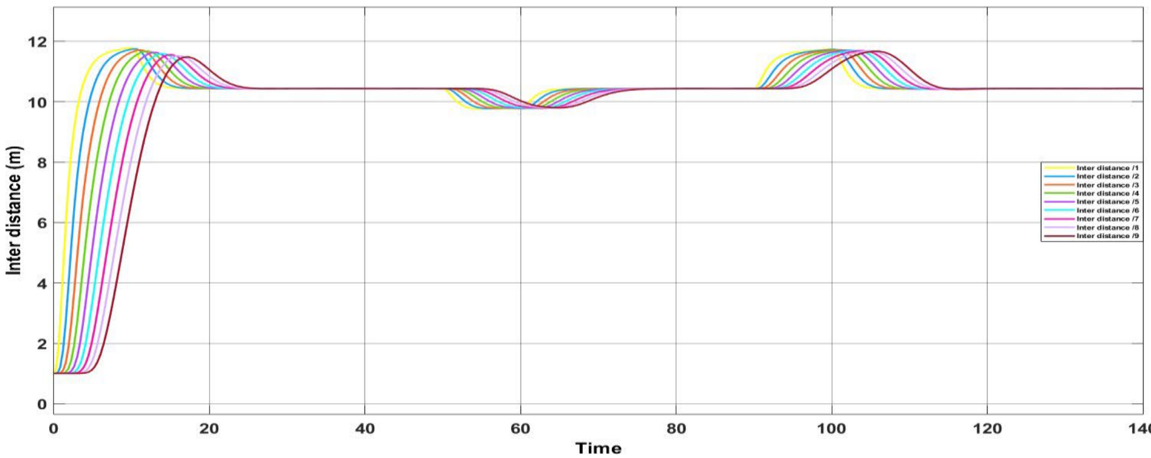


Figure 52 - Inter-Vehicle Distances in case of All Vehicles Are 4-wheel Driving.

In Figure 52, 4-wheel drive vehicles are in a platoon with μ = 0.5, and all the vehicles have initiated from the distance spacing of 1 meter. At a certain point the vehicles start moving linearly with irregular speeds. After 120 seconds it can be observed that the inter-vehicle distance becomes stable at approximately 10.25m.

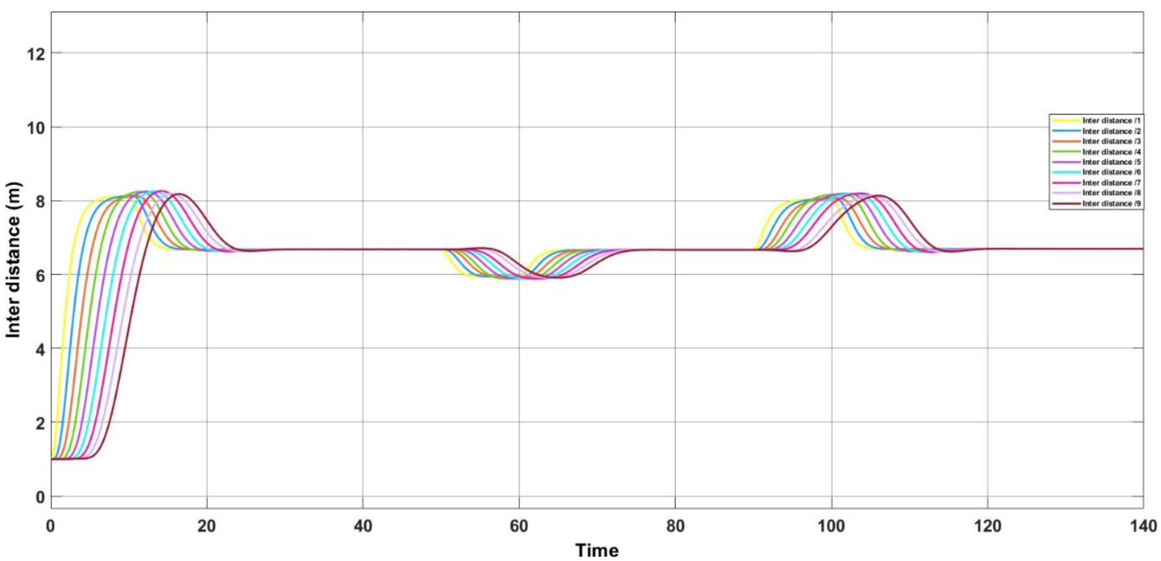


Figure 53 - Inter-Vehicle Distances When All Vehicles are Rear Wheel Driving.

It can be observed in Figure 53 that the rear wheels of the vehicle accelerate with 0.5 μ (half weight) from a 1-meter distance and travel smoothly with non-linear speeds. At this point, the inter-vehicle distance stabilizes at around 7 meters just around 120 seconds.

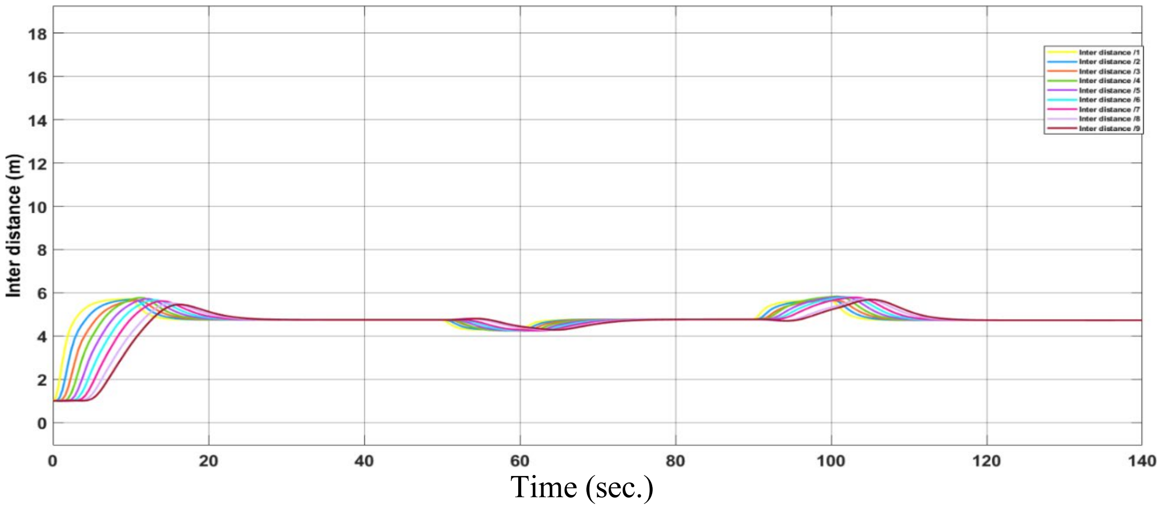


Figure 54 - Inter-vehicle distances in case of all vehicles are front driving.

It can be observed in Figure 54 that the front wheels of the vehicle platoon accelerate with 0.5 μ as they start from a 1-meter distance and travel smoothly with non-linear speeds. At this point, the inter-vehicle distance stabilizes at around 5 meters just before 120 seconds.

From Figure 52, Figure 53, and Figure 54, it can be observed that in the case of driving mode, the 4-wheel driving vehicles are stabilized at larger value of inter-vehicle distances followed by rear wheel drive vehicles then front wheel drive vehicles. This could be due to the acceleration capabilities of each vehicle, longitudinal traction forces generated by each vehicle type, inertial forces, etc.

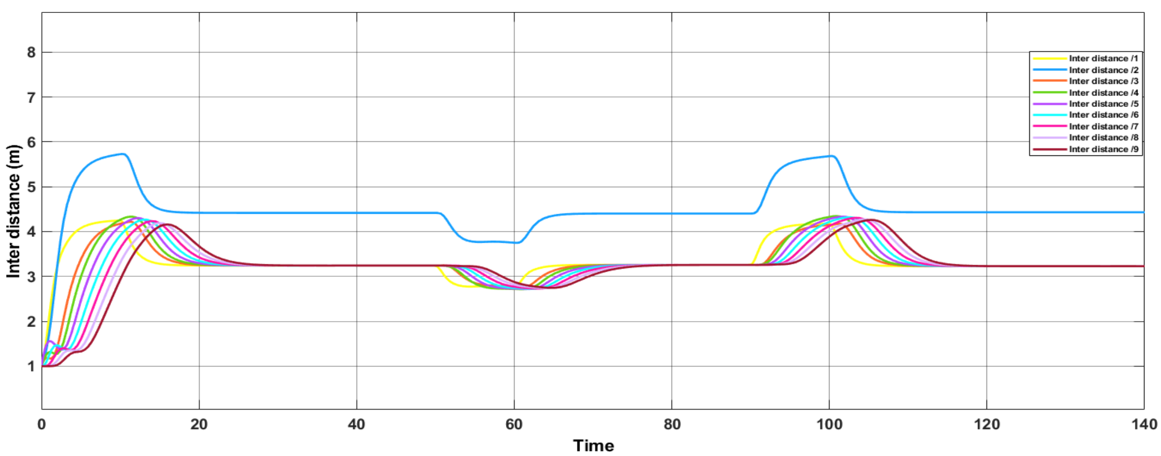


Figure 55 - Inter-vehicle distances in case of all vehicles are front driving except vehicle No.3.

In the simulation graph shown above in Figure 55, all vehicles are front driving except vehicle No.3. All the vehicles started covering the distance at the initial distance of 1 meter. All the vehicles moved with varying speeds at the beginning.

However, it can be seen that inter-distance of vehicle No 3 (behind vehicle No. 2) is around 4.30 meters while other vehicles' inter-distance stability was achieved at 3.10 meters, roughly at 120 seconds. This could be due to the different capabilities and dynamic characteristics of vehicle types (e.g. vehicle No. 3).

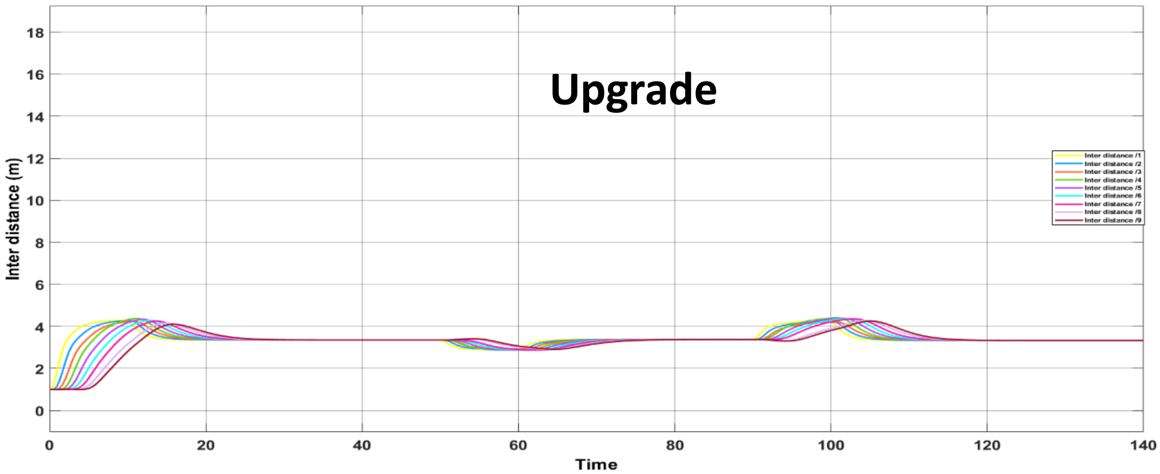


Figure 56 - Inter-Vehicle Distances in case of All Vehicles Are Front Wheels Driving on an Upgrade Road.

In Figure 56, all the vehicles are front wheel drive. The initial distance of the vehicles is marked at 1 meter and the vehicle platoon is going on an upgrade in the longitudinal direction. The inter-distance of the vehicles stabilizes before 120 seconds at approximately 3.80 meters.

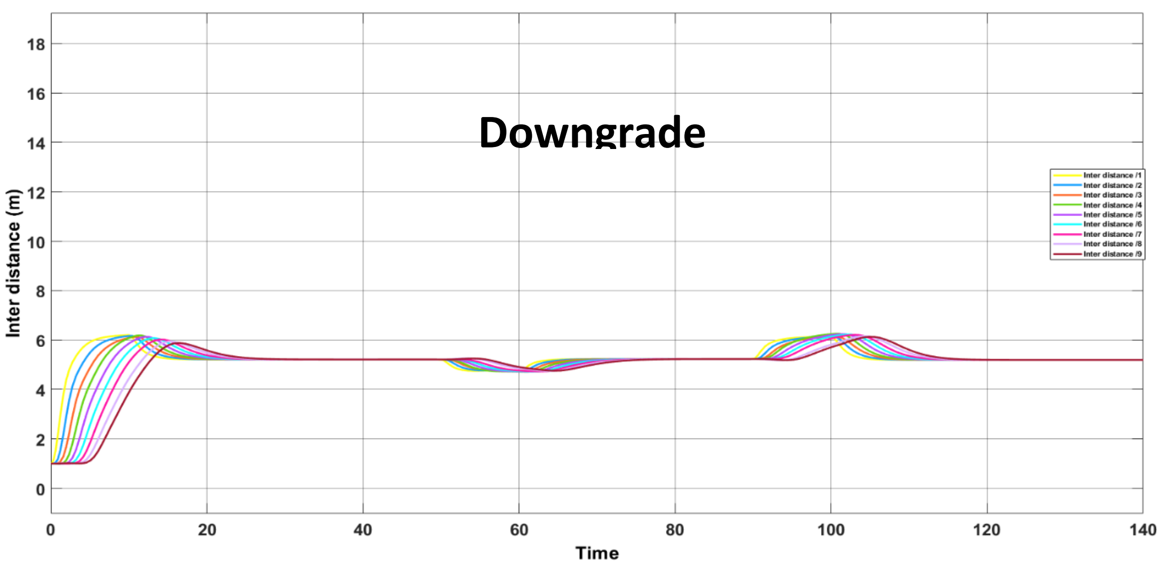


Figure 57 - Inter-Vehicle Distances in case of All Vehicles Are Front Wheel Driving on a Downgrade Road.

In Figure 57, all the vehicles are front wheels. The initial distance of the vehicles is marked at 1 meter, all vehicles are going an a downgrade. The inter-distance of the vehicles stabilizes before 120 seconds at approximately 5.5 meters.

Based on the simulation results presented in Figure 56 and Figure 57, it is clear that the inter-vehicle distances in a platoon vehicle are influenced by road grade direction (up or down). As expected, higher inter-vehicle distances are noticed in the case of downgrades and lower distances are observed in the case of upgrades.

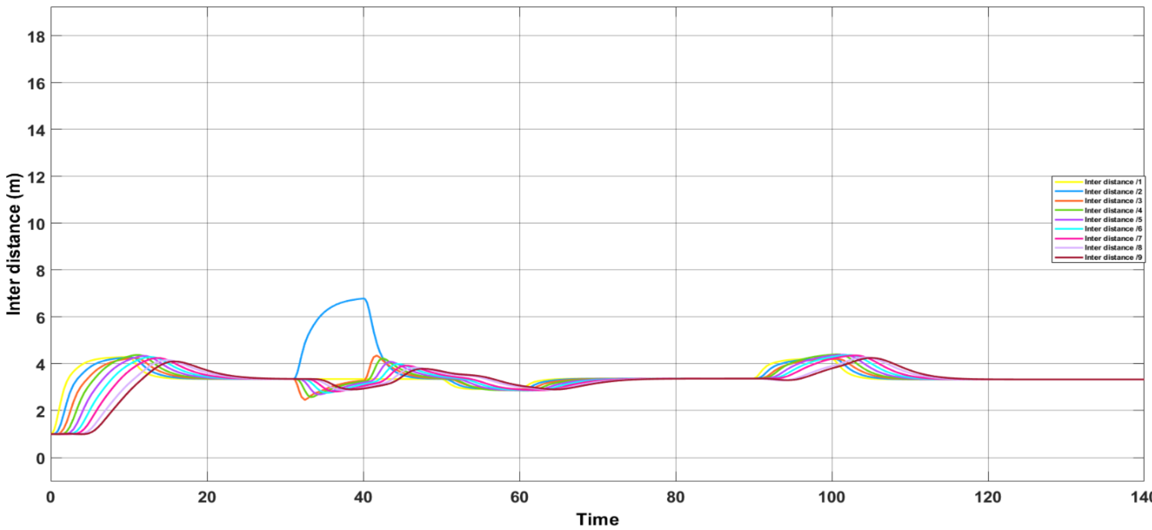


Figure 58 - Inter-vehicle distances in the case of all vehicles are front wheel driving on an upgrade road, with vehicle No.3 subject to braking.

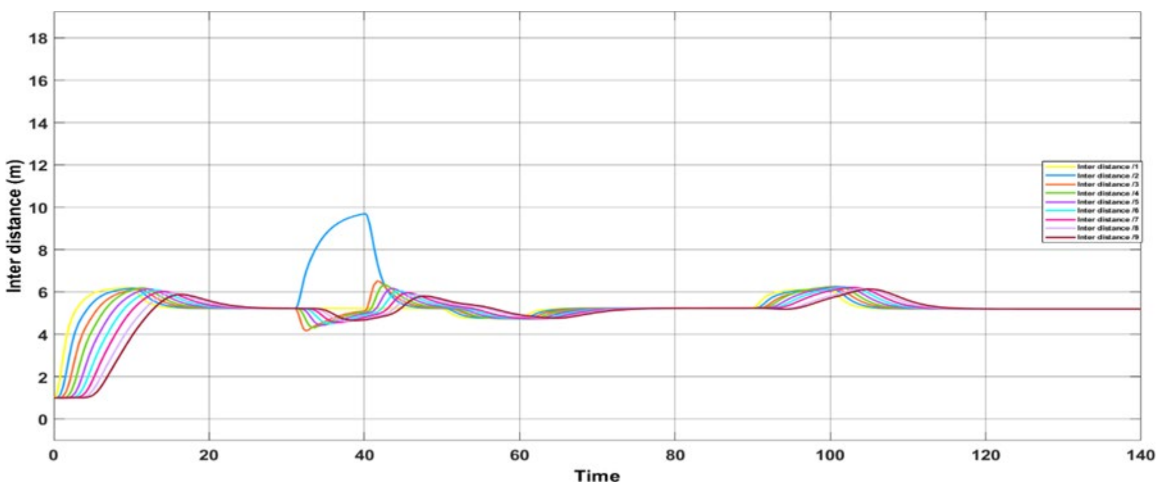


Figure 59 - Inter-vehicle distances in the case of all vehicles are front wheel driving a downgrade road, with vehicle 3 subject to braking.

When vehicle No. 3 is taking braking at a short interval of time, the distance between vehicles 2 and 3 is increased, as expected. This distance is higher than for the upgrade. After removing the braking, the inter-vehicle distance in the platoon gradually converged.

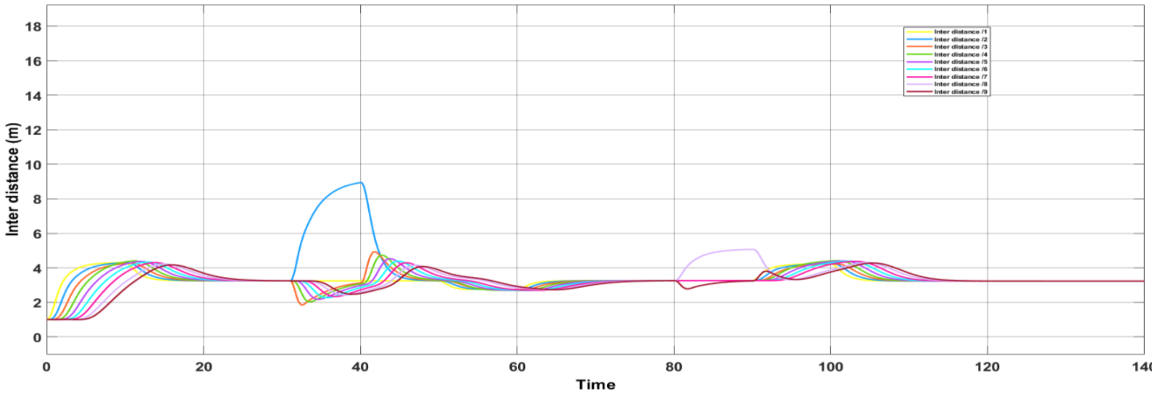


Figure 60 - Inter-vehicle distances in case of two different vehicles subject to small intervals of braking.

In Figure 60, vehicles No. 3, and No. 9 are subject to two small intervals of braking at two different times. The initial stage of the vehicles starts from the distance of 1 meter and are collectively moving smoothly, with speed increases and decreases. The inter-distance of vehicles for all vehicles stabilizes at about 3.8 meters before 120 seconds. As expected, the inter-vehicle distances between those vehicles taking braking and their preceding vehicles are increased during the braking period. After removing the braking, the vehicle spacing in the platoon converged to move smoothly.

Further, Figure 61 through Figure 63 evaluates the impact of deceleration rates (high, medium, and low) in the case of a road with different road frictions coefficients (μ) on the inter-vehicle distances. The platoons are subject to braking/deceleration. It is noticed that the inter-vehicle distances are influenced by the deceleration rates and road friction coefficients (μ). All vehicles in the system are converged, before the end of simulation time, at an inter-vehicle distance of approximately 9 meters when the road coefficient (μ) equals = 0.4. When road coefficient (μ) equals = 0.3, the inter-vehicle distance settled at approximately 11 meters, as expected due to less friction. Lastly, all vehicles in the system are converged to an inter-vehicle distance of approximately 13 meters when road coefficient (μ) equals = 0.2. Based on the above discussion, it can be stated that, during deceleration/barking mode, the inter-vehicle distance decreases as road friction coefficients increases, and vice versa.

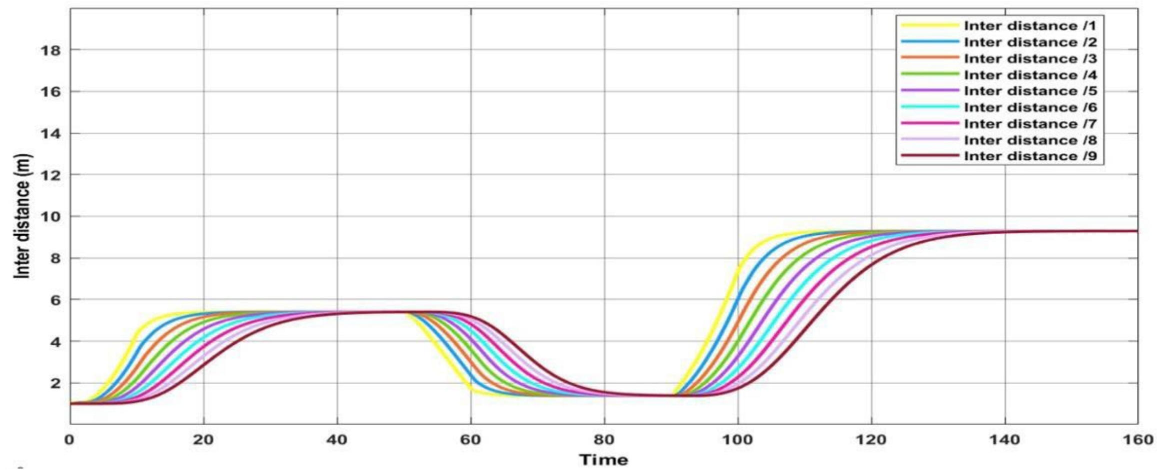


Figure 61 - Inter-vehicle distances in case of braking mode for vehicle platoon (μ =0.4).

A graph of a function

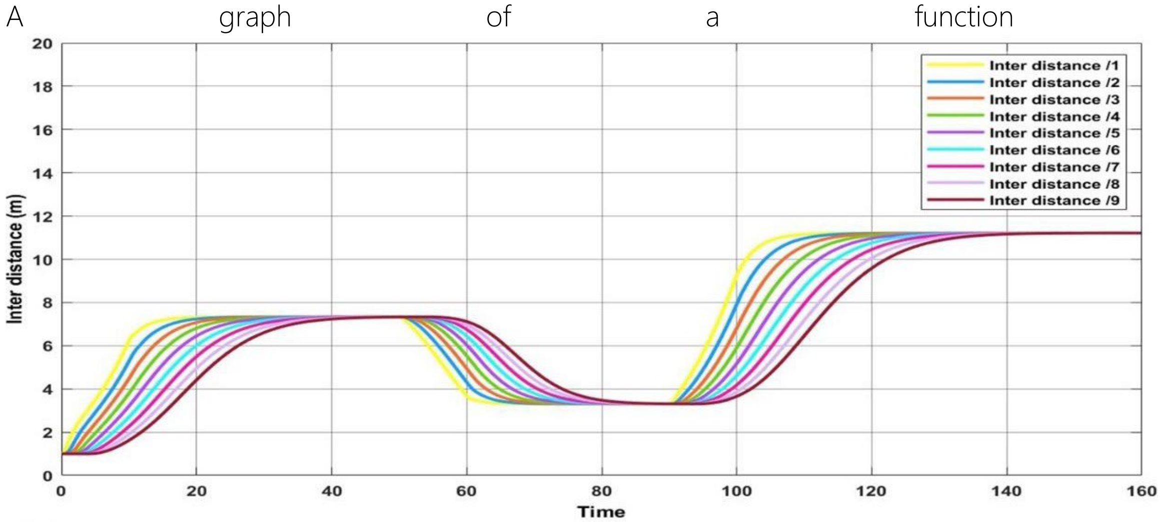


Figure 62 - Inter-vehicle distances in case of braking mode for vehicle platoon (μ =0.3).

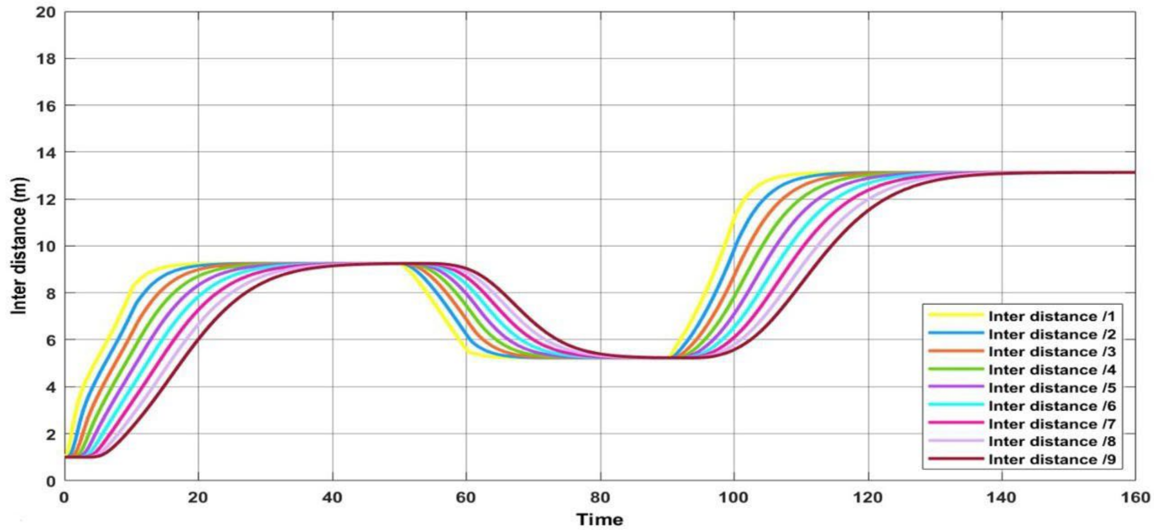


Figure 63 - Inter-vehicle distances in case of braking mode for vehicle platoon (μ =0.2).

VI. CONCLUSIONS AND RECOMMENDATIONS

Recent years have seen the emergence of CAV technologies, which hold great promise to reduce traffic accidents, enhance travel experiences, and boost the efficiency of transportation systems. With such technologies, it is feasible for a group of autonomous cars to travel together on the road in a platoon. These vehicles can communicate with one another and travel together with much smaller separations. Platoons are a tool that may be employed to improve safety, minimize fuel consumption, and smooth the flow of traffic.

A key factor in achieving those desired advantages is managing the vehicle platoon with optimal inter-vehicle spacing. Constant and variable spacing are the two policies available for the longitudinal control of a platoon of vehicles. String stability is provided by constant spacing, which calls for information from the leader. However, safety risks may be presented if the constant spacing is set too low. In comparison, string stability using variable spacing can be attained solely from onboard data, and it does not require much data from other vehicles (such as speed or location). The control parameters should be carefully chosen to maintain safety and effectiveness since the inter-vehicle distance might change more often with undershoots and overshoots. By utilizing the policy of variable spacing, this study has explored the dynamics in vehicle fleet operations.

By focusing on longitudinal control, this study proposed two platoon models: a basic or kinematic model in which the automobiles are modeled as a triple integrator and a comprehensive dynamic model that incorporates all vehicle forces and resistances. A modified headway-based distance longitudinal control policy was applied to both models to preserve stability and minimize errors in inter-vehicle spacing. MATLAB/Simulink was used to create, simulate, and evaluate those platoon models.

Various key findings were drawn from this research. A workable approach for analyzing the spacing error function, performing string stability analysis, and estimating control law parameters were developed for the fundamental model. In addition, a simulation work was undertaken to demonstrate that the proposed model can reduce inter-vehicle spacing, and adjust for changes in speed and acceleration by all the vehicles in the platoon after the stability condition is defined and the control law parameters are estimated. One of the major findings is that when compared to earlier work in literature, the basic model's outcomes are shown to be more expressive and meaningful. The suggested model also allows for modifying factors like the minimum space between vehicles, the starting positions of the platoon's vehicles, and the leader vehicle's speed. Thus, the results of the base model study suggest that an optimal distance between the vehicles can be maintained in different driving conditions.

Moreover, a mathematical model that considers all vehicle attributes and external resistance forces was created to simulate the real-world conditions. The basic Simulink model was then modified with specific vehicle dynamics and resistive forces. The study also simulated the behavior of the dynamic platoon under various vehicle conditions and environmental disturbances. The influences of the highway road friction, braking, variable speeds, and vehicle differences as disruptions to typical driving conditions were specified in a wide range of simulation runs. The results demonstrate that the suggested model is resilient to the investigated vehicle parameters and the external factors.

Different highway conditions and vehicle parameters may lead to various car-following distances in a platoon. The simulation results on inter-vehicle spacing in different scenarios showed that the dynamic model can control the overshoots and undershoots and keep the settling time to a small range. In particular, when members of the platoon adjusted their spacing due to unexpected breaking (such as pavement potholes, animal crossing, or bad weather), the reaction of the model was swift with logical results and the system was able to maintain string stability for the entire platoon and avoid collisions. The development and analysis of this model represents a good contribution to the work of platoon for CAVs by transportation authorities, researchers, and the auto industry. Hence, the proposed models have shown high effectiveness in a platoon and diverse driving conditions.

Although this study has conducted an in-depth model analysis in different conditions, further research and development may benefit from improvements in the following areas:

a. Exploring how the driving environment specifically affects the resultant inter-vehicle distances. Further quantification of this relationship helps identify any potentially unsafe situations for the vehicle platoons so that the car-following spacing may be adjusted in real time.
b. Evaluating and investigating more advanced methods to obtain the control law parameters.
c. Laterally and longitudinally controlled behaviors are the two most prevalent types of control. The current work focuses on longitudinal control only. Thus, future work on lateral control can contribute to the development of a complete and comprehensive platoon model.

VII. OUTPUTS, OUTCOMES, AND IMPACTS

A. Outputs

Presentations and Publications resulting from this study are listed below:

- Presentation. Development of a CAV Platoon Model Adoptive to Variations in Roadway and Weather Conditions. CICTP Global Symposium on Smart Transportation. Xian, China. July 12, 2023. Presenter: Ping Yi and Tariq Alqubaysi.
- Publications. DEVELOPMENT OF A V2V ENABLED VEHICLE PLATOON MODEL USING VARIABLE HEADWAY FOR SPACING CONTROL. *Control Engineering Practice*, submitted August, 2023. Authors: Dr Tariq Alqubaysi, Dr. Ping Yi (corresponding).
- Presentation. "Impact Analysis of Roadway Surface and Vehicle Conditions on Fleet Formation for Connected and Automated Vehicles." CCAT Global Symposium, April 2022. Presenter: Dr. Ping Yi.

B. Outcomes

This research project on vehicle platoon longitudinal control has yielded several significant outcomes. The study proposed and examined two distinct platoon models—an essential kinematic model and an encompassing dynamic model—both incorporating modified headway-based distance control policies. Through comprehensive simulations conducted using MATLAB/Simulink, the proposed models demonstrated their effectiveness in maintaining optimal inter-vehicle spacing and adjusting for changes in speed and acceleration within platoons. Additionally, the research successfully developed a resilient mathematical model considering vehicle attributes and resistance forces, showcasing its robustness against various disturbances and external factors. The findings contribute to the understanding of platoon stability and control, with implications for traffic engineering, the automotive industry, and academia.

C. Impacts

This research endeavor has yielded notable impacts on the advancement of autonomous vehicle technologies and platoon management. By proposing and validating two distinct platoon models, this study provides valuable insights into optimizing inter-vehicle spacing, enhancing platoon stability, and mitigating potential safety risks. The outcomes contribute to the broader goal of improving road safety, traffic efficiency, and fuel economy through intelligent platoon systems. The developed models have practical implications for autonomous vehicle deployment, transportation engineering, and industry practices, setting a foundation for safer and more efficient roadways in the future.

VIII. REFERENCES

AASHTO (2008). Driving down lane-departure crashes-a national priority. Rapport technique, American Association of State Highway and Transportation Officials, Washington, DC.

Abduljabbar, R., Dia, H., Liyanage, S., & Bagloee, S. A. (2019). Applications of artificial intelligence in transport: An overview. Sustainability, 11(1), 189.

Addi, K., Goeleven, D., & Rodić, A. (2006). Mathematical analysis and numerical simulation of a nonsmooth road-vehicle spatial model. ZAMM-Journal of Applied Mathematics and Mechanics/Zeitschrift für Angewandte Mathematik und Mechanik: Applied Mathematics and Mechanics, 86(3), 185-209.

Ali, A., Garcia, G. and Martinet, P. (2013), November. Safe highways platooning with minimized inter-vehicle distances of the time headway policy. In PPNIV13-IROS13 Workshop on Planning, Perception and Navigation for Intelligent Vehicles.

Ali, Alan, Gaetan Garcia, and Philippe Martinet. Minimizing the Inter-Vehicle Distances of the Time Headway Policy for Platoon Control on Highways. ICINCO(2013) - Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics. 2013.2:417–24. doi: 10.5220/0004497704170424.

Assanis, D., Filipi, Z., Gravante, S., Grohnke, D., Gui, X., Louca, L., ... & Wang, Y. (2000). Validation and Use of SIMULINK Integrated, High Fidelity, Engine-In-Vehicle Simulation of the International Class VI Truck. SAE transactions, 384-399.

Bagloee S., Tavana M., Asadi M., and Oliver T. (2016). Autonomous vehicles: challenges, opportunities, and future implications for transportation policies. Journal of modern transportation, 24(4), pp: 284-303.

Berkeley, I. T. S. (2017). Intelligent TransportationSystems and Infrastructure: A Series of Briefs for Smart Investments.

Bhoopalam A., Agatz N., and Zuidwijk R. (2017). Planning of truck platoons: A literature review and directions for future research. Transportation Research Part B: Methodological.

Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L. and Walters, J. (2014). Effects of next- generation vehicles on travel demand and highway capacity. FP Think Working group publication, pp: 1-31.

Bujanovic P. (2018). Developing vehicle platoons and predicting their impacts. Ph.D. Thesis, Faculty of the Graduate School, University of Texas at Austin, USA.

Campbell, M. et al. (2010). Autonomous driving in urban environments: approaches, lessons and challenges. Philosophical Transcations of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, pp: 4649–4672.

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Cho D. and Hedrick J (1989). Automotive powertrain modeling for control. Journal of Dynamic Systems, Measurement, and Control, 111, pp: 568–576.

Day, T. D. (1995). An overview of the HVE vehicle model. SAE transactions, 451-464.

Ghiasi A., (2018). Connected autonomous vehicles: capacity analysis, trajectory optimization and speed harmonization. Ph.D. Thesis, College of Engineering, University of South Florida, USA.

Gim, G., & Nikravesh, P. E. (1990). An analytical model of pneumatic tyres for vehicle dynamic simulations. Part 1: pure slips. International Journal of vehicle design, 11(6), 589-618.

Hedrick, J. K., Mcmahnon, D. H., & Swaroop, D. (1993). Vehicle modeling and control for automated highway systems.

Hingwe, P. S. (1997). Robustness and performance issues in the lateral control of vehicles in automated highway systems. University of California, Berkeley.

Hussein A. and Rakha H. (2022). Vehicle platooning impact on drag coefficients and energy/fuel saving implications. IEEE Transactions on Vehicular Technology 71(2), pp: 1199-1208.

Kim T. and Jerath K. (2016). Mitigation of self-organized traffic jams using cooperative adaptive cruise control, International Conference on Connected Vehicles and Expo (ICCVE). IEEE, pp: 7–12.

Kim, S. (2012). Design of the adaptive cruise control systems: An optimal control approach. University of California, Berkeley. Kinematic and dynamic vehicle models for autonomous driving control design

Kotwicki, A. J. (1982). Dynamic models for torque converter equipped vehicles. SAE Transactions, 1595-1609.

Li, Z., Chitturi, M., Zheng, D., Bill, A., Noyce, D. (2013). Modeling reservation-based autonomous intersection control in VISSIM. Transportation Research Record: Journal of the Transportation Research Board, (2381), pp: 81-90.

Litman, T. (2014). Autonomous vehicle implementation predictions. implications for transport planning. Victoria Transport Policy Institute Publication, 1-20.

Lorca, D., Milanes, V., Parra, I., Gavilan, M., Daza, I., Rastelli, P. and Sotelo, M. (2011). Autonomous Pedestrian Collision Avoidance Using a Fuzzy Steering Controller. Transactions on Intelligent Transportation Systems, Institute of Electrical and Electronics Engineers (IEEE).

Ma J., Li X., Shladover S., Rakha A., Lu Y., Jagannathan R., Dailey J., (2016). Freeway speed harmonization. IEEE Transactions on intelligent vehicles. 1 (1), pp: 78-89.

Mahmassani H. (2016). 50th anniversary invited article-autonomous vehicles and connected vehicle systems: flow and operations considerations. Transportation Science, 50(4), pp: 1140-1162.

Mannering, F. L., & Washburn, S. S. (2020). Principles of highway engineering and traffic analysis. John Wiley & Sons.

Martínez-Díaz, M., Al-Haddad, C., Soriguera, F. and Antoniou, C. (2021). Platooning of connected automated vehicles on freeways: a bird's eye view. Transportation research procedia, 58, pp.479-48

Mathew, T. (2009). Lecture notes in Transportation Systems Engineering. Indian Institute of Technology (Bombay), http://www. civil. iitb. ac. in/tvm/1100_LnTse/124_lntse/plain/plain. html.

McMahon, D. H., Narendran, V. K., Swaroop, D., Hedrick, J. K., Chang, K. S., & Devlin, P. E. (1992, June). Longitudinal vehicle controllers for IVHS: Theory and experiment. In 1992 American Control Conference (pp. 1753-1757). IEEE.

Milanés V., Godoy, J., Villagrá, J., Pérez, J. (2011). Automated on-ramp merging system for congested traffic situations. IEEE Transactions on Intelligent Transportation Systems, 12(2), pp:500-508.

National Highway Traffic Safety Administration (NHTSA), (2012). Preliminary statement of policy concerning automated vehicles.

IEEE Intelligent Systems and Their Applications, 13(3), 82-86.

Nouveliere, L., DUPONT-KERLAN, E., & Fontaine, H. (2002, March). Commandes robustes appliquées au contrôle assisté d'un véhicule à basse vitesse. In COLLOQUE FEMMES ET VILLES, 8 ET 9 MARS 2002, TOURS.

Olayode, I.O., Tartibu, L.K., Okwu, M.O. and Uchechi, U.F. (2020). Intelligent transportation systems, un-signalized road intersections and traffic congestion in Johannesburg: a systematic review. Procedia CIRP, 91, pp.844-850.

Olstam J., and Tapani A.. (2004). Comparison of car-following models. No. VTI report 960A.

Pacejka, H. (2005). Tire and vehicle dynamics. Elsevier.

Park, J.E., Byun, W., Kim, Y., Ahn, H. and Shin, D.K., (2021). The Impact of Automated Vehicles on Traffic Flow and Road Capacity on Urban Road Networks. Journal of Advanced Transportation, 2021.

Pham, H., Tomizuka, M., & Hedrick, J. K. (1997). Integrated maneuvering control for automated highway systems based on a magnetic reference/sensing system.

Rajamani R. (2006). Vehicle dynamics and control. Springer Science, 1st edition. Rajamani R. (2012). Vehicle dynamics and control. Springer Science, 2nd edition.

SAE automation level standards (2018). .https://www.sae.org/news/press-room/2018/12/sae- international-releases-updated-visual chart-for-its %E2%80%9Clevels-of-driving- automation%E2%80%9D-standard-for selfdriving- vehicles.

Salter, A. (2022). Will autonomous vehicles really put an end to traffic congestion? Available at: Will autonomous vehicles really put an end to traffic congestion? | 2025AD - Driven by Driverless

Shladover, S.E. (2018). Connected and automated vehicle systems: Introduction and overview. Journal of Intelligent Transportation Systems, 22(3), pp.190-200.

Swaroop D. (1997). String stability of interconnected systems: An application to platooning in automated highway systems. UC Berkeley: California Partners for Advanced Transit and Highways (PATH).

Swaroop D. and Rajagopal K. (1999). Intelligent cruise control systems and traffic flow stability.

Transportation Research Part C: Emerging Technologies, 7(6) pp: 329 – 352.

Swaroop D.and Huandra R. (1998). Intelligent cruise control system design based on a traffic flow specification. Vehicle Syst. Dyn., 30 (5), pp: 319-344.

Talebpour A. and Mahmassani, H. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. Transportation Research Part C: Emerging Technologies, 71, pp: 143-163.

Tomizuka M. and Hedrick J. (1993). Automated vehicle control for IVHS systems. In IFAC Conference, Sydney, Australia, pp: 109–112.

TRB, (2016). Highway capacity manual. Washington, D.C.: National Research Council.

Van B., Tampere C., Malone K., (2003). Modelling traffic flows with intelligent cars and intelligent roads. Intelligent Vehicles Symposium, Proceedings, IEEE, pp: 456-461, 2003.

Yeomans G. (2014). Autonomous vehicles: opportunities and risks. United States of America.

Zhang L., Zhang S., Zhou B., Jiao S., Huang Y. (2021). An improved car-following model considering desired safety distance and heterogeneity of driver's sensitivity. Journal of Advanced Transportation, Volume 2021.

Zhao, J. (2010). Contribution to intelligent vehicle platoon control (Doctoral dissertation, Ecole Centrale de Lille).

Zhao, J., & El Kamel, A. (2010, September). Coordinated throttle and brake fuzzy controller design for vehicle following. In 13th International IEEE Conference on Intelligent Transportation Systems (pp. 659-664). IEEE.

Zhou J. and Peng H. (2005). Range policy of adaptive cruise control vehicles for improved flow stability and string stability. IEEE Transactions on Intelligent Transportation Systems, 6(2), pp: 229–237.

APPENDIX

Performance Indicators

Part I: UTC Program -- Project-Wide Performance Indicators

UTC Name: Center for Connected and Automated Transportation (CCAT)
University: University of Michigan/University of Akron
Grant #: 69A3551747105

OSTR Goals

METRIC	Research Performance Measures	University of Akron
1. Number of transportation-related courses offered during the reporting period that were taught by faculty and/or teaching assistants who are associated with the UTC.	Undergraduate courses	
	Graduate courses	1
2. Number of students participating in transportation research projects during the reporting period funded by this grant.	Undergraduate students in research	
	Graduate students in research	2
3. Number of transportation-related advanced degree programs that utilize grant funds during the reporting period to support graduate students.	Masters level programs	1
	Doctoral level programs.	1
4. Number of students supported by this grant during the reporting period.	Undergraduate degrees	
	Masters degrees	
	Doctoral degrees	1
5. Number of students supported by this grant who received degrees during the reporting period.	Undergraduate degrees	
	Masters degrees	1
	Doctoral degrees	1
6. Number and total dollar value of research projects selected for funding during the reporting period using UTC grant funds (Federal and/or Recipient Share) that you consider to be applied research and advanced research.	Number of applied research projects	
	Dollar value of applied research projects	$75,000
	Number of advanced research projects	1
	Dollar value of advanced research projects	

Part II: CCAT UTC -- Project Specific Performance Indicators

UTC Name: Center for Connected and Automated Transportation (CCAT)
University: University of Michigan/University of Akron
Grant #: 69A3551747105

Technology Transfer Goals

1. OUTPUTS	Research Performance Measures	University of Akron
1.A. Disseminate research results through publications, conference papers, and policy papers	Technical reports	1
	Papers at conferences, symposia, workshops, and meetings	1
	Peer-reviewed journal articles	1
1.B. Develop inventions, new methodologies, or products	Annual number of research deployments	
1.C. Research projects funded by sources other than UTC and matching fund sources	Number of projects	
	Dollar amount of projects	
2. OUTCOMES	**Research Performance Measures**	
2.A. Incorporate new technologies, techniques or practices	Number of technology transfer activities that offer implementation or deployment guidance	
2.B. Improve the processes, technologies, techniques in addressing transportation issues	Number of research deliverables disseminated from each research project	
3. IMPACTS	**Research Performance Measures**	
3.A. Increase the body of knowledge and safety of the transportation system	Number of instances of technology adoption or commercialization	
	Number of conferences organized by the CCAT consortium members	
3.B. Improve the operation and safety of the transportation system	Number of instances of research changing behavior, practices, decision making, policies (including regulatory policies), or social actions	1

Leadership Development Goals

1. OUTPUTS	Research Performance Measures	
1.A Keynote speeches or invited speaker presentations	Number of media engagements	
	Number of academic engagements	1
	Number of industry engagements	
2. OUTCOMES	**Research Performance Measures**	
2.A Leadership positions held	Regional organizations	
	National organizations	
	International organizations	

2.B CCAT affiliated students holding leadership positions	Number of students	
Education and Workforce Development Goals		
1. **OUTPUTS**	**Research Performance Measures**	
1.A Number of Workforce Online learning modules created and developed toward the certification of completion training for the emerging CAT field technician	Number of learning modules	
1.B Development of Articulation agreements for C++ software programs and Applied Data Science program with partner institutions	Number of Articulation/Transfer Programs	
1.C Development of an active WCC Pre-Engineering Program in STEM disciplines leading to an AAS degree	Number of students completed Associates Degree for Pre-Engineering Science Transfer	
	Number of students completed Associates Degree for Engineering Technologist-Manufacturing Degree	
1.D Number of curriculum development and professional development activities for instructors in related CAT technologies	Number of Professional Dev. Activities in IT [CAT]	
	Number of participants	
1.E Number of K-12 Career pathways activities related to CAT career fields.	Number of K-12 Activities in CAT Career Areas	
	Number of participants	
Outreach Goals		
1. **OUTPUTS**	**Research Performance Measures**	
1.A Media stories referencing CCAT, CCAT research or other activities	Number of media stories	
1. B Newsletters, press releases, and website	Number of newsletters	
	Number of press releases	
	Number of website hits	
2. **OUTCOMES**	**Research Performance Measures**	
2.A Research Champions	Industry principals	
	Number of industries represented	
	Government principals	
	Number of government agencies represented	
Collaboration Goals		
1. **OUTPUTS**	**Research Performance Measures**	
1. A Collaboration with other agencies	Number of agencies providing matching funds	
	Number of agencies participating in CCAT events	
	Number of agencies committed to CCAT projects	
	Number of individuals from external agencies attending CCAT events	
1. B Collaboration with other organizations	Number of organizations providing matching funds	
	Number of organizations participating in CCAT events	1
	Number of organizations committed to CCAT Projects	1
	Number of individuals from external organizations attending CCAT events	