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Combined Lateral and Longitudinal Control for Vehicle Platooning

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July 29, 2021

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Resumo

Nos últimos anos, a crescente procura de mobilidade nas redes de transporte tem contribuído para uma saturação das infra-estruturas rodoviárias, particularmente nos grandes centros urbanos. Abordagens convencionais para este tipo de problema, como uma melhoria da capacidade rodoviária, já não são consideradas viáveis, uma vez que não conseguem acompanhar o constante crescimento de tráfego. Associado a preocupações ambientais e o desejo de minimizar o risco de acidentes, surge a necessidade de dimensionar novas soluções de transporte que visem solucionar estes problemas. Uma solução possível, que tem sido amplamente investigada, é o uso de pelotões de veículos.

O agrupamento de veículos em pelotão é considerado um tipo de condução cooperativa e automatizada onde um grupo de veículos circula com proximidade e estão interligados através de ligações V2V ou V2X. Como resultado, este possibilita uma maior fluxo rodoviário, reduzindo o consumo de combustível e a emissão de gases de efeito estufa. Ademais, verifica-se que o uso de pelotões de veículos possibilita uma condução mais segura para passageiros e evita congestionamentos fantasma. A grande maioria da investigação neste tópico concentra-se, exclusivamente, na automatização longitudinal, sendo que, em aplicações práticas, é necessário um controlador lateral, mesmo em trajetos estritamente retos.

Sendo assim, o objetivo desta dissertação é propor e analisar um controlador integrado longitudinal e lateral para aplicação em pelotões de veículos. Inicialmente, é analisado um controlador longitudinal com uma estratégia de controlo de seguimento de veículos. De seguida, uma estrutura de controlo lateral é adicionada ao controlador longitudinal previamente dimensionado, onde são discutidas duas estratégias de controlo distintas. Uma que se baseia em coordenadas globais e outra que utiliza o conceito de veículo virtual.

Abstract

In recent years, the ever increasing demand for mobility in transport networks has led to a near saturation of road infrastructure, particularly in large urban centres. Conventional approaches to this problem, such as improved road capacity, are no longer viable as they no longer keep up with the necessary vehicle throughput. Combined with environmental concerns and the desire to minimize the risk of accidents, there is a need for new generation transport methods that aim to solve the problems aforementioned. One possible solution, which has been extensively studied in literature, is vehicle platooning.

Vehicle platooning is considered a type of automated cooperative driving where a string of vehicles are driving in close proximity and are interconnected between each other through V2V or V2X links. As a result, vehicle platooning enable a higher road throughput, while reducing fuel consumption and greenhouse gas emissions. In addition to this, it has been found to be much safer for passengers and is capable of preventing ghost traffic jams. Most research on this topic has been solely focused on longitudinal automation, however in real world applications lateral control is needed, even in purely straight paths.

The purpose of this dissertation is thus to propose and analyze a combined lateral and longitudinal controller for vehicle platooning applications. Firstly, a longitudinal controller is evaluated in a vehicle following control strategy. Next, a lateral control structure is added to the previously mentioned longitudinal controller where two distinct control strategies are discussed. One that is based on global coordinates and another that employs the concept of a virtual vehicle.

Agradecimentos

Ao terminar esta etapa, no culminar da minha dissertação, existe um conjunto de pessoas às quais não poderia deixar de agradecer que, direta ou indiretamente, contribuíram para o meu percurso.

Primeiramente, gostaria de apresentar o meu sincero obrigado ao meu orientador, Professor Rui Esteves Araújo, por todo o valioso contributo, ajuda prestada e disponibilidade, sem o qual não teria sido realizável a concretização deste trabalho. Aos meus colegas e amigos, pelo apoio e incentivo, que não só me motivaram como tornaram mais claras todas as etapas difíceis.

À minha família, principalmente os meus pais e irmã, porque ninguém concretiza nada sozinho e, graças a eles, sempre tive exemplos de trabalho e perseverança a seguir. Não esquecendo todo carinho e encorajamento diário que me deram a confiança necessária para alcançar os meus objetivos. Por fim, à minha namorada, Bárbara, por todo o amor e apoio durante estes cinco anos.

Miguel Macedo

"For every complex problem there is an answer that is clear, simple and wrong."

H. L. Mencken

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
API	Application Programming Interface
BD	Bidirectional
BDL	Bidirectional-Lead
CACC	Cooperative Adaptive Cruise Control
CC	Cruise Control
CDG	Constant Distance Gap
CTG	Constant Time Gap
C-ITS	Cooperative Intelligent Transport Systems
C-V2X	Cellular Vehicle-to-Everything
DSRC	Dedicated Short Range Communications
ECU	Electronic Control Unit
EU	European Union
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
ITS	Intelligent Transport Systems
LKA	Lane Keeping Assistance
MANET	Mobile Ad Hoc Networks
MPC	Model Predictive Control
PATH	Partners for Advanced Transportation Technology
PF	Predecessor Following
PID	Proportional-Integral-Derivative
PLF	Predecessor-Leader Following
SAE	Society of Automotive Engineers
TPF	Two Predecessors Following
TPLF	Two Predecessors-Leader Following
VANET	Vehicular Ad Hoc Networks
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
WAVE	Wireless Access in Vehicular Environments

Chapter 1

Introduction

1.1 Context and Motivation

Transportation by ground traveling vehicles is an essential part of modern society and economy as it is the main source of mobility of goods and people. Hence, in recent decades there has been a steady increase of vehicles, mainly in the form of personal vehicles. This continuous growth has some obvious drawbacks as the available road infrastructure is limited. Particularly in urban areas, traffic jams are becoming increasingly more frequent and pose a risk for road safety and inefficiencies in mobility. In some cities like Rome or Paris, commuters in 2019 spent an average of 165 hours stuck in traffic per year, which is equivalent to almost seven days [1]. Besides resulting in time losses, traffic jams also increase the risk of accidents, fuel consumption and carbon emissions. Mitigating these emissions is a crucial part of the European Union (EU) policy for next generation transport emissions, since it has set a target to reduce them by at least 55% and to be completely climate neutral by 2050 [2].

If improving road capacity or increasing the average speed of an ordinary vehicle is no longer feasible, then other options must be taken in consideration in order to solve these problems. Therefore, research in Intelligent Transport Systems (ITS) is key to explore new solutions for personal and heavy-duty vehicles for the aforementioned problems. ITS are defined in the literature as systems that utilize current technologies that enable cooperative synergy between systems in order to develop and improve transportation of all kinds. Therefore, the main objective of ITS is to improve the efficiency of the transport network, through coordination of separate entities. In terms of scope, ITS can be focused on a single system, such as the highway network, or on coordination of different types of transportation. In the latter one, a system can be set up where an individual can effortlessly change from the road to the train network.

These new alternative transport systems often rely on some kind of an autonomous or self-driving vehicles. Therefore, the U.S. Society of Automotive Engineers (SAE) has created a classification system with six levels, ranging from no automation to full automation, in an attempt to become the initial regulatory framework for manufacturers of automated vehicles. Since then, it has become the *de facto* global standard. The levels of automation can be summarized as follows:

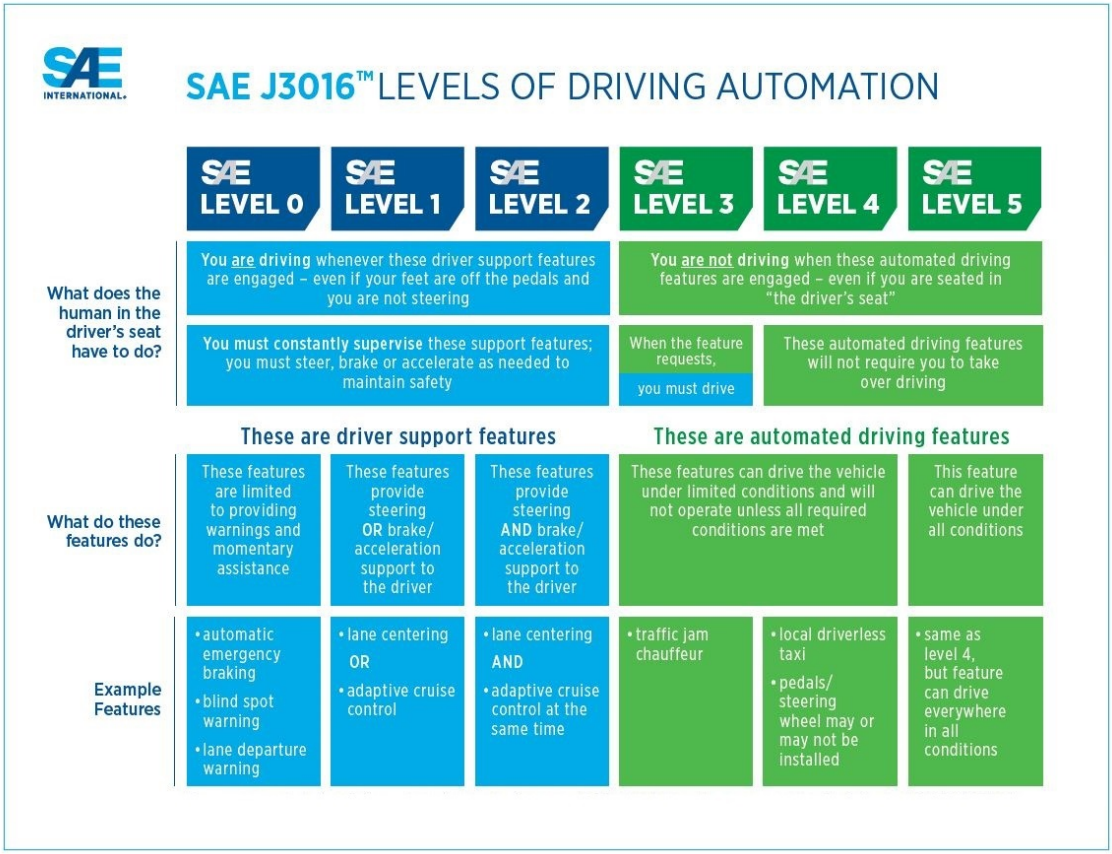


Figure 1.1: SAE levels of automation for self-driving vehicles [3].

- Level 0: The automated system has no sustained vehicle control. The human driver is in control of the vehicle.
- Level 1: The automated system may assist the human driver with steering or throttle controls, but not simultaneously. The human driver is still in control of the vehicle.
- Level 2: The automated system is responsible for the throttle and steering control of the vehicle, simultaneously if needed. The human driver must monitor the driving and handle possible corrections in situations that demand it.
- Level 3: The automated system is capable of performing all driving related tasks, including steering, throttle control and monitoring the driving environment in most circumstances. The human driver must still be ready to intervene in some situations, even though he can safely turn his attention away from the driving tasks when his input is not needed.
- Level 4: The automated system is capable of performing all driving related tasks, similarly to level 3, and can abort the driving (slow down and/or park) if the situation at hand calls for it. As a result, the human driver attention is not needed throughout the whole driving trip.

- Level 5: The automated system is capable of performing all driving related tasks in all circumstances. The human driver is not needed and is considered a passenger.

Vehicle platooning is a concept that employs a certain level of vehicle automation, which enables an automated longitudinal vehicle motion and, occasionally, the lateral vehicle motion. As a result, a car-following scenario based on platooning is achievable when the headway spacing between vehicles is continuously optimized and the driving tasks are delegated to the control system of an automated system. It can be described as a string of interconnected systems, where there is a preceding vehicle, which can be driven by a human, and follower vehicles that are automated. Since most of traffic jams or accidents are caused by human related errors, these systems can provide a way to greatly reduce the chance of these events from happening. Moreover, by connecting these vehicles with other entities (vehicles or infrastructure) and augmenting the awareness of its surroundings, through the use sensors, the efficiency of its route planning can be improved.

The advancement within this research field has lead to the development of new technologies that try to satisfy most of the needs previously mentioned. A proposed solution is Cooperative Adaptive Cruise Control (CACC), which is essentially an extension of the already popular Adaptive Cruise Control (ACC), where all vehicles can communicate between each other and with other entities through the use of wireless networks.

By definition, a CACC system in a vehicle can be categorized as a level 2, according to the aforementioned SAE classification, since a platoon is considered as a string of cooperative vehicles that communicate between each other and with external entities, rather than a complete self-driving system. CACC may automate throttle and steering inputs, but the driver is still responsible at all times for the safe driving of the vehicle. Academic projects that used this technology have shown a clear improvement on road throughput, fuel consumption and carbon emission when compared to ordinary driving. Nevertheless, there is still ongoing research that aims for better performing vehicle following systems.

1.2 Objective

The main objective of the dissertation is to design and implement a system capable of performing longitudinal and lateral control for vehicle platooning with a vehicle following strategy, where consecutive members of the platoon must maintain a distance that is specified by the spacing policy. The vehicle leader control structure is independent from the rest of the string, since its movement sets the platoon's path and overall behaviour. Therefore, each vehicle must be aware of its surroundings in order to make necessary adjustments in their trajectory and motion planning to maintain the formation. In real world applications, this is possible through the use of ranging sensors and image recognition systems. In addition to this, all vehicles are inter connected, with a certain information flow topology, through wireless vehicular ad-hoc networks in order to exchange relevant data. The designed control structure must also guarantee string and system stability is assured.

1.3 Report Structure

The remainder of this document is composed by four chapters. In Chapter 2, a background and literature review on the state of art is presented regarding the vehicle platooning field and its associated technologies. Chapter 3 presents the longitudinal platoon model and controller that is used in vehicle platooning in one dimensional maneuvers. Chapter 4 details the integrated longitudinal and lateral controller, where the vehicle dynamics are redefined and a lateral control structure is added to the previous longitudinal controller, enabling the platoon to carry out maneuvers in a two dimensional scenario. Finally, in Chapter 5, the developed work in the dissertation is briefly summarized and its main findings are highlighted, as well as proposing recommendations for future research.

Chapter 2

State of the Art

2.1 Vehicle Platooning

Vehicle platooning is a formation where a string of two or more ground travelling vehicles maintain a constant space/time headway from their lead vehicle at all cruising speeds. These vehicles follow one another with a small headway spacing led by the first vehicle, which is the platoon leader, and are interconnected between each other to exchange relevant information to maintain its formation. Moreover, these formations are maintained until a goal has been reached, usually when arriving at a certain location. As a result, it is considered a cooperative driving technique that can autonomous and automated. To accomplish interconnected platooning, interactions between three distinct modules (communications, control and sensing) are mandatory.

Platooning systems can be considered homogeneous or heterogeneous. In homogeneous platoons, all members are assumed to have the same characteristics (vehicle dynamics, access to wireless communication, communication topology, etc.). Conversely, members in heterogeneous systems may differ in these characteristics. It is noteworthy to mention that the concept of homogeneous platoon does not hold in real world situations, since vehicles can be manufactured by different automakers. As a result, each vehicle can have different characteristics and dynamics. In most platooning systems available, the platoon is assumed to be heterogeneous for control purposes.

All vehicle operations are automated and involve either merging/splitting with other platoons or individual vehicles joining or leaving the platoon. In both situations, the platoon leader is responsible for authorizing and coordinating the necessary driving maneuvers to complete the intended operation.

In heavy-duty vehicles, platooning can reduce fuel consumption up to 20% [5], due to the reduced air drag that vehicles are exposed to. Therefore, power demands to achieve the same cruising speed are lower. This leads to reduced fuel consumption which results in lower carbon emissions and higher economical savings, making it an area of interest for industries that rely on these type of vehicles. It is important to note that heavy-duty vehicles account for nearly 6% of



Figure 2.1: Illustration of the concept of platooning [4].

total EU emissions, which makes it a fundamental target in order to meet the EU's emission goal [6].

Traffic throughput can also be greatly improved in urban areas [7]. By reducing the inter vehicle distance, road capacity is improved significantly. It has been shown that highway capacity can be improved up to 43% if all vehicles achieve a platooning formation using only on-board sensors, such as radar and camera. In intersections, which are typically the culprit of bottlenecks, traffic flow rates can double when using vehicle platooning. Phantom traffic jams arise when, in dense traffic situations, a vehicle slows down, causing the following vehicle to slow down even more, due to the driver's delayed reaction. Therefore, this braking action is amplified throughout the rest of the string of vehicles, resulting in vehicle traffic stopping over a problem that does not exist. Vehicle platooning solves this problem, since by automating the the acceleration and braking mechanisms, it eliminates the driver's input delay.

Lastly, the main source of traffic accidents are a result of human error [8]. Hence, platooning helps to mitigate accidents, since most applications that use this formation rely on vehicle automation, where each platoon sets a safe headway spacing between each vehicle. This also leads to increased comfort, since a human driver is not solely responsible for the vehicle's safety at all times.

2.2 String Stability

One of the first definitions of string stability, in the context of vehicle following systems, was first mentioned by ching Chu [9] in 1997. According to the article:

> "A string of vehicles is stable if, for any set of bounded initial disturbances to all the vehicles, the position fluctuations of all the vehicles remain bounded and these fluctuations approach zeros as $t \rightarrow \infty$ "

Alternatively stated, it is necessary that, for a given string of vehicles, all position fluctuations are bounded and convergent towards a set value, should a disturbance exist in the string. Intuitively, a platoon is string stable if the disturbances are not amplified when propagating throughout the string, but rather decreases to zero. Furthermore, a platoon is considered string stable if any change in the speed of one vehicle does not lead to fluctuations in inter vehicular distances for the following vehicles. String stability focuses on the propagation of a disturbance along a string of vehicles, in contrast with conventional system stability, which is concerned with system states changes over a period of time. In addition to this, the stability of each individual system of the vehicle is not sufficient to guarantee that a platoon is string stable.

There are three main approaches for string analysis. First, the Lyaponov stability approach is the most formal out of the three, where string stability is studied through the use of Lyapunov asymptotic stability, which focuses on initial condition perturbations over the rest of the platoon [10]. The second approach uses the Fourier transform to analyse the stability of a string of vehicles of infinite length o. It uses a state space representation followed by an analysis of the corresponding eigenvalues [11]. Finally, the performance oriented approach is the most practical and easy method for string stability analysis. It assumes that a platoon is string stable when a perturbation, by the preceding vehicles, is reduced in the following vehicles, nullifying the effect. This guarantees that there are no collisions, enabling an hypothetical boundless string length. Mathematically, string stability can be verified if the transfer function of the position, speed or acceleration error of the preceding vehicle, to that of its following vehicle, has a magnitude that is less or equal to 1.

$$\left\| \frac{Y(s)}{U(s)} \right\| \leq 1 \tag{2.1}$$

where Y and U are the Laplace transforms of the error of the following and preceding vehicle, respectively.

Several other definitions exist in the literature regarding this notion of string stability that are more formal, complex and suitable for scientific research. For a more detailed analysis of most definitions and algorithms, Feng et al. [12] provides a state of the art of string stability for vehicular platoon control.

Figure 2.2 illustrates a simple example of string stability stability in a platoon of five vehicles, travelling from left to right. The leading vehicle is represented as the first and the last as the fifth. In this scenario, the leading vehicle is decelerating linearly for a period of time and there are different responses of the following vehicles. In (a), the string is considered to be stable since the disturbance caused by the braking maneuver of the leading vehicle is not amplified throughout the rest of the string. The following vehicles are capable of reducing its speed without any major fluctuations. On the other hand, in (b) the platoon is not string stable due to the fact that the response of each vehicle widely differs, displaying some overshoot. These fluctuations are amplified from vehicle to vehicle in the upstream direction. As speed fluctuates, so does the position of the vehicle and, as a result, the platoon members do not share a common spacing policy between each other. These situations increase the probability of head-tail collisions occurring.

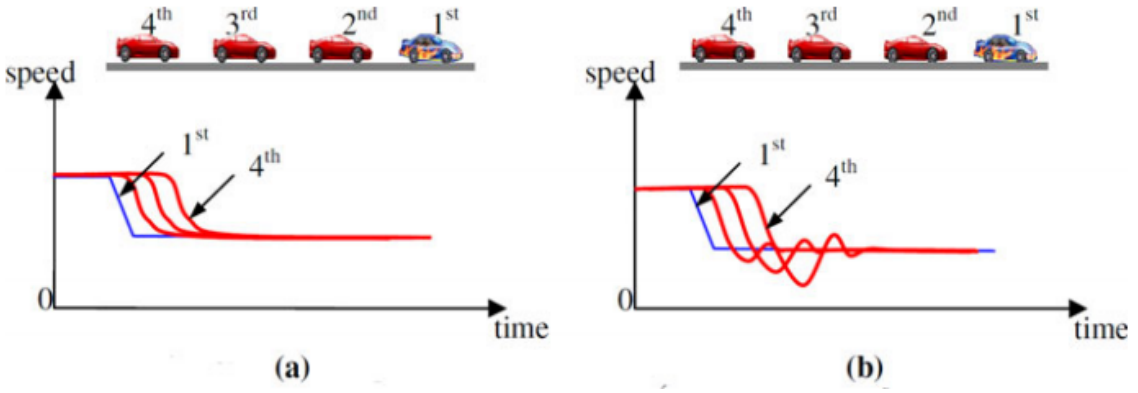


Figure 2.2: String stability: (a) stable; (b) unstable [13].

2.2.1 Longitudinal and Lateral String Stability

The longitudinal string stability is focused on the spacing distance between two consecutive platoon vehicles. Due to the constant braking and accelerations of each vehicle of the string, spacing irregularities can occur if there is not inter vehicle communication. This will result in oscillations that can propagate in the upstream direction of the platoon. In the literature, this phenomenon is usually referred to as the slinky effect [14]. It happens when vehicle i brakes and the distance d_i to the next following vehicle $i+1$ decreases. When vehicle $i+2$ also brakes, its distance to vehicle $i+3$ will decrease, but distance between vehicles i and $i+1$ increases. Evidently, this leads to a propagating disturbance along the inter vehicle distances of the platoon. Communication delays and actuator lag may further amplify this effect. Therefore, it is important that the controller responsible for the longitudinal motion ensure that this phenomenon is attenuated and that the spacing policy is respected, within its error margins.

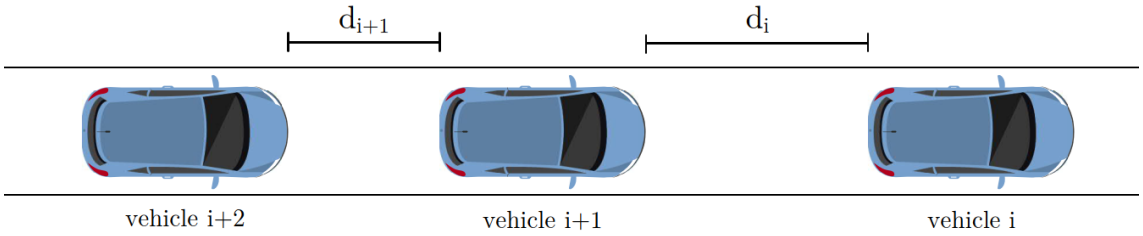


Figure 2.3: Slinky effect on inter vehicular distances.

Lateral string stability, on the other hand, is concerned with the mitigation of possible lateral deviation amplifications along the platoon. It aims to bound the deviation of each vehicle measured from the preceding vehicle's centre line. The controller must make sure that all vehicles stay in their designated lane or planned path. Otherwise, vehicles may swerve of the road, enter a neighbouring lane or have an unstable driving that might compromise the safety of the passengers or the platoon's stability. In the literature, the most popular method to guarantee a lateral string

stability is to assure that the sum of the lateral error in consecutive cars does not exceed the set override bounds.

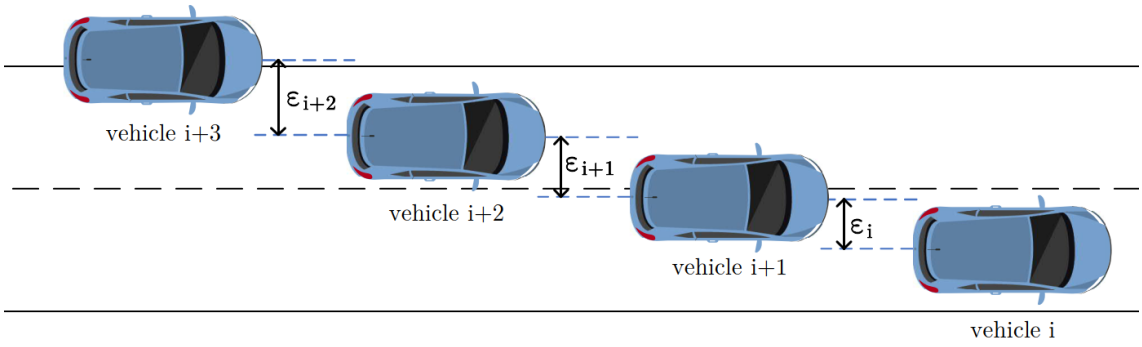


Figure 2.4: Unbounded lateral errors along a platoon.

2.3 Vehicular ad-hoc Networks

In platooning or any other coordinated driving technique it is necessary to have a mechanism of data exchange between vehicles and infrastructure. Modern vehicles are equipped with Electronic Controllable Units (ECU) that are capable of establishing communication with external systems, not only as a receiver or a transceiver, but also as a router. Therefore, it is possible to set up an interface linking all units through the use of Vehicular Ad Hoc Networks (VANET).

VANET is a wireless distributed architecture which was specifically designed for inter vehicle communication. They differentiate themselves from Mobile Ad Hoc Networks (MANET) in some features, as VANETs have an improved node mobility and a dynamic topology [15]. The use of these networks can be divided into two different types of applications: safety and non-safety applications. Safety VANET applications refer to systems that are crucial to the well-being of the driver of the vehicle, such as emergency warning alert and driving assistance [16]. This information is either presented to the driver or used as a toggle to automatically activate the corresponding safety system. Non-safety applications are systems that focus on improving the driver's comfort throughout the driving session. Examples of this are weather and traffic information systems or interactive communication.

There are three main types of communications that can be used with these networks: vehicle to vehicle (V2V), vehicle to infrastructure (V2I) or vehicle to everything (V2X). V2X is usually mentioned as a fusion between V2I and V2V or as a communication structure where the vehicle is connected to any relevant entity.

As standardization is a critical step in assuring that new technologies become viable, the U.S. Federal Communications Commission allocated 75 MHz of bandwidth from 5.850 to 5.925 Ghz to be solely used by Dedicated Short Range Communications (DSRC) in V2V and V2I communications [17]. Meanwhile, Europe allocated 5.855-5.905 GHz for Cooperative Intelligent Transport

Systems (C-ITS), which is essentially a different protocol stack with the same goal in mind as DSRC [18].

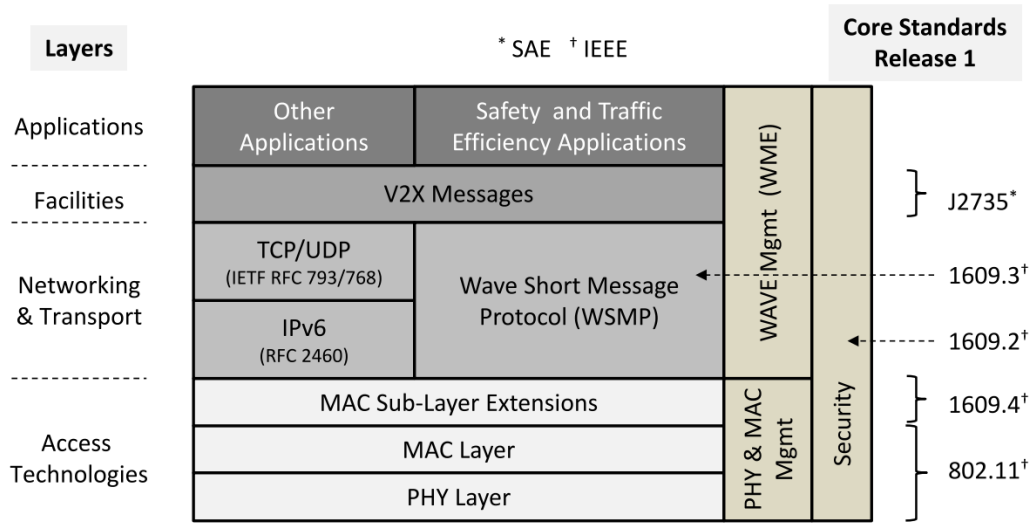


Figure 2.5: Protocol stack and related core standards for DSRC [18].

Wireless Access in Vehicular Environments (WAVE) is a United States' initiative in creating a DSCR-based protocol. It is based on IEEE 802.11p , which is an amendment of IEEE 802.11 standard. It is a variant that is specifically designed for communications between nodes that are connected for a short time interval. Moreover, it enables nodes to be synchronized with a common time reference and is considered a robust, high-throughput protocol [19]. WAVE uses 802.11p for the lower layers of its stack, physical and data link, and the IEEE 1609 family of standards for the remaining upper layers. ITS-G5 , Europe's standard for vehicular communication is a C-ITS based protocol and also based on IEEE 802.11p.

An alternative to the IEEE 802.11p is the integration of the VANET with mobile cellular networks, commonly referred as Cellular Vehicle-to-Everything (C-V2X). This technology was developed in order to expand the coverage area and to increase network throughput, through the use of the established cellular network. Furthermore, research has shown that latency can be reduced, in comparison to IEEE 802.11p, and that C-V2X can also be applied in short-range communications [20].

Prior to the standardization of DSCR, there was research in using short communication systems that were commercially available and ready for V2X communication, i.e. Bluetooth, Zigbee and Wi-Fi [21] [22]. However, it was found that adopting existing wireless networking technologies may lead to a lower performance in areas that are critical for VANETs, such as delays and data throughput.

2.4 Cooperative Driving

The introduction of communication networks in the automated driving ecosystem has paved the way for a new category of ITS, where vehicles can connect and interact with infrastructure and other vehicles. As a result, it is possible for these vehicles to interact and collaborate with their surroundings, enabling a more efficient driving experience.

Previously, some of the first commercial automated driving applications were focused on increasing driving comfort, of which Cruise Control (CC) and ACC are examples. Nowadays, both are widespread in current commercially available vehicles. Newer technologies, such as CACC, focus on increasing safety for passengers and road users. This is only viable because they rely on the use of wireless networks to gather information about its surroundings at all times, thus reducing the risk of traffic accidents and allowing an improved traffic flow.

2.4.1 Overview

One of the first automated vehicular control capable of delegating driving tasks to the ECU (Electronic Control Unit) that was implemented in commercial vehicles is the CC system. It allows to set a desired target speed without any additional control input from the driver while the ECU oversees the throttling and braking to maintain the reference speed. Studies have shown that the use of CC can lead to fuel savings up to 10.7% [23].

ACC is an extension of the CC system that adds perception of the surrounding environment of the vehicle, through the use of sensors. ACC differs from traditional CC since it enables a full control of the throttle and brake systems of the vehicle. It also incorporates a ranging sensor capable of measuring the distances. Therefore, ACC can maintain the vehicle at a predetermined space gap to the following vehicles, adjusting speed when necessary. Its main goal is to assist the drivers and act as a comfort feature for highway driving. Newer variants of ACC also provide a collision avoidance system, automated parking and stop-and-go system. These systems are designed towards urban driving areas where the ordinary capabilities of ACC are not often utilized. The stop-and-go system has the capability of stopping the car when the preceding vehicle is also stopping [24].

The widespread use of ACC in modern vehicles has led to further research in ways of improving longitudinal control in car-following scenarios. CACC is seen as an extension of ACC with the key difference that CACC systems receive additional information from other vehicles (V2V) and infrastructures (V2I) from wireless vehicular networks. Thereby, the vehicle is not limited to the information of the preceding vehicle as it has information from all the other vehicles, i.e. acceleration of a member of the platoon. From the infrastructure, the controller can receive, for example, data about further traffic ahead as part of an active traffic management approach.

Another motivation is reducing fuel consumption, especially at high speeds, i.e. highway driving, where fuel consumption is heavily influenced by air resistance. This effect is further minimized when shorter inter-distances are maintained in a platooning formation, reducing emissions of polluting gases. CACC also has benefits regarding safety, comfort and customer satisfaction.

It is considered more attractive to customers than ACC as it is considerably more responsive to forward vehicles' changes, especially when combined with collision warning/mitigation systems, providing an improved sense of safety and overall comfort. Another crucial advantage that CACC has over ACC is its ability to form more string stable formations, reducing the impact of disturbances from propagating from the leading vehicle to the rest of the string [25].

Regarding the performance requirements, these systems have to guarantee stability at all times. This means that the speed and headway spacing between all the vehicles must converge towards the desired values. Therefore, string and system stability must be achieved for the platoon. If this is not the case, it is likely that eventually a fault may lead to an accident. To guarantee string stability, the platoon should adopt a common spacing policy and a suitable V2V communication network. In addition to this, the controller that is responsible for distance and speed control should have a smooth transient response when the control scheme changes from one operation to the other. This is particularly relevant in urban areas where frequent transitions occur. The controller's actions manifest themselves as accelerations or decelerations, which are closely related to the comfort of the passengers. Excessive control action can make the passengers feel uncomfortable, anxious or nervous. Hence, the magnitude of acceleration and deceleration should be bounded in non-critical situations. However, in emergency stops, the vehicle should decelerate as quickly as possible to minimize the stopping distance and prioritize the safety of the passengers.

2.4.2 Vehicle Instrumentation

ITS rely on advanced sensing technologies to be aware of their surroundings and make real-time decisions. Due to the complexity of these systems, they often require multiple devices and, as a result, this is often one of the limiting factors preventing autonomous vehicles from reaching economic viability in mass production. Nevertheless, sensors are key components of ITS.

The main types of sensors used in autonomous vehicles for environment perception are lidar, radar, ultrasonic sensors and camera. Apart from these, GPS is often used for position detection, complemented with an IMU (Inertial Measurement Unit) to increase data accuracy [26].

Radar is a type of sensor which makes uses of the Doppler effect, through radio waves, to measure the angle, velocity and range of an object. It is considered a mature technology, but it is still being continuously improved, particularly for applications of autonomous driving [28]. The main advantages of this sensor are its range (up to 200m away), wide field of view (150 degrees) and low cost [29]. This sensor is able to work properly in most weather conditions, including rain, snow and fog. Furthermore, its data stream has a low overhead, which means it can be handled in real-time with low computer processing demands. The downside is that it has a low resolution, particularly in the vertical direction.

Ultrasonic sensors are electronic devices that measure the distance to an object by emitting sound waves. Its upside it that they are cheap, have small dimensions, work in all light and weather conditions. However, they have a short range, making them not suitable for detecting the speed of objects.

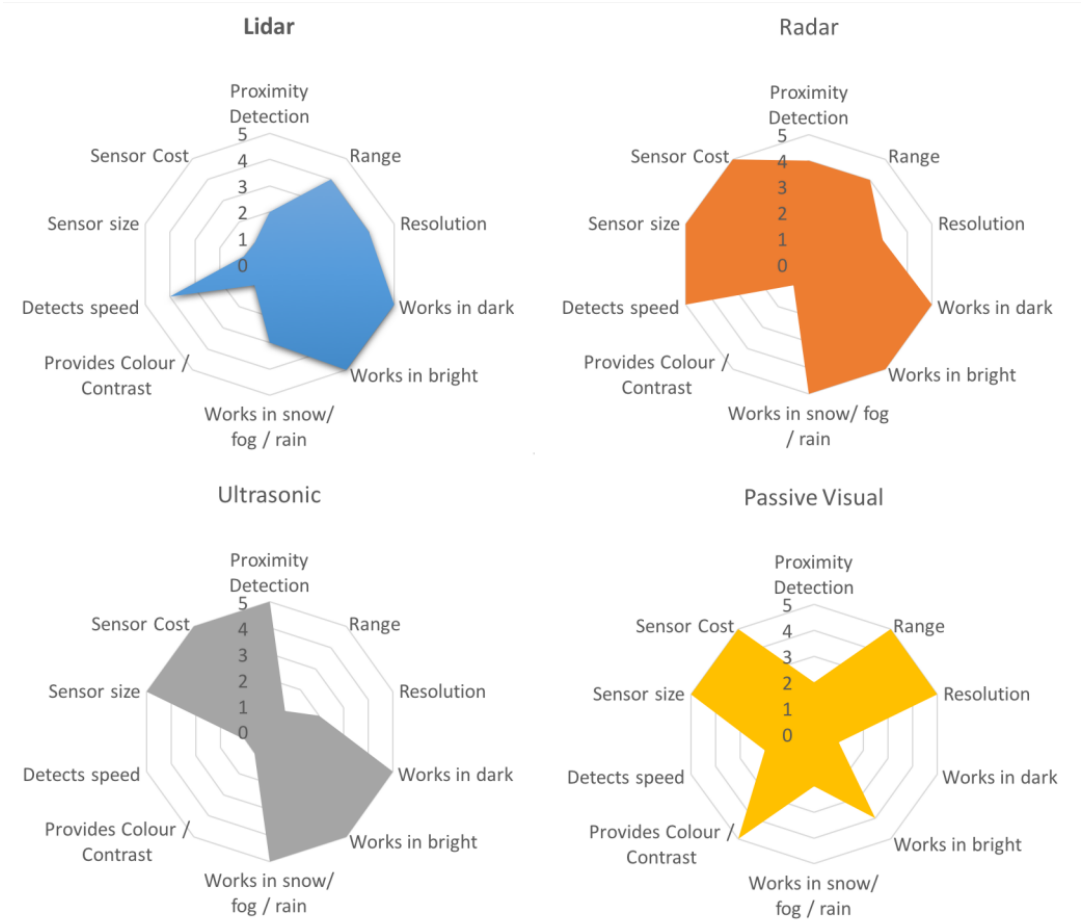


Figure 2.6: Comparison of characteristics of lidar, radar, ultrasonic sensors and passive visual (camera) [27].

Lidar is a sensor that uses an infrared laser to determine the distance to an object. Lidar refers to a light detection and ranging device, which uses an infrared laser to send millions of light pulses per second within a established pattern. Some lidar sensors have a rotating axis, which enables it to create a dynamic three dimensional map of its surroundings. It has high resolution which enables it to map static environments and detect and identify moving objects, such as vehicles or pedestrians. This sensor works properly in all light conditions, but it is not suitable for weather conditions that block its infrared laser, such as snow, rain or dust particles. Since it is a somewhat recent technology, its main downside is the high cost when compared to other alternatives, such as radar. Nonetheless, it is forecasted that the use of lidar will soon replace radar in applications of autonomous vehicles.

Cameras provide a continuous flow of images which are then used for image processing of the environment the vehicle is in. They are the best tool for spatial recognition, since they are able to recognize colour, contrast and enable optical recognition, contrarily to the aforementioned sensors. Cameras are widely available and more affordable. However, the computational power to

process its data is much more demanding than the other sensors.

Figure 2.6 gives an overview of the different characteristics of the sensors aforementioned.

2.4.3 Information Flow Topologies

Information flow topology describes how the vehicles exchange information with each other and how the flow of data is processed in a V2V scenario. Each topology has its own advantages and drawbacks, meaning that the requirements of the system will largely dictate which one would be used. Although, it has been shown that not all assure string stability in a platoon formation [30].

Figure 2.7 shows six possible information flow topologies: predecessor following topology (PF), predecessor leader following topology (PLF), bidirectional topology (BD), bidirectional leader topology (BDL), two predecessors following topology (TPF), two predecessors leader following topology (TPLF).

PF topologies are the least demanding topology in terms of communication complexity and infrastructure, since only the information from the preceding vehicle is needed. As a result V2V interactions are unicast and the data flows from the leader to the end of the string. This type of topology is the most commonly used in safety aimed approaches, although due to the lack of additional information regarding the remaining vehicles could lead to string instability [31].

BD approaches require two communication links with the preceding and following vehicle. They are used in some CACC systems, which use ranging sensors to measure headway spacing and speed of both vehicles, striving for improved string stability. The downside of this approach is that perturbations can be propagated upstream and downstream throughout the string, making string stability analysis complex.

PLF techniques are an extension of PF where all vehicles of the string maintain communication links with its preceding vehicle and the leader of the string. Therefore, each vehicle can directly react to changes in the leader in real time rather than waiting for its perturbation from the preceding vehicle, improving string stability. Since the leader must be connected to all vehicles, its messages are broadcasted to all the vehicles in the string. This is the same type of approach of BDL relatively to BD.

TPF and TPLF are both examples of multiple preceding following topologies. The main goal of this type of approach is to maximize the amount of relevant information available at all times to guarantee a good performance. Ploeg et al. [32] developed a TPF algorithm that showed promising results regarding string stability when compared to a PF approach. The drawback of these topologies is that it requires a complex communication network.

An additional alternative is to have a centralized control where a main controller is responsible for sending commands to each vehicle of the string. The main motivation for these types of approaches is to reduce the energy consumption of the system, however it requires a low latency network to be feasible.

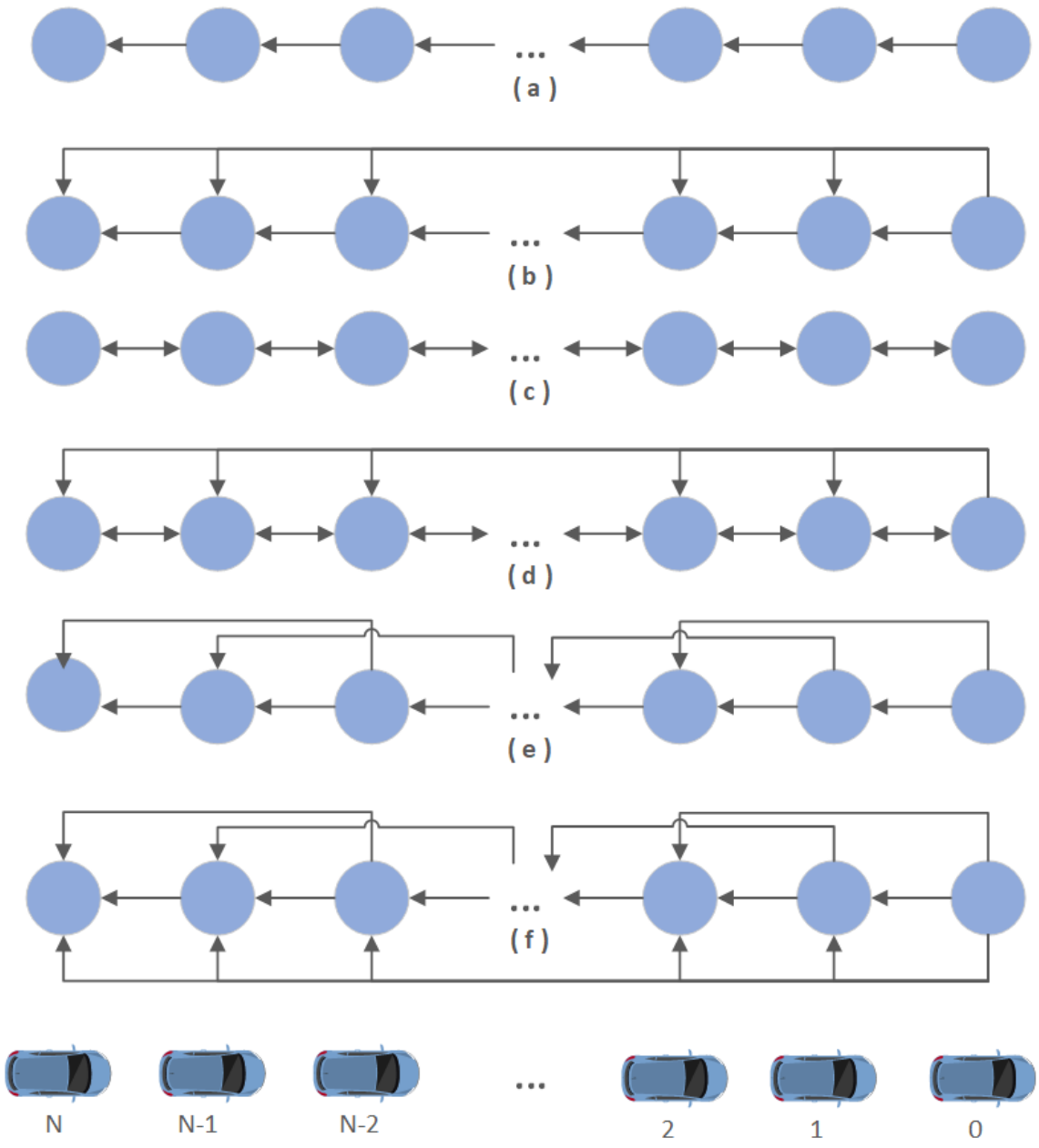


Figure 2.7: Information flow topologies: (a) PF, (b) PLF, (c) BD, (d) BDL, (e) TPF, (f) TPLF.

2.4.4 Spacing Policies

In vehicle platooning, the longitudinal controller is responsible for determining the acceleration or velocity of the following vehicle in order to maintain the desirable inter vehicle distance. This

distance is commonly referred, in literature, as the spacing policy. Currently, there are many different policies that have been proposed based on different types of feedback control. Some proposed strategies are strictly theoretical and were solely tested in computer simulations. In this section, only approaches that have been successfully tested and implemented in real-life scenarios will be mentioned, since they have proved to be viable under realistic conditions.

Most automated vehicle systems that rely on a platooning formation emphasize that a very close headway spacing in between vehicles reduces aerodynamic drag and maximizes road capacity. Constant Distance Gap (CDG) is a method where all vehicles maintain a constant headway spacing regardless of the speed of the vehicles. This method only assures stability when each vehicle knows the real-time behaviour of the platoon leader [33]. CDG offers performance advantages, however it is more difficult to implement when compared to the remaining methods and it requires a robust wireless communication system with minimal latency . From a safety standpoint, a minimal fault could lead to accidents if the headway spacing is small enough.

By contrast, variable spacing methods, such as Constant Time Gap (CTG), allows for a more flexible control of inter vehicle distances [30]. In CTG, the spacing between vehicles is determined by the time that it takes from the front bumper of the vehicle to the rear bumper of the following vehicle to pass a fixed location on the roadway. It is considered the strategy that best represents how human drivers handle a vehicle. As a result, it is the most adopted method in most commercially available ACC systems.

The two aforementioned strategies are considered linear approaches, however there are other different strategies that aim to target a specific objective, such as string stability, traffic throughput, fuel consumption or safety.

An example of these miscellaneous strategies is the Constant Safety Factor that focuses on improving safety in sudden braking situations [34]. This is an approach that guarantees that even a severe incident would not lead to an inter-platoon accident. It takes in consideration that all vehicles might have a different braking capability, otherwise a sudden braking maneuver by one of the vehicles might lead to a crash. One of the situations cited in the paper is a scenario where the platoons are separated by a close constant headway spacing policy and when a vehicle suddenly decelerates, it leads to an accident. To mitigate this, it proposes that a minimum distance between platoons is decided by taking in consideration the weakest acceptable braking of the next platoon leader. The disadvantage of this strategy is reduced traffic capacity.

Most research on spacing policies are focused on safety or string stability. Nevertheless, some approaches have been proposed to enhance the comfort where typical human driving behaviours are taken into consideration. The main goal is to operate similarly to a typical human driving. As a result, Fancher et al. [35] proposed a policy that was based on this behaviour. It showed improved driver's acceptance, but the drawback was that traffic flow stability could not be assured.

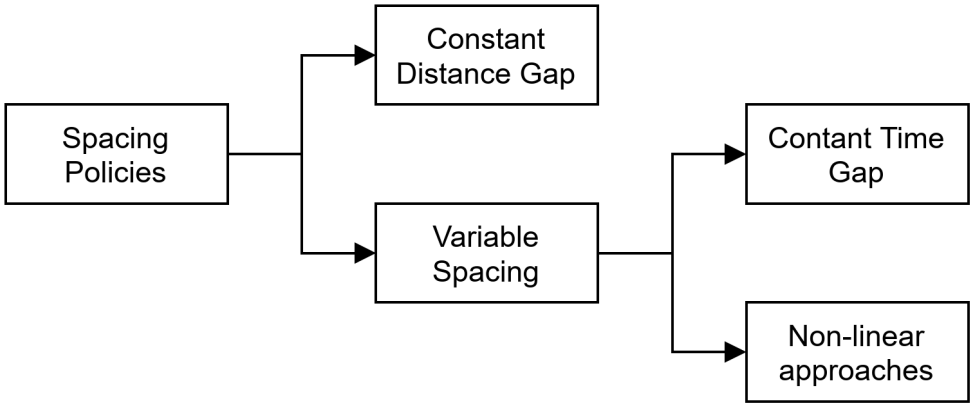


Figure 2.8: Overview of spacing policies classification.

2.4.5 System Architecture

The system architecture of connected cooperative vehicles can be divided into three distinct layers: perception, planning and control. Figure 2.9 depicts the interactions between each system and the environment. Moreover, V2X communications made between the vehicle and other entities can further improve the system's performance and efficiency, mainly in the perception and planning phase.

Perception is the first layer of the control architecture and is responsible for enabling each vehicle of the platoon to perceive its environment and provide the system with the necessary information for the following planning layer. All this data is received by the sensors installed on the vehicle, where two different sources can be distinguished: on board sensors, such as camera measurements, IMU or GPS data and information that is received by other entities, vehicles or infrastructure, via V2X links. The latter one may be common and shared to all members of the platoon, depending on the information flow topology chosen. This phase can be divided into two subsystems. Environmental perception refers to the mapping of the vehicle's surroundings, where the obstacles are located and the road signs or markings are detected. Localization is the subsystem responsible for tracking the position of the vehicle with reference to its environment.

The planning phase is responsible for making the necessary decisions that enable the platoon members to achieve its path goals by following the preceding vehicle while respecting the spacing policy and preserving string stability. Motion planning is the process that decides the sequence of actions to take in order to reach the specified goal, while aiming for the optimal route possible. These algorithms are assessed based on their completeness and computational efficiency. Behavioral planning is the process responsible for ensuring that the vehicle follows established road rules and ensures that it interacts safely with other entities.

The control layer oversees the vehicle's ability to carry out the planned actions generated by the previous processes. A more in depth overview of this layer is present in section 2.4.6.

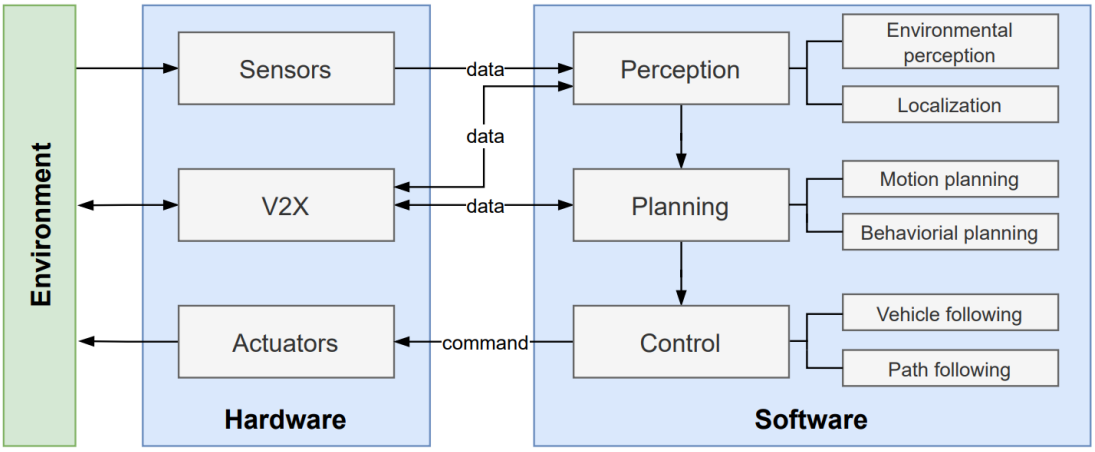


Figure 2.9: System overview of connected cooperative vehicles, adapted from [36].

2.4.6 Control Strategies

In the literature, there are several strategies that are used in vehicle platooning applications that try to guarantee the string stability and integrity. However, they can be roughly categorized into two different categories: path following and vehicle following approaches, which are visually represented in figure 2.10. Both approaches are viable and widely used with each one having its own advantages and drawbacks.

In the path following approach, the longitudinal and lateral control are independent of each other. The CACC or AAC system is responsible for the longitudinal control, meaning keeping a inter vehicle distance according to the designated spacing policy. The lateral controller is responsible for minimizing the lateral error, which is the distance between the reference path and the vehicle's position. Some proposed methods that implement this approach in real life scenarios are vision based lane-keeping systems, i.e. Lane Keeping Assistance (LKA). Studies have shown that this is not reliable in platoons with a short inter vehicle distance, since the lane markings might not be detected by the cameras [37].

By opposition, the vehicle following approach focuses on the premise that the vehicle tracks the preceding vehicle's position, velocity and orientation as to follow it. This data can be obtained through the combined used of V2V communication and sensors, such as lidar, or cameras. The spacing policy is used as the reference for the intervehicle distance. This approach is considered to be more reliable than the aforementioned while being easier to design and implement an algorithm. The main drawback is that the following vehicle controller uses the current position of the preceding vehicle. Thus, in curved paths, the driven path of each vehicle will deviate from each other, commonly referred as corner cutting.

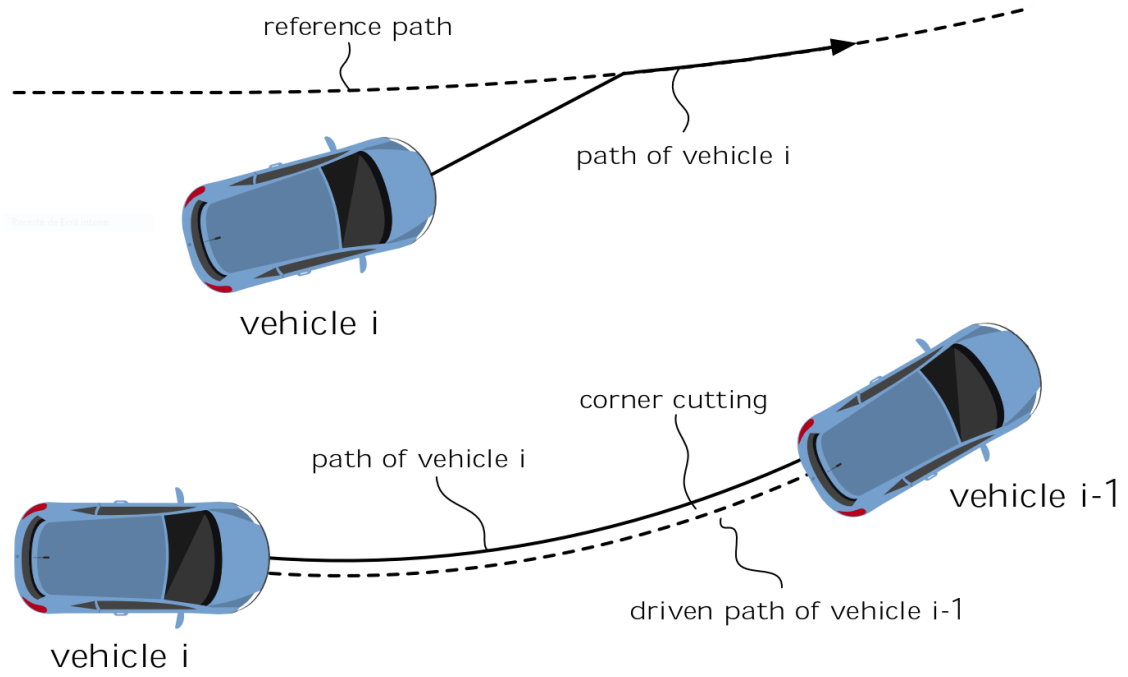


Figure 2.10: Path following approach (top) and vehicle following (bottom).

2.5 Control Structures

The control strategy chosen for a CACC approach is a necessary step to guarantee stability and the corresponding motion planning of each member of the platoon. The controller is responsible for calculating the dynamics of all the vehicles and executing the chosen algorithm. Its primary objective is to carry out the planned path by providing the corresponding inputs to the hardware layer. In vehicle platooning scenarios, the controller is often concerned with the position and velocity of each vehicle in relation to the surrounding environment.

In the literature we can find several examples of control techniques that propose both longitudinal and lateral control while ensuring that the chosen spacing policy is successfully implemented. The selection of an algorithm largely depends on the desired performance and the available communication links and its information flow topology. The following subsections provide a brief overview of the two most popular control strategies for these scenarios.

2.5.1 Model Predictive Control

Model Predictive Control (MPC) are a class of control algorithms that uses a model to predict future system behaviour and return control signals that are based in numerical optimization, within a certain time horizon. The calculations are made iteratively with a fixed time step and can be modified online to adjust to different conditions. This type of control was made to integrate the robustness of the control and the performance of optimal control. MPC was first developed for specialized control needs of power plants and petroleum refineries, but now can be found in other

areas, including automotive applications. In motion planning systems of platoons it is particularly useful, since it has the abilities to better handle nonlinearities and other system constraints. The cost function employed tries to minimize the speed and spacing error in relation to the preceding vehicle, leading to overall better efficiency and performance. The main limitation of a MPC is that in order to achieve a good performance, the model used should be completely linear, otherwise the desired performance is not guaranteed.

For a general MPC, an accurate discrete linear time model is firstly needed, where in a state space notation is represented as:

$$x(k+1) = Ax(k) + Bu(k) \tag{2.2}$$

$$x(0) = x_0 \tag{2.3}$$

where $x(k)$ is the state vector at sample time k and $u(k)$ is the control input, with A as the discrete system matrix and B the discrete input matrix. Following this, the optimizer block needs to be designed. The prediction algorithm requires that the previous model and the future predicted outputs are defined by the current values. Lastly, all these predictions are sent to the optimization block where, in each time step, an optimization problem is solved online based on the set cost function, constraints and future predicted values. All this process can be visualized in figure 2.11.

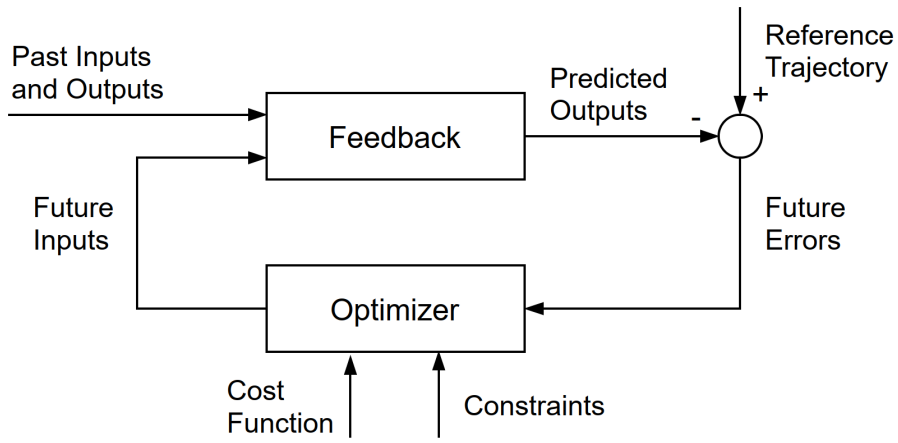


Figure 2.11: Basic structure of MPC controller.

There are two main ways of implement a MPC control system that are found in the literature for a platoon, which are centralized MPC and a decentralized MPC. A MPC system is considered to be centralized if the MPC controller if all vehicle states are known to compute control units. Conversely, a decentralized MPC implementations means that each vehicle computes its own control units. The main trade-offs between each alternative is ease of computation, where a decentralized approach is superior, and optimality, where the centralized is better. Ongoing research focuses on decentralized MPC, which is the only technique viable for large scale systems,

where the gathering of massive amounts of information from various agents and infrastructures becomes impossible for a centralized controller.

2.5.2 Feedforward/Feedback Control

Feedback control is, historically, the most employed type of control that is found in most applications. It compares the output signal with the desired output response and actively compensates unwanted deviations. As a result, it may modify the system's transient behaviour. A simple proportional-integral-derivative (PID) controller is the standard form for this type of control and its control law is formulated as:

$$u(t) = K_p e(t) + K_i + \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{2.4}$$

where e is the error signal and K_p, K_i and K_d is the proportional, integral and derivative gain, respectively. There are several methods of tuning a PID controller. Historically, one of the most popular and effective methods is the Ziegler-Nichols method, which is considered a heuristic method [38]. Nowadays, it is much more common to rely on computational software as to ensure consistent and correct tuning.

It is important to note that this approach has several limitations. Most notably, a feedback controller has a delayed response to error, since it only reacts to errors whenever they happen. In addition to this, these controllers suffer from having a coupled response, meaning the response to disturbances, noise and modeling errors are based on the same signal, rather than setting the response according to the reference, independently of the errors.

In order to overcome some of the limitations of the feedback controller, an additional degree of freedom can be added in the form of a feedforward term in the controller, as shown in figure 2.12. This term does not considered any output measurements of the system and, therefore, this type of control demands a more better understanding of the system. This method of control is known as the feedback/feedforward control or as the two degree of freedom controller. Table 2.1 provides a brief review of the advantages of each type of control method [39] [36].

Table 2.1: Feedback vs Feedforward control.

	Feedback	**Feedforward**
Affects stability of system	yes	no
Requires model of a system	no	yes
Removes unpredictable errors and disturbances	yes	no
Removes predictable errors and disturbances	no	yes
Removes errors and disturbances before they happen	no	yes

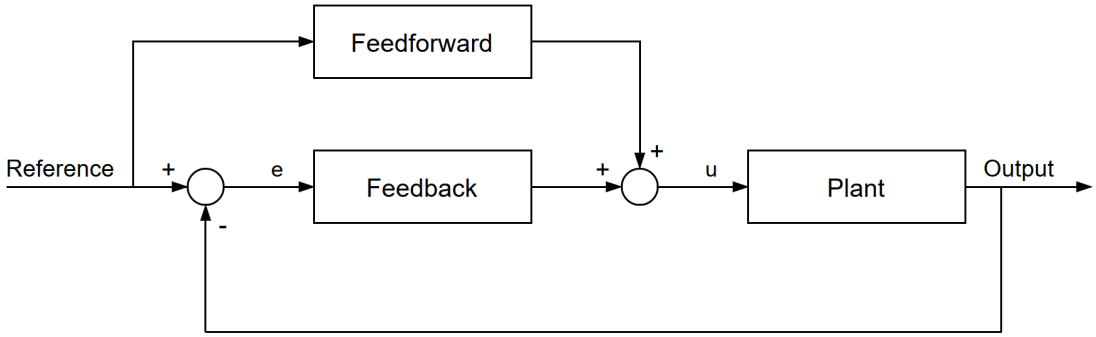


Figure 2.12: Feedforward/Feedback controller.

2.6 Academic Projects in Vehicle Automation

Beginning in the late 1990s, many projects interested in the prospects of improved traffic flow, safety and reduced vehicle emissions began implementing and testing platooning strategies in real world environments to verify their research. One of the first and most well known project was the California Partners for Advanced Transportation Technology (PATH) which sought to apply new technology to improve highway capacity and reduce traffic congestion, since California's highways were notorious for lengthy traffic jams and road congestion [40]. In 1997, their first major demo took place. It consisted in a eight vehicle platoon formation on a highway. Each vehicle was completely automated and was equipped with a vision-based lane detection, a radar, which measured the headway spacing, and were interconnected with low latency networks links. They successfully demonstrated the benefits inherent to platooning systems, particularly enhanced traffic throughput and reduced fuel consumption. This project is still ongoing and current research focuses on high level platoon coordination through the use of machine learning and computer vision in autonomous vehicles.

The CHAUFFEUR project was one the first programs of platooning in European soil and it was mainly funded by the EU [41]. It focused on researching closely coupled trucks in highways with the concept of "tow-bar", where in a platoon of trucks only the leading vehicle would need an active driver. Each vehicle had a vision based lane recognition, radar for obstacle detection, V2V links and a ACC longitudinal control for maintaining headway spacing. This program provided considerable advances in truck platooning applications with new types of architectures for the controller.

The Safe Road Trains for the Environment (SARTRE) program is an European project that aims to develop strategies and technologies for public highway platooning [42]. Its main goal was to demonstrate the feasibility of heterogeneous platoons, as well as studying platooning safety and fuel consumption, to reduce carbon footprint, while using already commercialized technologies. The framework used throughout this project was where the leader vehicle was driven by a human

driver and the following vehicles were linked via V2V network and were completely autonomous. The proposed longitudinal controller was capable of dynamically adjusting the speed and gap distance even while other vehicles were joining or leaving the platoon.

Chapter 3

Longitudinal Controller

This chapter presents a preliminary system study of a longitudinal controller for a homogeneous platoon with a simplified model for the vehicle dynamics. The control law implemented will be largely based on Ploeg et al. [43], which assumes that that all members of the platoon are interconnected and exchange data between each other about the vehicle's state.

It is assumed that for $i = 1, 2, \ldots N$, vehicle i is aware at all times of its velocity, acceleration and the distance to the preceding vehicle $i-1$. The implemented control law is tested on a platoon of three vehicles in a straight road lane, with different fixed velocities. A brief analysis of the impact of network delays in the communication also takes place.

3.1 Introduction

The increasing problems concerning traffic congestion and safety, have lead to research about the use of an automated longitudinal driving in highway scenarios as a way of maximizing road capacity and overall throughput. Longitudinal control is responsible for controlling the longitudinal motion of the vehicle and its states, such as acceleration, velocity and position through the use of the throttle and brake actuators. As a result, longitudinal controllers mostly employ a vehicle following approach, since the following vehicle has information about the position, velocity and acceleration of the preceding vehicle, at all times. In real world applications, the relative distance to the preceding vehicle is measured by radar, lidar or cameras. In the past, radar was the most employed sensor it is relatively inexpensive, has low computational requirements and works in most weather conditions. However, nowadays the use of a lidar sensor is far more frequent since it is the most accurate, even if it more expensive and requires more computational processing power. Velocity measurements are commonly estimated by Doppler radar, whereas the acceleration can not be theoretically calculated and only estimated from the velocity measurements of the preceding vehicle and its relative distance measurements. Alternatively, the advancements in wireless communication allow for vehicles to send and receive other vehicle's states in real time, such as position, velocity or acceleration, through V2X communication. This allows for a lower dependency on data acquired from the on board sensors.

Beginning in the 1970s, much reserach effort has been spent on various first generation automated control systems that mainly focused on automated throttle and braking actuators. Some of the first commercial outcomes was the Anti-lock Braking System, which was widely accepted and is still used nowadays as a key safety feature in modern vehicles. Later on in the 1990s, the California PATH project was established, which employed an eight vehicle platoon fully automated in purely longitudinal maneuvers. This program inspired similar projects in Japan and Europe, such as CHAEUFFEUR, SARTRE or AHSS, which all together represent a considerable research effort and have obtained encouraging results.

Currently, there are several systems, which were the result of decades of research, that are standard in modern vehicles, such as CC system, which automatically adjusts the throttle and braking actuators in order to maintain a pre-set speed. In addition to this, ACC and CACC systems are becoming ever more common. They have the capability of detecting the distance of the preceding vehicle and maintain a certain distance between them at all time. These systems are explored in more detail in section 2.4.

This chapter aims to formally present the vehicle platooning longitudinal controller that is going to be used throughout this dissertation and scrutinize its results.

The outline of this chapter is as follows. Section 3.2 first analyzes some of the basic longitudinal dynamics that an ordinary vehicle is subject to. Section 3.3 provides a brief description of what it is to be expected and the set objectives for the designed controller that should be met in the validation phase, while section 3.4 derives the platoon longitudinal model. Section 3.5 introduces the control law that is used for the controller of each vehicle of the platoon and mentions the information flow topology used. Section 3.6 details the simulations results of three different maneuvers and section 3.7 presents the final conclusions and possible improvements of the developed control system.

3.2 Longitudinal Dynamics

Understanding the vehicle longitudinal dynamics is the first step for a control system design. A exact vehicle model is complex system composed by non linear parts, such as the tyres, and non constant parameters, i.e. the vehicle's mass or the tyre road friction coefficient. The modeling of the tyre road interface is particularly detailed since there are numerous parameters that must be taken into account: pressure, dimension, weather and road condition, etc. In the literature, there are two widely used tyre models:

- Semi-empirical magic tire formula [44]
- Empirical Dugoff model [45]

Both sets of models have their own advantages and limitations that are extensively researched and documented. The magic tire formula requires unknown parameters which requires experimental testing in order to determine them, however it is considered the best for precise tyre forces

calculations. On the other hand, the Dugoff model has much lower computational demands than the magic tire formula, but is not suitable for driving scenarios with high slip values. For the purpose of this dissertation, a comprehensive review of tyre model is not needed and, as a result, it is used a simplified vehicle model where the vehicle is considered a rigid model moving in an inclined road.

Figure 3.1 maps the various forces that act on the vehicle at every time instant, both internal and external and table 3.1 presents the definition of all the model parameters and the respective units that are going to be used throughout this section.

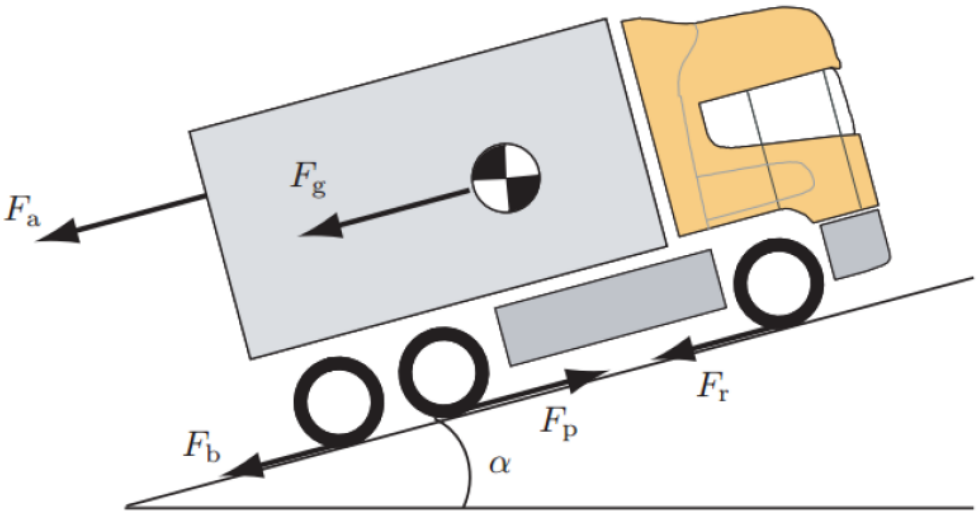


Figure 3.1: Illustration of the longitudinal forces acting on a vehicle in motion [46].

Table 3.1: Longitudinal forces parameters.

Symbol	Description	Unit
m	Vehicle mass	[kg]
v	Vehicle velocity	[m/s]
v_w	Longitudinal wind velocity	[m/s]
C_D	Aerodynamic drag coefficient	[-]
C_{rr}	Rolling resistance coefficient	[-]
ρ	Air density	[kg/m^3]
A_F	Vehicle's frontal area	[m^2]
g	Gravity constant	[m/s^2]
α	Road slope	[degrees]

Using Newton's second law of motion and a force balance along the vehicle longitudinal axis, a non linear longitudinal model is derived:

$$m\dot{v} = F_p - F_{res} - F_b \tag{3.1}$$

Forces F_p and F_b represent the forces applied by the propulsion and braking vehicle actuators, respectively. The system that is in charge of delivering torque to the wheels and, therefore, generates a positive force in the direction of the longitudinal motion is called the propulsion system. In modern vehicles, it is comprised by the engine, transmission and drivetrain. The braking system is responsible for reducing the vehicle's speed by reducing the wheel angular velocity through friction. F_{res} represents the sum of the forces that are intrinsic to vehicle motion and are responsible for energy losses: aerodynamic drag , tire rolling resistance and gravitational force.

$$F_{res} = F_a + F_r + F_g \tag{3.2}$$

The aerodynamic drag (F_a) are losses caused by the drag that derives from the air pressure difference between the front and rear part of the vehicle and the friction between the air and the vehicle surface, which acts as a braking force.

$$F_a = \frac{1}{2}\rho C_D A_F (v + v_w)^2 \tag{3.3}$$

Gravitational forces (F_g) appear whenever the vehicle is driving in non flat surfaces, meaning $\alpha \neq 0$. Since this is a force that is induced by the Earth's gravitational pull, it can either counteract (negative) or assist (positive) the vehicle motion depending on the road slope α.

$$F_g = mg \cdot sin(\alpha) \tag{3.4}$$

The tires are the only interaction that happen between the vehicle and the road. Due to this, these interactions are essential for vehicle dynamics analysis. Tire rolling resistance (F_r) losses are a result of resistive frictional force between the road surface and the wheels. Since these are not perfectly circular and there is contact deformity that happens between road and tyre, the vehicle suffers from energy losses that are dissipated as heat.

$$F_r = C_{rr} mg \cdot cos(\alpha) \tag{3.5}$$

3.3 Control Objective

The desired operation of each member of the platoon is to accurately follow its preceding vehicle while respecting the spacing policy set in place. It is assumed that all vehicles are interconnected through the use of a vehicular ad-hoc network (Section 2.3). Even though, string stability is not a main topic to tackle in this dissertation, it is important to ensure that the behaviour of the platoon is not unstable. String stability refers to the property that spacing errors are guaranteed to not amplify in the upstream direction of a vehicle platoon (Section 2.2).

Based on this, the controller design and its specific spacing policy and control laws must fulfill the following objectives:

1. Each vehicle must respect at all times the spacing policy.

2. Depending on the chosen information flow topology, each vehicle is interconnected to its corresponding vehicles by a wireless network and exchange relevant data.

3. If there is a disturbance, its acceleration and velocity effect must decrease in the upstream direction of the string, guaranteeing the string stability of the platoon.

4. The steady state error of the spacing distance between each vehicle should converge towards zero.

5. The controller should be robust for different velocities.

3.4 Platoon Model

In the following proposed control approach there is no notion of a longitudinal model of a single vehicle. Instead, the model that is going to be used for the longitudinal control is based on the behaviour of the whole platoon, rather than a single vehicle. An additional state variable is added that focuses on inter vehicle distance of consecutive vehicles in the string. This is needed since the main purpose of a longitudinal control is to regulate and uphold the spacing policy.

Consider a platoon of N vehicles where d_i is the distance between vehicle i and its preceding vehicle $i-1$ and v_i is the velocity of vehicle i, as depicted in figure 3.2. The platoon is assumed to move in one dimension, from left to right in a straight line. The position of the rear bumper of vehicle i with respect to a fixed reference point is denoted by x_i. Each vehicle is also assigned a length.

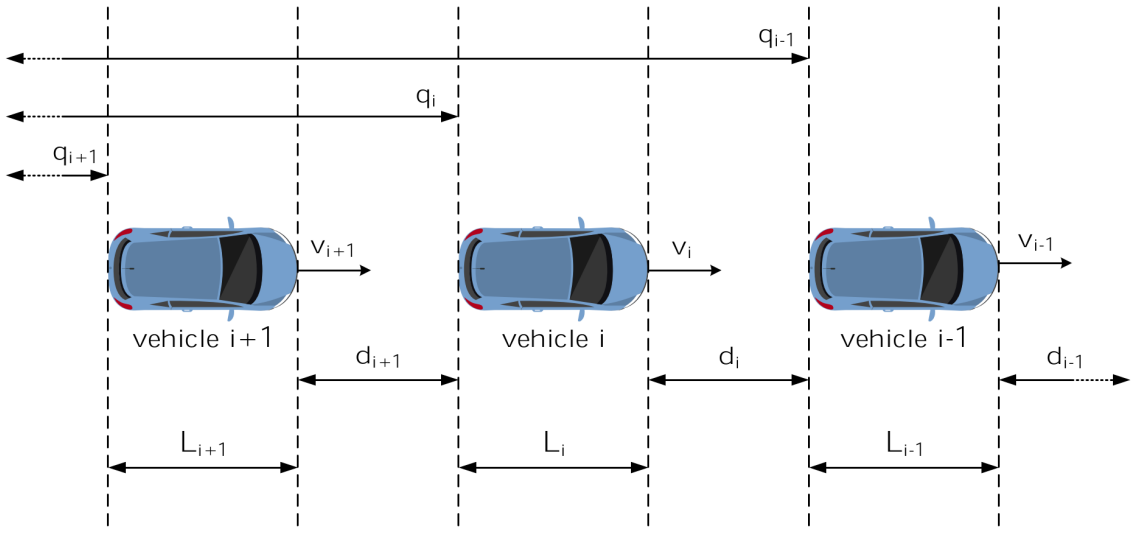


Figure 3.2: Schematics of a three vehicle platoon.

Firstly, it is necessary to design a model that describes the dynamics of a vehicle platoon for the latter formulation of a control law. It is assumed that all vehicles have identical characteristics,

meaning it is a homogeneous platoon. Research has shown that each vehicle can be adequately represented by the following nonlinear model [47] [33]:

$$\begin{bmatrix} \dot{d}_i \\ \dot{v}_i \\ \dot{a}_i \end{bmatrix} = \begin{bmatrix} v_{i-1} - v_i \\ a_i \\ f_i(v_i, a_i) + g_i(v_i)\eta_i \end{bmatrix} \tag{3.6}$$

where a_i is the acceleration of vehicle i and η_i is the engine input. The time argument t is omitted for better readability. Functions $f_i(v_i, a_i)$ and $g_i(v_i)$ are defined as:

$$f_i(v_i, a_i) = -\frac{2C_d}{m_i} v_i a_i - \frac{1}{\tau_i}\left[a_i + \frac{C_d}{m_i} v_i^2 + \frac{d_{mi}}{m_i}\right] \tag{3.7}$$

$$g_i(v_i) = \frac{1}{m_i \tau_i(v_i)} \tag{3.8}$$

where C_d is the aerodynamic drag coefficient, m_i the vehicle's mass, d_{mi} the mechanical drag and τ_i the time constant representing engine dynamics, which is assumed to be identical in all vehicles.

Assuming that all parameters in 3.7 and 3.8 are known *a priori*, we adopt the following engine input:

$$\eta_i = m_i u_i + C_d v_i^2 + d_{mi} + 2\tau_i C_d v_i a_i \tag{3.9}$$

where u_i is the input signal. This signal is not a direct force, rather a it be interpreted as the desired acceleration of vehicle i. Substituting 3.9 in 3.6 yields a simplified a_i term where:

$$\begin{bmatrix} \dot{d}_i \\ \dot{v}_i \\ \dot{a}_i \end{bmatrix} = \begin{bmatrix} v_{i-1} - v_i \\ a_i \\ -\frac{1}{\tau} a_i + \frac{1}{\tau} u_i \end{bmatrix} \tag{3.10}$$

This is the platooning model that is used in the longitudinal controller. Therefore, it is disregarded possible energy losses, such as aerodynamic drag, tyre rolling resistance or engine dynamics.

3.5 Control and System Design

The main objective of this control law is for each vehicle to follow its preceding vehicle at a desired distance d_r. In this particular case, a CTG spacing policy is adopted, where the spacing between vehicles is defined as the time that it takes from the front bumper of the vehicle to the rear bumper of the following vehicle to pass a fixed location on the roadway. More information

about spacing policies can be found in Subsection 2.4.4. In literature, this policy is also commonly referred as constant time gap spacing and is formulated as:

$$d_{r,i} = r + hv_i \tag{3.11}$$

where r is the standstill distance and h is the time gap, in seconds. The first vehicle in the platoon, index $i = 1$, does not have a preceding vehicle so 3.11 is not valid for this vehicle.

Moreover, spacing error e_i is defined as:

$$e_i = d_i - d_{r,i} \tag{3.12}$$

$$e_i = (q_{i-1} - q_i - L_i) - (r + hv_i) \tag{3.13}$$

where q_i is the position of the rear bumper of vehicle i and L_i its respective length. The main objective of the controller is, therefore, to minimize the spacing error of vehicle i in such a way that is convergent to zero.

$$\lim_{t \to \infty} e_i(t) = 0 \tag{3.14}$$

As previously mentioned, the first vehicle of the platoon, commonly referred as the leading vehicle, should be considered separately since it can be driven by a human. Following this, the control law is designed with the error states based in 3.13 as:

$$\begin{bmatrix} e_{1,i} \\ e_{2,i} \\ e_{3,i} \end{bmatrix} = \begin{bmatrix} e_i \\ \dot{e}_i \\ \ddot{e}_i \end{bmatrix} \tag{3.15}$$

Then, it is clearly inferred that the error states are based on differentiating the spacing error as:

$$\begin{cases} e_{3,i} = \ddot{e}_i \\ \dot{e}_{2,i} = e_{3,i} \\ \dot{e}_{1,i} = e_{2,i} \end{cases} \tag{3.16}$$

By continuously differentiating error state equation while using equations 3.10 and 3.13, yields:

$$\dot{e}_i = v_{i-1} - v_i - ha_i \tag{3.17}$$

$$\begin{aligned} \ddot{e}_i &= a_{i-1} - a_i - h\Big(-\frac{1}{\tau} a_i + \frac{1}{\tau} u_i \Big) \\ &= a_{i-1} + \frac{h-\tau}{\tau} a_i - \frac{h}{\tau} u_i \end{aligned} \tag{3.18}$$

$$\begin{aligned}\dddot{e}_i &= \Big(-\frac{1}{\tau}a_{i-1}+\frac{1}{\tau}u_{i-1}\Big)+\frac{h-\tau}{\tau}\Big(-\frac{1}{\tau}a_i+\frac{1}{\tau}u_i\Big)-\frac{h}{\tau}\dot{u}_i \\ &= -\frac{1}{\tau}\Big(a_{i-1}+\frac{h-\tau}{\tau}a_i-\frac{h}{\tau}u_i\Big)+\frac{1}{\tau}u_{i-1}-\frac{1}{\tau}u_i-\frac{h}{\tau}\dot{u}_i \\ &= \frac{1}{\tau}\ddot{e}_i-\frac{1}{\tau}(h\dot{u}_i+u_i)+\frac{1}{\tau}u_{i-1}\end{aligned} \tag{3.19}$$

which becomes:

$$\dot{e}_{3,i} = -\frac{1}{\tau}e_{3,i}-\frac{1}{\tau}\zeta_i+\frac{1}{\tau}u_{i-1} \tag{3.20}$$

where:

$$\zeta_i = h\dot{u}_i+u_i \tag{3.21}$$

This new input ζ is interpreted as a new input for vehicle i. It is used to stabilize the error response, while compensating for the previous input u_{i-1} of the preceding vehicle. Thus, ζ control's law is as follows:

$$\zeta_i = \begin{bmatrix}k_p & k_d & k_{dd}\end{bmatrix}\begin{bmatrix}e_{1,i}\\ e_{2,i}\\ e_{3,i}\end{bmatrix}+u_{i-1} \tag{3.22}$$

where k_p, k_d and k_{dd} are the controller gains and u_{i-1} is the feedforward term that is obtained from the output of the preceding vehicle and is obtained through wireless communication links. Therefore, we conclude that this control design will be using a predecessor following information flow topology.

Substituting 3.21 in 3.22, it is obtained the control law for the controller of the vehicle, with the original input u:

$$\dot{u}_i = -\frac{1}{h}u_i+\frac{1}{h}(k_pe_{1,i}+k_de_{2,i}+k_{dd}e_{3,i})+\frac{1}{h}u_{i-1} \tag{3.23}$$

As to summarize the error dynamics and is consequent derived control law:

$$\begin{bmatrix}\dot{e}_{1,i}\\ \dot{e}_{2,i}\\ \dot{e}_{3,i}\\ \dot{u}_i\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ -\frac{k_p}{\tau} & -\frac{k_d}{\tau} & -\frac{1+k_{dd}}{\tau} & 0\\ \frac{k_p}{h} & \frac{k_d}{h} & \frac{k_{dd}}{h} & -\frac{1}{h}\end{bmatrix}\begin{bmatrix}e_{1,i}\\ e_{2,i}\\ e_{3,i}\\ u_i\end{bmatrix}+\begin{bmatrix}0\\0\\0\\ \frac{1}{h}\end{bmatrix}u_{i-1} \tag{3.24}$$

From the derived control law in 3.24 and from the platoon model in 3.10, it is inferred that a control structure based on a feedback and feedforward is needed, as shown in figure 3.3. The feedback term is responsible for comparing the output of the obtained inter vehicle distance with the desired spacing policy, where as the feedforward term of v_{i-1} originates from the preceding vehicle and it is transmitted to the following vehicle through communication links in a predecessor

following topology. The data exchanged through these may be subject to time delays which will be discussed in section 3.6.

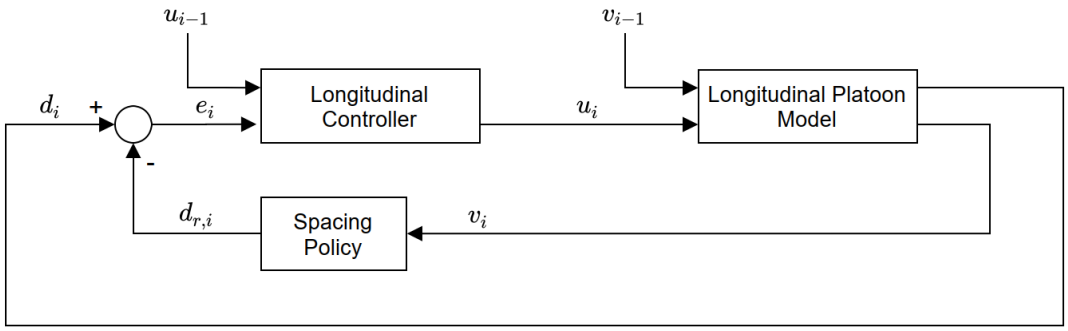


Figure 3.3: Control structure for longitudinal control.

On the other hand, the leading vehicle of the platoon has an independent control structure of the rest of the platoon, since its movement defines the behaviour of the platoon. As a result, its control structure is a simple feedback PI controller, as seen in figure 3.4. The feedback term used is the vehicle's output velocity, which is compared to reference desired velocity. Therefore, in the leading vehicle, the system is controlled by its velocity error followed by the controller block that has as its output a signal u_0, which is meant to simulate the throttle and brake actuators of the vehicle by its driver.

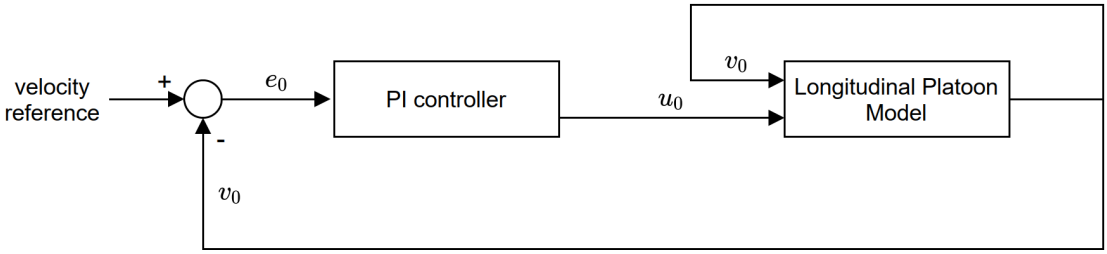


Figure 3.4: Control structure of the platoon's leading vehicle for longitudinal control.

3.6 Simulation Tests

In this section, the proposed longitudinal control structure is studied in a homogeneous platoon of three vehicles throughout a series of simulations. All simulations scenarios share the same spacing policy of CTG and is formulated as shown in equation 3.11. The parameters used for the following simulation are:

$$\begin{cases} h = 0.8\text{s} \\ r = 1.0\text{m} \end{cases} \tag{3.25}$$

Furthermore, all controller gains are obtained in an iterative manner through the use of numerical computation software, in order to obtain suitable gain values. In this case, the controller gains chosen for the control law depicted in equation 3.24 are as follows:

$$\begin{cases} k_p = 1.3 \\ k_d = 3.1 \\ k_{dd} = 0.2 \end{cases} \tag{3.26}$$

For the leading vehicle, its control parameters were chosen in the same iterative manner, which yielded:

$$\begin{cases} k_p = 1.0 \\ k_i = 0.5 \end{cases} \tag{3.27}$$

In addition to this, all inter vehicle communication are subject to a time delay of 0.1s, which was shown to be the standard time delay in real world application of V2V links [48]. All vehicles share the same τ, which is a time constant that is interpreted as the engine dynamics. It has a value of 0.1.

In the following subsections, three different tests are used that aim to analyze the vehicle platoon response to different velocity inputs, which aim to simulate both real world and hypothetical scenarios. The proposed tests are:

- System response to a positive step signal
- System response to a square signal
- System response to a positive step signal with communication delays

3.6.1 Test 1: System response to a positive step signal

Firstly, a three vehicle platoon is tested for a velocity reference input of the leading vehicle, in the form of a positive step signal. These simulations have the intended purpose to assess the controller performance of the proposed control objectives in section 3.3. It is understood that this type of

instantaneous speed transitions do not have any resemblance of real life scenarios, however the motivation of these experiments is to test the stability of these systems in extreme situations.

In the first test the step signal starts at a initial velocity of 0 m/s and transitions to a final velocity of 5 m/s, at $t = 7$s. As for the initial positions of the three vehicles, they have a inter vehicle distance of one meter. In one dimension coordinates, the initial positions are:

$$\begin{cases} x_0(0) = 2\text{m} \\ x_1(0) = 1\text{m} \\ x_2(0) = 0\text{m} \end{cases} \tag{3.28}$$

As previously mentioned, the controller must assure the CTG spacing policy with the parameters in 3.25. This means that for the different velocities, a different inter vehicle distance is expected. For the first velocity of 0 m/s:

$$\begin{aligned} d_r &= r + h \cdot v \\ &= 1 + 0.8 \cdot 0 \\ &= 1\text{m} \end{aligned} \tag{3.29}$$

Similarly, for the final velocity of 5 m/s:

$$\begin{aligned} d_r &= r + h \cdot v \\ &= 1 + 0.8 \cdot 5 \\ &= 5\text{m} \end{aligned} \tag{3.30}$$

Figure 3.5 shows the simulation results of the proposed test. Firstly , these figures show that string stability is assured in the platoon with the proposed control structure, since all of the signal oscillations (distance, velocity and acceleration) did not propagate throughout the string. Instead, these oscillations are attenuated in the upstream direction, which reveals a convergent steady state response for each of the vehicle's states. The spacing policy is also respected in both velocities as they match the desired distance previously calculated. The leading vehicle always has a inter vehicle distance of zero, as it does not have a preceding vehicle to calculate its distance to it. As result, this signal is meaningless for result analysis. It is important to note that this is relevant for all tests. Finally, the system response is also adequate for platooning applications, considering it has a smooth transition, rather than an aggressive one, which wouldn't be representative of commercial solutions for vehicle platooning.

3.6.2 Test 2: System response to a square signal

In this scenario, a three vehicle platoon is subject to a square like signal for the velocity reference of the leading vehicle, where the transition from different speeds is made with a ramp, rather

than an instantaneous change shown in test 1. The intent of this change is to try to simulate somewhat realistic scenarios of acceleration and braking operations. The maneuvers starts with a null velocity and at $t = 7$s, the leading vehicle starts accelerating and reaches a velocity of 10 m/s at $t = 12$s. After some time at $t = 22$s, it starts decelerating until it is completely stopped at $t = 27$s.

The initial position of all three vehicles is at the origin of the one dimension reference, meaning $x = 0$. This same initial position of all vehicles is purely hypothetical and, obviously, is not possible in real world experiments. Nevertheless, it is still noteworthy to study in these conditions. According to the chosen spacing policy, the expected inter vehicle distances in steady state response are 1m and 9m for a velocity of 0 m/s and 10 m/s, respectively.

As depicted in figure 3.6, the system response for a square signal is considered string stable as all the signals (distance, velocity and acceleration) are attenuated in the upstream direction of the platoon. Initially, it can be denoted that the members of the platoon do not respect the spacing policy, since all vehicles share the same position and, for a null velocity, the platoon must have a inter vehicle distance of 1m. As a result, the platoon initiates a maneuver to amend the distance where the following vehicles go backwards (negative velocity) and shortly after come to a full stop. Throughout the remaining maneuver, the control system correctly imposes the chosen spacing policy.

Contrarily to the previous test, the transition from different velocities of the reference signal is gradual and not instant. Thus, it is now possible to evaluate the response time of the control system to velocity changes. The velocity of the platoon members correctly follows the reference of the leading vehicle in a timely manner, which is characteristic of a suitable control structure for real world applications.

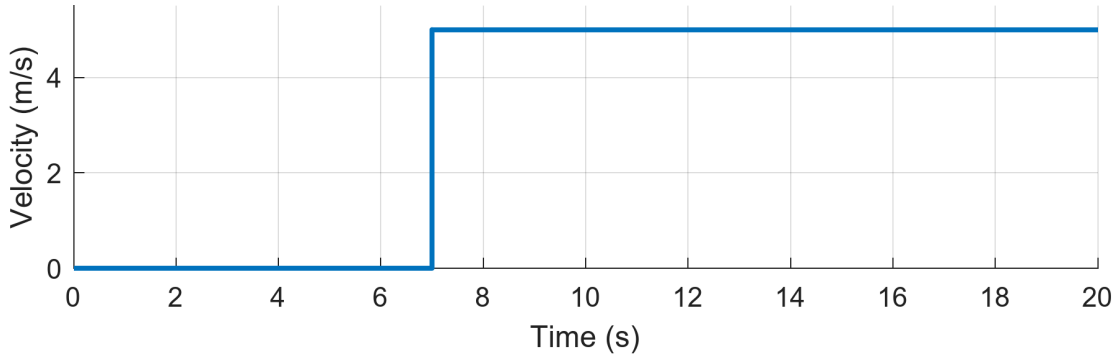
3.6.3 Test 3: System response to a positive step signal with communication delays

The aim of the final test, it is studied the impact of severe communication delays in the inter vehicle communication links between members of the platoon. As previously mentioned, the communication delay used in the tests is 0.1s, which is the approximate time in real world V2V communication links. In this test, it is used a communication delay of 2s.

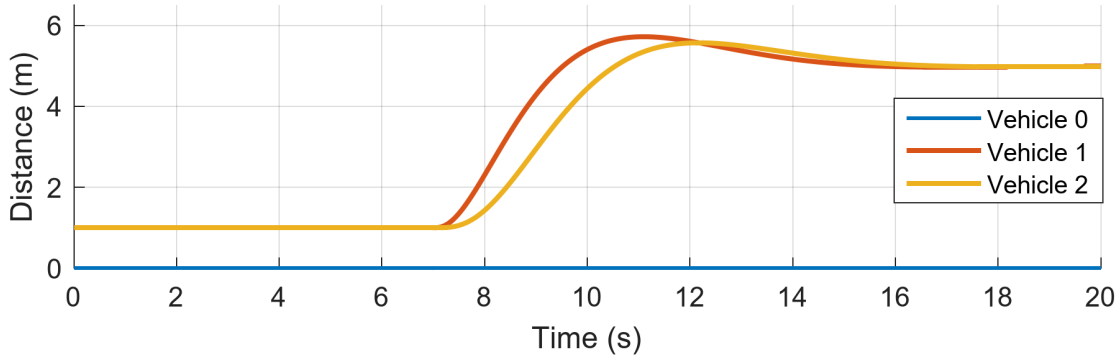
The planned maneuver is essentially the same as the first test, where the velocity reference of the leading vehicle is a positive step signal. It starts at a initial velocity 0 m/s and finishes at a velocity of 20 m/s, with an instantaneous velocity transition at $t = 7$s. Regarding the initial positions, each member of the platoon is also separated by a distance of 1m. Moreover, the expected inter vehicle distance throughout the maneuver is 1m and 17m for a velocity of 0 m/s and 20 m/s, respectively.

One of the main concerns when studying the proposed controller was whether or not it was capable of supporting time delays, within the V2V communication links, as this is one of the main factors that could contribute to longitudinal string instability. However, figure 3.7 shows that, even though there is a considerable communication delay, each member of the platoon is still capable of completing the intended maneuver with the chosen spacing policy. In addition to this, each of

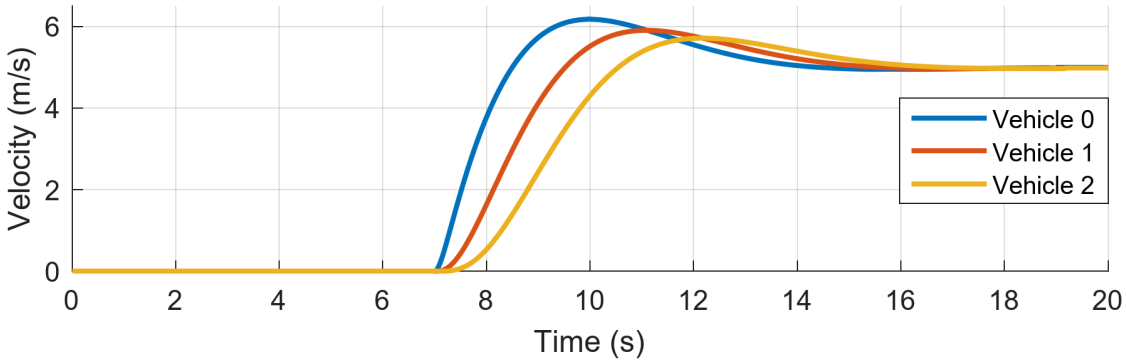
the vehicle's state signal was attenuated throughout the string, which revealed that string stability was assured, as required.



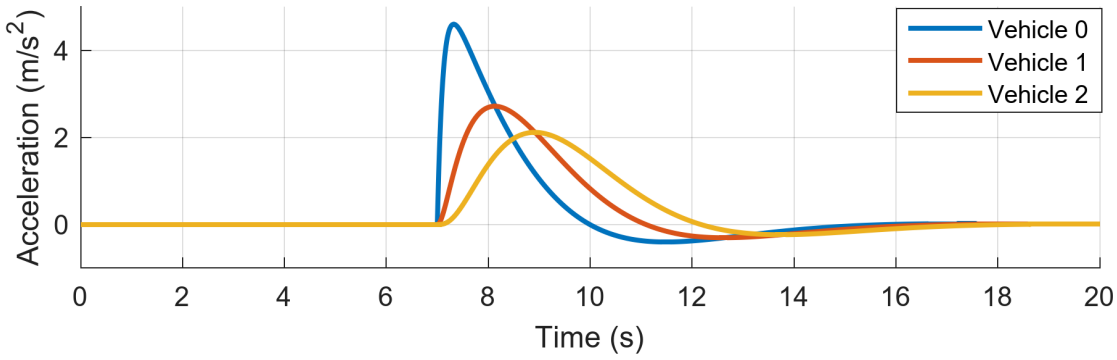
(a) Velocity reference for the leading vehicle.



(b) Inter vehicle distance.

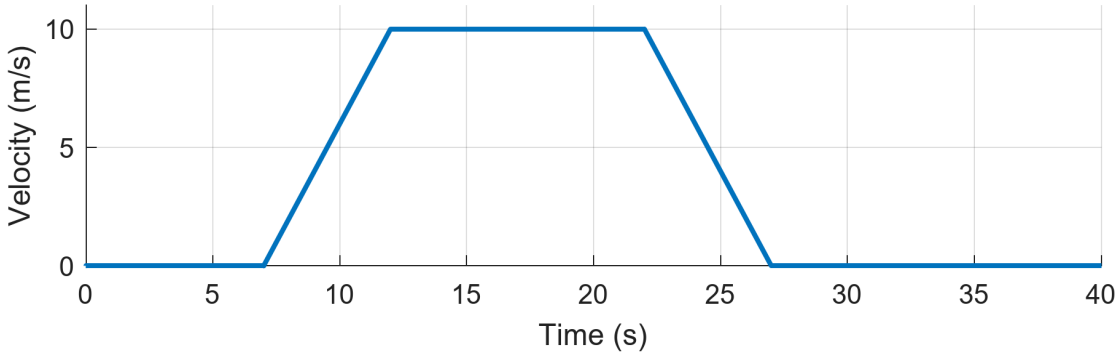


(c) Vehicle velocity.

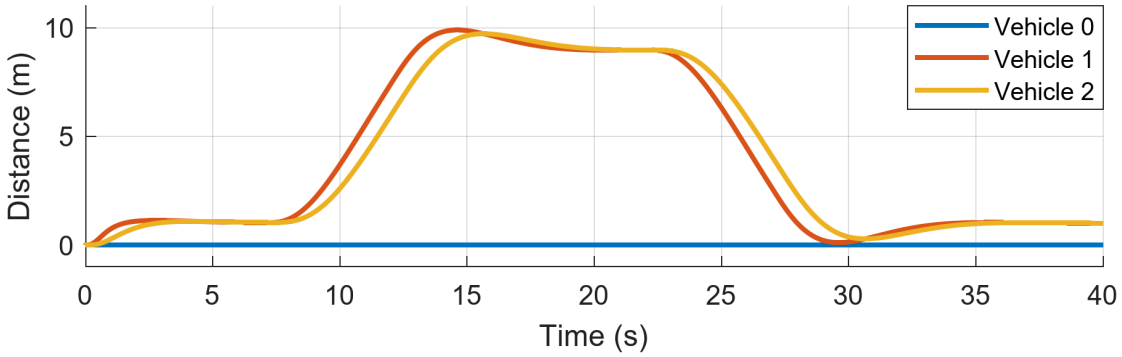


(d) Vehicle acceleration.

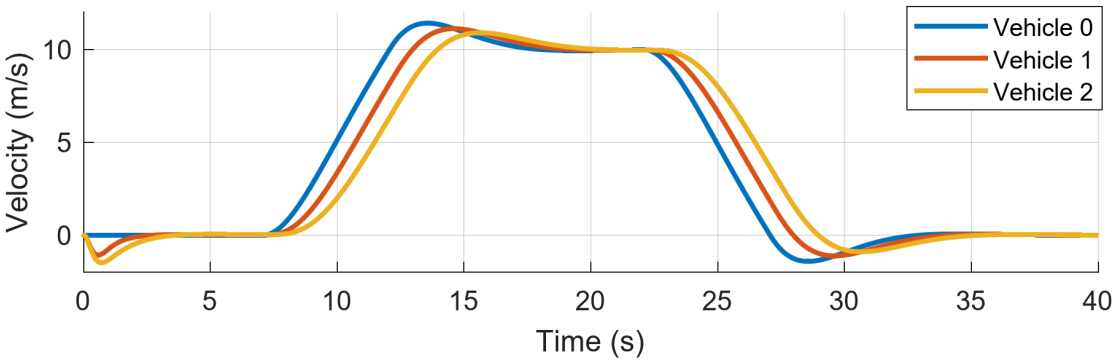
Figure 3.5: Test 1 results.



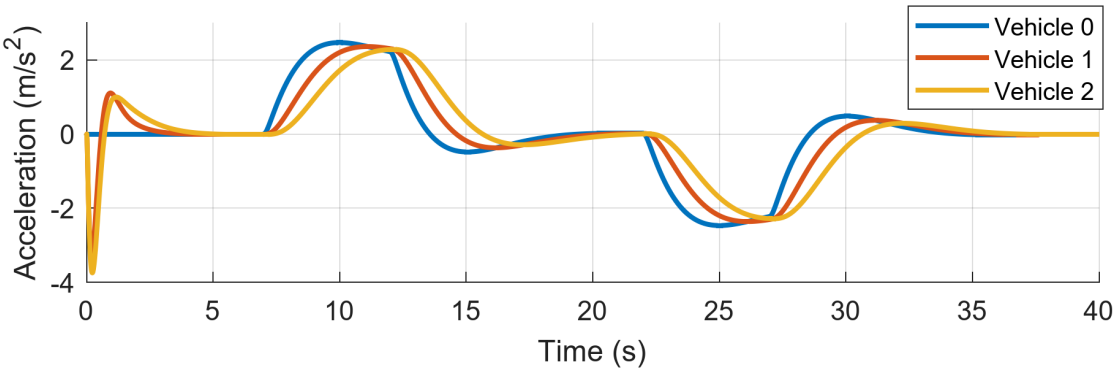
(a) Velocity reference for the leading vehicle.



(b) Inter vehicle distance.

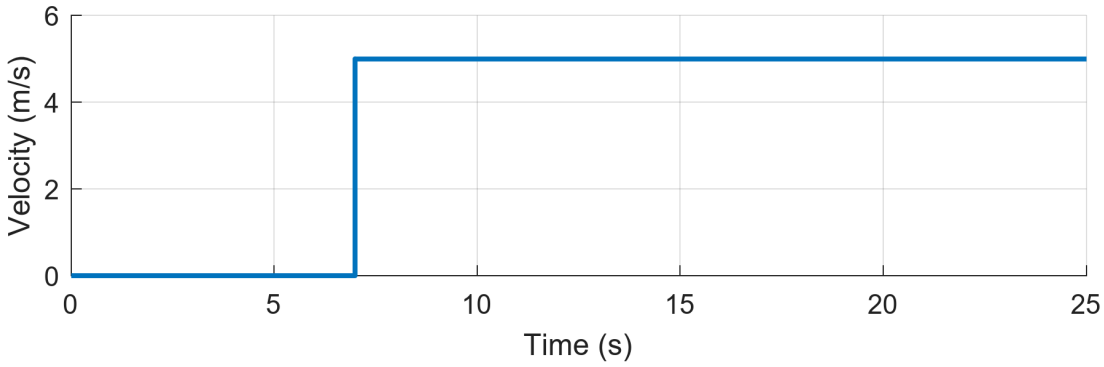


(c) Vehicle velocity.

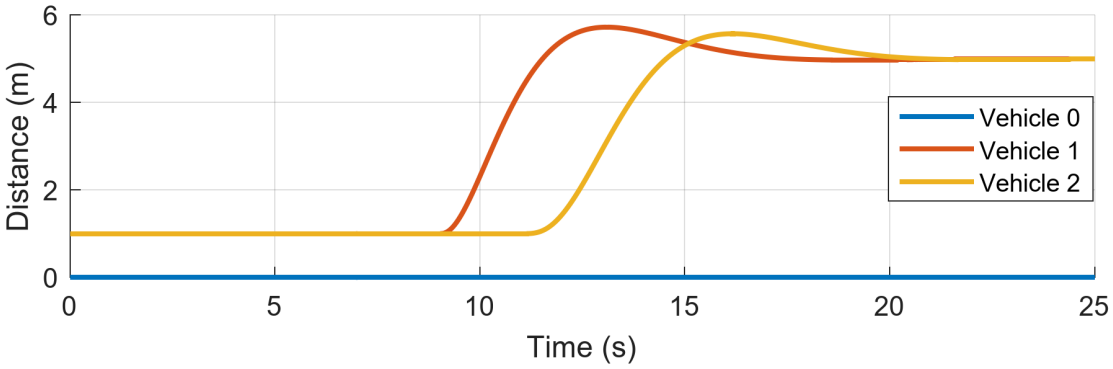


(d) Vehicle acceleration.

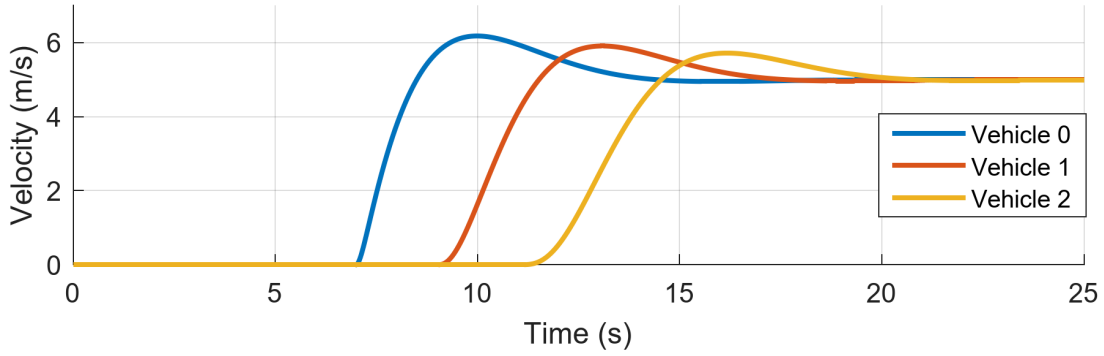
Figure 3.6: Test 2 results.



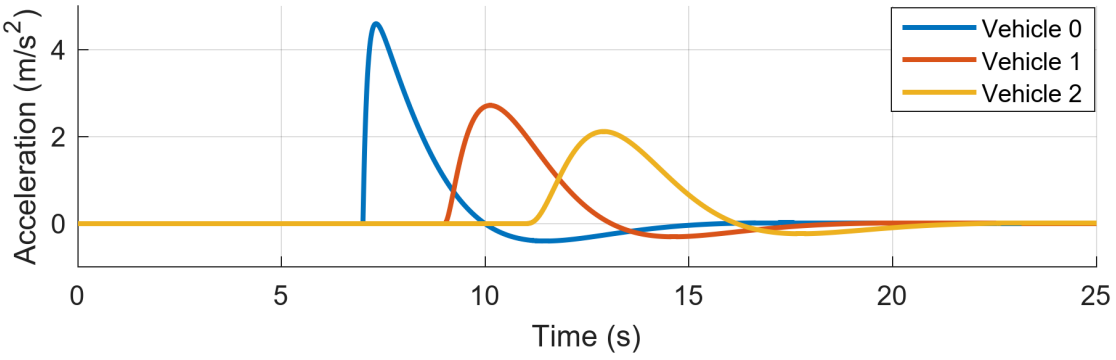
(a) Velocity reference for the leading vehicle.



(b) Inter vehicle distance.



(c) Vehicle velocity.



(d) Vehicle acceleration.

Figure 3.7: Test 3 results.

3.7 Discussion

In this chapter, a vehicle longitudinal control system for a interconnected homogeneous platoon was designed that assumed a simplified model for the dynamics of each vehicle. The proposed control structure was validated through a series of tests that outlined different maneuvers. These simulations showed that all of the outlined objectives in section 3.3 were met, including string stability and the spacing policy.

Nevertheless, future improvements regarding the system response to reference velocity changes in the leading vehicle still remain. As shown in test 2 (section 3.6.2), whenever there is a negative change, in this case from $v = 10$ m/s to a standstill, the velocity signal of the members of the platoon suffers a overshoot, which results in a limited period of time where it is negative and only then does the vehicle completely stop. This is not desired in real world applications of vehicle platooning, since it is bothersome for the passengers from a comfort point of view and could be potentially dangerous in mixed traffic scenarios, where platoons share the same road with ordinary personal vehicles. Therefore, it is noteworthy to explore, in future research, new methods of minimizing overshoot in maneuvers that could lead to a change of sign.

In addition to this, the proposed control structure only supports a platoon of identical vehicles. A possible improvement is to redesign the control design to support different vehicles within the same string, i.e. a heterogeneous platoon.

Chapter 4

Integrated Longitudinal and Lateral Controller

This chapter presents an additional lateral control structure to the previous longitudinal controller presented in chapter 3, where two different approaches are studied, tested and compared. The first control structure relies on using global Cartesian coordinates to enable a vehicle following strategy. However, this approach is not ideal in certain vehicle maneuvers. As a result, a second strategy based on a virtual vehicle design is proposed that sets out to minimize the limitations and errors of the previous approach.

4.1 Introduction

According to the America Association of State Highway and Transportation Officials (AASHTO), lane departures are the main cause of fatal accidents and account for almost 60% of total highways crashes in the United States, causing more than twenty five thousand deaths annually. In the same document, it was reported that a crash in a curved path is three times more likely to happen than in straight road segments. Human related errors are the major culprit of the previously mentioned accidents [49]. Hence, there is a need for a additional lateral control structure in the previously referenced longitudinal controller.

In the literature there are two main possibilities to design integrated longitudinal and lateral controller. Some research treats both components as a coupled system, which has shown significant improvement within the control performance [50]. However, the vast majority of research and development has been on independent control systems, where the longitudinal component is focused on maintaining the chosen spacing policy and the lateral component is responsible for executing the necessary maneuvers to maintain string stability. There are two designs possibilities that the lateral controller can follow: lane keeping, path following and vehicle following.

Lane keeping is considered a niche approach that doesn't a reliable way of being implemented in real world applications. Rajamani et al. [51] used a magnetic marking system where the vehicles sense the embedded magnets on the road to measure lateral errors and correct its trajectory. This

was proven reliable with a good performance. However, it is not viable to implement magnets in lanes in order to use this system in ordinary roads.

Another study developed a path following approach by using a vision based system [52]. The cameras that were embedded in the vehicle had a sufficient field of view to observe the road and through image recognition algorithms, the vehicle could follow a path reference, which, in this case, are the road lanes. The downside of this method is that it is vulnerable to the visibility of road lanes. If the weather conditions obstruct the road markings, such as snow, the vehicle can not continue its automated driving. This is the reason why some approaches have a secondary system that falls back on a vehicle following method.

Lastly, a vehicle following approach consists in tracking the position of the preceding vehicle based on a global coordinate system. This is the method that is going to be explored throughout this chapter. It is assumed that a vehicle's global coordinates are measured by a GPS like instrument and communicated between vehicles via a V2V communication link. This approach is sometimes referred, in the literature, as look ahead.

The outline of the chapter is as follows. Section 4.2 outlines the main control objectives that the designed controller must follow and section 4.3 derives the platoon vehicle model. Section 4.4 details the control law and the system design based on a global coordinate system, while section 4.5 presents its simulation results. Section 4.6 introduces a new control law based on the concept of a virtual vehicle and section 4.7 indicates its simulation results. Finally, section 4.8 provides an overview of the chapter, as well as its main findings.

4.2 Control Objective

The control objectives that are expected of the combined controller are essentially the same as the ones discussed in chapter 3.3. This means that the proposed controller must assure core objectives, such as string stability, spacing policy and inter vehicle connectivity. It is important to note that it is necessary that the string stability is guaranteed in both longitudinal and lateral types of motion as discussed in section 2.2.1. In addition to this, since the vehicle is presumed to make lateral maneuvers, the controller must fulfill additional objectives:

1. The controller should support typical road driving maneuvers, such as lane changing and overtaking a vehicle.

2. The steady state error for the vehicle's states and steering should converge to zero.

4.3 Vehicle Model

Throughout this section, there are two distinct coordinate systems that are used. One is the global coordinate system (X, Y, Z), which is fixed to an arbitrary location and is, therefore, used to define the global position and orientation of the vehicle. The other is the vehicle local coordinate system (X_l, Y_l, Z_l), where the origin of this system is fixed to the position and orientation of the vehicle's

centre of mass. This means that the local coordinate system is responsible for describing the motion of the vehicle. Figure 4.1 illustrates these two distinct coordinate systems. Moreover, it is assumed, in this section, that the vehicle's states (acceleration and velocity) with regards to the global coordinates system are written in uppercase letters, while the local coordinate system are depicted in lowercase.

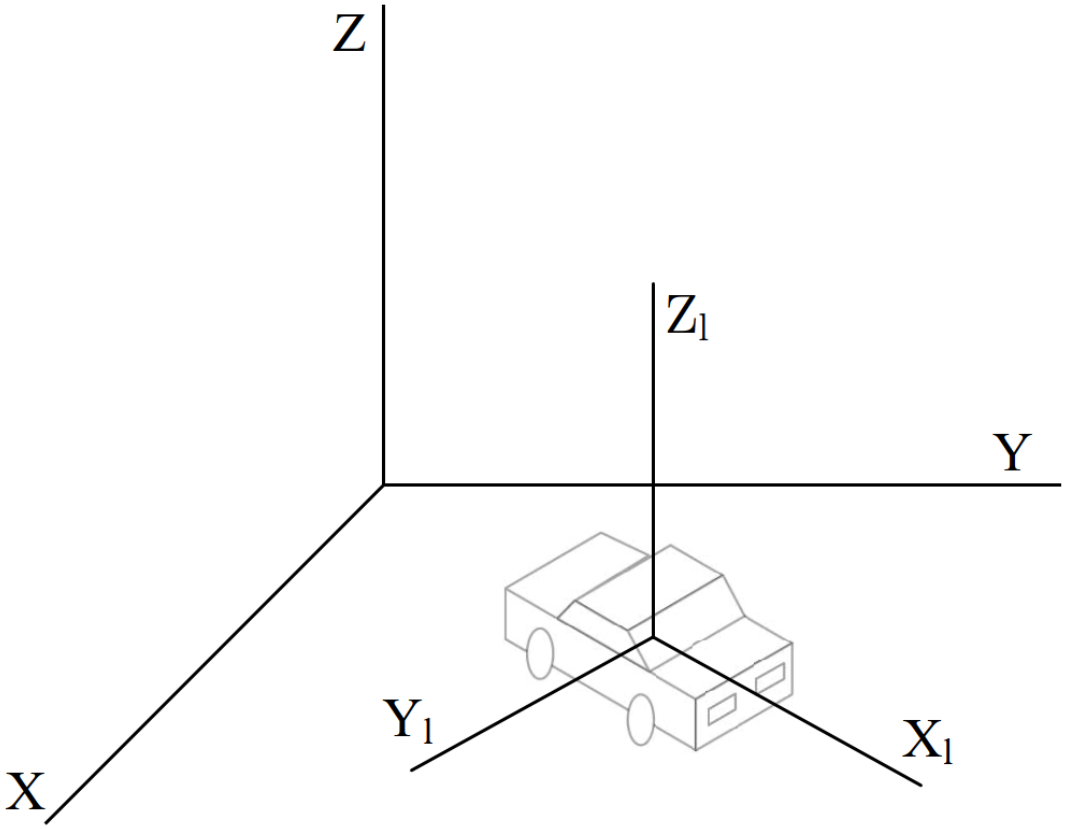


Figure 4.1: Global and local coordinate system.

4.3.1 Lateral Vehicle Model

In order to add an additional degree of freedom to the purely longitudinal model of the vehicle platoon, it is necessary to formulate a lateral vehicle model. This is the first step to assure that each member platoon can support lateral maneuvers.

One of the most commonly used techniques to describe a simplified model of the lateral dynamics of a vehicle is the bicycle model with two degrees of freedom. In this dissertation, the chosen degrees of freedom are represented by the side slip β and yaw angle ψ, since it allows for a reasonably accurate description of the vehicle's states without the use of complex modeling. This is not supposed to represent a high fidelity model of a real world vehicle in complex maneuvers, since these are subject to numerous non linear dynamics. This simplified bicycle model is suitable to express a normal driving behaviour. In this approach, each pair of front and rear

wheels are represented by a single tyre, which are at a constant distance between each other in the same longitudinal axis x. Besides this, the bicycle model viability depends on the following assumptions:

- The vehicle moves in a flat surface.
- The longitudinal velocity of the vehicle is interpreted as a time dependent system parameter.
- All of the vehicle's mass is concentrated at its centre of gravity, which remains at a constant position.
- Rolling, pitching and lifting motion from the tyres is disregarded.
- The aerodynamic forces ti which the vehicle is subject to are negligible.
- The road curves are of small to moderate radius.

Figure 4.2 depicts the bicycle model described in this section. It is assumed the vehicle has a front wheel only steering, represented by δ_f.

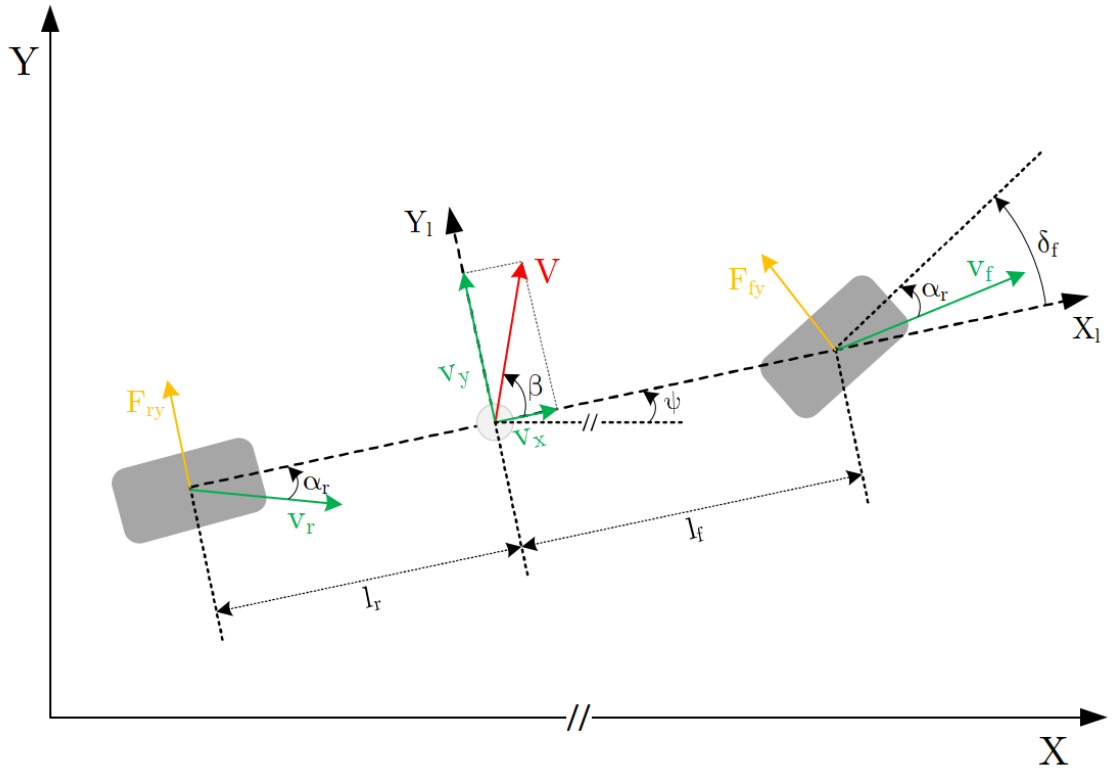


Figure 4.2: Illustration of lateral dynamics of a vehicle using a bicycle model.

By applying Newton's second law, the following equations are derived:

$$ma_y = F_{ry} + F_{fy} \tag{4.1}$$

where m is the vehicle mass, a_y the total lateral acceleration, F_{ry} and F_{fy} the lateral tyre forces of rear and front tyres, respectively. The total lateral acceleration a_y is the sum of the acceleration along the local Y_l axis $\dot{v}_y$ and the centripetal acceleration $\dot{x} \cdot \dot{\psi}$.

$$a_y = \dot{v_y} + v_x \cdot \dot{\psi} \tag{4.2}$$

By substituting 4.2 in 4.1, the vehicle motion can be described as:

$$m(\dot{v_y} + v_x \cdot \dot{\psi}) = F_{ry} + F_{fy} \tag{4.3}$$

The lateral forces F_{ry} and F_{fy} are proportional to the slip angle α, which is the angle between the tyre orientation and the velocity vector (v_r and v_f). The slip angles of the rear (α_r) and front tyre (α_f) can be written as:

$$\alpha_r = -\beta_r \tag{4.4}$$

$$\alpha_f = \delta_f - \beta_f \tag{4.5}$$

where δ_f is the steering angle and β_j, with $j \in \{r, f\}$, is the tyre side slip, which is angle between the local longitudinal axis of motion and the velocity vector of the rear and front wheel, respectively. The side slip value may not be the same for each tyre, since they can have different velocities. The angle β_j is defined as:

$$\beta_j = \frac{v_{y,j}}{v_{x,j}} \tag{4.6}$$

where $v_{y,j}$ and $v_{x,j}$, with $j \in \{r, f\}$, is the lateral and longitudinal velocity component of the rear and front tyre, respectively. It is important to note that the longitudinal velocity component has the same value for both wheels, since they share the same longitudinal axis. Regarding the lateral velocity component, it depends on the lateral velocity of the vehicle at its centre of mass and the yaw rate. Using a small angle approximation, the following expressions for the slip angles can be deduced:

$$\alpha_r = -arctan\left(\frac{v_y - l_r\dot{\psi}}{v_x}\right) \approx -\frac{v_y - l_r\dot{\psi}}{v_x} \tag{4.7}$$

$$\alpha_f = \delta_f - arctan\left(\frac{v_y + l_r\dot{\psi}}{v_x}\right) \approx \delta_f - \frac{v_y + l_r\dot{\psi}}{v_x} \tag{4.8}$$

where l_r and l_f are the distance from the rear and front vehicle to the center of gravity, respectively. The arctangent can be neglected since the value of the argument will be within the linear region ($v_x \gg v_y$). As a result, the lateral forces are described by the following mathematical

expressions:

$$F_{ry} = C_{\alpha r}\Big(-\frac{v_y - l_r\dot{\psi}}{v_x}\Big) \tag{4.9}$$

$$F_{fy} = C_{\alpha f}\Big(\delta_f - \frac{v_y + l_r\dot{\psi}}{v_x}\Big) \tag{4.10}$$

where $C_{\alpha r}$ and $C_{\alpha f}$ are the cornering stiffness of the rear and front tyre, respectively. Substituting 4.9 and 4.10 in 4.3 yields the expression for the lateral acceleration:

$$\dot{v_y} = -\frac{C_{\alpha f} + C_{\alpha r}}{mv_x}v_y + \Big(\frac{C_{\alpha f}l_f - C_{\alpha r}l_r}{mv_x} - v_x\Big)\dot{\psi} + \frac{C_{\alpha f}}{m}\delta_f \tag{4.11}$$

To obtain the final expression for the angular acceleration, it is needed the moment equation around the z axis that describes the yaw dynamics:

$$I_z\ddot{\psi} = l_f F_{fy} - l_r F_{ry} \tag{4.12}$$

where I_z is the moment of inertia around the z axis. Likewise, by substituting 4.9 and 4.10 in 4.12, the expression for the angular acceleration:

$$\ddot{\psi} = \frac{C_{\alpha f}l_f - C_{\alpha r}l_r}{I_z v_x}v_y - \frac{C_{\alpha f}l_f^2 - C_{\alpha r}l_r^2}{I_z v_x}\dot{\psi} + \frac{C_{\alpha f}l_f}{I_z}\delta_f \tag{4.13}$$

In matrix notation, the previous expressions can be modeled as:

$$\begin{bmatrix}\dot{v_y}\\ \ddot{\psi}\end{bmatrix} = \begin{bmatrix}-\frac{C_{\alpha f}+C_{\alpha r}}{mv_x} & -\frac{C_{\alpha f}l_f - C_{\alpha r}l_r}{mv_x} - v_x\\ -\frac{C_{\alpha f}l_f - C_{\alpha r}l_r}{I_z v_x} & -\frac{C_{\alpha f}l_f^2 + C_{\alpha r}l_r^2}{I_z v_x}\end{bmatrix}\begin{bmatrix}v_y\\ \dot{\psi}\end{bmatrix} + \begin{bmatrix}\frac{C_{\alpha f}}{m}\\ \frac{C_{\alpha f}l_f}{I_z}\end{bmatrix}\delta_f \tag{4.14}$$

In 4.14, the longitudinal velocity v_x is assumed as a time dependent system parameter rather than a state, since v_x is typically handled as a constant by both lateral and longitudinal controllers in platooning applications. Furthermore, equation 4.14 describes the vehicle's lateral dynamics using lateral position and yaw rate as the state variables. However, these state variables can be redefined as the side slip and yaw rate. As per Abe [53], v_x and v_y can also be written as:

$$v_x = V \cdot cos(\beta) \approx V \tag{4.15}$$

$$\dot{v_x} = -V \cdot sin(\beta) \cdot \dot{\beta} \approx -V \cdot \beta \cdot \dot{\beta} \tag{4.16}$$

$$v_y = V \cdot sin(\beta) \approx V \cdot \beta \tag{4.17}$$

$$\dot{v_y} = V \cdot cos(\beta) \cdot \dot{\beta} \approx V \cdot \dot{\beta} \tag{4.18}$$

By substituting 4.15-4.18 in 4.13 and 4.11, these equations are rewritten with a new state vector $x = [\beta \quad \dot{\psi}]^T$:

$$\dot{\beta} = -\frac{C_{\alpha f} + C_{\alpha r}}{mV}\beta + \Big(-\frac{C_{\alpha f} l_f - C_{\alpha r} l_r}{mV^2} - 1\Big)\dot{\psi} + \frac{C_{\alpha f}}{mV}\delta_f \delta_f \tag{4.19}$$

$$\ddot{\psi} = -\frac{C_{\alpha f} l_f - C_{\alpha r} l_r}{I_z}\beta - \frac{C_{\alpha f} l_f^2 + C_{\alpha r} l_r^2}{I_z V}\dot{\psi} + \frac{C_{\alpha f} l_f}{I_z} \tag{4.20}$$

In space state notation:

$$\begin{cases} \dot{x} = Ax + B\delta_f \\ y = Cx + D\delta_f \end{cases} \tag{4.21}$$

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\psi} \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{C_{\alpha f}+C_{\alpha r}}{mV} & -\frac{C_{\alpha f} l_f - C_{\alpha r} l_r}{mV^2} - 1 \\ -\frac{C_{\alpha f} l_f - C_{\alpha r} l_r}{I_z} & -\frac{C_{\alpha f} l_f^2 + C_{\alpha r} l_r^2}{I_z V} \end{bmatrix}}_{A} \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{C_{\alpha f}}{mV} \\ \frac{C_{\alpha f} l_f}{I_z} \end{bmatrix}}_{B} \delta_f \tag{4.22}$$

$$\begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}}_{C} \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ 0 \end{bmatrix}}_{D} \delta_f \tag{4.23}$$

Similarly to the previously mentioned equations, the vehicle velocity V is as a time dependent system parameter rather than a state. This is the lateral vehicle model that is used in this document.

Throughout this section, the vehicle motion has been expressed in local coordinates. However, it is also possible to express the vehicle motion with fixed coordinates on the ground, i.e. global coordinates, as this enables a study of each vehicle individually.

Knowing the vehicle's side slip β, yaw angle ψ and the magnitude of the velocity vector V at the centre of gravity, the heading angle of the vehicle with respect to the X axis (global frame) θ is:

$$\theta = \beta + \psi \tag{4.24}$$

Consequently, its global frame longitudinal and lateral velocity is:

$$V_x = V cos(\theta) \tag{4.25}$$

$$V_y = V sin(\theta) \tag{4.26}$$

Therefore, the global Cartesian coordinates of the vehicle (x_v and y_v) is deduced by integrating both longitudinal and lateral velocity at each time step. Moreover, the distance from the origin of the global coordinate system is:

$$D = \sqrt{x_v^2 + y_v^2} \tag{4.27}$$

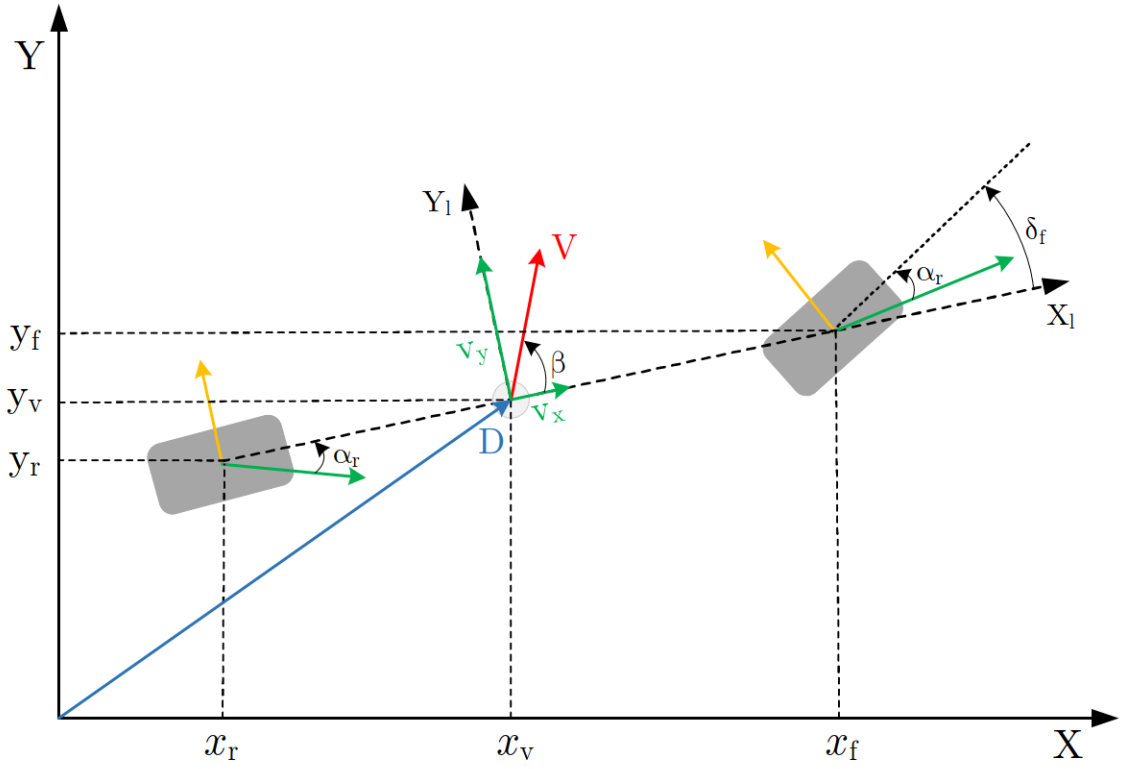


Figure 4.3: Illustration of global Cartesian coordinates of a vehicle using a bicycle model.

4.3.2 Combined Longitudinal and Lateral Model

In order to have a platoon of vehicles capable of performing all types of maneuvers that are characteristic of an ordinary driving experience, it is necessary that there is a combined longitudinal and lateral vehicle model that is adapted for platoons. Since the longitudinal model is fed by the output of the longitudinal controller and the lateral model is also fed by its controller, the control system must be designed with this in consideration. There are two alternative methods for designing these systems: uncoupled and coupled approaches.

An uncoupled approach disregards any coupling effects between the longitudinal and lateral models. Therefore, each model is completely independent from one another and the controller is obtained by combining both models. Experiments where a vehicle had an independent longitudinal and lateral controller, which were fed by its velocity and angular velocity, respectively, displayed remarkable results in low speeds. However, in higher velocities, the vehicle became unstable. Thus, it was concluded that this approach was not suitable for urban driving [54]. Since this dissertation focuses on vehicle platooning at road cruising speeds, a coupled approach is proposed, where the coupling effects between the two distinct models are taken into consideration.

In this proposed combined model, the output velocity of the longitudinal model presented in equation 3.10 is one of the parameters of the lateral model of the vehicle, as in equation 4.22. This mean that this parameter is interpreted by the lateral model as the magnitude of the velocity vector,

rather than the velocity value in the global longitudinal axis. As such, this is considered a coupled approach. With this integrated model, it is now possible for the vehicle platoon to perform new maneuvers that require operations in both longitudinal and lateral directions.

4.4 Controller and System Design

It should be noted that the proposed controller design is supposed to be an extension of the previously presented longitudinal controller, in section 3.5, with a lateral component. Therefore, this controller employs essentially the same longitudinal controller, with a few necessary tweaks.

Similarly to section 3.5, the main objective of this proposed control law is for vehicle i to correctly follow vehicle $i-1$ at a desired distance $d_{r,i}$. However, in this case the desired distance can be divided with respect to the global coordinates X and Y axis. Since, the heading angle of vehicle i, θ_i, is known, which can be interpreted as the angle between the vehicle motion and the X axis, the desired distance for CTG spacing policy can be formulated as:

$$d_{r,i} = r_i + hv_i \tag{4.28}$$

$$d_{rx,i} = \Big(r_i + hv_i\Big) cos(\theta_i) \tag{4.29}$$

$$d_{ry,i} = \Big(r_i + hv_i\Big) sin(\theta_i) \tag{4.30}$$

where r_i is the standstill distance, h is the time gap, in seconds, and v_i is the velocity of vehicle i. Assuming that there is inter vehicle communication and that each vehicle can sense its own the position p_i and the position of the preceding vehicle p_{i-1}, as depicted in figure 4.4 where each vehicle is represented by its centre of mass, the following spacing error is derived:

$$e_i = d_i - d_{r,i} = \Big(p_{i-1} - p_i\Big) - d_{r,i} \tag{4.31}$$

where d_i is the distance between consecutive vehicles. Since p_i is the position of vehicle i and can be decomposed in x and y coordinate (x_i, y_i). The spacing error can also be written as:

$$e_{x,i} = \Big(x_{i-1} - x_i\Big) - d_{rx,i} \tag{4.32}$$

$$e_{y,i} = \Big(y_{i-1} - y_i\Big) - d_{ry,i} \tag{4.33}$$

The error component in the global X axis (e_x) feeds the longitudinal control developed throughout chapter 3 and is, therefore, responsible for regulating the longitudinal distance between vehicles with reference to the desired distance d_{rx}.

The error component in the global Y axis (e_y) feeds the PI controller, which is responsible for regulating the lateral distance between vehicles with reference to the desired distance d_{ry}. The

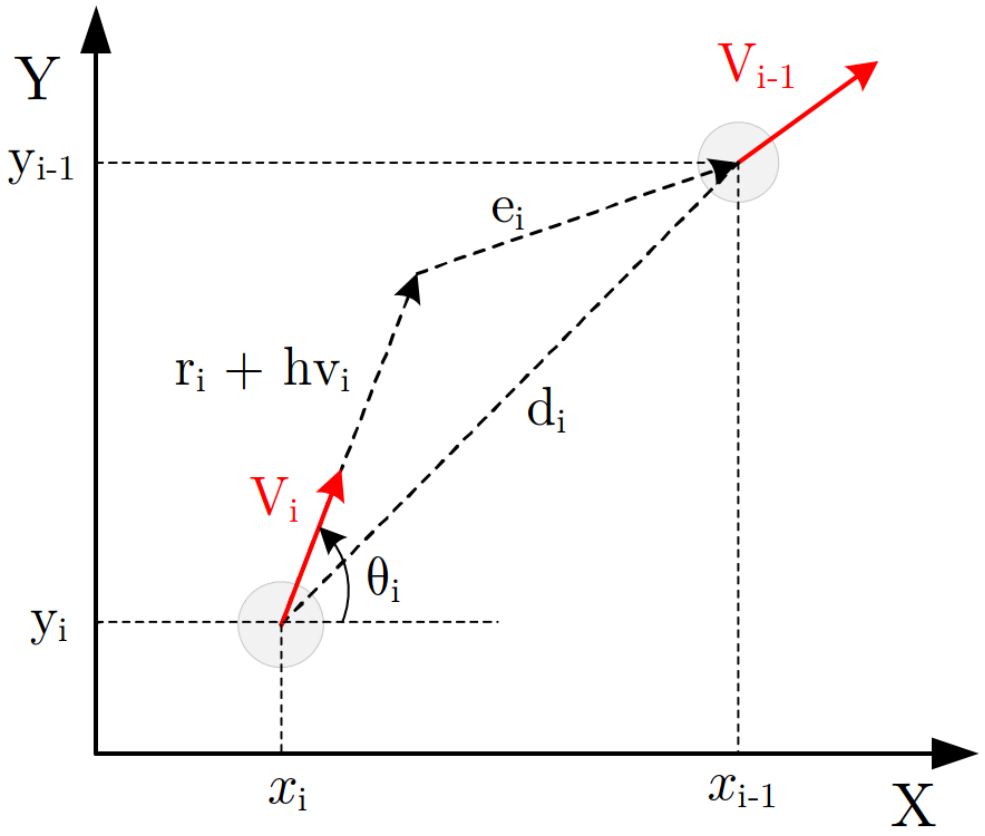


Figure 4.4: Error schematics for consecutive vehicles in a vehicle following approach.

output signal represents the steering angle of the front wheels and is limited to $[-1.5, 1.5]$ rad, to simulate the maximum turning maneuvers of real world vehicles. Furthermore, this signal acts as an input to the integrated vehicle model and is denoted by δ_f.

Since this lateral component is going to be added to the longitudinal controller developed in chapter 3, the overall structure of the integrated controller is still considered a feedback/feedfoward controller. The feedback term arises from the fact that to generate a spacing policy and calculate the error dynamics, the output velocity has to be compared to the distance between vehicles, as shown in equations 4.28 and 4.31. The feedforward term is required for the longitudinal controller and represents the velocity of the preceding vehicle that is transmitted through V2V communication links in a predecessor following topology. Figure 4.5 illustrates the control structure used, where the error calculations, previously explained, are simplified in a single block.

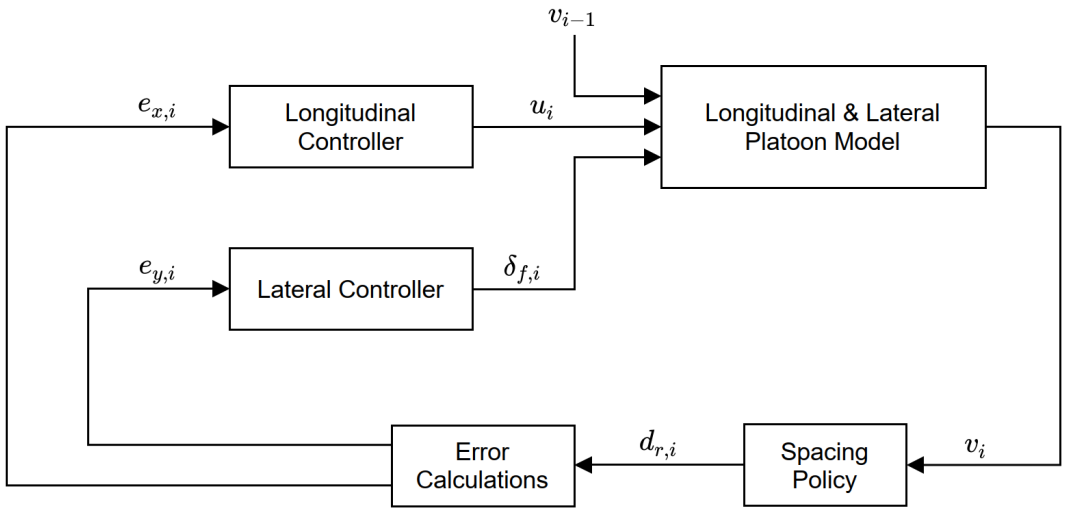


Figure 4.5: Control structure for integrated longitudinal and lateral control.

The control structure of the leading vehicle is similar to its longitudinal counterpart, but with an added reference of the steering angle to the vehicle model to enable lateral maneuvers. This vehicle has a distinct control structure from the rest of the platoon, since its movement defines the behaviour of the string. Moreover, it is based on a PI feedback controller, where the output velocity of the vehicle is compared to the reference desired velocity, as seen in figure 4.6.

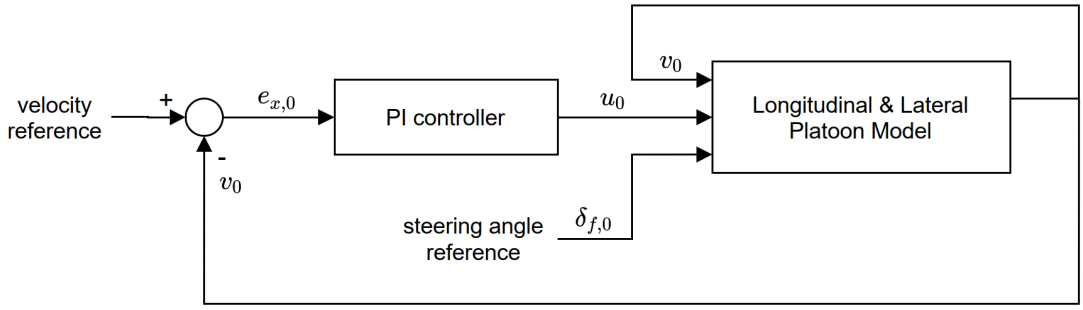


Figure 4.6: Control structure of the platoon's leading vehicle for integrated longitudinal and lateral control.

4.5 Simulation Results

In this section, the performance of the proposed longitudinal and lateral controller is tested throughout a series of simulations in a homogeneous platoon of three vehicles. As for the spacing policy,

a CTG approach is, once again, used where its parameters are as follows:

$$\begin{cases} h = 0.8\text{s} \\ r = 1.0\text{m} \end{cases} \tag{4.34}$$

The controller gains used for the longitudinal controller and for the PI controller of the leading vehicle are the same as the ones used in the previous simulations (section 3.6). As for the lateral controller, its gains are determined in an iterative manner aided by numerical computation software. The chosen controller gains strike a balance between a suitable sensitivity to curvature changes while also having a fitting signal convergence (equation 4.35).

$$\begin{cases} k_p = 4.7 \\ k_i = 2.4 \end{cases} \tag{4.35}$$

The information flow topology chosen is predecessor following and each wireless communication link is subject to a time delay of 0.1s. With respect to the integrated longitudinal and lateral model, the parameters used are shown in table 4.1. In the following simulations, different velocity values are used to evaluate its effect in the overall stability of the system. However the main focus of these tests is to evaluate the lateral controller performance in platooning applications. As for the generation of a trajectory, the path driven for the vehicle is defined by the steering input reference of the leading vehicle.

Table 4.1: Integrated vehicle model parameters.

Parameter	**Value**
l_f	1.6 m
l_r	1.1 m
$C_{\alpha f}$	0.55 MN rad^{-1}
$C_{\alpha r}$	0.60 MN rad^{-1}
m	1500 kg
I_z	2500 kg m^2

For the purpose of evaluating the effectiveness of the proposed control system, two different maneuvers are proposed: double lane change maneuver and sine steer maneuver

4.5.1 Test 1: Double Lane Change Maneuver

The platoon is imagined to be driving in a horizontal two lane straight road, where both lanes travel in the same direction. The platoon is initially at a standstill (null velocity) separated by a inter vehicle distance of 3m in the longitudinal axis. This means that the initial global position

coordinates $\big(x_i(0), y_i(0)\big)$ for all three vehicles are as follows:

$$\begin{cases} \big(x_0(0), y_0(0)\big) = \big(6,0\big)\text{m} \\ \big(x_1(0), y_1(0)\big) = \big(3,0\big)\text{m} \\ \big(x_2(0), y_2(0)\big) = \big(0,0\big)\text{m} \end{cases} \tag{4.36}$$

In this proposed maneuver, the platoon is at first parked and progressively accelerates until it reaches a cruising speed of 5 m/s. After that, the leading vehicle starts to change lane and, after reaching it, begins to, once again, linearly accelerate until it reaches its final velocity 10 m/s. This is meant to simulate a typical overtaking maneuver between two vehicles. Finally, after some time, the platoon returns to its original lane. As for the CTG spacing policy, all members of the platoon must maintain an inter vehicle distance of 5m and 9m for the set velocities of 5 m/s and 10 m/s, respectively.

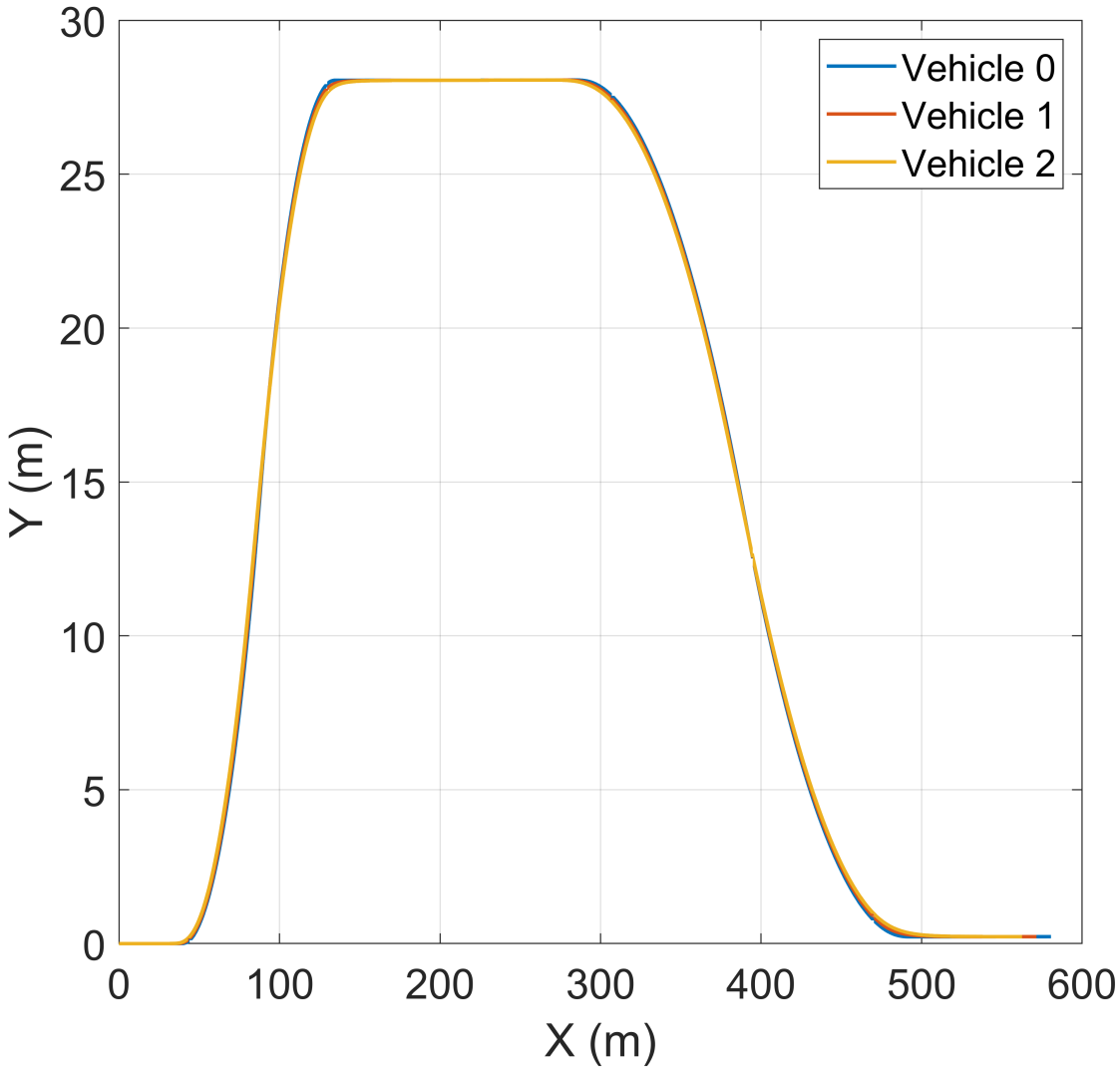


Figure 4.7: Driven path of the three vehicle platoon in a double lane change maneuver.

Figure 4.7 describes the driven path of the platoon in the double lane change maneuver in a XY graph. This figure shows that the developed longitudinal and lateral controllers are capable of using a vehicle following approach for vehicle platooning applications. Even though the turning maneuver is quite smooth, it is still possible to denote that there is some cornering cutting behaviour in the last phase of the transition between lanes. Figure 4.8 shows the zoomed in figure of the second cornering maneuvers driven the platoon where it is possible to observe some lateral deviation error between each of the vehicle's driven path. In the next section, a specific test is done to further analyze this problem.

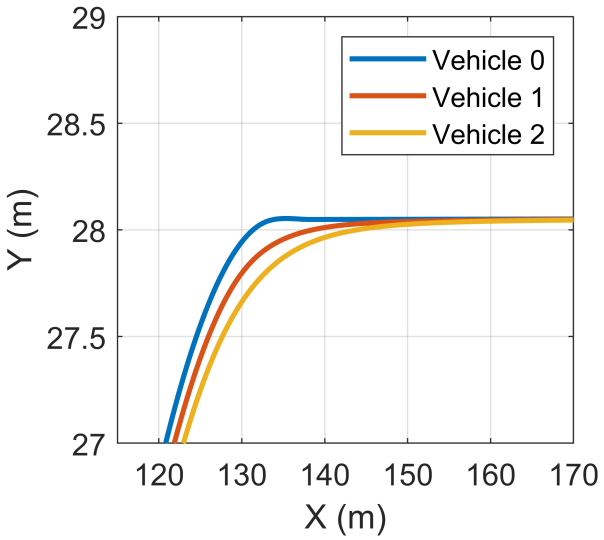


Figure 4.8: Zoomed in driven path of the three vehicle in the second cornering maneuver.

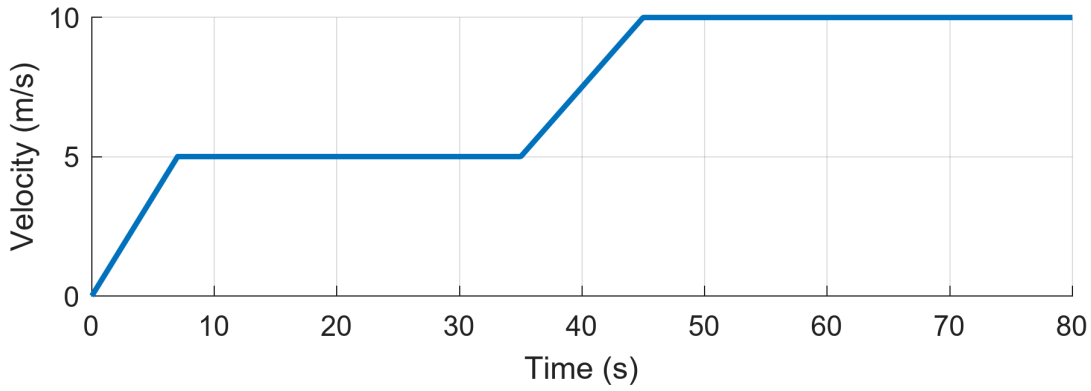
Figure 4.9 illustrates the signal evolution for the steering angle of each member of the platoon and all relevant vehicle states: inter vehicle distance and velocity. Furthermore, it is possible to infer the specific time instants where the platooning begins the change lane maneuvers ($t = 10$s and $t = 50$s) and both take, approximately, 20s to finalize it.

Concerning the steering angle graph, the signal of vehicle 0 (leading vehicle) represents the steering reference to which the following vehicles' steering angle must converge to. In the first turning maneuver, the steering reference has a value of 0.8 rad and 0.2 rad for the first and second change lane maneuver. Furthermore, it is possible to observe the effect of the PI controllers for the lateral controller. In this case, it was chosen to have a slower and smoother response rather than an under damped response in order to simulate a more realistic approach to real world applications, since it would be considered more comfortable for the passengers.

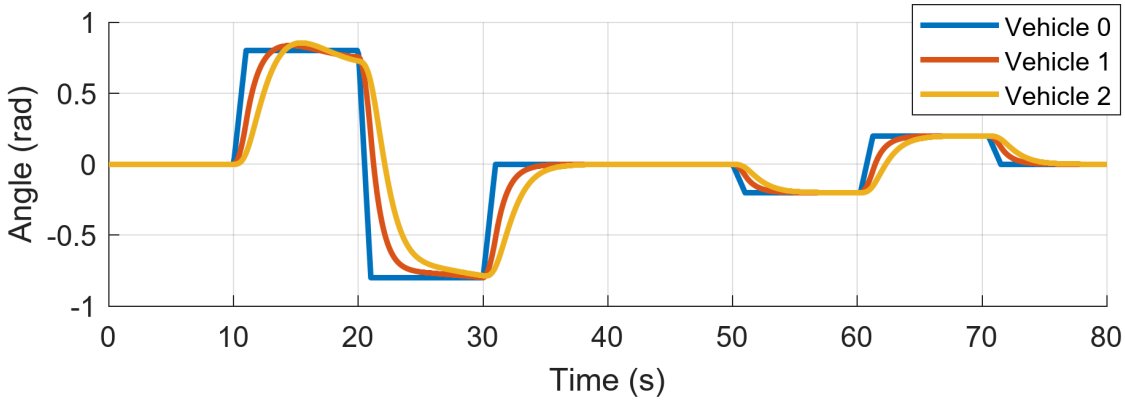
As for the inter vehicle distance graph, it can be denoted that the spacing policy is, mostly, respected throughout the simulation, as the distances for both steady state velocities matches the aforementioned values of 5m and 9m. Nonetheless, it is noteworthy to mention that whenever the vehicle is in turning maneuvers, the inter vehicle distance signal oscillates, while still being within

a minimal interval to the the desired value. Due to this, the initial transition from 3m to 5m is slower than desired. Similarly to this, the velocity graph also shows some speed oscillations in turning maneuvers. However, the velocity system response is much faster and stable than the inter vehicle distance system response.

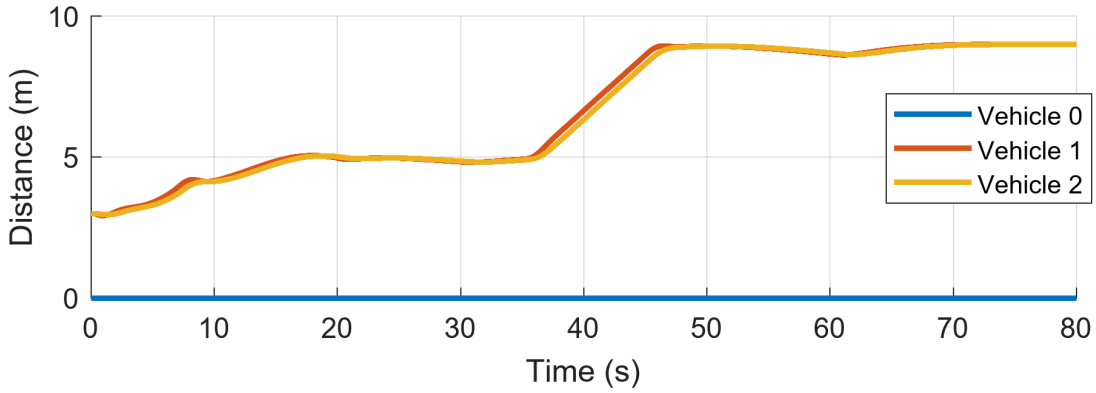
Finally, the system response to a double lane change maneuver is considered string stable since all signals from the vehicle state (acceleration and distance) are attenuated in the upstream direction of the platoon.



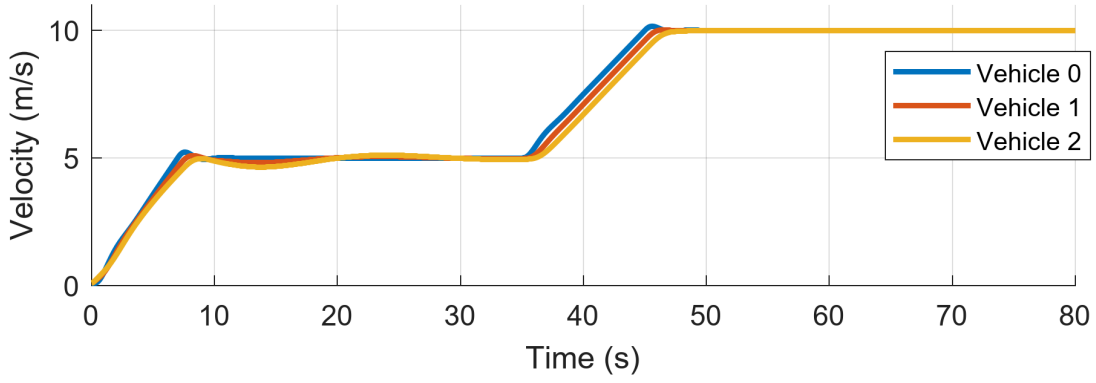
(a) Velocity reference for the leading vehicle.



(b) Vehicle steering input.



(c) Inter vehicle distance.



(d) Vehicle velocity.

Figure 4.9: Test 1 results.

4.5.2 Test 2: Sine Path Maneuver

As previously mentioned in section 2.4.6, the type of control strategy employed, that is based on a vehicle following approach, might lead to a phenomenon called corner cutting. This can happen in scenarios where there is a continuous turning maneuver and generates a deviation on the driven path of the following vehicles. This test is meant to study if the proposed controller might suffer from it, especially in cornering maneuvers.

Therefore, the proposed maneuver to analyze this behaviour is a driven sine like path by the three vehicle platoon. The platoon is initially parked in a horizontal lane and each vehicle is separated by 2 m.

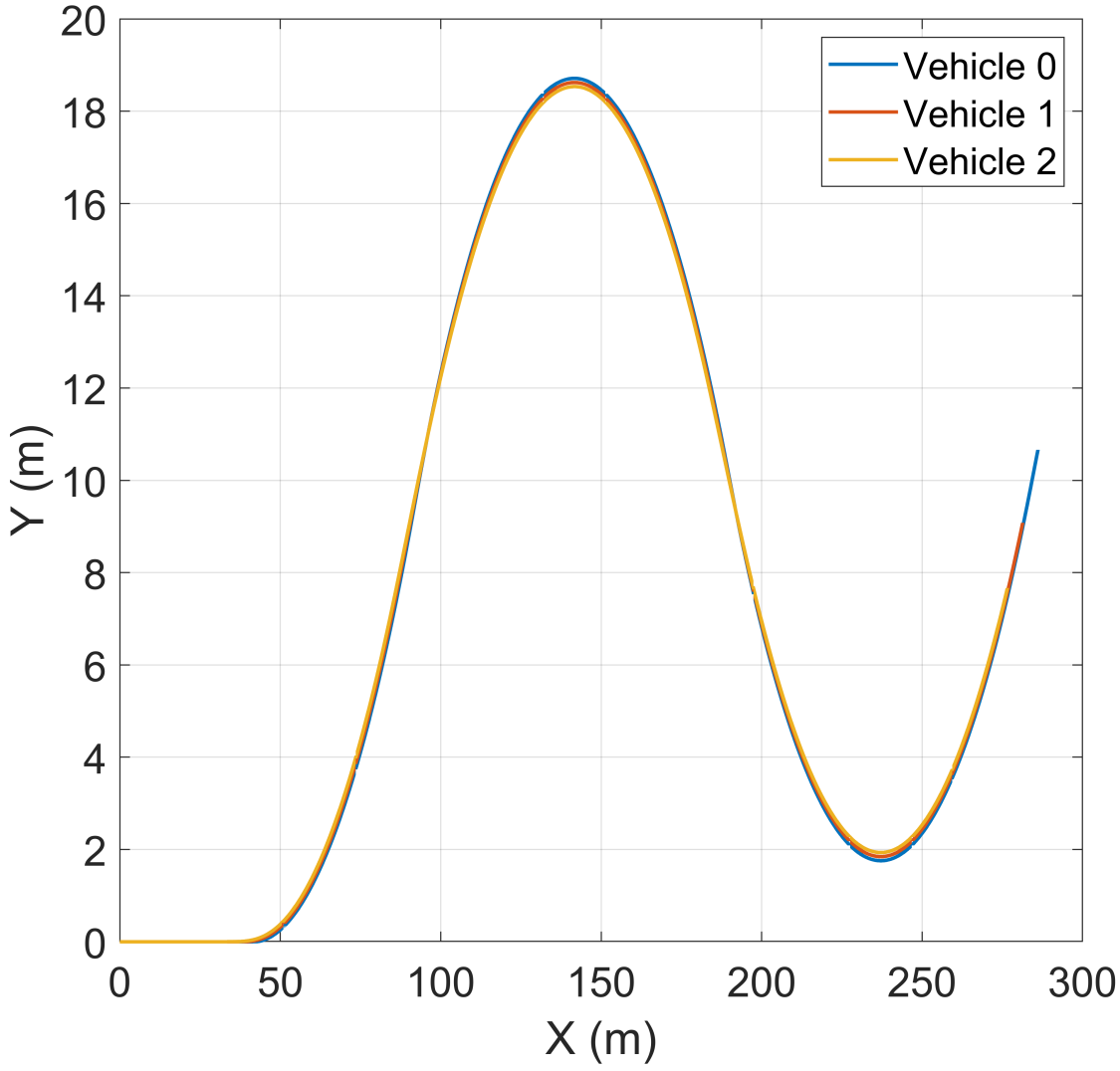


Figure 4.10: Driven path of the three vehicle platoon in a sine path maneuver.

Following this, the platoon gradually accelerates until it reaches its final cruising velocity of 5 m/s, which means that, according to the spacing policy, the inter vehicle distance must be 5 m

at all times. After some time, the platoon begins its turning maneuver and starts the sine path maneuver. Figure 4.10 illustrates the total driven path of the platoon in this proposed maneuver. Similarly to the previous test, the proposed control structure is capable of enabling the following vehicles to correctly follow the path reference of the leading vehicle. However, it is possible to denote some corner cutting phenomenon in the turning maneuver along the peaks of the sine path, even if this figure does not have the appropriate resolution to study it in detail. Therefore, figure 4.11 provides a zoom overview of figure 4.10 of the both sine path peaks as to see the magnitude of the lateral deviation.

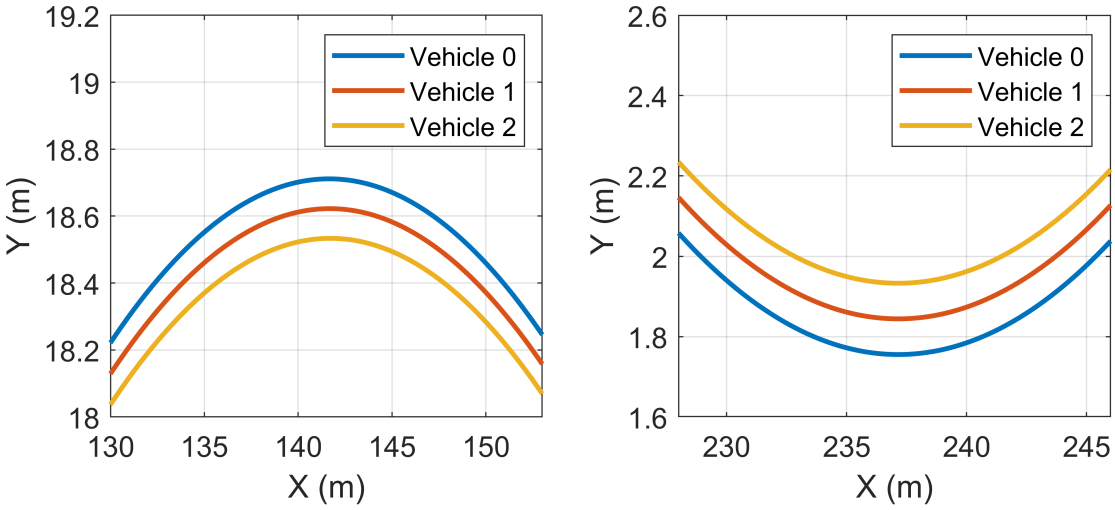
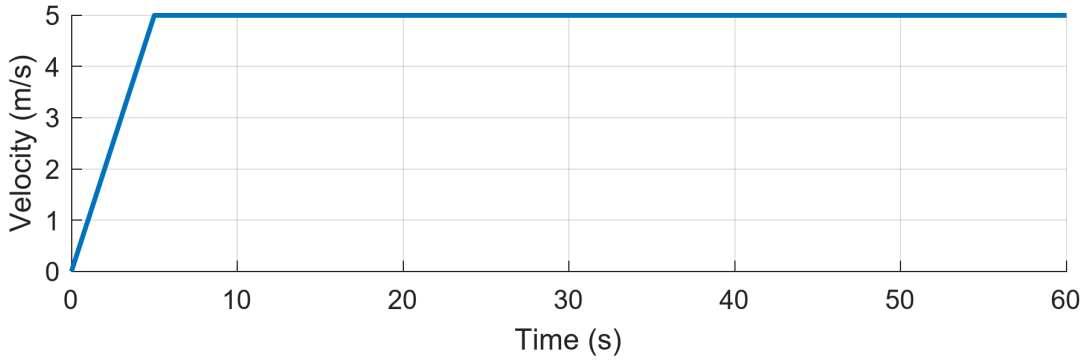


Figure 4.11: Zoomed in driven sine path of the three vehicle in the upper (left) and lower (right) peak.

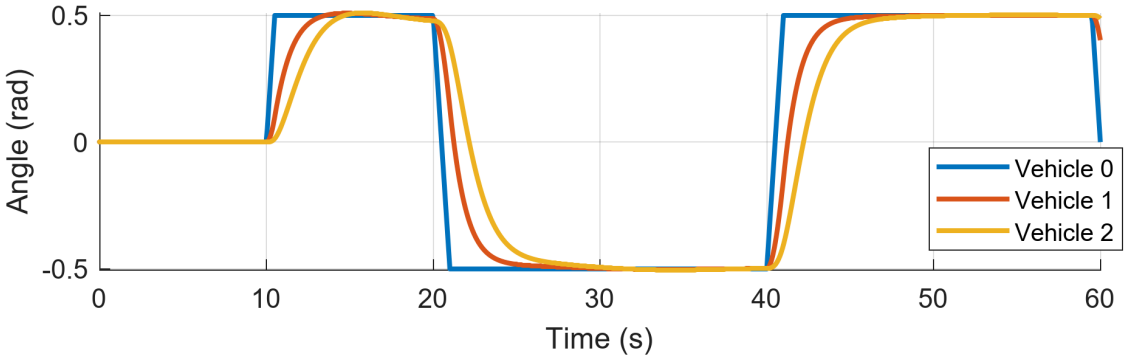
In this figure, there is a position error of 0.1m from the following vehicles that is propagated in the upstream direction of the platoon. One possible way to resolve this is to employ a virtual vehicle controller design, which is explored in depth in section 4.6.

Besides this, figure 4.12 illustrates the relevant signals for each member of the platoon: steering, inter vehicle distance and velocity. From this, it is possible to infer that the platoon is capable of maintaining a inter vehicle distance of 5m throughout the maneuver, even if there are slight oscillations which are a consequence of the constant turning maneuver. This type of behaviour is also shown in the previous test. Regarding the velocity, each member of the platoon is able to converge to the reference value in a timely manner and have minimal steady state error. In both graphs, the error signal of each following vehicle is attenuated. As such, the system response to this maneuver is string stable.

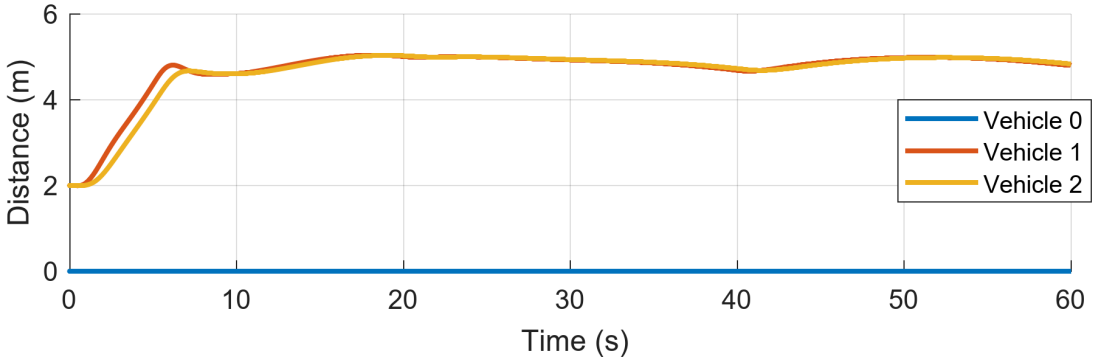
Finally, the steering angle of the following vehicles converge to the steering reference, represented by vehicle 0. As expected, the lateral controller also enables a smoother and slower system response to steering changes for this sine path maneuver.



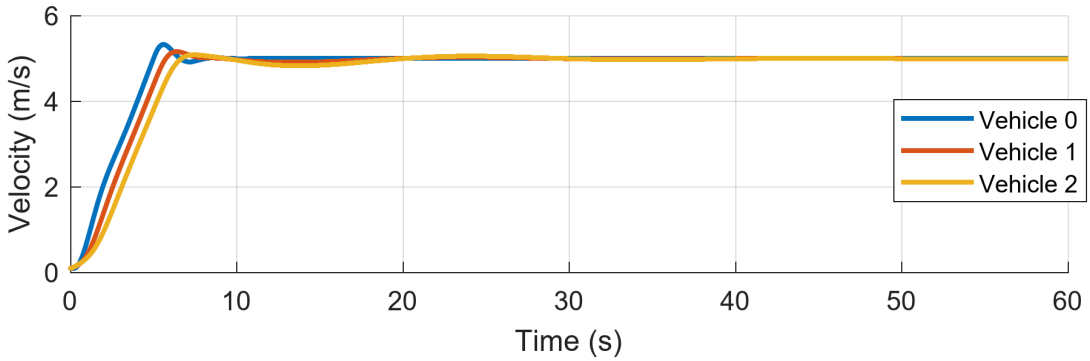
(a) Velocity reference for the leading vehicle.



(b) Vehicle steering input.



(c) Inter vehicle distance.



(d) Vehicle velocity.

Figure 4.12: Test 2 results.

4.6 Virtual Vehicle Controller and System Design

The previous proposed controller employs a vehicle following approach for the control strategy. This means that the following vehicles utilizes the global position of the preceding vehicle, in real time, to adapt its path trajectory through the use of steering angle and throttle/brake actuator. However, the main disadvantage of this strategy, as seen on section 4.5.2, is that the driven path of the follower vehicle when compared to the path of the leading vehicle has a positional error. This behaviour is typically known in the literature as corner cutting and originates from cornering maneuvers. In this movement, the follower vehicle senses a position error and tries to correct it as to preserve the spacing policy. That is, the vehicle steers too soon, instead of waiting and turning in the correct cornering point. As a consequence, this creates a driven path offset between vehicles. The only maneuver that guarantees null lateral error is on a straight path. This phenomenon is a limitation of the vehicle following approach that was implemented in the previous section.

One possible method of guaranteeing that vehicle i turns at the precise cornering point is to employ the concept of a virtual vehicle as the tracking point for it. This is, essentially, an extension vector that performs a mathematical translation of the centre of mass of vehicle $i-1$ to another location in space. The main motivation for using an extension vector is to compensate the lateral errors that originate from the chosen spacing policy. As a result, this approach allows for vehicle i to track the virtual point of vehicle $i-1$, enabling it to turn at the correct cornering point.

The extension vector, defined as s_{i-1}, indicates the new virtual centre of mass of vehicle $i-1$, starting from its real position, and is perpendicular to its velocity vector. It can be interpreted as the new position tracking point for vehicle i. It is important to note that this extension vector approach is only used in turning maneuvers.

As shown in figure 4.13, the spacing error is redefined as:

$$e_i = (p_{i-1} + s_{i-1}) - \Big(p_i + (r_i + hv_i)\Big) \tag{4.37}$$

The components of the extension vector s_{i-1} can be decomposed in its x and y coordinates as:

$$s_{x,i-1} = s_{i-1} cos(\frac{\pi}{2} - \theta_{i-1}) = s_{i-1} sin(\theta_{i-1}) \tag{4.38}$$

$$s_{y,i-1} = s_{i-1} sin(\frac{\pi}{2} - \theta_{i-1}) = -s_{i-1} cos(\theta_{i-1}) \tag{4.39}$$

Therefore, the spacing error components can be derived as:

$$e_{x,i} = \Big(x_{i-1} + s_{i-1} sin(\theta_{i-1})\Big) - \Big(x_i + (r_i + hv_i) cos(\theta_i)\Big) \tag{4.40}$$

$$e_{y,i} = \Big(y_{i-1} - s_{i-1} cos(\theta_{i-1})\Big) - \Big(y_i + (r_i + hv_i) sin(\theta_i)\Big) \tag{4.41}$$

Following this, it is needed to add to the control system some notion of path planning. In this particular approach, it is assumed that vehicle platoon will perform a turning maneuver with a

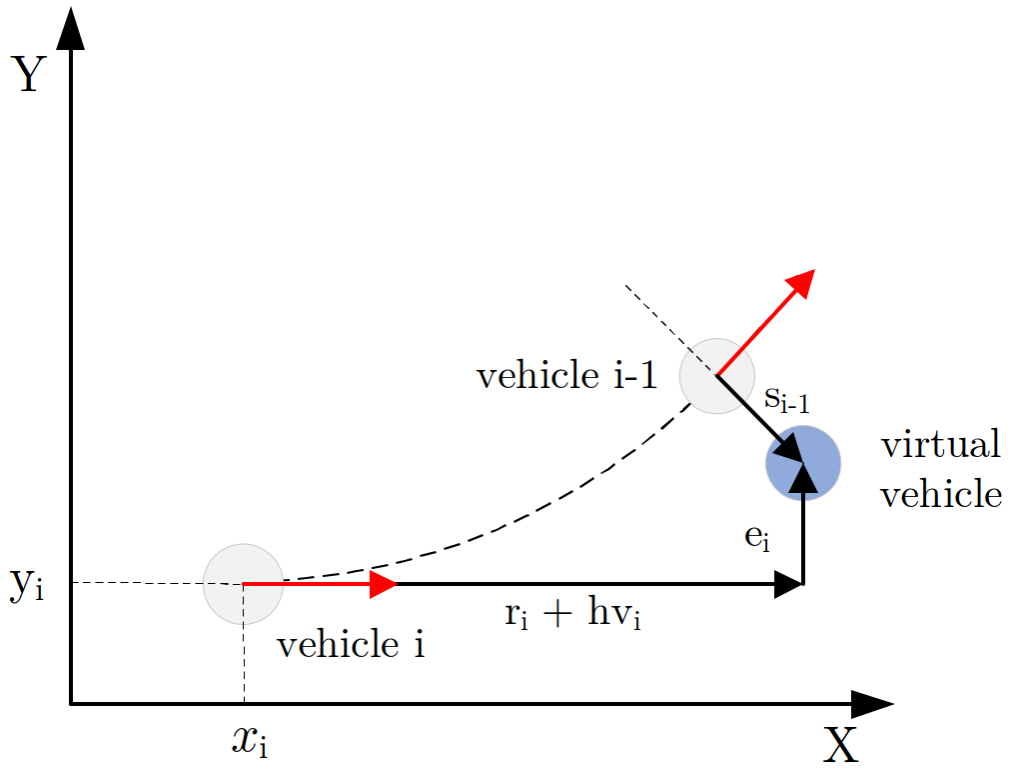


Figure 4.13: Error definition for virtual vehicle controller design.

known fixed radius. Since the direction of the extended vector s_{i-1} is always perpendicular to the velocity vector of vehicle $i-1$, only the magnitude of s_{i-1} needs to be calculated. This means that the angle difference between the preceding and following vehicle velocity vector must be always smaller than $\frac{\pi}{2}$ rad, so the extended vector can be defined. Moreover, it is assumed that the spacing error components, e_x and e_y, are equal to zero, as to facilitate the analysis of the reference path.

The turning maneuver is defined as:

$$R_{i-1}^2 + (r_i + hv_i)^2 = (R_{i-1} + s_{i-1})^2 \tag{4.42}$$

where R_{i-1} is the radius of the reference path. Figure 4.14 shows the schematics of a typical turning maneuver. Rearranging the terms on equation 4.42, yields the following equation for the magnitude of the extended vector s_{i-1}:

$$s_{i-1} = -R_{i-1} + \sqrt{R_{i-1}^2 + (r_i + hv_i)^2} \tag{4.43}$$

Equation 4.43 is only employed in turning maneuvers. In straight paths, the value of the magnitude of s_{i-1} is zero. One possible downside to this approach relies on the fact that the magnitude of s_{i-1} must be calculated *a priori*. As a result, the vehicle must know the turning radius at a certain velocity and steering angle before it starts the maneuver.

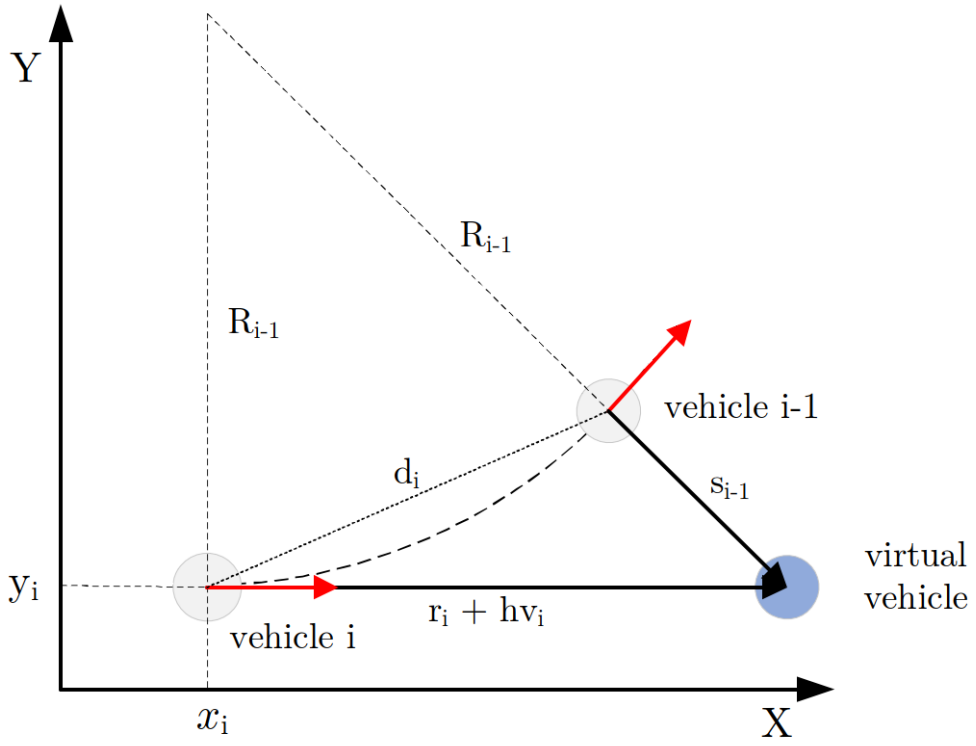


Figure 4.14: Comparison between the distance between consecutive vehicles d_i and the extension vector s_{i-1}.

4.7 Simulation Results

In this section, it is tested the performance of the new longitudinal and lateral controller with a virtual vehicle approach, which aims to reduce the corner cutting effect along the driven path of the platoon. As such, the two tests previously mentioned are re-evaluated with this new controller and the results are compared. All vehicle model parameters, lateral controller gains and spacing policy used in these simulations are exactly the same as ones defined in table 4.1, equation 4.35 and 4.34. Furthermore, it is used the predecessor following information flow topology with a 0.1s time delay in each communication link.

The main purpose of these simulations is two fold. First, the double change maneuver is used to primarily study the system response, particularly in the vehicle's state, to the new controller design. Second, the sine path maneuver is used to analyze the influence of this controller in the driven path of all three vehicles, since this maneuver is more susceptible to corner cutting.

4.7.1 Test 1: Double Lane Change Maneuver

As previously mentioned, the specific parameters of this maneuver are explained in detail in section 4.5.1. In sum, this maneuver consists of a ordinary overtaking scenario where the platoon is driving in a horizontal two lane road, where both lanes travel in the same direction. The platoon is

initially parked where each vehicle is separated by 3m and throughout the maneuver, there are two distinct speeds used: 5 m/s and 10 m/s. This means that according to the chosen spacing policy, each platoon member must have a inter vehicle distance of 5m and 9m, respectively.

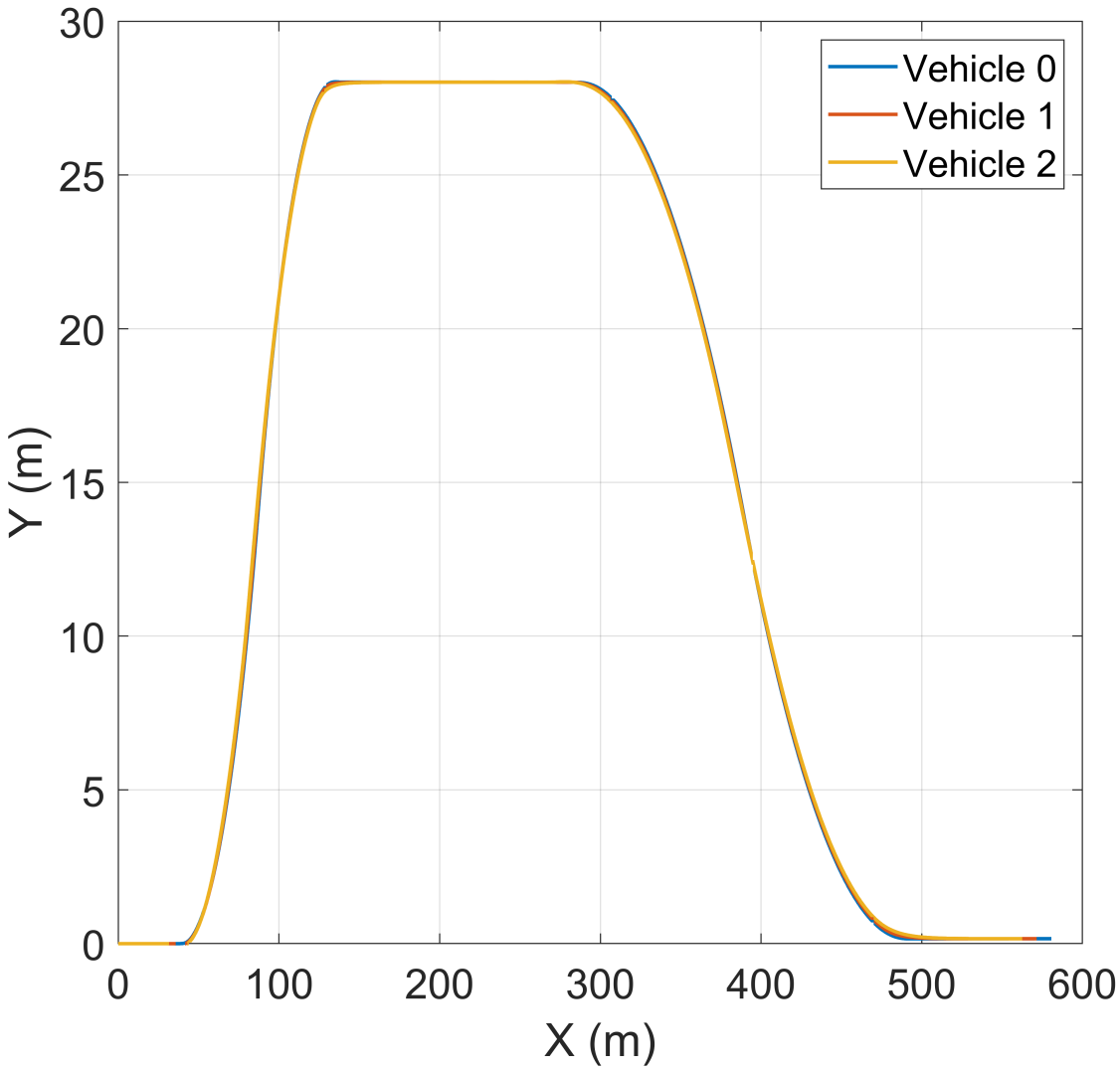


Figure 4.15: Driven path of the three vehicle platoon in a double lane change maneuver with a virtual vehicle controller design.

Figure 4.15 shows the driven path of the three vehicle platoon in a XY graph. This figures shows that, similarly to the previously presented controller, the new virtual vehicle controller design is also capable of enabling each vehicle to follow the driven path of the leading vehicle. However, the main purpose of this controller is to further optimize the cornering maneuver by the platoon. Figure 4.16 shows the exact same zoomed in graph as the one presented in the previous test in figure 4.8. This reveals an improved corner cutting behaviour, particularly in the convergence of paths immediately before and after the corner. Some divergence in the corner

driven path of vehicle 2 compared to the reference is still denoted, although there is a smaller difference in distance.

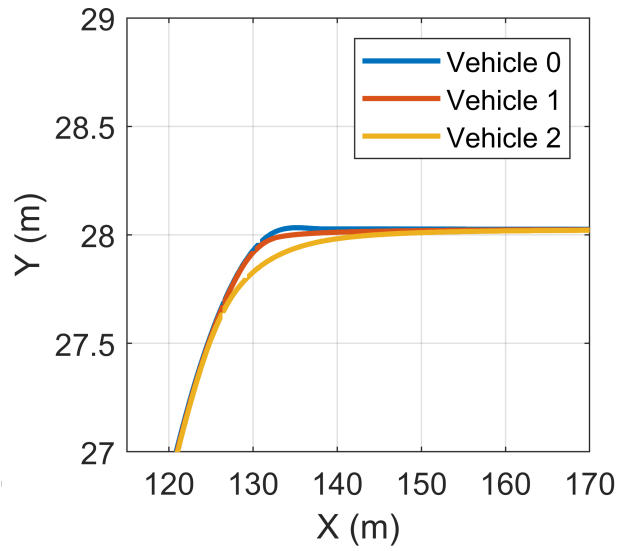
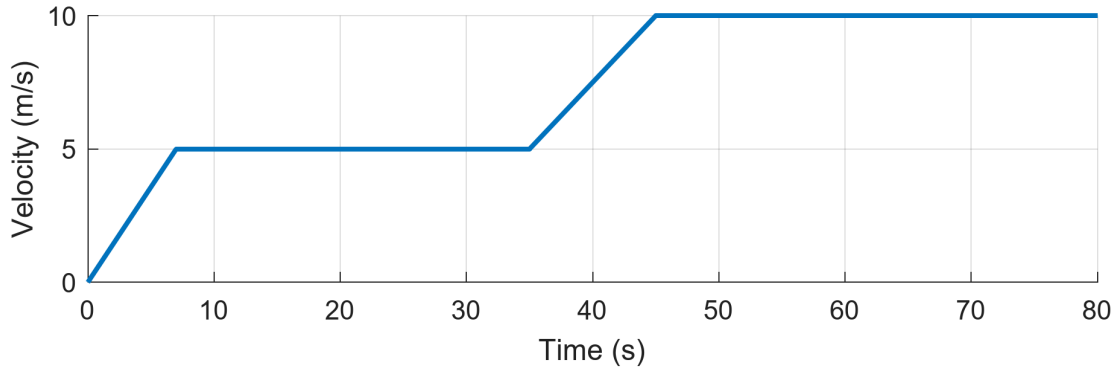


Figure 4.16: Zoomed in driven path of the three vehicle platoon in the second cornering maneuver with a virtual vehicle controller design.

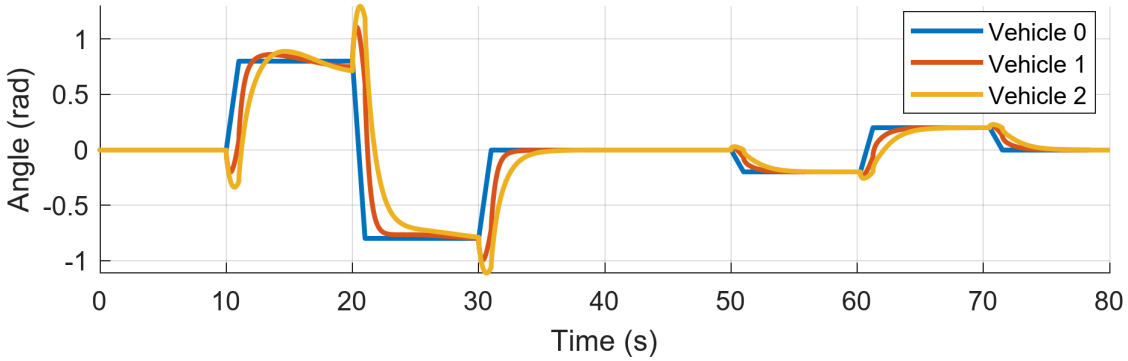
Figure 4.20 shows the data of each vehicle's relevant states, i.e. velocity, inter vehicle distance and its correspondent steering angle.

Firstly, the steering angle graph has a behaviour that is considerably different than the one presented in the previous test. Particularly in the first lane change maneuver ($t = 10$s to $t = 31$s), whenever there is a transition between different steering angles in the reference (vehicle 0), the following vehicles' response has a substantial initial negative overshoot. In this test, the same lateral controller gains were used as in section 4.5.1. However, it was observed that this type of response ensued regardless of different gain values. The same system response is present in the second lane change maneuver ($t = 50$s to $t = 71$s), but has a much lower magnitude. Besides this, the system response is slow and smooth as expected, in order to mimic real world platooning applications, and each vehicle's steering signal converges towards the desired value.

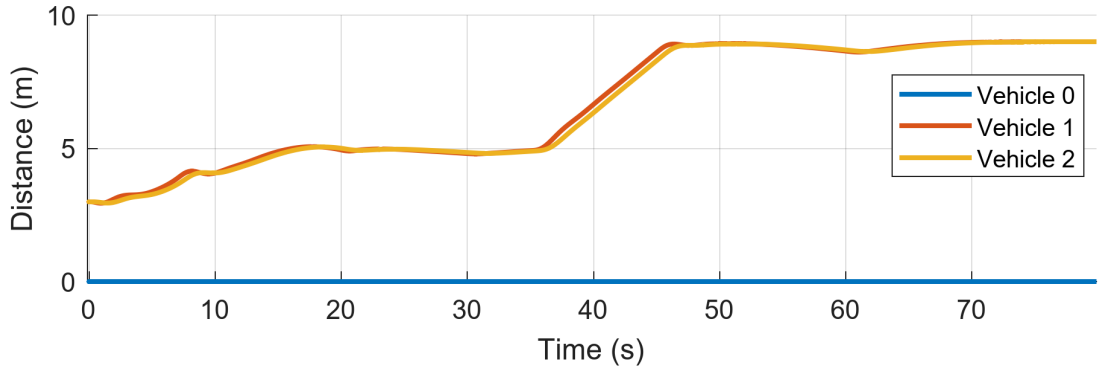
Regarding the inter vehicle distance and velocity graph, the system response for each member of the platoon is essentially the same as the one registered in section 4.5.1. The spacing policy is respected at all times for both velocities at a distance of 5m and 9m, with some slight oscillations whenever there is a turning maneuver. However the initial distance transition, from 3m to 5m, is slower than expected when compared to the previous control approach. As for the velocity graph, each vehicle is able to correctly keep up with the reference speed changes in a timely manner. Since both of these graphs show that the signals from each vehicle are attenuated in the upstream direction of the string, the system response for this maneuver can be considered string stable



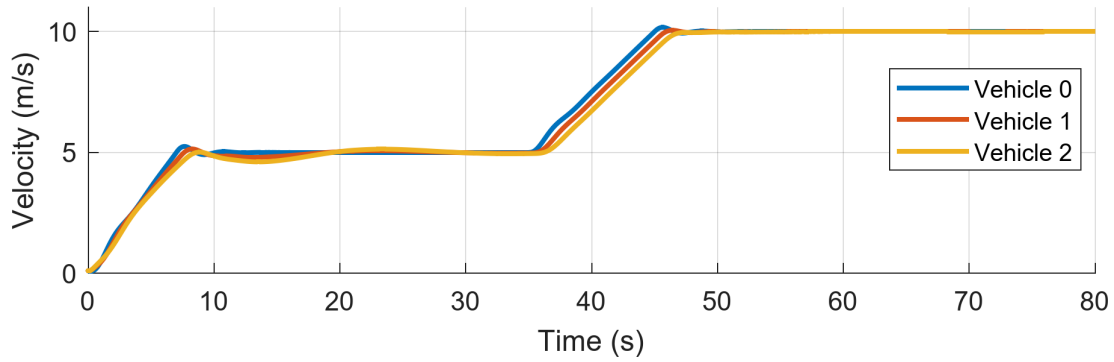
(a) Velocity reference for the leading vehicle.



(b) Vehicle steering input.



(c) Inter vehicle distance.



(d) Vehicle velocity.

Figure 4.17: Test 1 with virtual vehicle controller results.

4.7.2 Test 2: Sine Path Maneuver

Similarly to the first test, the parameters of this maneuver are explained thoroughly in test 2 of the previous simulation results (section 4.5.2). In short, this aim of the sine path maneuver is to analyze the impact of the new proposed controller in corner cutting scenarios. Initially, all members of the string are parked in a horizontal lane and have a inter vehicle distance of 2m. Following this, the leading vehicle linearly accelerates until it reaches a final cruising speed of 5 m/s and begins the sine path maneuver. Therefore, according to the spacing policy, each platoon member must have an inter vehicle distance 5m.

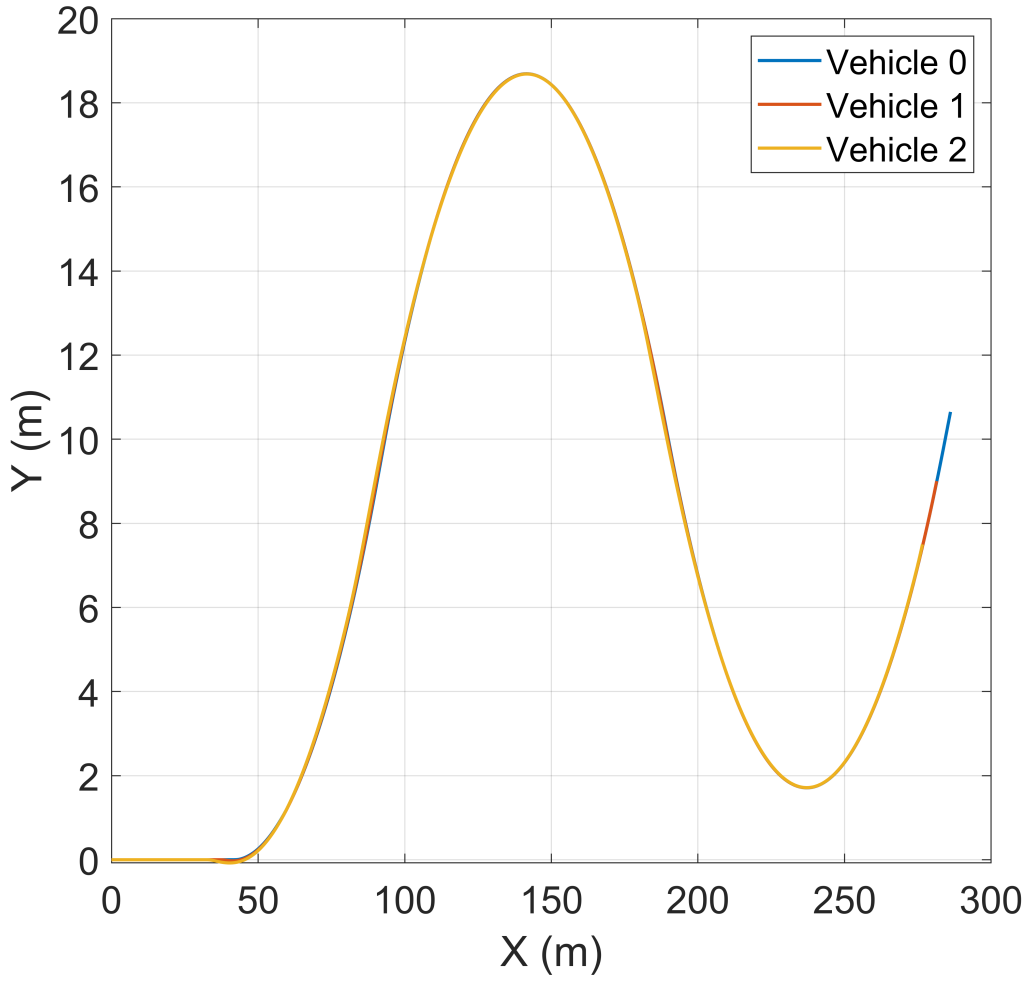


Figure 4.18: Driven path of the three vehicle platoon in a sine path maneuver with a virtual vehicle controller design.

Figure 4.18 illustrates the driven path of three vehicle platoon. In this figure, it is clearly denoted that there is a substantial improved convergence in the driven path, especially in the peaks of the sine path. Figure 4.19 presents the exact same zoomed in driven path graph as the one previously showed in figure 4.11 where it was reported that there was a position error of 0.1 m

between consecutive vehicles. By using this new controller, the position error obtained was 0.003 m, which practically means that this error was completely nullified.

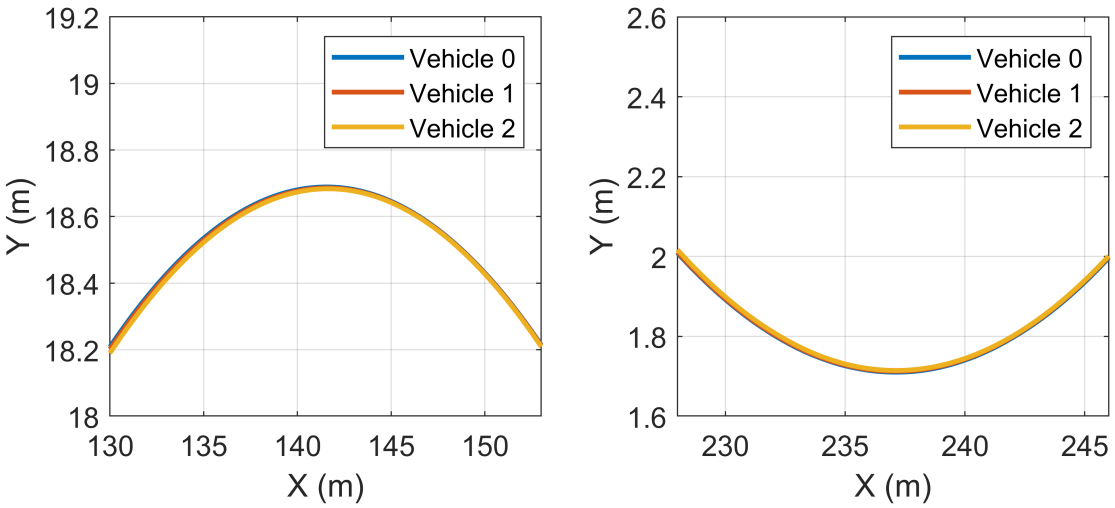
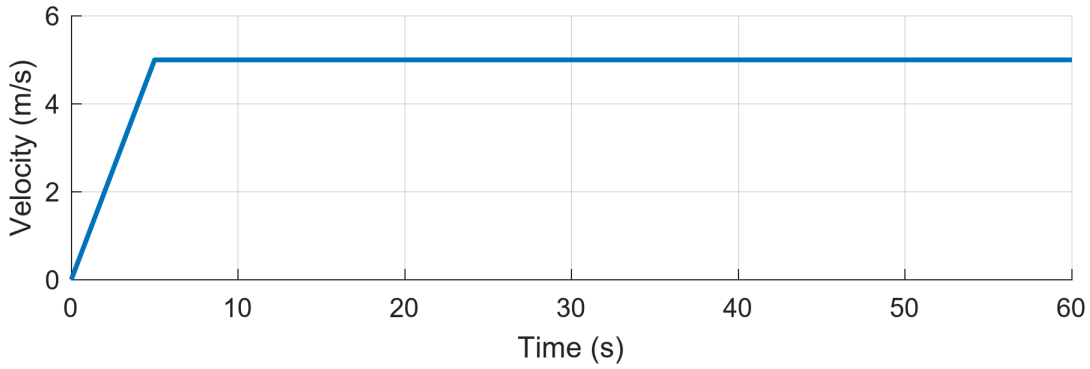
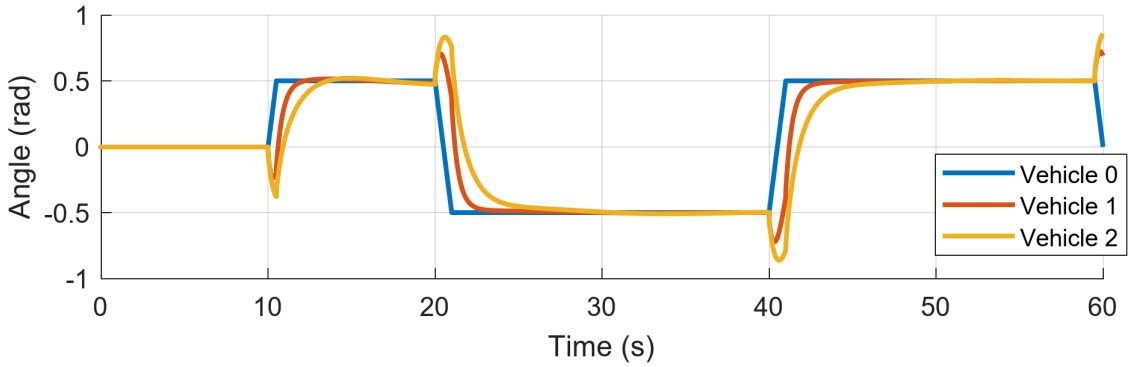


Figure 4.19: Zoomed in driven sine path of the three vehicle in the upper (left) and lower (right) peak with a virtual vehicle control design.

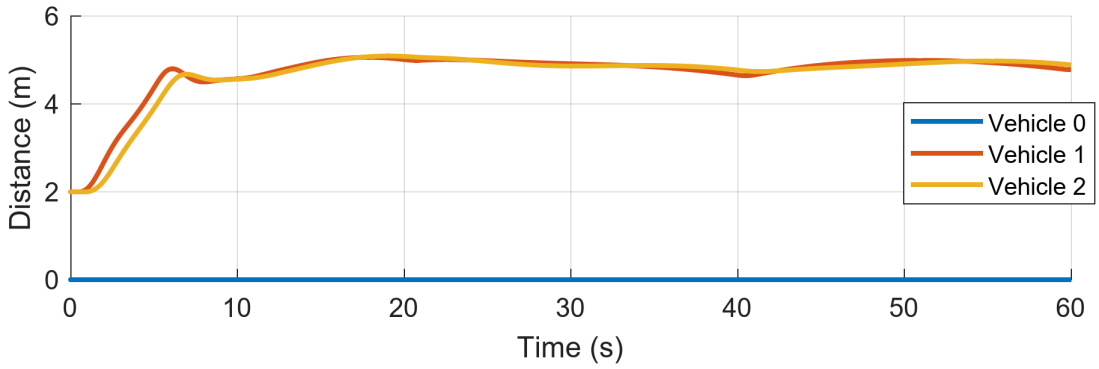
Regarding the vehicle's states and steering input seen on figure 4.20, the system response, with the exception of the steering angle, is exactly the same as the one described in section 4.5.2. This means that the new controller still ensures string stability in the platoon in this maneuver and that the spacing policy is respected throughout the test. As for the steering angle, the same overshoot effect described in the previous test (section 4.7.1), also takes place in this simulation. This suggests that this behaviour is inherent of the lateral controller used, instead of being generated by a certain maneuver.



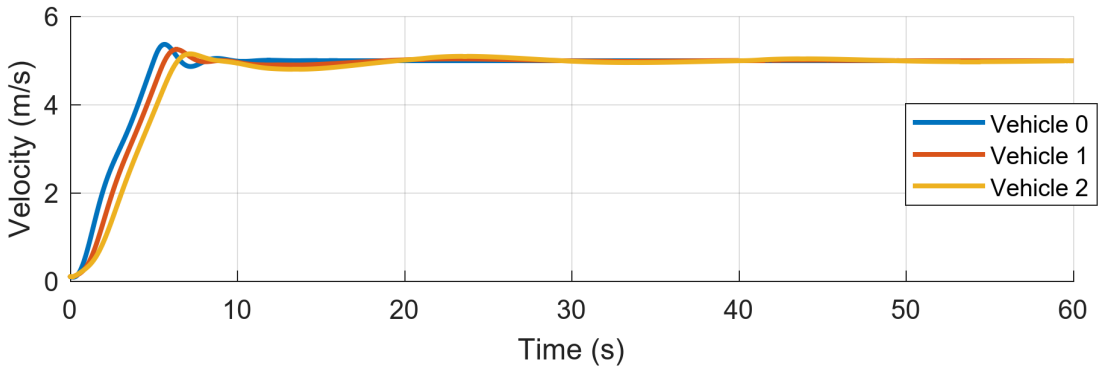
(a) Velocity reference for the leading vehicle.



(b) Vehicle steering input.



(c) Inter vehicle distance.



(d) Vehicle velocity.

Figure 4.20: Test 1 with virtual vehicle controller results.

4.8 Discussion

In this chapter, it was proposed an integrated longitudinal and lateral control system capable of platooning application for a string of interconnected and homogeneous vehicles. Firstly, the lateral vehicle model was deduced, followed by the integrated longitudinal and lateral model that are connected by the vehicle longitudinal speed. Next, the first lateral controller based on global coordinates was presented and tested. It was found that the following vehicles were able to correctly follow the driven path of the leading while using a vehicle following approach for the control design and satisfying the spacing policy requirement. This controller was tested in two distinct maneuvers: double lane change and sine path. However, the main disadvantage of this strategy was that by only using the current position information of the preceding vehicle, the platoon suffers from corner cutting in turning maneuvers, meaning that there is a position error between the driven path of the leading vehicle when compared to the path of the following vehicles. This error is amplified in the upstream direction of the string, which would lead to severe position errors if the platoon is made of multiple vehicles.

To ensure a better performance, a second approach for the lateral controller was designed, where the error dynamics are redefined in order for the follower vehicle to track a virtual vehicle in turning maneuvers, that is based on the position of the preceding vehicle with respect to an extension vector. The new tracking point aims to ensure that the following vehicles turn at the same position the preceding vehicle did, instead of corner cutting. The controller was tested in the same two maneuvers previously mentioned and its results showed a clear improvement over the previous lateral controller solely based on global coordinates. The sine wave path maneuver displayed excellent results, since all positional errors were successfully eliminated, while in the double lane change maneuver the corner cutting behaviour was minimized, although not completely eliminated. Therefore, the proposed virtual vehicle controller design was proven to compensate the corner cutting phenomenon, while respecting the spacing policy throughout both maneuvers.

Chapter 5

Conclusion

5.1 Main Conclusions

In this dissertation, the focus of the developed work was to design a longitudinal and lateral control system while using a vehicle following approach for a platoon of vehicles. Therefore, the main goal was to enable the follower vehicles of a platoon to drive the same path as its preceding vehicle while satisfying the spacing policy requirement. The design of each controller is done in distinct steps.

As a first step, the longitudinal controller is deduced, where it is assumed no particular vehicle model and instead, there is a platoon model that aims to ensure that the string of vehicles can travel in one dimension, at different velocities, while guaranteeing the spacing policy requirement and string stability. Following this, an additional lateral control structure is added to the system with reviewed vehicle dynamics. For the vehicle model, it is used a relatively simple bicycle model, that is commonly used in the literature for platooning applications and has two degrees of freedom. The lateral model is integrated with the previous longitudinal platoon model by sharing the longitudinal velocity value to its lateral counterpart. Next, the control law based on global coordinates using a vehicle following approach is presented and tested. It was found that this type of technique was suitable for platooning applications while assuring the spacing policy and string stability. The downside was that the following vehicles' driven path suffered from corner cutting in turning maneuvers. To solve this, a new control approach is proposed where the concept of virtual vehicle tracking point is employed. The follower vehicle tracks the position of the preceding vehicle with respect to an extension vector. The purpose of this approach is for the follower vehicle to turn at the same position as the preceding vehicle did, preventing corner cutting. Simulation tests revealed positive results, where the corner cutting phenomenon was completely eliminated or sufficiently minimized.

5.2 Future Work

Based on the obtained results and development methodology, there are some suggestions for future work. One important aspect to study that was not taken into consideration was to analyze the string stability of the proposed system design *a priori*. Throughout this dissertation, the string stability was evaluated based on the obtained results rather than based on the transfer functions through the use of formal methods, such as Lyaponov stability analysis in the time domain or in the frequency domain. Furthermore, this document does not explore string stability with different spacing policies.

Another suggestion relies on the fact that both control structures developed assume that the platoon is homogeneous, meaning that all vehicles are identical and share the same parameters, which results in the same dynamic behaviour. Therefore, it is assumed that the control input can be the same for all members of the string, simplifying the system design. However, in real world applications this is not guaranteed. A future research possibility consists in developing a controller capable of supporting different types of vehicles within the same platoon.

Finally, V2V communication link delays were only studied in the initial longitudinal controller. For the combined controller, it was assumed that each link had a 0.1s delay, which is characteristic of real world applications, but not sufficient to compromise string stability. As such, it is recommended a thorough validation of the combined controller in severe communication delays. Since these controllers employ a vehicle following in a two dimensional scenario, it is expected that sensing the position of the preceding vehicle with a sufficient delay could compromise the system's stability.

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