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Reversible Lane and Platooning Control With Connected Vehicles

by

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REVERSIBLE LANE AND PLATOONING CONTROL WITH CONNECTED VEHICLES

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Abstract

In this thesis a platooning control algorithm is introduced, by utilizing information provided by the formation leader and the preceding vehicle. The Constant Time Headway Policy was implemented to the controller logic, combined with the leader's acceleration as the headway term, which ensures string stability. Additionally, in order to evaluate and optimize the controller's behaviour a traffic scenario with a sinusoidal input as the leader's acceleration was performed. The optimized gains were acquired after numerous simulations. Furthermore, in order to ensure the controller's reliability and safety a second simulation was performed. The scenario involved a heavy braking incident with the main purpose to ensure a safe inter-vehicle distance in case of emergency braking.

The main traffic scenario involved the A38(M) Aston Expressway located in Birmingham, United Kingdom, with a further introduction of a Reversible Lane System (RLS). This system utilizes the traffic densities of each traffic direction, which were available by two different systems. The first one, exploits inductive loop detectors to determine the road parameters and then feed them to the RLS. The second system is referred to a Road Side Unit (RSU). The RSU receives data transmitted by the vehicles, which have WiFi capabilities, allowing for it to determine the road density and then inform the RLS. Furthermore, in order to evaluate the overall performance of the platooning control algorithm, two traffic scenario were simulated. The first one involved only human-driven cars, without any capabilities of forming platoons or cooperate, while the second scenario integrated platoons inside the original traffic.

The results showed that the introduction of platoons inside the traffic network greatly enhances the road performance, by reducing congestion, leading to higher flow rates and vehicle speed profiles. Finally, the integration of the RLS further enhances the traffic conditions by eliminating the traffic congestion. Concerning the RLS's data extraction method, a slightly better performance is seen by the RSU, as the simulation results have showed.

Keywords: platooning control; reversible lane control; road side unit; vehicle-to-infrastructure communication.

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Chapter 1

Introduction

1.1 Motivation

The year 1886 was marked as the beginning of a new era, when the German inventor Karl Benz created and patented the first mass production car. With the advancements in technology and the vigorous growth of industrialization, the performance and the cost of a single car was constantly improving, becoming more accessible to the wider population. Nowadays, cars are thought to be very common with a presence in almost every family, considering that in 2016 there were approximately 295 million cars registered in Europe [1]. Although, most of people spent from one or less to several hours of daily driving, depending on the country or job and family status, there are some disadvantages of this technology.

First of all, driving is considered as the least safe transport mean [38]. Every year thousand of people die in car accidents involving drivers, passengers and pedestrians. This is demonstrated in Figure 1.1, where the annually fatalities from car accident is presented. The advancements in road infrastructure and vehicle technologies have enhanced the safety of the car, which can be seen from the reduction of death rates from previous years. Although, this drop in fatalities is enormous there is plenty more space for development in order to save more lives.

Furthermore, another major issue that vehicle transportation faces concerns the contribution in green house emissions. Particularly, in Europe around the 23% of the total CO_2 emissions is produced by transportation travel, due to which more than 72% concerns road travel [22]. Additionally, thousand of hours are wasted in traffic congestion, which contributes a big factor in total emissions of road travel. Although, in recent years there is a massive shift in greener energies like electric or hybrid vehicles and technologies to alleviate traffic congestion, green house emissions produced by vehicles continue to harm the environment.

To tackle this problem, countries and big automotive industries around the world are developing new tools and technologies to enhance the transportation travel. The year 2019 was marked

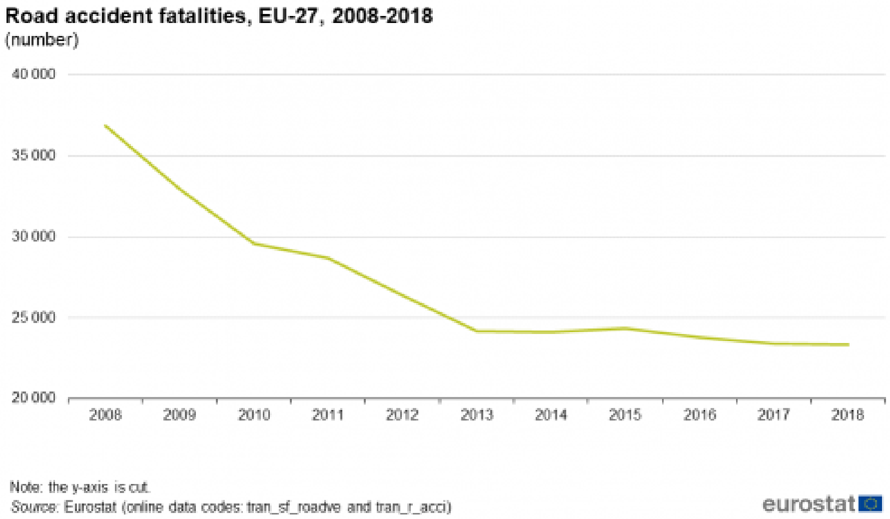


Figure 1.1: Fatalities from car accidents in Europe. Source EuroStat [23].

as a major step towards telecommunications by deploying the first 5G antennas for the broadband cellular network. This technology enables fast and consistent data exchange throughout the network. Such technologies can also be utilized by the automotive industry for the use of inter-vehicular communications. Another approach is the use of wireless networks such as the IEEE.802.11p standard [28]. The use of wireless networks enable vehicles to transfer data creating a connected road network consisting of traffic lights, road side units, other vehicles, etc. Such communication offers many benefits like collision avoidance, route guidance, alert drivers about weather conditions further down the road, etc. Furthermore, numerous technologies, taking advantage of those networks, are gradually emerging creating the future of transportation travel. In the up-coming years technologies like the autopilot for autonomous/automated vehicles (AV), Cooperative Adaptive Cruise Control (CACC), and Platooning Control (PC) for navigation will become a major part of the daily routine [51], [9], [19].

1.2 Contribution

The escalating growth of vehicle use combined with the increase in population has a major impact on road congestion. More specifically, motorways, located near high density populated areas, are facing problems related to this. Either, this phenomenon is observed from one direction or both, technologies like the Intelligent Transportation Systems (ITS) can provide solutions to alleviate this issue [7]. In more detail, technologies like the CACC and PC can procure higher road density through smaller inter-vehicle distances without any penalty in speed. Furthermore, systems like Reversible Lane (RL) [52] can provide extra lanes for one direction at a time, whenever dense traffic or congestion is detected, increasing the vehicle flow and road's capacity.

This Thesis focuses on the development and implementation of a platooning control algorithm of homogeneous vehicles based on the Constant Time Headway Policy [16], combined with a reversible lane system [6]. The concept of the algorithm is build on the distance, speed and acceleration errors, taking also into consideration information acquired by wireless communication between the platoon's leader and the preceding vehicle. The case study is based on the A38M Aston Expressway located in Birmingham, UK, which utilizes a Reversible Lane System (RLS) with three lanes per direction and one buffer lane, making a total of seven lanes [6]. Based on the triangular fundamental diagram (FD) and the densities of each road's direction, the RLS is capable of taking decision depending on the traffic conditions [6]. The necessary data are provided by inductive loop detectors located in each lane. When a decision is taken, the system closes one lane from the low density directions, allowing only two lanes to operate, while it enables the buffer lane for the high density flow, allowing four lanes to operate in total. Furthermore, a Road Side Unit (RSU) is implemented as an additional data acquiring method for the RLS, which is then compared with the inductive loop detector's method. It is worth noting, that in this thesis the benefits of platooning are taken into consideration, like the congestion alleviation and the higher road density without speed penalty. For this reason, the simulations and results are based only on fully formed platoons in stable conditions, without scenarios of vehicle entering or leaving the formation.

In order to evaluate the controller's performance and also simulate the RLS of A38M, the SUMO (Simulation of Urban MObility) simulator was chosen [30]. The preference of this software was based on the compatibility with the OMNeT++ Discrete Event simulator [49], which is capable of simulating networks communications. Furthermore, VEINS (Vehicles in Network Simulation, [43] was used as an extension of the above simulators, which implements vehicle communication protocols and more, combined with its further extension PLEXE [39], extending the software further to create and design platooning control algorithms fairly simple. From the VEINS side, an RSU was implemented and also an algorithm to handle the RL decision logic [6]. Several cases were simulated comparing the infrastructure performance depending on the existence or not of platoons, the use or not of the RLS and the traffic data extraction method, via inductive loops or wireless data through the RSU.

To the best of our knowledge, this is the first work in the relevant literature that integrates platooning control with an RLS while a full communication layer is implemented via the IEEE.802.11p protocol to allow AVs to exchange information with an RSU. The developed framework and results obtained showed that the implementation of platoon inside the traffic combined with an RLS can greatly enhance the traffic conditions, achieving higher vehicle flow rates and less traffic congestion. Such technologies can provide an easy and inexpensive solution to the constant rising problem of road congestion. Although, there are many benefits, another kind of congestion is yet to be completely solved. Network congestion posses a great threat to this technologies, as it can lead to false outcomes due to packet losses.

1.3 Thesis structure

The rest of the diploma thesis is structured as follows:

- Chapter 2 concerns the literature review for the existing technology of autonomous vehicles, the working principles and characteristics of the vehicular networks, the state of art for the ACC, CACC and Platooning systems, an overview in the Reversible Lane Systems and the basic working principles of a Road Side Unit .
- Chapter 3 describes the main objectives of this thesis, which are the main case study, the developed Platoon algorithm, which is based on the Constant Time Headway Policy combined with data provided by the platoon leader and the preceding vehicle, the Reversible lane decision control, which utilizes a triangular fundamental diagram combined with the road densities and finally the implementation of a Road Side Unit.
- Chapter 4 presents the results of the simulations compared with two different traffic scenarios (with and without platoons) and four further case studies, based on a scenario without an RLS, a scenario which utilizes one combined with induction loops, a further enhancement by replacing the induction loop with a RSU and finally a comparison of the proposed algorithm with a well known and established platoon controller.
- Chapter 5 concludes the thesis and outlines research directions for future work.

Chapter 2

Literature review

In this chapter the background for the understanding of vehicle automation and platooning is presented. At first, several automation technologies, the levels of automation and the various types of sensors and actuators are briefly discussed. Moving on, an introduction to the vehicular networks is presented, which is crucial for the understanding of the cruise control technologies that are then discussed. Finally, the working principles and applications of a reversible lane system and a road side unit are provided.

2.1 Vehicle automation

In the last decades, the advancements in technology provided enhancements to vehicle's systems to become more automated, allowing more stability and safety for the drivers. Some of those systems are thought to be simple and standard for every vehicle, while some others are more rare and complex. Both categories provide the necessary information to the vehicle for monitoring and decision making. To achieve the ultimate goal of total vehicle's autonomy, progression and perfection of each system and harmonic cooperation between them must be accomplished. In this section several automation systems are discussed, concerning some simple and ordinary technologies, like the Anti-lock braking system, and some more advanced ones, as for example the vehicle autopilot system.

2.1.1 Anti-lock braking system

From the early 70s cars where equipped with automatic technologies such as the Anti-Lock Braking System (ABS). The ABS is used mostly in every vehicle nowadays. The purpose of this system is to prevent the lock of wheels in a heavy braking incident and provide stability and steering to the driver. By utilizing speed sensors on each wheel the system monitors the wheel's speed and if a brake block incident is detected then it releases the brake pressure momentarily (see

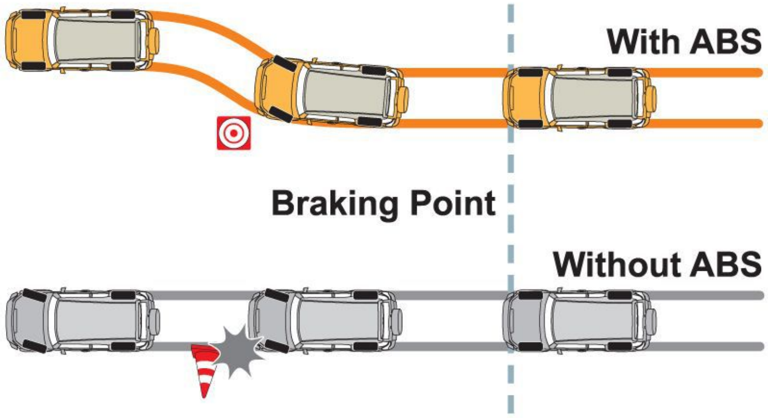


Figure 2.1: The anti-lock braking system.

Figure 2.1). After the rapid release the system re-engage the brakes in order to reduce the wheel rotation speed. Those steps are repeated continuously allowing the wheel to partially rotate and doing so it prevents the car from skidding on the road [10].

2.1.2 Electronic control unit

The Electronic Control Unit (ECU) is responsible for reading the car's sensors signals and analysing the results by emitting commands to the internal subsystems for optimal performance. The development of such control units (see Figure 2.2) and their integration to the automotive industry was started in the late 70s to early 80s. Since then, the development and capabilities of the ECU was expanded providing more functionalities to the cars and their users [3]. Some of the well known functionalities that ECU can provide, are the control of air-fuel ratio, ignition timing, launch control, gear control, etc.

2.1.3 Lane change assist

More and more vehicles in the automotive industry are equipped with a variety of sensors and automation technologies. The integration of such sensors provide new automation systems like the Lane Change Assist (LCA). When changing lane, a driver should always consider the vehicle's mirrors in order to avoid collision with up-coming or nearby vehicles. Although, mirrors are used for many decades as the sole solution of this problem, it is most certain that it cannot provide the best results. There are many occasions that nearby vehicles, which were located in the blind spot of the mirror's field of view, caused the driver to change lane risking an imminent collision. The LCA system offers a different approach to this problem by providing the driver with an alert either via a sound or vibration to the steering wheel. This is done by utilizing radar sensors around the car and detecting the up-coming and nearby vehicles. Radar sensors provide speed

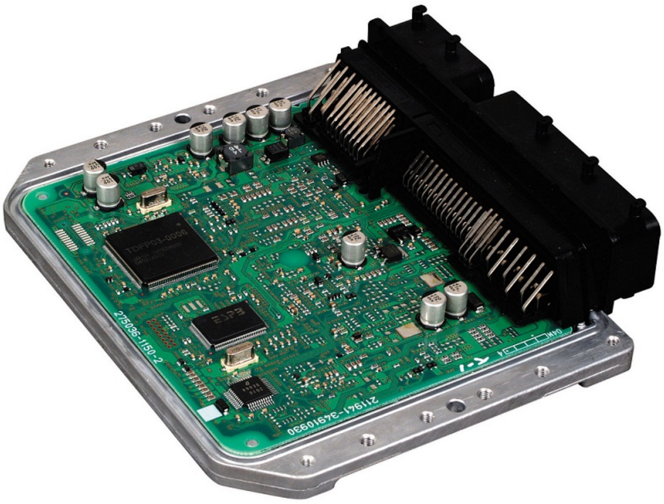


Figure 2.2: Electronic Control Unit (ECU).

and acceleration data for every object allowing the system to predict their position in the future and estimate a possible collision.

In [54] a personalized LCA system was proposed with a driver-behaviour identification strategy. Specifically, depending on the driver's inputs during normal conditions, a behavioural profile is created, which then allows the system to engage with a personalized planning and warning output, leading to the optimal operation.

2.1.4 Autopilot

From the early day of aviation, airplanes where equipped with an autopilot. The autopilot is an automation system which is responsible for maintaining control and navigating through the environment. The vastness of space in high altitudes combined with the absence of traffic where airplanes are involved, lead to the relative simple development of the autopilot. In contrast with the airplanes, vehicles operate in a more complex and unpredictable environment making a very challenging task the development of an autopilot.

Recent advances in sensors technologies, image and data processing signaled the beginning of many automation technologies including the autopilot. Vehicles equipped with a variety of sensors are able to take control and make decisions in various scenarios, closing the gap between a proper development of such technology. One of the most promising examples is Tesla's autopilot (see Figure 2.3) which is already available in the model S car. This system offers level 2 automation (see Section 2.2), which means that the system takes control of the car's steering and acceleration. The driver must always be aware of the situation and must often take briefly control of the steering wheel in order for the autopilot to continue operate [19].

Figure 2.3: Version 7.0 software for Tesla Autopilot (Model S).

2.2 Levels of automation

There are six levels of Automation, introduced in 2014 by the SAE International [26], including manual driving, which describes the functionalities and capabilities of a car.

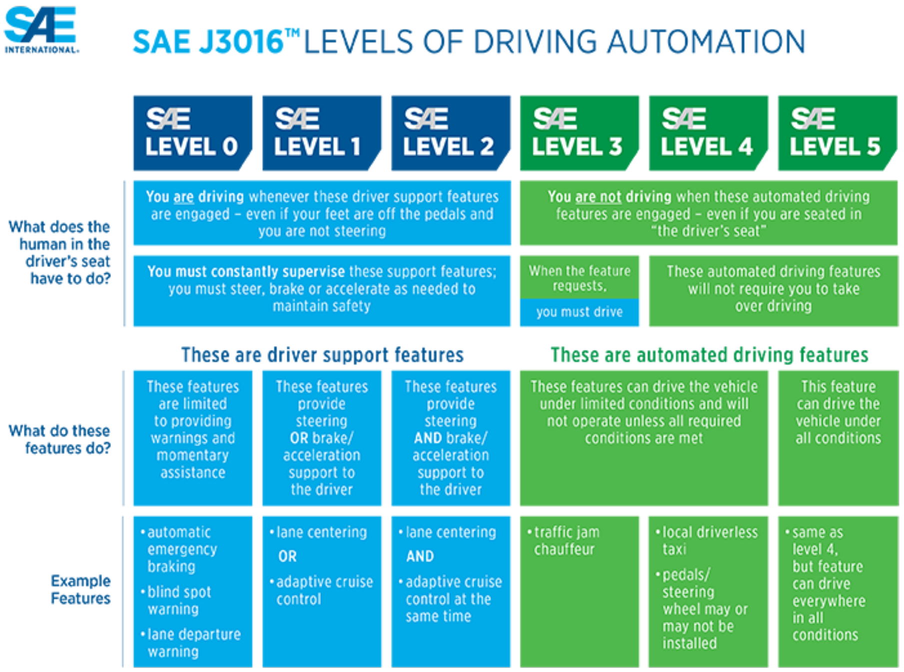
Level 0 (or No Automation) is referred to cars that are equipped with minimum to none automation systems, providing only support to the driver in certain occasion, such as an emergency braking event where the system engages brakes.

Level 1 (or Driver Assistance) automation provides assist of the car's lateral or longitudinal control by its subsystems allowing the driver to have the major control.

Level 2 (or Partial Driving Automation) is described as the ability of the car to have control over longitudinal and lateral. Although the system might be capable of maneuvering through different traffic scenarios, the driver must always pay attention to the road in case of failure to the automation system. One of the most well known level 2 automation is the Tesla Autopilot and the Cadillac Super Cruise System.

Level 3 (or Conditional Driving Automation) allows the driver to be occupied with other tasks in certain situations, rather than paying attention to the road while the car drives by itself. Even though level 3 automation has the total control of the vehicle, in cases of emergency the driver must be alerted to take control of the car if necessary. This implies that such systems must provide adequate time and communication to the driver in order to be updated of the incoming situation and take actions with the safest possible manner.

Level 4 (or High Driving Automation) is referred to cars with high automation potentials. In other words, it means that the automation systems are capable of maintaining control of the vehicle even in emergency scenarios allowing the driver to be completely distracted with other tasks. While, such automation provides the above capabilities, there is a limit for various traffic scenarios, like heavy rain or dirty and unclear road, where the system would not be able to operate as intended and prompting the driver to take control. Companies like



SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/ acceleration support to the driver	These features provide steering **AND** brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Figure 2.4: Levels of driving automation standard for self-driving vehicles , SAE International 2018 version [26].

Uber, Google and Waymo are currently developing vehicles to meet the demands of level 4 automation.

Level 5 (or Full Driving Automation) provides the ultimate automated vehicle by making the presence of the driver obsolete without the need to take any actions. Such systems are capable to work in every possible traffic layout without facing problems and compromising the safety of passengers inside.

2.3 Sensors and actuators

In order for a vehicle to be able to perform various tasks it must be able to have an understanding about its environment and take actions considering the decisions it makes. By utilizing a big variety of sensors the vehicle is capable of detecting the surroundings and the conditions of the road. Moreover, the use of actuators provides the necessary tools to have control over the car's subsystems and eventually managing the total road behavior [21].

2.3.1 In-vehicle sensors

A numerous amount of sensors is installed inside a car in order to monitor its functionality and subsystems. Some of them play a major role to the level of autonomy. One of the most common sensors is the *accelerometer*, which provides the precise acceleration of the vehicle. By exploiting

Figure 2.5: Bosch's short-and-long range radar.

this data the car is able to determine the direction of its movement whether it is longitudinal or lateral.

Steering angle sensors provide the current angle of the steering wheel. As mentioned before in order to attain level 1, or above, automation the vehicle must be able to have some sort of control for direction and steering. By analyzing the data received from the steering sensor, the vehicle is able to determine whether it is moving in a straight line, a curve or rapidly changing course, providing the necessary information for a decision in a future event.

Another type of sensor which monitors the wheel's rotational speed is called *wheel speed sensor* with a mounting location near the wheels. That type of sensor provides crucial information to the traction control and anti-lock braking systems.

2.3.2 Radar sensors

The main functionalities of radar sensors are the measurements of distance, speed and object detection and can be categorized as short range (SRR) and long range radars (LRR) (see Figure 2.5).

The SRR utilize the 24 GHz frequency with 250 MHz bandwidth and a high angle cone detection. Their main responsibility is to provide obstacle detection mostly used for rear and side views, collision avoidance by monitoring the distance of nearby cars or parking assistance. The escalating appearance of vehicles with automation technologies and wide use of SRR let to the decision, by the European Telecommunications Standards Institute (ETSI) and the Federal Communications Commission (FCC), for congestion reasons of the used frequency, that the 24 GHz frequency must be shifted to 79 GHz. This frequency allows the safe development of SRR technologies focused on the automotive industries without competing with space or facing interference by other services inside the 24 GHz band.

The LRR operate under the 77GHz band, which provides higher resolution and their main purpose is for measuring the distance , speed and obstacle detection. With a smaller cone detection

Figure 2.6: CCD camera.

the LRR can operate to a higher distance range up to 200 m. The main applications are for detecting upcoming collisions or monitoring the up-head and preceding vehicles, which is used mainly for cruise control technologies.

2.3.3 Vision systems

Vision systems utilize different image depiction and processing technologies such infrared, stereovision systems, Charged Coupled Deviced (CCD) (Figure 2.6) and Complementary Metal Oxide Semiconductor (CMOS) sensors.

The range of these sensors depend highly on the image resolution and it is considered as inferior to those of radar and laser sensors. The high resolution in close distances combined with image processing technologies, provide a very accurate object detection making such sensors ideal for applications like lane detection, pedestrian or biker detection, etc. The major issue that these technologies are facing is the diverse visibility and illumination scenarios, like shading or entering a tunnel, which affect the performance of the sensor.

2.3.4 Laser or light scanners

Laser scanner or most commonly known as Light Detection and Ranging (LIDAR) technology is another type of sensor used by the automotive industry. The working principle of laser scanner is based on a laser pulse emitted from the device, based on certain characteristics, with sole purpose to reflect into objects. By measuring the time interval between those two incidents the scanner can calculate the distance of the object [50].

The detection range of LIDAR is considered to be a few meters up to 200 m. The main benefit of this technology is the extremely good resolution provided even in high distances. Considering the field of view laser scanners can provide even a 360 degree detection. Although, such sensors provide high resolution, the major drawback is that in cases of bad weather conditions, the performance and resolution deteriorate. Another minor issue this technology faces is the big bulky

Figure 2.7: Waymo Lidar Technology.

size of the sensor which makes it difficult to integrate in a vehicle and also not being appealing to the eye (Figure 2.7). Such drawback seems to fade away because of the recent advances in technology that offer smaller and cheaper laser scanners.

2.3.5 Ultrasonic sensors

Ultrasonic sensors have a similar working principle with those of laser scanners. The difference between those two technologies is the use of ultrasonic waves in order to calculate the time variation between the original wave and its echo, which is reflected from the object. The range of ultrasonic sensors is a few meters with high detection rate and accuracy making them ideal for parking assist application or nearby object detection. Considering the low cost and small size these sensors are vastly used in the automotive industry.

2.4 Vehicular networks

The growing need for faster, safer and more efficient means of transportation, combined with the escalating development of communications and data processing technologies leads to the development and deployment of intelligent transportation systems (ITS). In order to achieve ITS technologies, the further development of inter-vehicular communications is in dire need. Technologies like the Mobile Ad-Hoc Network (MANET), the Long Term Evolution (LTE), the Dedicated Short-Range Communications (DSRC) etc., provide a mean of transmission, enabling data to be exchanged between vehicles [37], [28], [27]. The method and the recipient target, which the communication has a major role in safety and dissemination of the information.

2.4.1 Wireless technology

In 1999 the Federal Communications Commission of the United States reserved, in the 5.9 GHz band, 75 MHz for the DSRC for applications involving intelligent transportation systems. Particularly, the physical layer and the Medium Access Control (MAC), utilizes the IEEE 802.11p standard, which is an amendment of the 802.11, purposed for ITS applications. The IEEE 802.11p (see Figure 2.8) offers a more robust signal due to the sorter bandwidth of its channels (10 MHz bandwidth) compared to the 20 MHz offered by the 802.11 [28]. The coverage range can be defined from 300 meters up to 1000 meters with also a 27 Mb/s data rate. Furthermore, it is based on an Orthogonal Frequency Division Multiplexing (OFDM), providing also random MAC addresses and IPv6 for the network routing [36]. For applications like ITS where the environment is constantly moving (between the sender and receiver) and a short communication time period is critical, the IEEE 802.11p offers a Basic Service Set (BSS) where authentication and association is not required.

Concerning the upper layers of the DSRC they are managed by the IEEE 1609 standard, which is also known as Wireless Access in Vehicular Environments (WAVE). Its main purpose is to provide security primitives, access priority parameters, routing and channel switching. The IEEE 1609 standard can be split into sub-standards depending on their role like the 1609.1 is referred for application services, the 1609.2 for security services, the 1609.3 for networking services while the 1609.4 for multi-channelling. It is worth mentioning, that based on the IEEE 1609, the ETSI developed the ITS-G5. In this standard two types of messages exist, the Cooperative Awareness Messages (CAMs) and the Decentralized Environmental Notification Messages (DENMs). The first type is referred to the vehicle's periodically transmission of data, like speed and position, in order to inform other vehicles around. DENMs are event-triggered messages, meaning that when an event occurs, like a collision, the vehicle transmits data to inform about the situation. The main asset that ITS-G5 offers is the Decentralized Congestion Control (DCC), which is specially created for scenarios with high vehicle density, might lead to network congestion and performance drop. By tampering with the transmission power, rate, access, etc, it can maintain the network load under a specific threshold [7].

The LTE, also known as the fourth generation cellular radio network is thought by many scientists and automotive industries as the future of wireless communications. This technology is based on the Universal Mobile Telecommunications System (UMTS) providing several enhancement to its predecessor limitations. By utilizing also the OFDM logic, the LTE transmits several data streams instead of a single one reducing the mutlipath effect. With a 20 MHz bandwidth, the achievable data rates can be up to 100 Mb/s, yielding also low latency, which is less than 30 milliseconds. The low communication delays combined with the high transmission data rates makes this technology suitable for infotainment applications, referring to information and entertainment

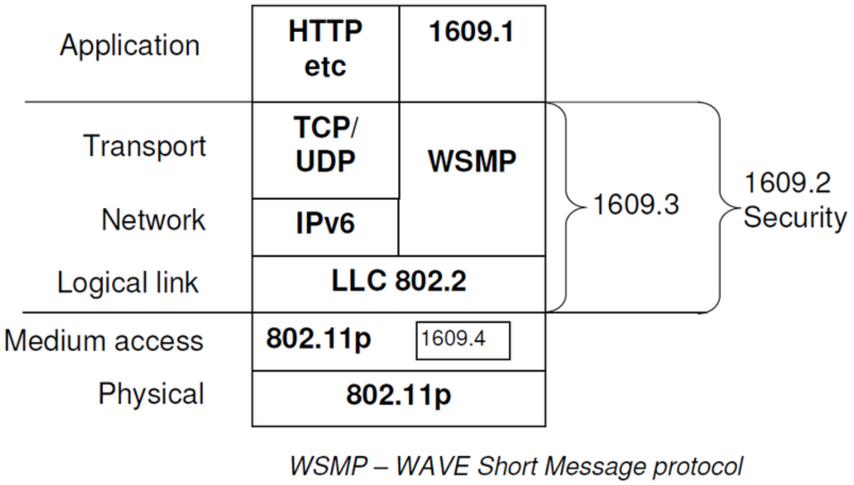


Figure 2.8: IEEE 802.11p Protocol. Source [45].

data [37]. Especially the low latency achieved even in high mobile environments, provides a crucial advantage for applications concerning road safety, like in the event of an accident occurring a couple of meters ahead. Furthermore, the already existing infrastructure combined with the high coverage range provided by the LTE has attracted the attention of many investors seeking to deploy this technology in the immediate future. Although, the LTE technology is very promising, it utilizes a centralized approach, meaning that every communication is obliged to pass from a common access point. In cases of malicious attacks, this centralized approach is very susceptible leading to safety issues. The development of adequate protocols for communication's safety is very important in order to allow such technology to be deployed.

Recent advancements in communication technology has lead to the further enhancement of the LTE communication network, by deploying the fifth generation of cellular radio network, which is commonly known as 5G. By leveraging the existing LTE infrastructure and extending its capabilities the 5G communication network can be fairly simply implemented [40]. The main benefits of this technology is the low latency and high data rates, which can be considered from 50 Mbps up to couple Gbps, depending on the network conditions. Although, 5G antennas provide small coverage range independently, a high overall coverage range is expected by the additional deployment of transmission devices. Several issues have troubled the scientific community about the deployment of 5G network, concerning mostly the network availability and congestion. In order to tackle this problem, scientist are currently studying the benefits of Device-to-Device (D2D) communications, allowing for data exchange between two users in proximity with a direct link. This kind of communication method is referred to as cognitive radio, which is able to be dynamically self-program and self-configure, depending on the network conditions [13]. Furthermore, it can detect automatically the available channels, allowing it to alter its transmission settings accordingly in order to facilitate multiple coexisting wireless communications.

2.4.2 Vehicle communication methods

There are two type of communications concerning a road network, which refers to vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Both types of communications in order to deliver data utilizes node to node, known as unicast, or multicast or broadcast connections. The difference between them is that for unicast there is communication between two nodes or vehicles, for mutlicast, multiple targets receive information, and in broadcast a single node or vehicle is transmitting information to everyone around it. Depending on the application and the need of information, a vehicle must be able to achieve the above types of communications. For example, in case of an incident, like a collision, the involved vehicle should be able to broadcast an emergency message alerting all the vehicles nearby.

Depending on the information and the environment, a single-hop or multi-hop delivery scheme must be chosen. The single-hop method is referring to a unicast, multicast or broadcast communication, where the information is delivered to the recipient without any further action. On the other hand, multi-hop routing concerns the communication between vehicles where the recipients, depending on their position, rebroadcast the original message further up and down the road. The main purpose of multi-hop routing is to propagate emergency or accident or weather condition related information to very large distances, because there is an absence of infrastructure or the vehicle's communication range is not enough. Several protocols have been developed to achieve multi-hop routing with the main goal to minimize the network congestion by the information's rebroadcast. The Mobility-Centric Data Dissemination Algorithm for Vehicular Networks (MDDV)[12] provides information propagation by running a localized broadcast routing algorithm to detect and deliver the message to the desired target finding the shortest path available. This protocol is heavily affected by the number of V2V communications and road density. Another multi hop routing system is the Fast Broadcast (FB) protocol. By transmitting heart-beat messages the algorithm can estimate the distance and prioritize the farthest node in order to pass the information further away [12].

2.5 Cruise control systems

2.5.1 Cruise control

Cruise Control (CC) can be considered as the starting point for the development of an autopilot in the automotive industry by maintaining a constant speed from a given input chosen by the driver. In order to achieve that, the system controls the throttle position of the vehicle and makes adjustment depending on variables, like the angle of the road or wind speed etc. To engage CC the driver must accelerate to the desired speed in order for the system to start functioning. This is done to avoid undesired acceleration by the system that might lead to collision with the preceding vehicle.

The main application of this system can be observed in highway scenarios where the road is quite strait without traffic lights, pedestrians and constant stops. One of the major advantages provided by the system is the fatigue relief for the driver. While driving big distances in motorways, the driver must always have his/her foot on the throttle pedal in order to accelerate or maintain vehicle's speed. By introducing CC the driver can move his/her foot in the rest pad, making the driving less tedious. Furthermore, fuel economy is considered as a big advantage of this technology, considering that while the system maintains constant speed the fuel consumption is remaining stable. It is very ordinary problem, while driving big distances the speed of the vehicle oscillates between the desired speed or the speed limit of the road, because the driver is also occupied by paying attention to the road. Such oscillation sometimes leads to lose of power, which must be regained by increasing the fuel consumption. Because CC takes into consideration only the vehicle's speed and not the surroundings, some incidents were observed where the preceding car slowed down and the quick reaction of the driver was to engage the throttle pad and not the brakes, leading to collision with the car ahead.

In [35] a Proportional-Integral (PI) controller that utilizes the speed error is introduced:

$$\ddot{x}_{\text{des}}(t) = -k_p(V_x - V_{\text{ref}}) - k_I \int_0^t (V_x - V_{\text{ref}})\, dt, \tag{2.1}$$

where $\ddot{x}_{des}$ is the desired acceleration, V_x is the vehicle's speed, V_{ref} is the desired speed, and k_p, k_I are control gains. By defining the following term, $x_{\text{des}} = \int_0^t V_{\text{ref}}\, dt$, the equation 2.1 can be rewritten as,

$$\ddot{x}_{\text{des}}(t) = -k_p(\dot{x} - \dot{x_{\text{ref}}}) - k_I(x - x_{\text{des}}), \tag{2.2}$$

where $\dot{x}_{\text{ref}}$ and $\dot{x}$ are the desired and vehicle's speed, respectively, while $x - x_{\text{des}}$ is the spacing between a fictitious vehicle traveling with the desired reference velocity.

2.5.2 Adaptive cruise control

Adaptive Cruise Control (ACC) is the evolution of cruise control by taking into consideration not only the vehicle's speed but also the surroundings, such as obstacles ahead or nearby. This system utilizes a broad range of sensors like radars, vision or laser scanners in order to acquire data concerning the environment around the car. Such data refers to the speed and acceleration of the surrounding vehicles and obstacle detection. By taking the above into consideration the ACC system can determine the position and speed of the vehicle ahead and its surrounding in the immediate future, enabling the system to make decisions for upcoming events. As a result, if the preceding vehicle starts to decelerate, the car's radar will detect this movement, alerting the system to also decelerate in order to keep a safe distance between the vehicles. ACC controllers also take into account the movement from the cars beside and behind the vehicle. In some cases when the rear vehicle starts to accelerate rapidly the controller will take evasive action in order to avoid collision.

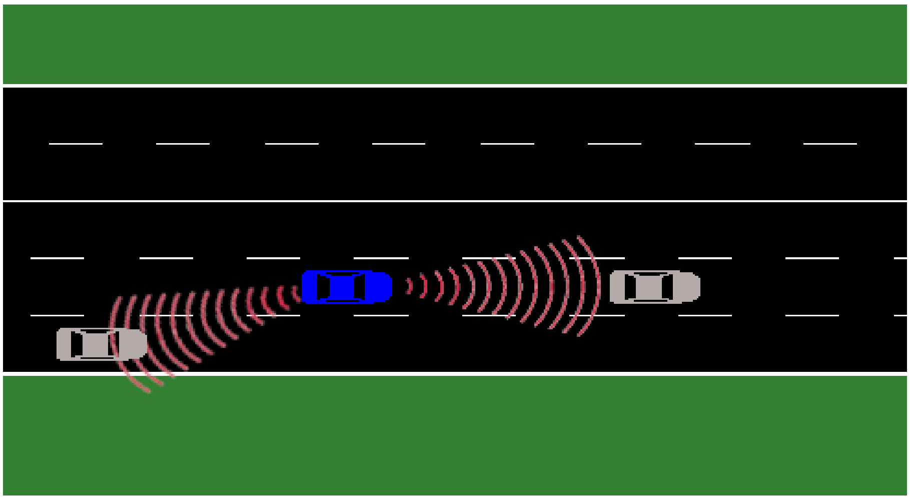


Figure 2.9: Adaptive Cruise Control (ACC).

Recent advances in sensor technologies, concerning robustness and cost related topics, gave the opportunity for many automotive companies to develop and integrate their own ACC system to their modern car models. More and more companies like Mercedes, Audi, Google are promoting the new generation of automated cars where they include automation systems like ACC. In the upcoming years the old and simple CC might give its place permanently to its successor.

In [15], a Constant time-gap (CTG) spacing policy is proposed to provide a control law for ACC applications:

$$\ddot{x}_{i,\mathrm{des}}(t) = -\frac{1}{h}\left[\dot{\varepsilon}_i + \lambda(\varepsilon_i + h\dot{x}_i)\right], \tag{2.3}$$

where $\ddot{x}_{i,\mathrm{des}}$ is the desired acceleration, $\dot{x}_i$ is vehicle's speed, $\dot{\varepsilon}_i$ and ε_i are the inter-vehicle spacing and its derivative, h is the time gap parameter and λ is a design parameter.

2.5.3 Cooperative adaptive cruise control

As explained above ACC utilizes data concerning the vehicles ahead. Although this technology might give an edge comparing to human driver, there is much more potential for this system. Specifically, when there is an obstacle ahead in the road and mediate a few cars, the ACC will start to decelerate only after the preceding car starts too. In Figure 2.10, the first car that detects the obstacle will start to decelerate alerting only the previous one that there is an incident, which then will start its deceleration too. This delay propagates all the way back at the end of the car line. Even though the ACC controller maintains a safe distance, enough even in cases of emergency braking from the car ahead, there is a better approach to this problem.

Cooperative Adaptive Cruise Control (CACC) takes advantage of ACC system and enhances its functionality by introducing V2V and V2I communications (see Figure 2.11). More specifically, some or all of the vehicles are equipped with antennas enabling them to broadcast and receive messages from other devices. Such communication networks can be achieved with the

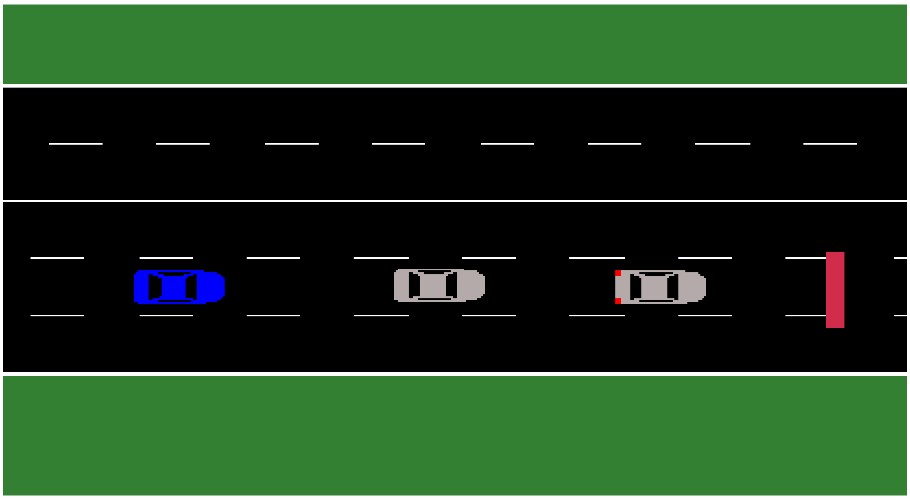


Figure 2.10: Response delay of ACC.

use of WiFi or cellular technologies. The implementation of this system provides the ability for each car to be connected with the surroundings allowing the constant flow of data between cars and infrastructure.[51]

The main purpose of V2V communications is to transfer data like acceleration, speed or alerts between vehicles in a very short amount of time (a few milliseconds) and range. V2I communications serve the same purpose as V2V but also have a higher coverage range and provide extra information to the vehicles. In some scenarios V2I is handling the communication between vehicles, giving them instructions on how to proceed. Inter-Vehicular Communications (IVC) can be exploited to alert nearby vehicles for an up-coming event such as an emergency braking or an obstacle ahead. As it was mentioned before, by simply using ACC in similar scenarios, a delay in reaction will be produced that would be increased and propagate down the line. With the use of V2V and V2I communications vehicles will be alerted almost instantly giving them the advantage of extra time to plan and act smoothly to solve the problem, like deviating from a lane to avoid traffic jam or obstacles ahead.

In order for vehicles to be CACC capable they require not only to be equipped with a variety of sensors but also to utilize a controller to handle the data received. Numerous controllers have been created to achieve CACC. In [33] they developed an algorithm based on the Constant Time Headway Policy (CTHP), which utilizes the vehicle's velocity to adjust the inter-vehicle distance. Furthermore, the spacing, velocity and accelerations errors are also taken into consideration, with the control law being presented below:

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}(k_p e_{1,i} + k_d e_{2,i} + k_{dd} e_{3,i}) + \frac{1}{h}u_{i-1}, \tag{2.4}$$

where $\dot{u}_i$ and u_i are the acceleration and speed of the vehicle i respectively, u_{i-1} is the speed of the preceding vehicle, h is the time headway parameter, k_p, k_d and k_{dd} are control gains and $e_{1,i}$, $e_{2,i}$, $e_{3,i}$ are the spacing, velocity and acceleration errors. It is worth noting that, the spacing error

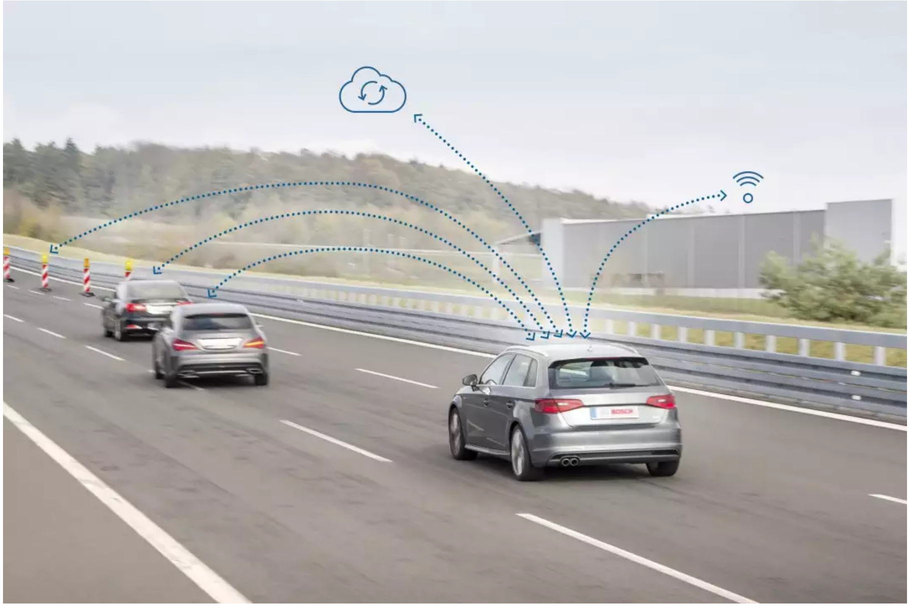


Figure 2.11: Cooperative Adaptive Cruise Control (CACC).

includes the CTHP term as $e_{1,i} = (s_{i-1} - s_i - L_i) - (r_i + hv_i)$, where s_i refers to the vehicle's position, L_i concerns the vehicle's length and r_i is the standstill inter-vehicle distance.

2.5.4 Platooning control

In the automotive industry the formation of a group of vehicles in a road scenario is called *platooning*. Platooning can be thought as an extension of CACC as it utilizes the principles of V2V and V2I communications. More specifically, it is referred to the creation of a vehicle group that shares information and cooperates in order to move with the same manner (same speed, acceleration, distance etc.).

The structure of a platoon can be split into two parts, with the first one being the leading vehicle or also known as the leader of the platoon and the second part to be considered as the rest of vehicles (see Figure 2.12). By using V2V communications each vehicle in the platoon shares its own data like the position, speed, acceleration but also receives data. Depending on the control algorithm, the data each vehicle receives varies between, leader's information, the preceding vehicle or in some cases the previous or the last platoon member. The leader being the first vehicle in the platoon monitors the traffic ahead, enabling him to adjust the acceleration, speed and direction of the formation in order to maintain a safe environment for the passengers. By propagating the data down the platoon member line each vehicle is able to follow the leader's path. There is an extensive research concerning the manner and effect of the delay and control algorithm for the platoons which is called *string stability* [25]. Particularly, in order for a platoon to be considered safe it must be *string stable*, meaning that any delay in the data received from the other members should not lead to oscillations down the line which might cause collisions [29], see also Section 2.5.5.

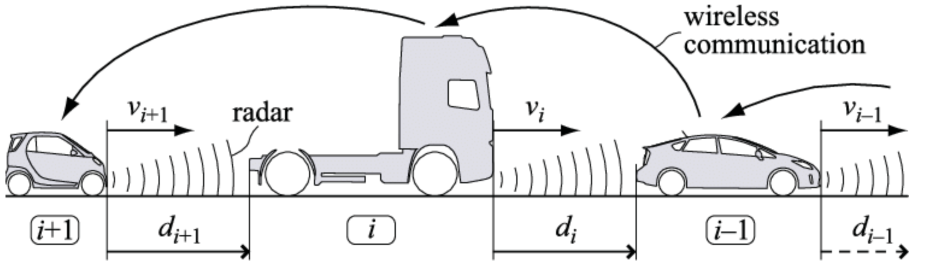


Figure 2.12: Vehicle Platooning. Image from [33].

The vigorous growth of global population combined with the enormous increase in vehicle usage the last decades, has created an escalating problem in the transportation field which concerns road's congestion. The existing road infrastructure, without taking into consideration an expensive expansion, can assimilate a specific flow of vehicles. Scientists are constantly trying to improve and invent new technologies, like Hyperloop or Tesla's underground road tunnel, to alleviate the congestion of the network. Although those technologies present a new perspective to transportation travel, a more simple and cost efficient way is considered to partially solve the problem. By increasing the road density which means more vehicles in a stretch of road, can reduce dramatically the congestion phenomenon. In order to achieve that, the use of smart vehicles with CACC capabilities can reduce the inter-vehicle distances, without the risk of safety or speed lost, which then can be interpreted as an increase in road density. An even better approach can be offered by the formation of platoons. As it was mentioned before, it can achieve very small inter-vehicle distances because of the communication and harmonic movement of the platoon. It is important to mention that platooning can also increase fuel economy by reducing the drag from the air. The leading vehicle acts as a barrier that moves and break the air in front of the formation providing less dense air to the following vehicles that move in its wake [18].

The introduction of V2V and V2I communications provide the necessary tools for technologies like CACC and Platooning to be developed. Although, those applications are created with the purpose of enhancing the road capabilities and experience, scientists are concerned that such technologies are prone to malicious attacks. Particularly, when a platoon is formed the key factor for the system's safety, which extends to the safety of the passengers, is the fast and precise data received from the platoon members. Malicious attacks like hacking can expose vulnerabilities of the system leading to catastrophic results like collisions [5]. The most dangerous hacking is thought to be the interference with the data exchange between the vehicles, feeding them with false information like the speed of the preceding vehicle, position or even an up-coming incident alert. Given the nature of Platooning, meaning relative high speeds with very small inter-vehicle distances, it is very susceptible to hacking. Although, CACC utilizes the same communications technologies, it is less vulnerable to attacks because at all times the in-vehicle sensors are capable of maintaining a safe distance and speed from the surrounding vehicles. To solve this threat, scientists are developing specialized systems and communications protocols in order to protect the vehicles from malicious attacks.

The benefits for implementing platooning control in road networks has attracted the interest from governments and automotive companies. The European Commission (EC) funded in 2009 the Safe Road Trains for the Environment project also known as SARTRE in order to investigate the behaviour of vehicle platooning [11]. In more detail, they formed platoons by placing a single driver inside the leading vehicle followed by autonomous vehicles equipped with antennas to transmit and receive data. Additionally, the US Federal Highway Administration (FHA) has funded a research project involving truck platooning. Notably, PATH (Partners for Advanced Transit and Highway) is also involved with platooning control projects in the US [42]. Furthermore, technologies concerning Intelligent Vehicle/Highway System (IVHS) where tested from the early 90s [48] as a two vehicle platoon control system. In Japan the Energy ITS project involves an automated truck platoon and their effectiveness on energy saving [47].

As it was mentioned before, specially designed controllers have been developed in order to achieve autonomous driving. As platooning control being a part of CACC technologies and an uprising enhancement in autonomy, scientists focused to develop controllers especially for platooning. In [4] a flatbed platoon towing model is considered, where a virtual tow truck is introduced loaded with the platoon vehicles. Between the vehicles an unidirectional spring damper is virtually placed, allowing for a better platoon model approach. Furthermore, they considered the CTHP term as the velocity differentiation between the ego vehicle and the leader, leading to the control law:

$$W_i = -k_a \dot{u}_i + k_v(u_{i-1} - u_i) + k_p(e_i - h(u_i - u_l)), \tag{2.5}$$

where $W_i = \ddot{x}_i$, $\dot{u}_i$ and u_i are the acceleration and speed of vehicle i respectively, u_{i-1} is the speed of the preceding vehicle, u_l is the speed of the leader, h is the time headway, k_a, k_v and k_p are control gains and e_1 is the spacing error. The results of the proposed algorithm shows that an enhanced string stability is achieved, allowing for a small inter-vehicle distance without any collision occurrence.

2.5.5 String stability

String stability is a fundamental notion to develop a platooning control algorithm, concerning AVs. Specifically, a platoon is considered to be *string stable* when there is no amplification of position, speed or acceleration error towards the rear of the line [35]. This is a crucial feature for platoon safety, because string unstable systems can cause oscillations to their individual distance, speed and acceleration leading to traffic jam or even collisions. A distinction between two types of string stability, concerning a *homogeneous* and *heterogeneous* platoon is considered [31]. In a homogeneous platoon, string stability refers to the same vehicle dynamics and spacing policy, while heterogeneous must take into account the differentiation between each vehicle.

The term string stability was first introduced in [32] and defining it as the ability of the vehicle string to attenuate disturbances as they propagate down the string. In [41] showed that the absence of data, provided by leader, eliminates the ability of the string to reach stability. Further research

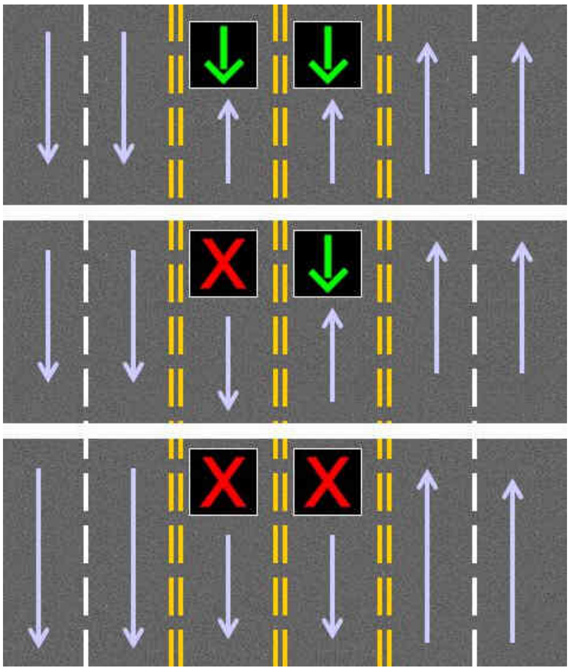


Figure 2.13: Reversible Lane System (RLS).

showed that when the desired inter vehicle spacing is constant it is impossible to achieve string stability [17].

2.6 Reversible lane systems

From the very beginning of vehicle use it was observed that specific road networks were prone to congestion. Particularly, during the day some roads faced problems from a single direction, meaning that there was a massive movement of cars to one location. Such behavior can be simply explained by the daily routine, where most of the people start their day early in order to get to theirs jobs. This phenomenon can be observed by the increased traffic in the morning. Although, this surge in vehicle flow can be seen for only one direction, during the day this phenomenon can be shifted, meaning that at some point the other direction will be congested. A solution to this problem was introduced from the early days of road traffic by enabling one or several lanes to be used for both directions (see Figure 2.13). This kind of lanes are referred to as Reversible Lane Systems (RLS) or also known in some countries as Tidal Flow Lane Control Systems [52]. Particularly, such systems allow specific lanes to be bidirectional, which are also called buffer lanes, enabling them to be used from one traffic direction at a time. When a high vehicle flow is required from the opposite stream the lane shifts its direction to alleviate the congestion. The advantage of this technology is that it offers different road capacity depending on vehicle demand making the road more dynamic to different traffic scenarios.

In order for the RLS system to operate properly, without creating confusion or risking the driver's lives, it utilizes different warning systems with the purpose of informing the vehicles

Figure 2.14: Reversible lane warning system.

about the available operational lanes. The most common way is the use of traffic lights placed along the length of the lane to alert the driver about the lane's direction (see Figure 2.14). Another RLS used to clarify the lanes directions is located in San Francisco at the Golden Gate bridge, which uses physical barriers that are moved and placed between the opposite lanes by specialized machinery. This barrier provides additional safety to the system by prohibiting any illegal movement in the opposite direction or the buffer lane. Some systems, that utilize the traffic light method, in order to maintain safety between the opposite direction lanes are disabling one more lane to the low density flow. Particularly, when the signal is given for the buffer lane to open for the desired direction, the system disables one lane from the opposite direction in order to always maintain an empty lane between the two flows.

A major role in the functionality and performance of an RLS is the time decision which the system operates for a given direction [53]. Various systems have been developed to handle the control for the lane's direction change. Some systems utilize defined traffic peak hours, extracted by daily data, which enable or disable the lanes for one direction. In Sydney for example, at the Spit Bridge in the morning there are three lanes available heading South and one heading North, while in the afternoon this analogy is reversed. This system offers a simple and inexpensive approach to the RLS, facing though the disadvantage for not taking into account the present traffic flow. Another system utilizes inductive loop detectors (see Figure 2.15) to calculate each direction's density, feeding with data a control algorithm to take decision about closing or opening the buffer lanes. In [6] a control law that takes advantage of real-time inductive loop detector data is introduce, in order to provide the optimal operation for the RLS. Although, the installation of inductive loops and their maintenance is quite expensive, this system provides a better control of the reversible lane because it monitors and takes decisions depending on the current traffic flow. In some cases, the responsibility for the decision making, is assigned to a human operator who changes the direction of the lane depending on the traffic flow provided by Close-Circuit Television (CCTV) system.

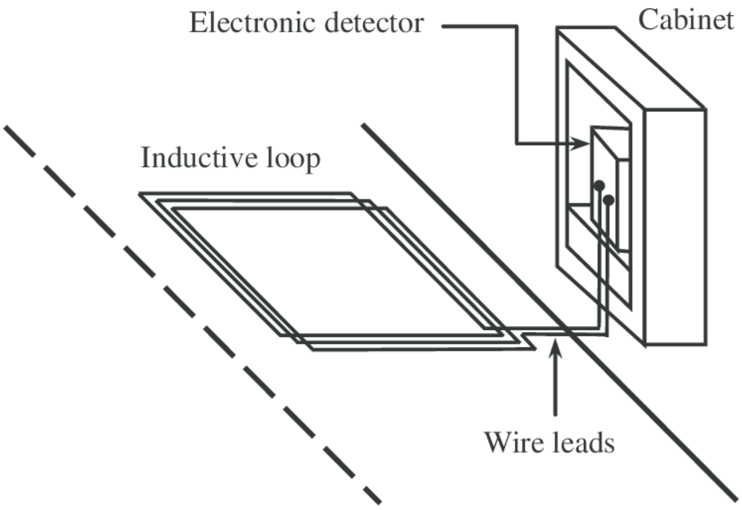


Figure 2.15: Inductive loop detector.

2.7 Road side units

The improvements in communication technologies combined with the dire need for ITS, drives the community and scientists to develop and utilize new technologies, which will provide a new approach to problems that have been for years. Systems like the Road Side Unit (RSU) allows the deployment of IVC technologies with numerous possibilities and advantages, simultaneously closing the gap between high tech infrastructure and existing ones. Specifically, an RSU can be used in various traffic scenarios providing V2I communications. This technology implies several benefits, like a higher coverage range allowing more vehicles to stay connected inside the network, communication between infrastructure to infrastructure (I2I) providing data, like road and traffic condition several kilometers away, allowing a better route planning by the vehicles. Furthermore, in some cases this technology can provide higher computational power, meaning that it can host hundreds of V2V or V2I communications at the same time.

Numerous applications and research is currently done considering RSU. For example, in [2] the researchers are developing an algorithm used by an RSU in order to give instructions to vehicles on how and when they should pass an intersection, aiming for an optimal performance without the need of vehicles to stop very often at the traffic lights. In order to achieve that, the RSU must communicate with every vehicle, calculate their trajectory and then take decisions, depending on the optimal solution for which vehicle should pass. Applications like this can further implement platooning control such as platoon formations that are created before the intersection with the purpose of passing it as a formation and not as one vehicle at a time. Additionally, RSU can provide necessary data to other control systems, like the total vehicle number inside a specific coverage range or the traffic condition of the road at a specific point, making it a perfect candidate for applications involving reversible lane systems.

2.8 Summary

A brief literature review was presented, in order to explain some information and terms that will be used later on. Starting on, several automation technologies were discussed, pointing to some simple but yet important systems and also to some more complicated and advanced like the autopilot. Moreover, the six levels of automation that explains and categorize a vehicle's capabilities was presented. Furthermore, the most important aspect of vehicle automation technologies, that refers to the sensor system was discussed, providing an insight to the tools that a vehicle utilizes in order to achieve some automation tasks. Another important aspect of automation technologies, concerns the vehicular communications and their capabilities. These technologies are getting more and more popular, while advancement in communication methods are completed. Additionally, several cruise control systems were discussed, by presenting their main functionalities and their control laws that are responsible for their performance. In the last part a brief introduction to the reversible lane systems and the road side unit technologies was presented, pointing to their potentials as a traffic congestion relief method.

In the next chapter, a brief case overview of the work completed in this thesis is presented. Furthermore, the vehicle dynamics and the forces exerted on a vehicle are explained, in order to provide a better understanding about the governing physics. Based on those dynamics and several control policies, the development of the proposed platooning control algorithm is presented, providing also an insight in the evaluation and optimization process of it. Additionally, the control law for the reversible lane system is discussed, combined with the Road Side Unit implementation.

Chapter 3

Reversible lane system and platooning control

This chapter presents the developed reversible lane and platooning control system. The basic physics and dynamics of a vehicle, which are necessary for the development of the proposed system, are described. A detailed description of the controller's characteristics, the evaluation and the tuning process of its parameters, is presented below, with the main purpose to achieve a good and stable performance during the main simulations. Furthermore, an extensive report is presented for the Reversible Lane System (RLS), the parameters on which the tidal decision is based on. Additionally, a brief display of the RSU implementation characteristics and functions are presented at the end of this chapter.

3.1 Case study

The main goal of this thesis is to introduce and evaluate the performance of a platooning control algorithm that is based on the Constant Time Headway Policy [16], combined with a reversible lane system [6]. A highway environment was chosen, with a fully formed traffic, that included human-driven cars and connected vehicles. Each platoon utilized the proposed controller, with the purpose to maintain a small inter-vehicle distance. In order to accomplish high performance, data acquired from the preceding and the leader's vehicle were introduced. Additionally, an Intelligent Transportation Systems (ITS) was also integrated, concerning a Reversible Lane System, in order to further evaluate the performance of the controller. The control law for the RLS switching policy was based on the research in [6] and was further integrated to the simulations. The data acquiring method for the switching policy was performed by Inductive-Loop Detectors, located in each lane.

Besides, a Road Side Unit was implemented, in order to calculate the road density, by transmitting beacons to the connected vehicles. The RSU was responsible for the RLS switching policy, by transferring the density data to the system. A comparison between the two data acquiring methods was completed with the purpose to understand the benefits of ITS technologies like the RSU.

The SUMO (Simulation of Urban MObility) simulator [30] was used for the evaluations. SUMO was integrated with the OMNeT++ Discrete Event simulator [49], which is capable of simulating networks communications. Furthermore, VEINS (Vehicles in Network Simulation, [43] was used as an extension of the above simulators, which implements vehicle communication protocols and more, combined with its further extension PLEXE [39], extending the software further to create and design platooning control algorithms fairly simple. The RSU and the algorithm to handle the RL decision logic [6] were implemented in VEINS. Several cases were simulated comparing the infrastructure performance depending on the existence or not of platoons, the use or not of the RLS and the traffic data extraction method, via inductive loops or wireless data through the RSU.

3.2 Vehicle dynamics

One of the most important aspect of technologies like ACC, CACC and PC is the longitudinal control of the vehicle. Researchers and big automotive manufacturers are constantly trying to develop better and more detailed vehicle models, which describes the physics and forces that are exerted on the car. An adequate understanding of vehicle dynamics plays a major role in designing controllers for intelligent systems, like CACC. Furthermore, the power-train dynamics, that refers to the transmission of motion produced by the car's engine, is crucial for technologies like platooning, especially when delays are generated by these dynamics, which may have a major impact to the system's performance. For example, when a need for higher speed arise and the power-train cannot cope with the demands, the performance of the platoon deteriorates, leading to a possible augmentation in the inter-vehicular distances.

When a vehicle is moving in a strait or inclined road, four different forces exerts upon it. As shown in Figure 3.1 those refer to, the aerodynamic or drag force, the gravitational force, the longitudinal tyre force of the front and rear tyres, and the rolling resistance [35]. The force that is generated by the engine is transmitted to the vehicle's wheels, which then rotate to create the appropriate motion. This implies that the engine force is integrated to the longitudinal forces, which will be described further down. The following equation describes the vehicle's dynamics compared to the above exerted forces:

$$m\alpha = F_{\text{long}} - F_{\text{drag}} - F_{\text{rolling}} - mg\sin(\theta), \tag{3.1}$$

where m represents the vehicle's mass, α is the acceleration, F_{long} represents the longitudinal forces, F_{rolling} represents the rolling resistance force, g is the gravity acceleration and θ is the angle of the road. In the next section, the power-train dynamics are presented, which describe

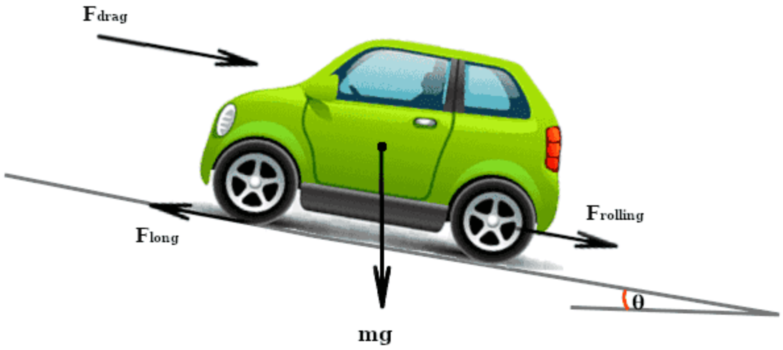


Figure 3.1: Forces exerted on a vehicle.

how motion, generated by the engine, is transmitted to the wheels through the engine shaft and the gearbox.

3.2.1 Longitudinal tyre forces

Concerning the longitudinal tyre forces, they are produced from the friction between the tyres and the ground, and their performance depends heavily on the vehicle's and tyre's characteristics. Firstly, the vertical load on the tyre which originates from the vehicle's weight and the forces exerted on the center of gravity, can impact the tyre's performance. The vertical load is mostly responsible for the amount of surface that is in touch with the road. Bigger surface produces better friction between the tyre and the road, increasing the driving control of the vehicle, although a penalty of resistance forces is produced. Furthermore, the characteristics of the tyre, like the friction coefficient, which varies between tyre manufacturers, has a major role in the vehicle dynamics. There are many occasions where the vehicle's tyres lost friction between the road, whether from bad weather conditions or tyre wear, leading to a total lose control of the car. Additionally, the difference between the rotational and the longitudinal velocity compared with the longitudinal velocity is referred to as *slip ratio*. The equation that describes slip ratio is given by:

$$\text{Slip Ratio} = \frac{r_{\text{tyre}}\omega_{\text{tyre}} - V_{\text{long}}}{V_{\text{long}}}, \tag{3.2}$$

where r_{tyre} is the tyre's radius, ω_{tyre} is the rotational velocity of the wheel and V_{long} is the longitudinal velocity [35].

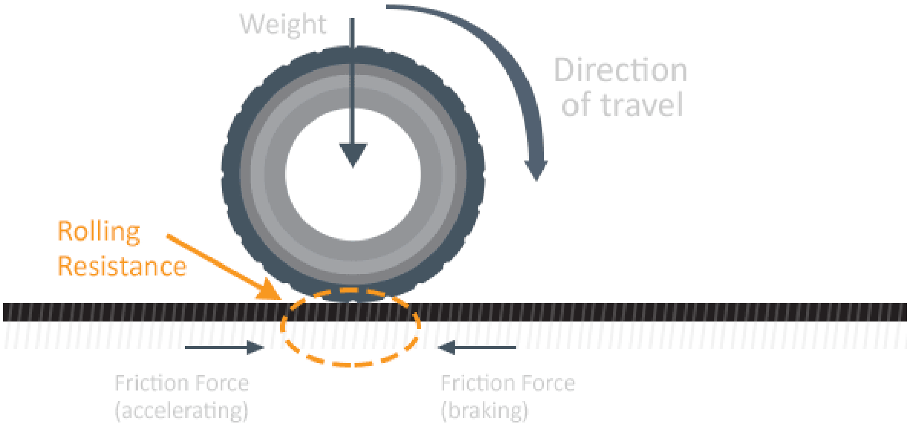


Figure 3.2: Tyre's rolling resistance.

3.2.2 Rolling resistance forces

When a vehicle moves, there is contact between the tyre and the road. Because of the forces exerted on the tyre by the vehicle's dynamics and the road's normal reaction force, combined with the soft material which tyres are made, like the rubber, a deformed region is created in the contact patch. Considering the elasticity of the tyre, part of the energy that is absorbed due to the deformation is released back, because the material tends to reshape to its natural form. Although, the ratio of the energy that is released back from the elasticity of the rubber is enough, part of it is dampened due to the internal structure of the material. The *rolling Resistance* (see Figure 3.2) refers to the inability of the tyre to release back all the energy that it absorbed due to deformation.

The rolling resistance force acts negative to the vehicle's movement because the tyres cannot transfer all the energy from the drive-train to the road, leading to lose of power. The equation that refers to this force is:

$$F_{\text{rolling}} = fF_{\text{normal}}, \tag{3.3}$$

where F_{rolling} is the rolling resistance force, f is the rolling resistance coefficient and F_{normal} is the normal load exerted on the tyres [24]. Taking into consideration that the vertical forces on the tyre are not centered with the center of gravity of the wheel, a small torque is produced due to this. For rough calculation the equation 3.3 is used where the rolling coefficient f includes the estimation of the small torque that is produced.

3.2.3 Drag force

When a vehicle is moving on the road, it pushes away air in order to pass through it. The reaction force of this movement is called *drag Force*. The drag is consisted by two type of forces, with the first one referring to friction and the second one to pressure drag. Particularly, drag friction is created by the viscosity of the air on top of the car's surface, meaning that the layers of air touching the vehicle's surface adhere and slow down. Gradually the upper layers are gaining velocity until they reach the free stream speed. This gradually velocity profile generates a big amount of drag due to the friction between it and the free stream air. On the other hand, pressure drag is created when two areas of the car, have different pressure due to the air moving around vehicle. For example, when a vehicle is moving, a high pressure point is observed on the front area of the car, while at the back a lower pressure field is created, due to mostly lack of air. This absence of air is heavily dependent of the vehicle's aerodynamic shape. This suction area creates a huge amount of drag, forcing big automotive manufactures to constantly enhance the vehicle's aerodynamic shape. As a result, less drag means less effort for the engine to pass through the air, leading to fuel economy. Although, this kind of drag cannot be totally avoided, technologies like platooning utilizes this effect as a benefit, by reducing the front pressure of each platoon member by being in the suction area of the preceding vehicle. This mean that the leader acts like a barrier that opens through a way for the platoon members to move relative freely of drag. The drag force of an object can be obtained by math equations or fluid dynamics simulations. The general equation which calculates the drag force.

$$F_{\text{drag}} = \frac{1}{2} C_d \rho A V^2, \tag{3.4}$$

where F_{drag} is the drag force, C_d is the drag coefficient, ρ is the air density, A is the frontal-area of the object and V is the relative speed between the air and the vehicle [8]. The drag coefficient can be obtained by scientific tables for ordinary objects, like a sphere, or by fluid dynamics simulations.

3.3 Power-train dynamics

As it was mentioned before, the engine of the vehicle produces the power to rotate the wheels in order for the vehicle to move. This force can be partially explained through the F_{long} which describes the longitudinal forces on the tyre. Although, this force is responsible for the vehicle's movement, it is not totally related to the forces produced by the engine. Particularly, a rotational force perpendicular to the vehicle's movement is produced by the engine, that shifts to each axle in order to transfer this motion to the tyres. The components that are responsible for the transmission and connection of the produced motion is called *power-train* (see Figure 3.3). The involvement of those components can have a major impact to the vehicle's performance, because they are responsible for the partial loss of energy due to friction, but most importantly they define how the engine's power is distributed to each axle and each wheel.

3.3.1 Engine

As a vehicle moves on the road, several forces are resisting its movement, as it was described by (3.1). In order for the vehicle to overcome those forces, a power source is needed. The engine of the vehicle provides the necessary torque to rotate the wheels in order to move the car. Whether

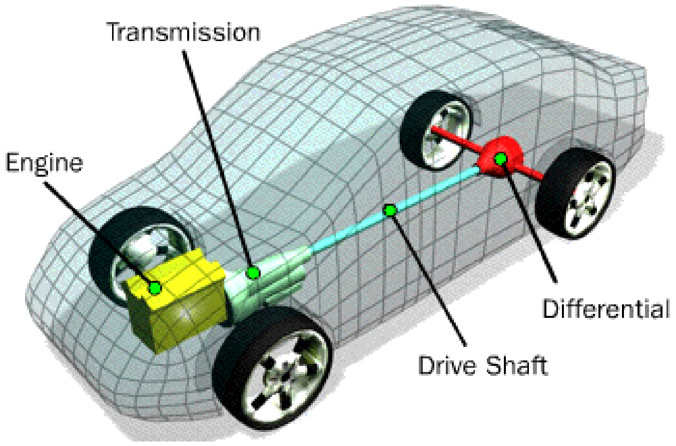


Figure 3.3: Vehicle's power train.

the engine utilizes combustion or electricity the main principle for its dynamics remains the same, meaning that the engine must produce torque, in order to rotate the engine shaft which connects to the transmission and further to each axle, leading to rotation of the wheels. Several parameters are responsible for an engine performance, as an example the combustion volume or the cubic centimeters of the engine, the mass flow of air through the intake, various tuning parameters like the spark plugs ignition timing etc. The major role for overcoming the resistance forces while the vehicle is moving, can be related solely to the engine, meaning that better performance can lead to a huge increase in acceleration, speed etc.

Several equation have been developed over the years, describing the engine's dynamics. The following equation provides an insight in the produced power for an internal combustion engine:

$$P = 2\pi N T, \tag{3.5}$$

where P is the power produced by the engine, N the revolutions per second of the engine and T is the torque that the engine provides. Furthermore, an equation that relates the desired power, that is needed to be produced by the engine, and the drag forces in order to maintain constant speed is given by:

$$P_r = \left(fmg + 0.5\rho_a C_d A V^2\right) V, \tag{3.6}$$

with f being the rolling resistance coefficient, m the vehicle's mass, ρ_a is the air's density, C_d is the drag coefficient, A the frontal area of the vehicle and V is the vehicle's speed [46].

3.3.2 Transmission

Transmission has a major role in the overall performance of the vehicle, because it is responsible for the amount and type of power that is transferred to the wheels. One of the main features that the transmission provides is the engagement or disengagement of the engine shaft through the clutch. This mechanism is crucial to vehicles when in need for sudden disengagement of the power, produced by the engine or simply to have a smooth transition between the vehicle being inert and start moving. Furthermore, by utilizing different gear's radius and ratios the transmission can convert the produced power by the engine, for more torque to the wheels, such as scenarios that the vehicle must move in a high inclined road, or to provide more speed to the vehicle by increasing the rotational velocity of the wheels.

A fundamental understanding of transmission's working principles is very important while designing the power train of a vehicle, because as explained above it is responsible for the vehicle's performance. The basic transmission dynamics in a steady state operation is:

$$T_w = \frac{T_t}{G_{\text{ratio}}} \quad \text{and} \quad \omega_w = \omega_t G_{\text{ratio}}, \tag{3.7}$$

with T_w being the wheel's torque, T_t the transmission's torque, G_{ratio} the gear's ratio, ω_w and ω_t is the wheel's and transmission's speed [35].

3.3.3 Wheels

The last part that is responsible for the delivery of power to the road in order for a vehicle to move are the wheels. After the transmission, the produced forces are delivered to the wheels through the differential, which is responsible for an evenly or unevenly distribution of power to the wheels depending on the road scenario. For example, when a vehicle is turning left, the right wheels have to travel bigger distances compared to the left ones, which are located in the inner radius of the turn. This means that the right wheel have to move faster in order to cover the bigger distance and not slip or skid on the road. This unevenly distribution of power is produced by the differential. The description of the wheel dynamics, in relation to the longitudinal forces that were presented previously is:

$$I_w \dot{\omega}_w = T_w - R F_{\text{long}}, \tag{3.8}$$

where I_w is the wheels inertia, ω_w is the wheel's speed, T_w the torque exerted on the wheel, R is the tyre radius and F_{long} is the longitudinal tyre force [24].

3.4 Platooning control

As mentioned before in order for a platoon to be considered safe and efficient there is a dire need of data, received from other vehicles of the formation. In this thesis those data are acquired from the OMNeT++ Discrete Event simulator and the VEINS extension for V2V communications [49], [43]. The vehicle dynamics are simulated by SUMO [30]. The next section presents the design of the proposed platooning controller for efficient reversible lane operations.

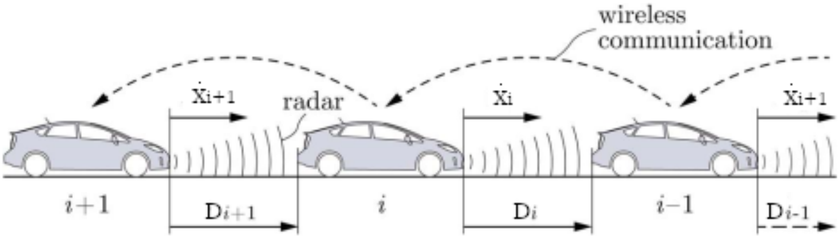


Figure 3.4: Platoon Formation. Image from [34].

3.4.1 Controller design

The main objectives of the controller is to ensure passenger's safety, increase traffic density by maintaining small inter-vehicle distances and achieve string stability. The starting guideline for designing the platoon controller was based on the spacing error e_i of every vehicle i inside the platoon, which is provided by (see Figure 3.4):

$$e_i = x_{i-1} - x_i - D, \tag{3.9}$$

where x_{i-1} is the position of vehicle $i-1$, which refers to the preceding vehicle of i, x_i is the position of vehicle i and D is the desired inter-vehicle distance. Specifically, the term $\Delta X_i = x_{i-1} - x_i$ concerns the actual space between the two vehicles, measured from the front bumper of each car.

Note that when the error is zero the actual space between two vehicles tends to the distance D, which does not count for the vehicle's length. As mentioned before, a homogeneous platoon is considered, leading to the further enhancement of (3.9) by adding the term L which refers to the vehicle's length. So, the spacing error equation can be rewritten as:

$$e_i = x_{i-1} - x_i - L - D. \tag{3.10}$$

In (3.10) when the spacing error tends to zero, the equation equals the desired inter-vehicle distance with the actual one, measured from the front bumper to the preceding's rear bumper. This method is called in literature as *Constant Spacing Policy* [14], which provides safety to the platoon by maintaining always a constant inter-vehicle distance. Additionally, the actual inter-vehicle distance can be acquired by a radar sensor to feed the controller. On the other hand, the stability and performance of the platoon is inferior, because the control law takes into consideration only data from the preceding vehicle, leading to huge inter-vehicle distances in order to maintain safety and avoid collisions.

In [17] a new control law was introduced, which considers an additional term to the spacing error, and is referred as the *Constant Time Headway Policy* (CTHP). By supplying feedback control from the leader's or the preceding vehicle's velocity, the CTHP provides further robustness in string stability for various scenarios, even though that this kind of control leads to non-zero steady state errors. The CTHP reads:

$$e_i = x_{i-1} - x_i - L - D - h_w u_i, \tag{3.11}$$

where h_w is the time headway parameter and u_i is the vehicle's speed. When the control law tends to zero the inter-vehicle distance is equal to the desired distance and the additional term $\Delta X_i = D + h_w u_i$, increasing the inter-vehicles distance due to the proportional term of speed. Numerous researches where focused on the optimization of the h_w time headway compromising between inter-vehicle distance and stability. In [4] they used a different approach for the headway term, by utilizing the difference between vehicle's and leader's velocity ($u_i - u_l$), achieving very small inter-vehicle distances while maintaining stability.

Taking into consideration the above and the research provided in [16], the proposed control algorithm of this thesis is based on the CTHP combined with the leader's acceleration as the headway term. The employed platooning control reads:

$$\dot{u}_i = k_d(x_{i-1} - x_i - L - D - S\ddot{x}_l) + k_v(\dot{x}_{i-1} - \dot{x}_i) + k_a(\ddot{x}_l - \ddot{x}_i), \tag{3.12}$$

where S is the time headway parameter, $\dot{x}_{i-1}$ and $\dot{x}_i$ is the front's and ego's (vehicle i) speed, $\ddot{x}_l$ and $\ddot{x}_i$ is the leader's and ego's acceleration and k_d, k_v, k_a are control gains. The next section presents how the control gains are determined in the considered case study.

The goal of the controller is to adjust the vehicle's speed in order to maintain a constant distance between the preceding vehicle combined with the headway term, which involves the leader's acceleration. The main purpose of the headway term is to provide an additional feedback control from the leader, in order to adjust the desired inter-vehicle distance based on the traffic conditions ahead of the platoon. It must be noted, that the data for the inter-vehicle distance is acquired by radar sensors, while the preceding vehicle's speed and the leader's acceleration is provided by V2V communications.

3.4.2 Controller optimization and evaluation

To assess the controller's performance and also tune the control gains for the best results, several requirements were monitored. The main objective that the controller must guarantee, is string stability combined with minimum as possible deviation from the desired inter-vehicle distance. Parameters like the time response or speed and acceleration pattern of the platoon, for example vigorous acceleration and deceleration, where also monitored. To acquire the results for the controller's performance as mentioned before, two kind of simulations were performed:

Scenario I: A sinusoidal input scenario, where the leader of the platoon accelerates and decelerates in a sinusoidal pattern.

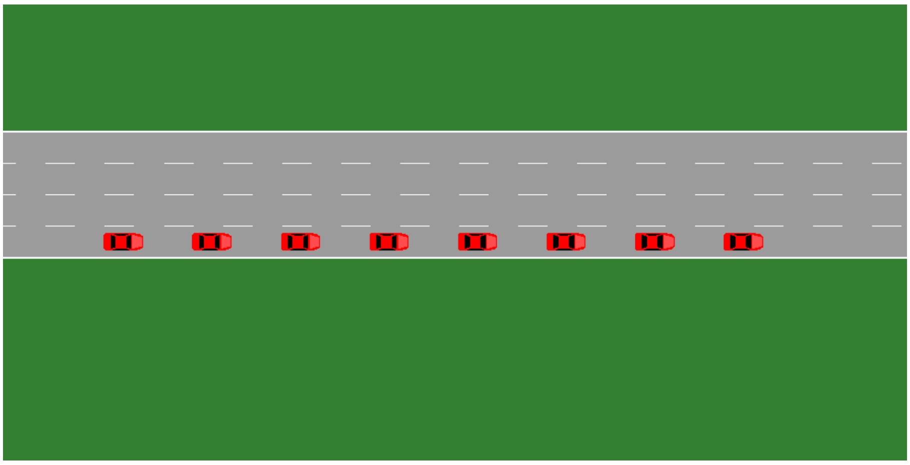


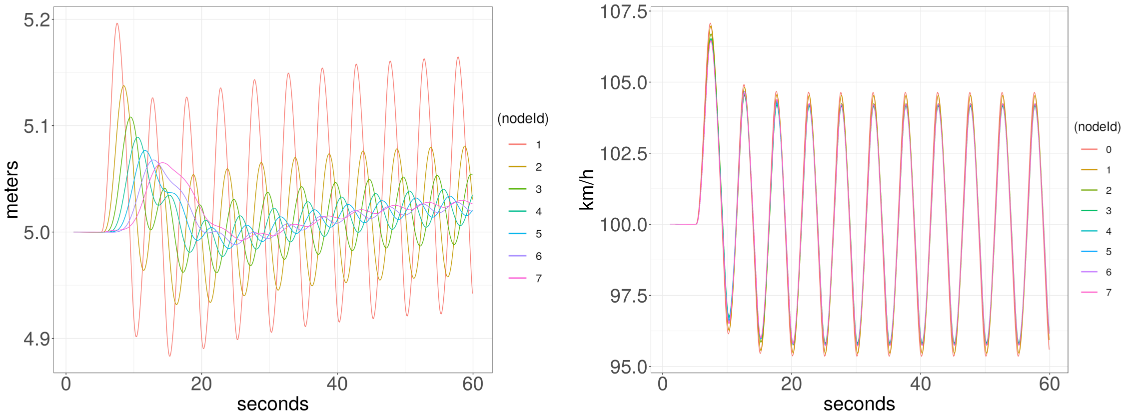
Figure 3.5: Platoon formation in SUMO.

Scenario II: A heavy braking incident scenario to test safety and stability, where after five seconds from the start of the simulation the platoon leader starts to decelerate.

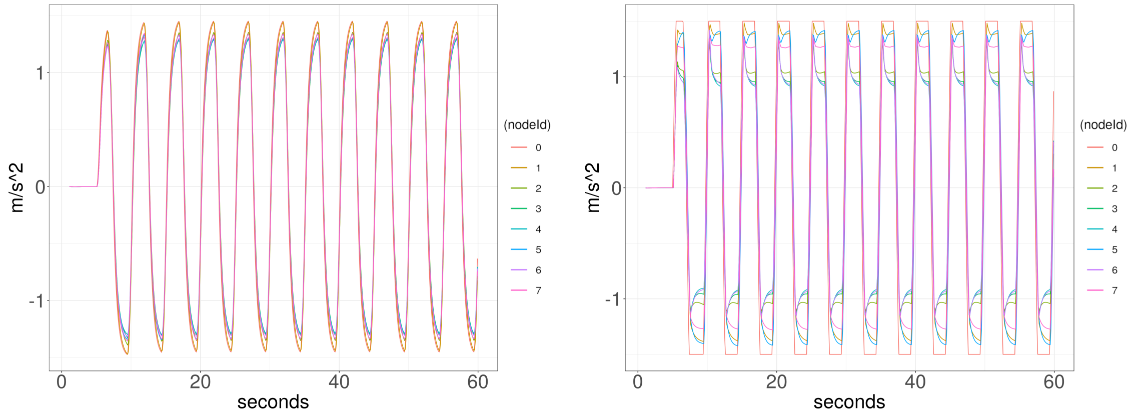
Simulation scenario I: In simulation Scenario I, a platoon of eight homogeneous vehicles is introduced in a straight highway simulation of a single direction (see Figure 3.5). For simplicity, the platoon is inserted as a steady state regime, meaning that all vehicles have the same desired inter-vehicle distance and the leader's speed and acceleration. The leader's max speed is considered to be 100 $\mathrm{km/h}$ and the vehicles length equals to five meters. After five seconds from the start of the simulation the leader's acceleration starts to oscillates based on a sinusoidal input with 10 $\mathrm{km/h}$ amplitude and 0.2 Hz frequency. The total simulation time is set to 60 sec, which provides enough time to monitor the performance of the platoon. Additionally, a small inter-vehicle distance (parameter D) equal to five meters was chosen in order to filter easier the string unstable cases. Several simulations were performed in order to optimize the controller's gains. This kind of traffic scenario can provide enough data for the understanding of the platoon's string stability. Specifically, the following condition was used for the evaluation of platoon's string stability [35]:

$$||e_i||_\infty \leq ||e_{i-1}||_\infty, \tag{3.13}$$

The infinity norm concerns the least upper bound of its absolute value, meaning that the maximum absolute value of the maximum spacing error decreases while it propagates through the formation [35]. By analyzing the data from the simulations, without taking into consideration the cases where a collision was occurred, several control gain values were attained. Further examination of the simulation data, like the average inter-vehicle distance achieved from the platoon at the end of the simulation, proved to be an excellent tool for reducing to the possible best cases. Specifically, if the controller's gains were unsuitable then a possible oscillation around the desired inter-vehicle distance would be monitored leading to the exclusion of the case. The last step of the evaluation process, considering the sinusoidal scenario, was the compliance of the controller's spacing error



(a) Inter-vehicle distance diagram (b) Speed diagram



(c) Acceleration diagram (d) Controller's acceleration diagram

Figure 3.6: Controller's diagrams for sinusoidal input.

with (3.13). This process was achieved by observing the distance, speed and acceleration diagrams of each platoon member.

After the evaluation process, the gains of (3.12) were set to: $k_d = 0.5$, $k_v = 10.5$, $k_a = 13$ and $S = -0.5$. Specifically, Figure 3.6 shows four different diagrams, extracted from the simulation, presenting the results of the above gains and parameters of the control algorithm. Each one is represented by eight different lines which depict the platoon members behaviour and performance from node zero up to seven. The platoon leader is not taken into consideration in Figure 3.6a because the measured distance refers only to a possible obstacle ahead, which in this case scenario is none. Furthermore, the number of each node is set from zero to seven, where zero is linked to the leader and seven to the last platoon vehicle, as clearly shown in Figure 3.4.

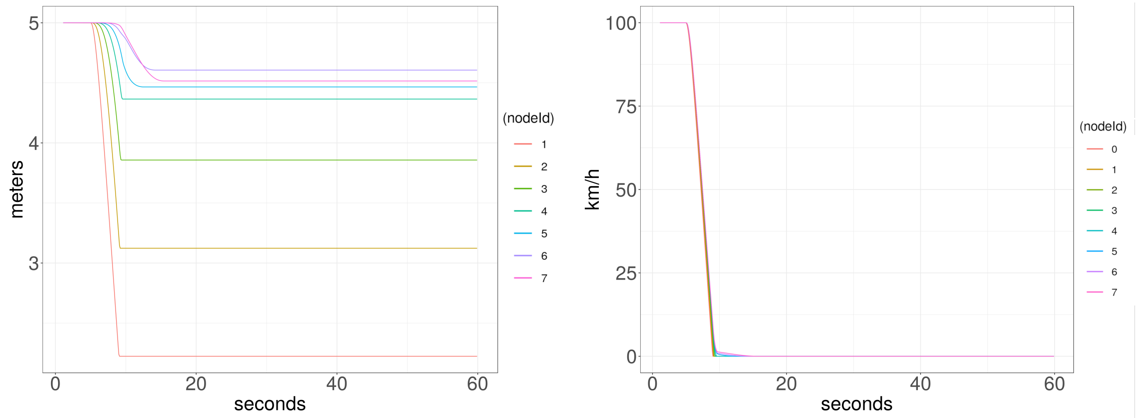
Starting the controller's evaluation, Figure 3.6a is thoroughly examined because it depicts the inter-vehicle distance of each platoon member for the whole simulation. After five seconds from the start of the simulation node's 1 inter-vehicle distance starts to oscillate because of the leader's sinusoidal behaviour. This kind of oscillation is propagated also to the rest of the platoon with a decreasing amplitude moving to the back. Additionally, taking into consideration the condition (3.13) it is clearly shown that there is no increase in spacing error while propagating through the platoon line. The biggest inter-vehicle distance deviation can be observed to node 1, which refers to the second platoon member located behind the leader. Although, there is oscillation to the distance parameter, its amplitude is considered fairly small with the highest value being up to 0.2 meters. It is worth noting, that the distance parameter of each platoon member oscillates near to five meters, which is set to be the desired inter-vehicle distance as described by parameter D of (3.12).

Figure 3.6b provides an insight of each vehicle's speed response. In this diagram the leader's speed oscillation is also presented in order to give a more accurate image of the platoon's performance. By analyzing the curves and also taking into account the controller's design, each vehicle is trying to match its speed with the preceding one. The small deviation of speed profiles is due to the delay of communication data and response of each vehicle. This behaviour can be explained by the effort of node 1 to match the leader's speed, producing a small speed error between those two vehicles. Although, seemingly this error shows to increase down the platoon line, it is considered not to, because the error refers to each vehicle and its preceding one. This means, that the error between each platoon member is increasing compared to the leader's, but decreasing compared between two vehicles.

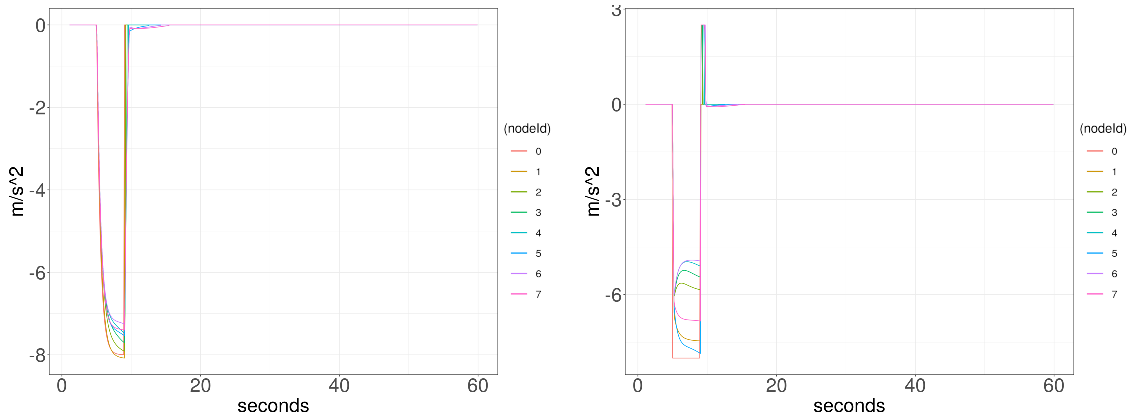
Figure 3.6c depicts the acceleration profiles of each platoon member. Clearly it shows that each vehicle is trying to achieve the leader's acceleration. This kind of oscillation is produced by the sinusoidal scenario. Furthermore, the term $\ddot{x}_l$ in (3.12), which refers to the leader's acceleration, is used to minimize the acceleration error of each vehicle.

Finally, Figure 3.6d presents the controller's acceleration. Similar to the previous figure, each vehicle is trying to match their controller's acceleration to the leader's one. Comparing with other simulation results a big impact of the controller's acceleration is caused by the headway parameter S whether it is positive or negative. In the positive scenario, the headway term has a negative value due to equation 3.12, leading to a small deceleration of the vehicle when the leader accelerates. This deviation caused small oscillations to the controller's acceleration, but due to the data provided by the preceding vehicle and the headway parameter value the overall performance of the controller was good. Comparing with the negative value of S, this phenomenon is reversed leading to a better controller performance and achieving faster rise time and amplitude of the acceleration.

Simulation scenario II: The second scenario was specifically chosen to test the controller's safety and stability. It is referred to a heavy braking incident scenario, where after five seconds from the start of the simulation the platoon leader decelerating at 8 $\mathrm{m/s^2}$. The simulation scenario is similar to the sinusoidal, meaning that the platoon length is consisted of eight vehicles and they are inserted in stable state, moving through a strait road with speed equal to 100 $\mathrm{km/h}$. Figure 3.7 shows four diagrams reporting the inter-vehicle distance of the platoon members, the speed and acceleration profile of each vehicle and the controller's acceleration of each member.



(a) Distance diagram (b) Speed diagram



(c) Acceleration diagram (d) Controller's acceleration Diagram

Figure 3.7: Controller's diagrams for braking scenario.

Figure 3.7a depicts the inter-vehicle distance of the platoon members. After analyzing the diagram, it is clearly observed that node 1, which is the closest to the platoon leader, is suffering with the smallest inter-vehicle distance, while in contrast moving to the back the distance is gradually getting closer to the desired D parameter of (3.12). This can be explained by the fact that after the leader starts to decelerate the first vehicle to detect that, is node 1, allowing for minimum reaction time of the vehicle. While going further back of the platoon line and with the utilization of V2V communications combined with the specific design of the controller, which uses data from the leader and the preceding vehicle, an alert such as a vigorous deceleration is transmitted from the head of the platoon to the other members, allowing them to have lower response time and start decelerating faster. Although, the five meters are not maintained after the heavy braking incident, the smallest value observed is around 2.5 meters and considering the vehicle's speed, it can be thought as safe.

Figure 3.7b shows the speed profile of the platoon members, which can be observed almost as identical. A small time deviation can be seen which is produced by the response delay of the platoon members. The last two diagrams represent the acceleration of each member and their controller's acceleration.

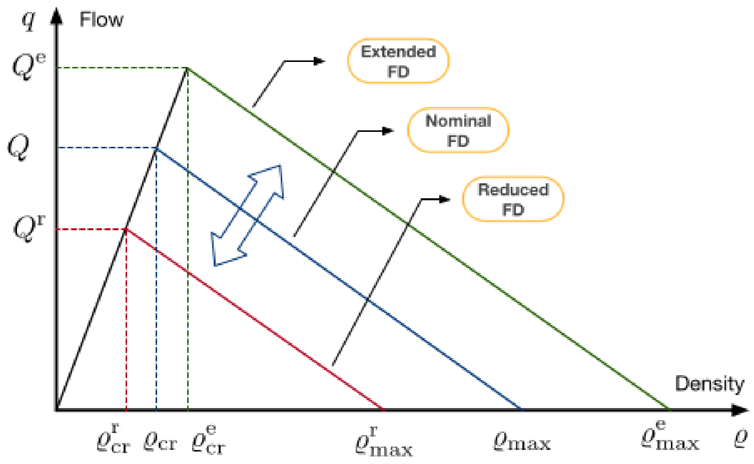


Figure 3.8: Triangular fundamental diagram and switching logic. Source [6]

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3.5 Reversible lane system

3.5.1 Reversible lane switching control policy

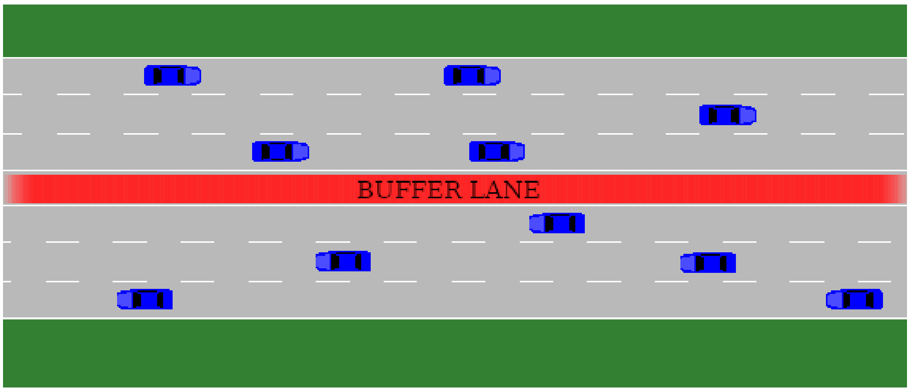
As it was mentioned before, in this thesis an RLS is combined with a PC and implemented. In order to perform simulations that includes the RLS, a control algorithm must be created and inserted into the simulation software. Based in the research from [6] the proposed control algorithm was implemented. A brief introduction of this algorithm is presented below.

In order to create an RLS control algorithm, real data acquired from the motorway is required. By utilizing the technology of inductive loop detectors placed in each lane, real data from the motorway was available for tuning the control algorithm. The logic behind the proposed algorithm is based on the triangular fundamental diagram (FD) of the road traffic (see Figure 3.8). By analyzing the real-time densities of each direction the algorithm can decide if it will take any action.

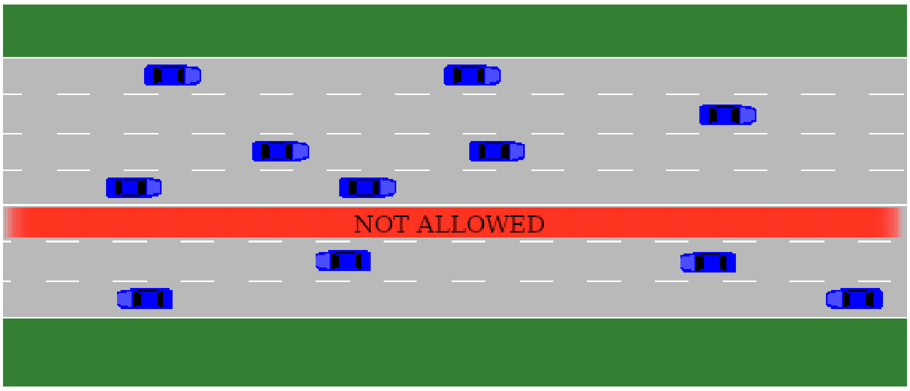
Furthermore, by providing a critical density ϱ_{cr} derived from the available real data the below control law was introduced [6] as:

$$u(k+1) = \begin{cases} 1 & \text{if } \varrho_A(k) > \gamma \varrho_{cr} \text{ and if } \varrho_B(k) \leq \gamma^r \varrho^r_{cr} \\ -1 & \text{if } \varrho_B(k) > \gamma \varrho_{cr} \text{ and if } \varrho_A(k) \leq \gamma^r \varrho^r_{cr} \\ 0 & \text{otherwise} \end{cases}, \tag{3.14}$$

where ϱ_A and ϱ_B are the density of Northbound and Southbound at the given time, γ and γ^r is the controller's parameter and ϱ^r_{cr} is the critical density for the reduced flow, meaning that from this value and lower the density of the road is considered to be small. By analyzing the control law it



(a) Buffer lane closed



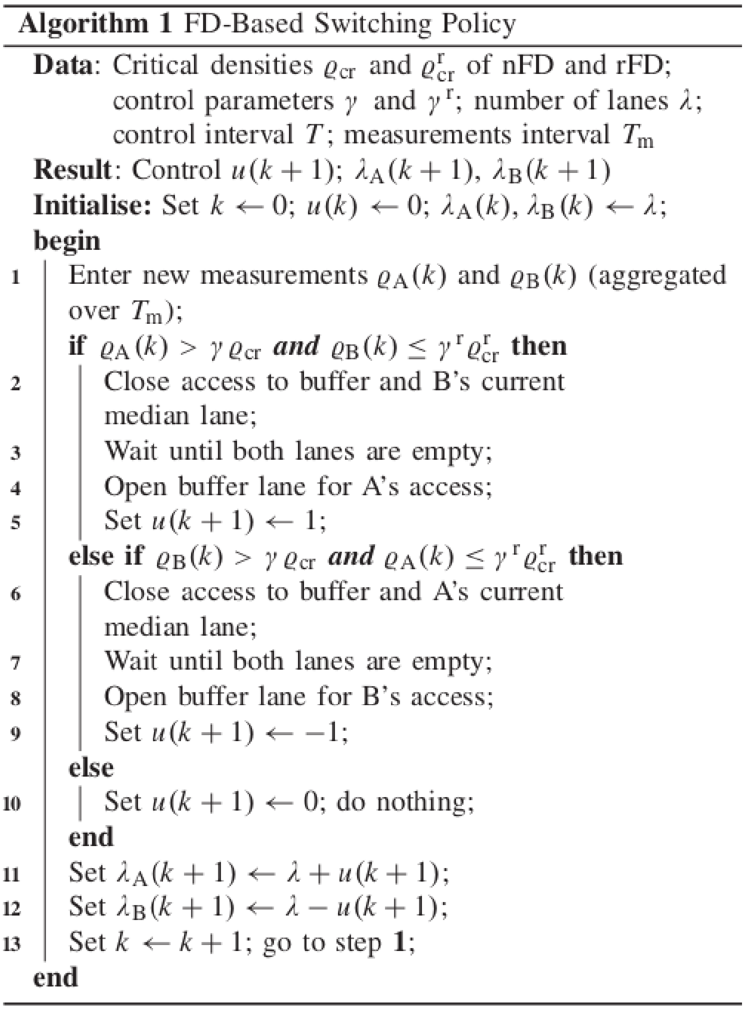
(b) Buffer lane opened for northbound traffic

Figure 3.9: Simulation model for the reversible lane system.

can be observed that in order for the system to open the buffer lane for one direction, it must firstly have higher road density from the critical one and secondly the density of the opposite direction must be lower than the reduced critical value. This term ensures that the system will not open the buffer lane for one direction in case both are congested.

For the simulation setup, the above control law was implemented in VEINS because it is responsible for the simulation of wireless data, which will be utilized from the algorithm. The programming logic is very similar to the control law, see Appendix B.1. Particularly, when a decision is taken from the RLS, the simulator firstly closes the buffer lane, if it was open in the first place, and waits to empty (see Figure 3.9). Only then is starts closing the secondary or median lane from the low density direction. When both the buffer and the median lanes are empty the algorithm opens the buffer lane for the high density flow. This way it is ensured that if there is a vehicle inside the buffer lane and the algorithm takes a decision which will lead to the disabling of it, the vehicle can change lane or continue its way until it exits the tidal flow. Figure 3.10 shows the proposed switching policy of the employed RLS.

This control policy is calculated every simulation time step, taking into account the densities of each direction which are provided from the inductive loops or the road side unit every 1 minute. Although, the calculation are completed every time step, the control law is able to make decision only every 10 minutes. This time gap was chosen because it optimizes the performance of the



```
Algorithm 1 FD-Based Switching Policy
Data: Critical densities $\varrho_{\mathrm{cr}}$ and $\varrho^{\mathrm{r}}_{\mathrm{cr}}$ of nFD and rFD;
      control parameters $\gamma$ and $\gamma^{\mathrm{r}}$; number of lanes $\lambda$;
      control interval $T$; measurements interval $T_{\mathrm{m}}$
Result: Control $u(k+1)$; $\lambda_{\mathrm{A}}(k+1)$, $\lambda_{\mathrm{B}}(k+1)$
Initialise: Set $k \leftarrow 0$; $u(k) \leftarrow 0$; $\lambda_{\mathrm{A}}(k)$, $\lambda_{\mathrm{B}}(k) \leftarrow \lambda$;
begin
1     Enter new measurements $\varrho_{\mathrm{A}}(k)$ and $\varrho_{\mathrm{B}}(k)$ (aggregated
      over $T_{\mathrm{m}}$);
      if $\varrho_{\mathrm{A}}(k) > \gamma\,\varrho_{\mathrm{cr}}$ and $\varrho_{\mathrm{B}}(k) \leq \gamma^{\mathrm{r}}\varrho^{\mathrm{r}}_{\mathrm{cr}}$ then
2         Close access to buffer and B's current
          median lane;
3         Wait until both lanes are empty;
4         Open buffer lane for A's access;
5         Set $u(k+1) \leftarrow 1$;
      else if $\varrho_{\mathrm{B}}(k) > \gamma\,\varrho_{\mathrm{cr}}$ and $\varrho_{\mathrm{A}}(k) \leq \gamma^{\mathrm{r}}\varrho^{\mathrm{r}}_{\mathrm{cr}}$ then
6         Close access to buffer and A's current
          median lane;
7         Wait until both lanes are empty;
8         Open buffer lane for B's access;
9         Set $u(k+1) \leftarrow -1$;
      else
10        Set $u(k+1) \leftarrow 0$; do nothing;
      end
11    Set $\lambda_{\mathrm{A}}(k+1) \leftarrow \lambda + u(k+1)$;
12    Set $\lambda_{\mathrm{B}}(k+1) \leftarrow \lambda - u(k+1)$;
13    Set $k \leftarrow k+1$; go to step 1;
end
```

Figure 3.10: Algorithmic scheme for the RLS switching policy [6].

system [6] and also to avoid any vigorous changes that might lead to the drivers confusion. The critical densities were set to $\varrho_{cr} = 120$ veh/mi and $\varrho^{r}_{cr} = 80$ veh/mi and the control parameter equal to $\gamma = \gamma^{r} = 1$.

3.5.2 Road side unit implementation and communications

In this thesis an RSU is implemented in order to handle the communication between the vehicles and the decision making of the RLS (see Figure 3.11). Particularly, each vehicle inside the simulation can transmit and receive data via wireless communication, as explained before, allowing for V2V and V2I communication. The main goal of this device is to calculate the road density of each direction using the V2I communications and then pass the data to the RLS system in order to make a decision. This means that the need for inductive loop detectors will be obsolete, leading to the reduction of maintenance costs and with the additional benefit of a better estimation of the real road's density.

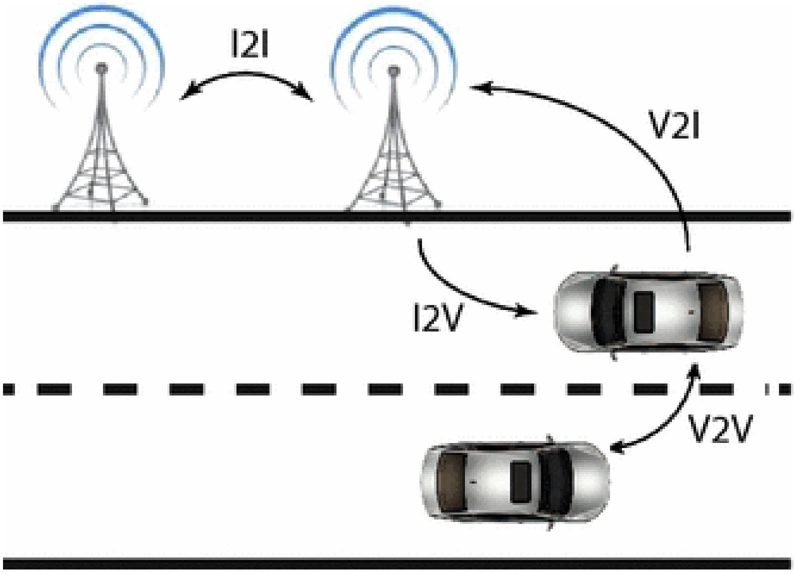


Figure 3.11: A road side unit with V2X communications.

VEINS handles the communications for each vehicle [43], its location was chosen in order to implement the RSU, allowing for an easy access between the applications and commands provided by the software. Additionally, a separate standalone application was developed to handle the RSU's communications between the vehicles, the calculations and decisions that the unit must complete and the connection and data transfer to the RLS, which is presented in Appendix A.1. Furthermore, an application module was also developed for each vehicle, in order to handle the communication process and the data exchange between the RSU and each node, see Appendix A.2.

The communication range of the RSU was set to be around 600 meters coverage radius, although it can be much higher up to 1km (see Figure 3.12). The chosen radius was set in order to reduce the total transmitted messages by the vehicles, which would possible cause high rate of packet loses due to network interference, to reduce the computational power of each simulation and most importantly to simulate a realistic vehicle's communication range which is set to be around 400-600 meters. The main purpose of the RSU is to calculate the road density for each direction in order to pass those data to the RLS system. To achieve that the below communication hand-shake was introduced. From the start of the simulation every 5 seconds the RSU sends a beacon, including a simple text message and an Provider Service Identifier (PSID). The main purpose of the PSID number is to separate the various messages that may occur during the simulation, like for examples transmitted messages from a platoon member, in order for each car to identify that the message comes from an RSU. Inside the coverage range the vehicles that received the beacon and identified its origins, assemble a response message which include various data concerning the vehicle. Particularly, each vehicle when receives a beacon from an RSU, it creates a message that includes their identity number, which is unique during the simulation, their lane, speed, road id that they are driving on and a PSID number, which obviously is different from the RSU's.

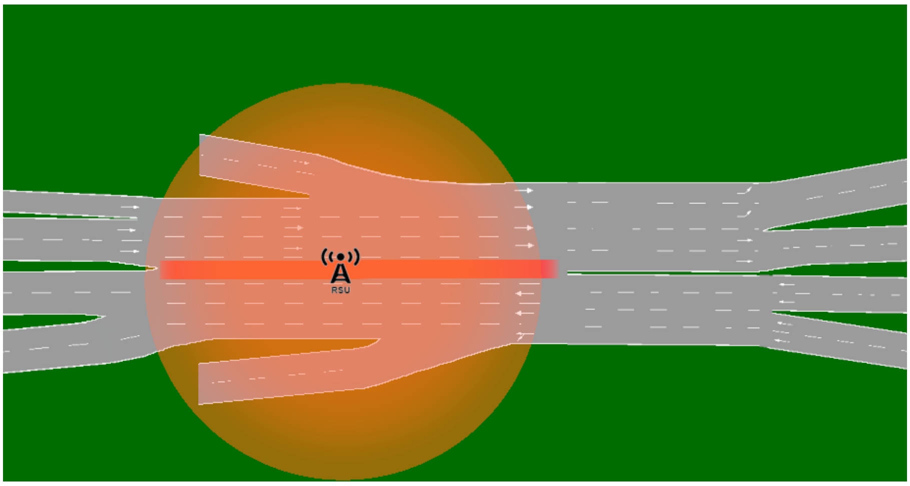


Figure 3.12: RSU coverage range.

First of all, the identity number provides a clear image about which car has sent a message back to the RSU and when. This is very important because as it was mentioned above the RSU send a beacon every 5 seconds. Inside the 5 second period the RSU expects to receive one message from each vehicle inside the coverage range, leading to the calculation of the total number of vehicle from the past 5 seconds. If for any reason a vehicle transmits a second message then the RSU will register another vehicle and the total count will fall off from the real one. By providing an identification list of all the vehicles registered the past 5 second this problem can be resolved. Moving on, the data referring to the road id is required in order for the RSU to calculate for each direction the total number of vehicles. This is crucial because the RLS system utilizes the density of each flow in order to make a decision as was explained above. Furthermore, the PSID number from the vehicle's message is required with the aim to avoid possible confusion to the other vehicle when they receive the message. This means that the vehicles inside the simulation should only response to a message that comes from an RSU and discard anything that has a different origin. After the 5 seconds period the RSU can calculate the density of each direction. By gathering the total number of vehicles driving in one direction and knowing that its coverage range is approximately 600 meters around it, which in total is 1.2km for each road direction, the density of each flow can be calculate as:

$$\text{Density (veh/mi)} = \frac{\text{Total Number of Vehicles}}{\text{Total Road Length (mi)}}. \tag{3.15}$$

A major problem that was observed during the simulation was the enormous number of messages that were simultaneously transmitted. For this reason, a random transmission delay was introduced to each messages transmitted from the vehicles in order to alleviate the network. Particularly, when a vehicle receives a beacon ,which is originated from an RSU, it re-transmits the message after 0.5 seconds. The main purpose of this delay is to provide enough time for every message to arrive to its destination, even though the given delay time is considered more than enough. If for some reason an instant rebroadcast message was available, then network congestion might occur. On top of the 0.5 seconds, a random delay between 0.01 seconds up to 2 seconds is further added in order to differentiate the transmission time between each vehicle. When high density flow occurs and multiple vehicles are transmitting simultaneously messages the network gets busy, leading to severe packet losses and messages delays. The above random time window provides enough differentiation of each message transmission allowing for multiple vehicles to operate and transmit data inside the same network. As it was explained above, every 5 seconds the RSU is able to determine the road density of each flow. Although this approach provides very accurate results, it leads to miscalculations considering the operation time of the RLS which is set to 10 minutes. Specifically, if the RLS makes a decision depending on the data provided by the RSU from the past 5 seconds then the operation would be faulty. A clear image of the traffic conditions is needed not only with a very good accuracy, but also with the passage of time. A congestion phenomenon can occur in a small area of the road, for different reasons ,like a sudden deceleration of a vehicle, increasing the local density of the road. If this area is inside the coverage range of the RSU then it will detect a high density flow which will then signal the RLS to operate for the given direction. In order to tackle this problem, an average density during a 1 minute time span is calculated from the RSU, which then is passed down to the RLS.

Concerning the platoons, a modification of their application layer was performed in Plexe to respond accordingly to the RSU beacon. Firstly, a different PSID was added to handle the inter-platoon communications, with the purpose to avoid confusion from the transmitted messages produced by the platoon members, which involves data transferred for the platoon control algorithm. Secondly, the platoon leader was chosen to handle the communication hand-shake with the RSU in order to further reduce the total transmitted messages. Specifically, when a platoon is created, the total number of vehicles involved is registered and available to all the members. When a beacon message is transmitted from the RSU and the leader of the platoon receives it, it transmits back the message with the road ID, speed, lane, the appropriate PSID and the platoon's ID. Additional information is included inside the message which concerns the total number of vehicles involved in the platoon. By utilizing that, the need for each member to transmit their own message and information is obsolete. For that reason, if a platoon member, except the leader, receives a beacon from the RSU it will not respond.

3.6 Summary

In this chapter an overview of the case study, concerning the proposed control algorithm combined with a Reversible Lane System and a Road Side Unit as an additional data acquiring method, was presented. Additionally, the vehicle's dynamics were explained, as they pose an important role for the designing of a vehicle controller. Concerning the platoon controller, its design was based on the spacing error and the Constant Time Headway Policy, by further utilization of data transmitted by the preceding and the leader's vehicle. The evaluation and optimization process was based on two different scenario, with the first one considering a sinusoidal input as the leader's speed, while the second one referring to a heavy braking incident. Both scenarios were chosen in order to evaluate the performance of the proposed controller and also to optimize its gains, with the purpose to achieve minimum inter-vehicle distance deviations and string stability.

Furthermore, the control law of the RLS was thoroughly explained. Based on the triangular fundamental diagram of the road traffic and real data, the control law was optimized. Two data acquiring methods were used for the feedback control law of the RLS. The first method utilizes Induction Loop Detectors placed on each lane, except the buffer lane, while the second one refers to a Road Side Unit. The RSU is responsible for a communication hand-shake between the connected vehicles inside the simulation, in order to acquire the density of each road flow.

Moving on, in the next chapter the results of the simulations are presented. Several cases were performed, by inducing only human-driven cars, mix traffic scenarios with platoons and human-driven cars and the activation of the RLS by utilizing one of the two data acquiring methods each time.

Chapter 4

Application and simulation results

This chapter presents the simulations results from the application of the developed reversible lane system with platooning control in the A38M Aston Expressway, Birmingham, United Kingdom. For the evaluation, a number of traffic and control scenarios were considered using data from inductive loop detectors as well as data obtained from a road side unit via V2X communications.

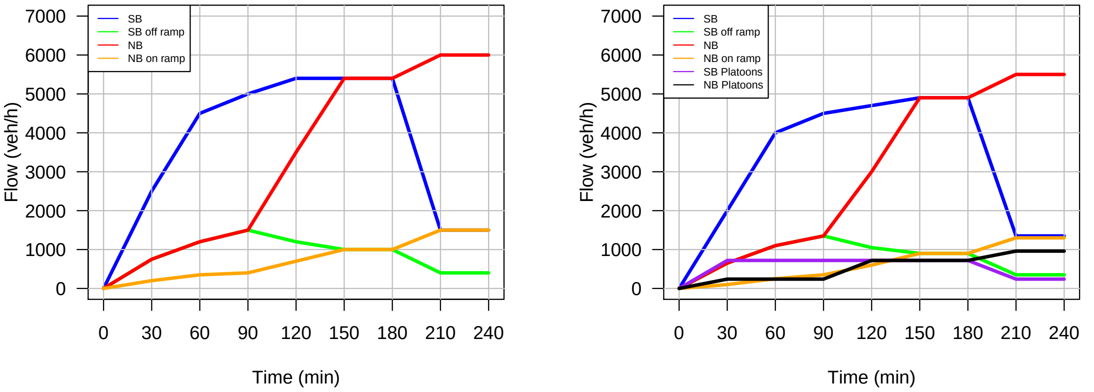
4.1 The A38(M) Aston Expressway

The reversible lane system that in this thesis is examined concerns the A38(M) Aston Expressway, Birmingham, United Kingdom. This motorway stretch is operational since 1972, with a total length of around 2 miles or 3.6 km, connecting the M6 motorway with the city center of Birmingham. For about 1.1 miles a functional RLS system is deployed providing seven operational lanes. The tidal flow policy refers to three lanes for each direction, Southbound or Northbound, and one as a buffer lane, the red highlighted area in Figure 4.1. Inside the 1.1 mile motorway section, one on-ramp is located at the northbound direction and one off-ramp at the southbound. When the RLS is engaged one lane located in the low density direction is closed while the buffer lane opens for the other direction, meaning that at any given time there is always a non-functional lane between the two flows, whether it is the buffer or a secondary lane. Specifically, the system operates with two lanes for the low density flow and four lane for the congested direction. The managing method for whether a lane is open or closed is provided by electronic overhead signs located along the way of the road. Furthermore, the decision algorithm for the system is based on a fixed-time control, meaning that in the morning four lanes are operational for the Southbound directions, which involves traffic moving toward the Birmingham's city center, while in the evening the effect is reversed, allowing four lanes to operate for the Northbound direction. Note that, in the intermediate time from the traffic congestion period, the A38M operates under normal conditions with three lanes for each direction and the buffer lane being closed.

(a) A38(M) top view

(b) Electronic overhead signs

Figure 4.1: A38(M) Aston Expressway. The red highlighted area is the middle buffer lane. Source Google Maps.



(a) Traffic demand for a traffic scenario without platooning control

(b) Traffic demand for a traffic scenario with platooning control

Figure 4.2: Traffic demand scenarios.

4.2 Traffic and control scenarios

The main objective of this thesis is to introduce a platooning control algorithm, with or without connected vehicles, in traffic scenarios including a reversible lane system. To effectively evaluate the performance of the proposed system two different traffic scenarios were considered.

The first traffic scenario is referred to the A38(M) with the presence of only human-driven vehicles, meaning that there is a complete absence of platoons inside the simulation. The second traffic scenario implements platoons, with a varying size between 6 to 10 members, for both southbound and northbound flows combined with human-driven vehicles. In Figure 4.2 the two traffic demand scenarios are presented. The main goal of those two different scenarios is to introduce similar traffic demands and compare them with each other.

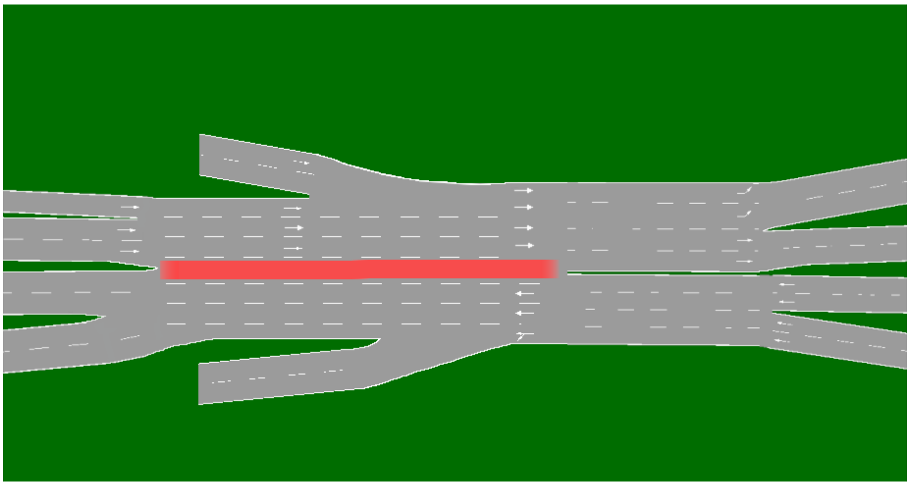


Figure 4.3: A simplified model of the A38(M) in SUMO.

Additionally, each traffic scenario includes five variations, with the purpose to further evaluate the platooning control combined with the reversible lane system. The five control scenarios are as follows:

Control Scenario 0: No reversible lane system is engaged.

Control Scenario 1: The reversible lane system is engaged, while traffic information is obtained by inductive loop detectors.

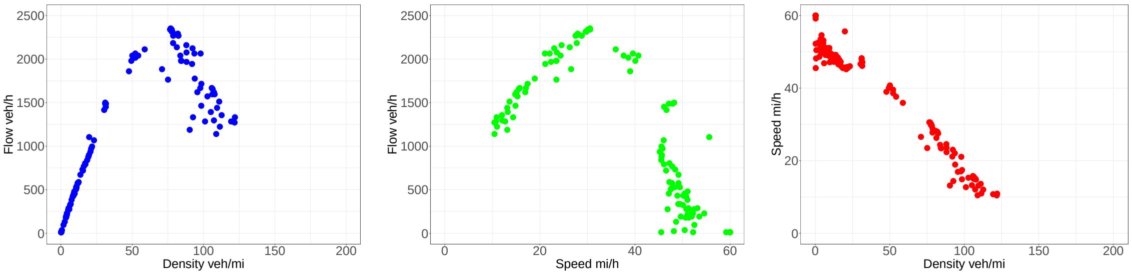
Control Scenario 2: The reversible lane system is engaged, while traffic information is obtained by the road side unit via V2I communications.

Control Scenario 3: Flatbed control with reversible lane system, while traffic information is obtained by inductive loop detectors.

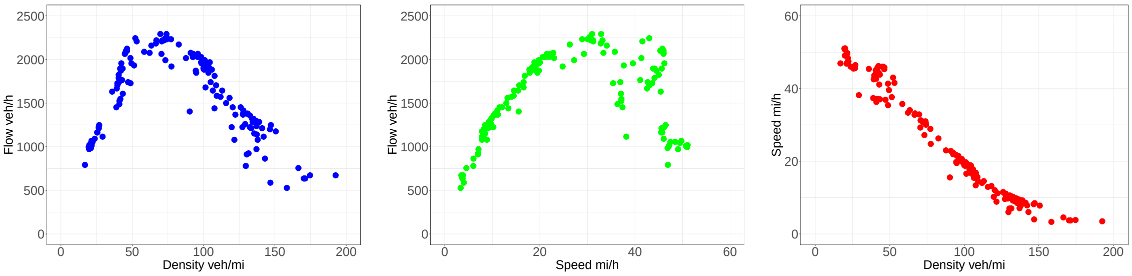
Control Scenario 4: Flatbed control with reversible lane system, while traffic information is obtained by the road side unit via V2I communications.

Control Scenario 0 involves a typical road scenario of A38(M), where three lanes, for each flow, are always operational while the buffer lane remains closed. Control Scenario 1 implements the RLS while utilizing data obtained from inductive loop detectors placed in each lane of the motorway. As explained before, the density is calculated and feed-back to the RLS in order to take an operational decision. Control Scenario 2 takes advantage of connected vehicles to send data to infrastructure, like an RSU, in order to calculate the density of each lane. In this scenario all the vehicles are considered to be able to transmit wireless data to the RSU.

Finally, two additional control scenarios were performed concerning the proposed controller in [4], which is briefly explained in Section 2.5.3. The main purpose of these scenarios (Control Scenarios 3 and 4) are to compare the proposed algorithm and the already well known and established flatbed platoon controller. The additional two control cases consider that the RLS is engaged using either the inductive loop detectors or the RSU data acquiring method.



(a) Flow-Density Diagram (b) Flow-speed diagram (c) Speed-density diagram



(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

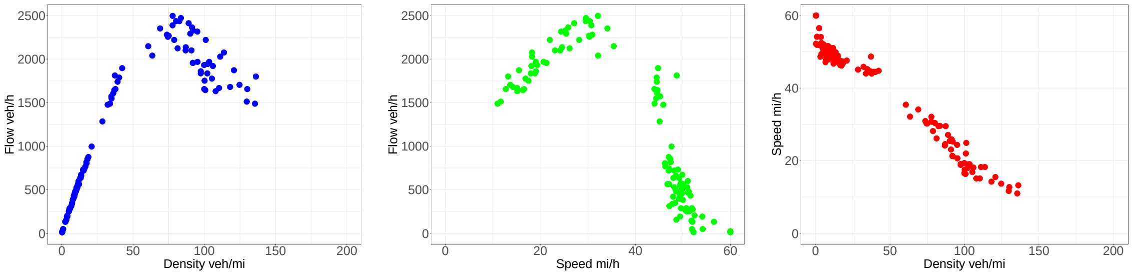
Figure 4.4: Flow-density-speed diagrams for Control Scenario 0. (a)–(c) NB traffic direction. (d)–(f) SB traffic direction.

4.3 Evaluation

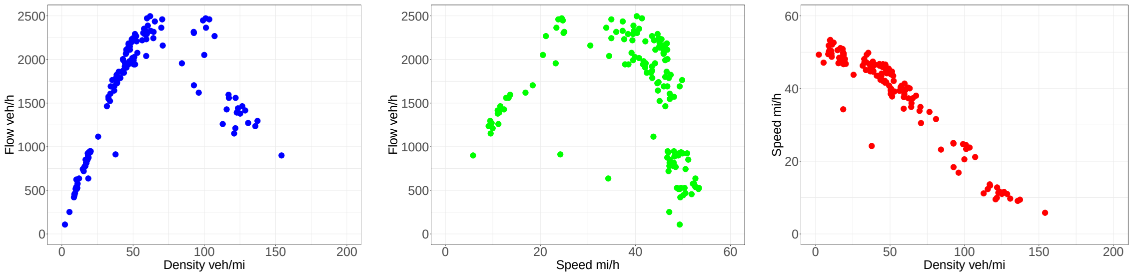
As aforementioned, five control cases for two different traffic demand scenarios were simulated to assess the performance of the proposed platooning and reversible lane control system. Several diagrams are presented below for each scenario, describing the traffic characteristics of each simulation. Specifically, for each control case six diagrams were generated, presenting the flow-density, flow-speed and speed-density relationships for the northbound (NB) and southbound (SB) traffic in the considered A38(M) motorway stretch. In the assessment, each control scenario is firstly evaluated for the two different traffic demand scenarios and then it is compared with the other rival control cases.

Figures 4.4–4.5 present the obtained results for the Control Scenario 0, which does not involve a reversible lane system. Starting from Figure 4.4, some slight differences can be observed between the NB and SB flows. Specifically, the NB flow shows greater speed profiles from the SB, higher flow rates and a slightly less traffic density. This can be explained from the fact that a high density flow for a bigger period of time is simulated for the SB direction of traffic. This results to traffic congestion for the majority of the simulation period, leading to slower moving vehicles and lower flow rates. Additionally, the same behavior can be seen in Figure 4.5.

Moving on, some major differences can be observed between the two traffic scenarios. Firstly, a higher flow rate combined with a lower density can be monitored by comparing the flow-density diagrams of the two scenarios. Specifically, Figure 4.5d shows that for a density around 50 veh/mi a flow of 2250 veh/h can be achieved, while in Figure 4.4d for the same density the flow is 2000

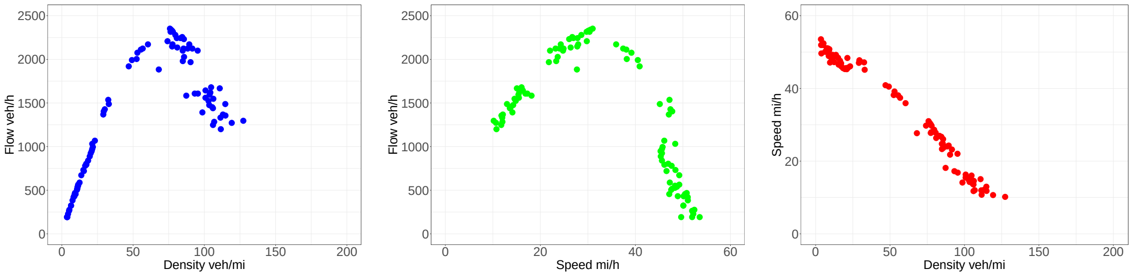


(a) Flow-density diagram (b) Flow-speed diagram (c) Speed-density diagram

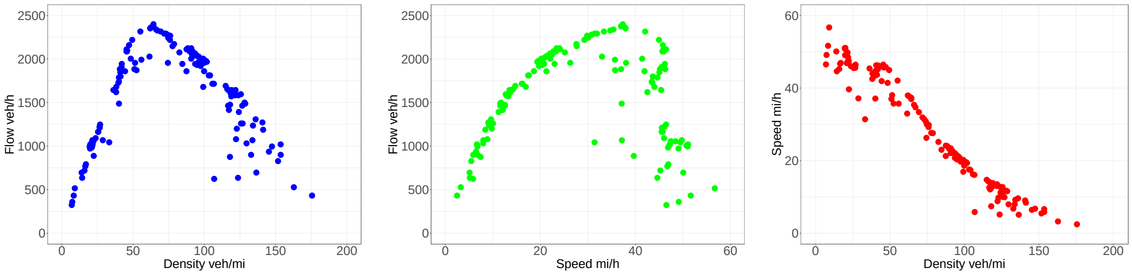


(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

Figure 4.5: Flow-density-speed diagrams for Control Scenario 0 with platoons. (a)–(c) NB traffic direction. (d)–(f) SB traffic direction.



(a) Flow-density diagram (b) Flow-speed diagram (c) Speed-density diagram

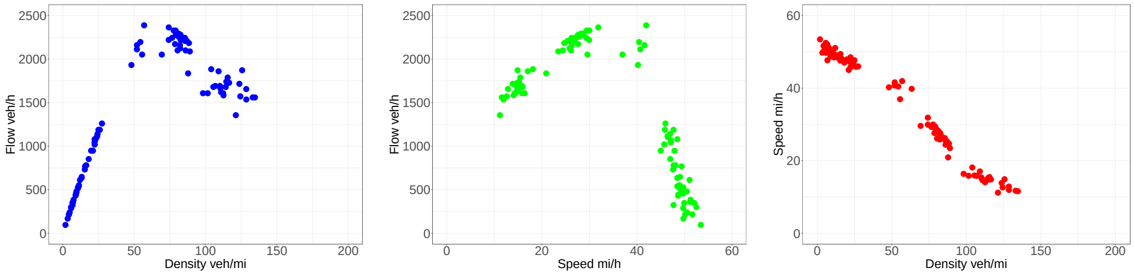


(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

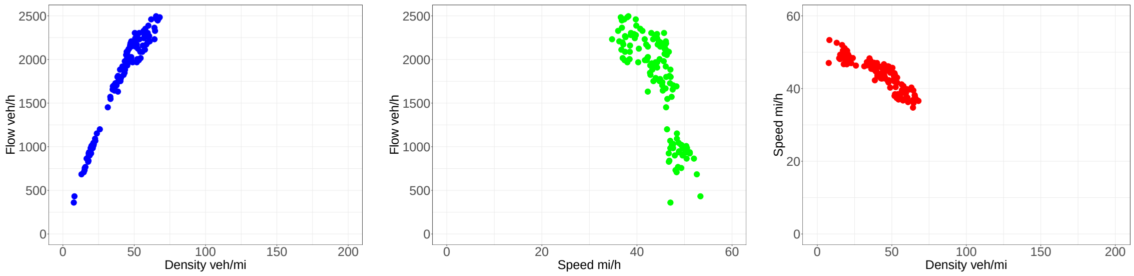
Figure 4.6: Flow-density-speed diagrams for Control Scenario 1 without platoons. (a)–(c) NB traffic direction. (d)–(f) SB traffic direction.

veh/h. This is due to the platoon implementation, which achieves smaller inter-vehicular distances leading to higher road density.

Furthermore, an improvement in traffic congestion can be seen for the platoon traffic scenario. The speed-density diagram provides an insight about the traffic conditions at each simulation. Figure 4.5f shows that most of the data are seen around 50 veh/mi as a density and 40-50 mi/h, which

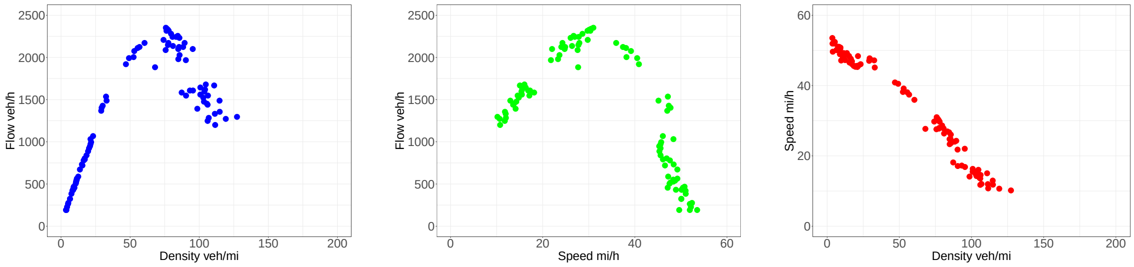


(a) Flow-density diagram (b) Flow-speed diagram (c) Speed-density diagram

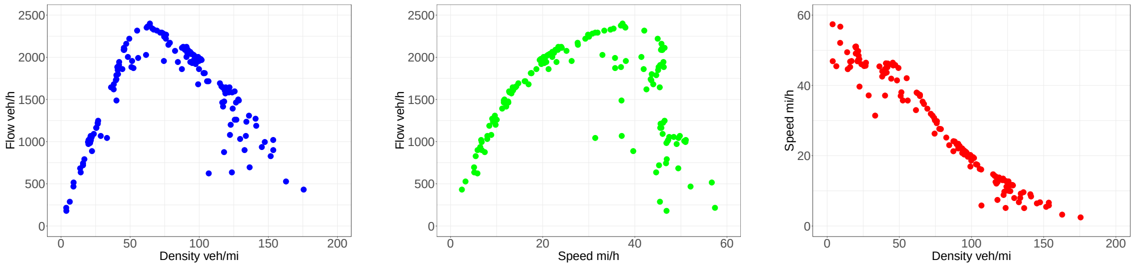


(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

Figure 4.7: Flow-density-speed diagrams for Control Scenario 1 with platoons. (a)–(c) NB traffic direction. (d)–(f) SB traffic direction.



(a) Flow-density diagram (b) Flow-speed diagram (c) Speed-density diagram

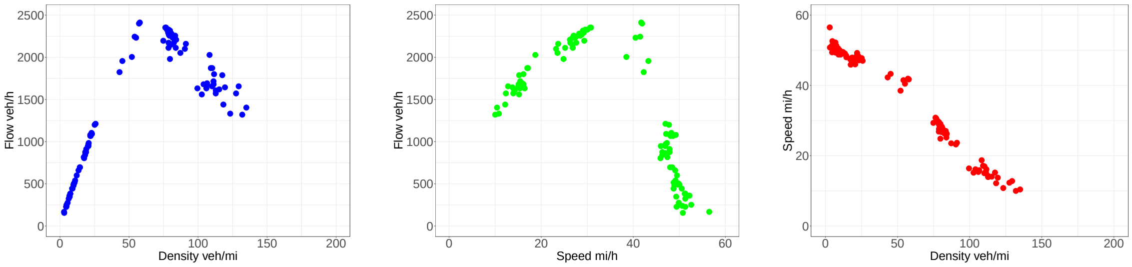


(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

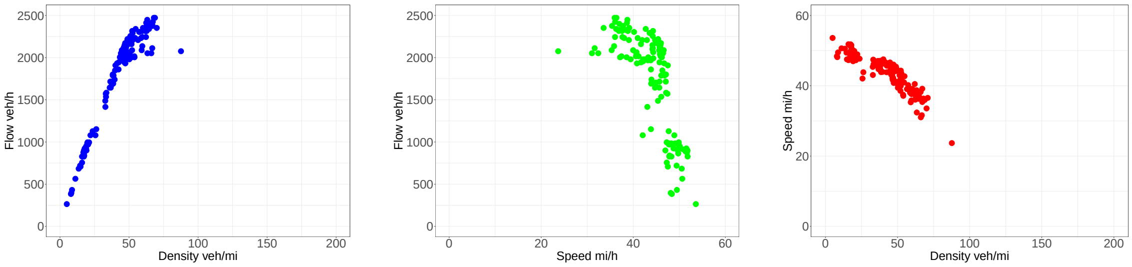
Figure 4.8: Flow-density-speed diagrams for Control Scenario 2 without platoons. (a)–(c) NB traffic direction. (d)–(f) SB traffic direction.

indicates that there was a smaller traffic congestion compared to the other scenario. Additionally, by analyzing the flow-speed diagrams, it is clearly depicted that for the scenario that involves the platoons higher traffic speed arises for the same traffic flows, leading to the conclusion that there is less traffic congestion.

Concerning the Control scenario 1, which involves the RLS that utilizes data from inductive-loop detectors, further enhancement in traffic conditions can be observed. Firstly, comparing the



(a) Flow-density diagram (b) Flow-speed diagram (c) Speed-density diagram



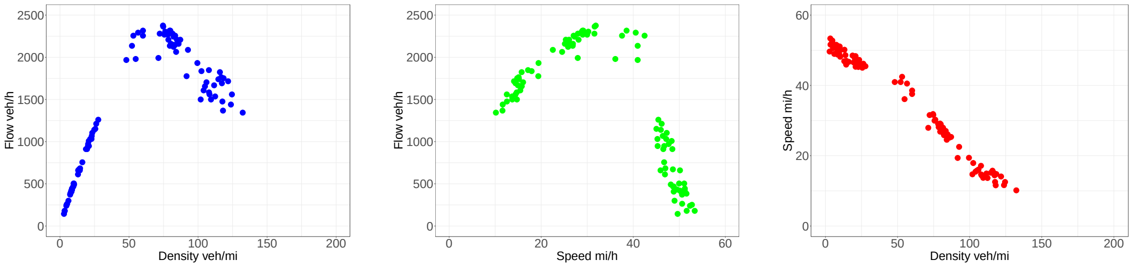
(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

Figure 4.9: Flow-density-speed diagrams for Control Scenario 2 with platoons. (a)–(c) NB traffic direction. (d)–(f) SB traffic direction.

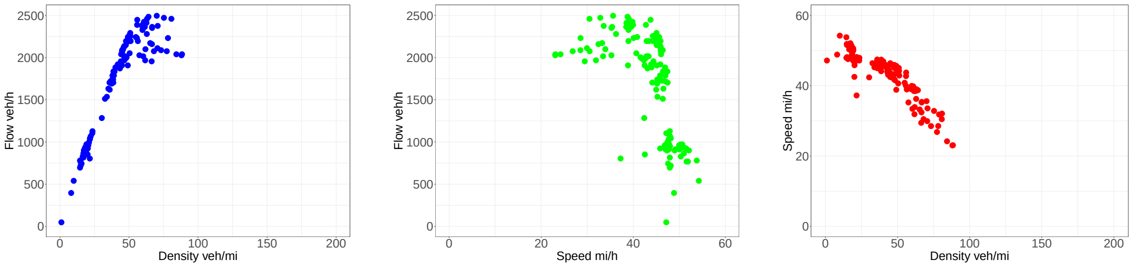
two scenarios that simulate platoon or non platoon traffic, a similar behaviour can be observed as the previous control scenario from Figure 4.6 and 4.7. Notably, the traffic that includes only human-driven car shows an increase in road congestion comparing with the platoon involved traffic. Furthermore, comparing the two control scenarios its is clearly observed that the implementation of the RLS increases dramatically the traffic performance. By analyzing the diagrams from Figure 4.7 it can be seen that the traffic congestion is almost eliminated. Specifically, for the SB current the vehicles moves mostly without traffic congestion ahead and in free flow speed. This is depicted clearly by the flow-speed and speed-density diagrams. Additionally, only low road densities prevail to the majority of the road. The differentiation between the SB and the NB flows is mostly related to the on-ramp, which is located from the NB side, due to the slight traffic congestion at the intersection between the ramp and the highway.

Control Scenario 2 implements an RSU to handle the data collection for the traffic density. This simulation is performed in order to demonstrate the benefits of intelligent vehicles, that can transmit data and connect with other vehicles and infrastructure. Figures 4.8–4.9 presents the traffic data that were collected for the two traffic scenarios. By observing the results, a similar behaviour can be noted with the Control Scenario 1. Firstly, the implementation of platoons inside the simulation greatly enhances the road conditions leading to congested-free traffic. Furthermore, the speed-density diagram from Figure 4.9f shows that the majority of the vehicles moves freely with relatively high speeds. Comparing Control Scenario 1 and Control Scenario 2 almost no differences can be observed by the presented diagrams.

Figures 4.10– 4.11 display the flow, speed and density diagrams for the Flatbed controller. A thorough examination of the presented figures shows a similar behaviour with the previous cases of platoon integration in the traffic flow. Both Scenario 3 and 4 presents high flow rate combined

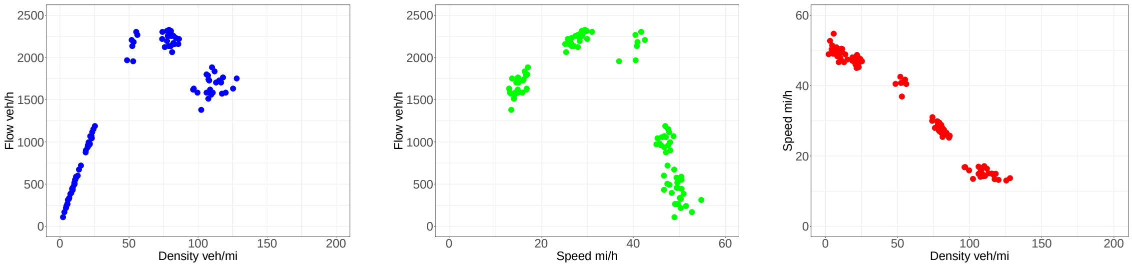


(a) Flow-density diagram (b) Flow-speed diagram (c) Speed-density diagram

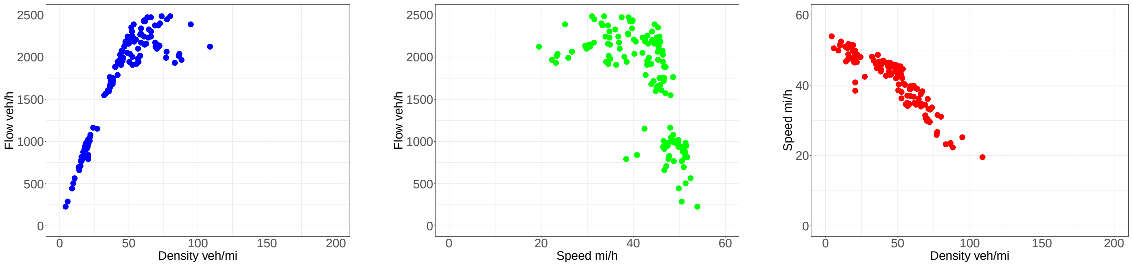


(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

Figure 4.10: Flow-density-speed diagrams for Control Scenario 3 with the flatbed controller. (a)–(c) NB traffic direction. (d)–(f) SB southbound flow.



(a) Flow-density diagram (b) Flow-speed diagram (c) Speed-density diagram

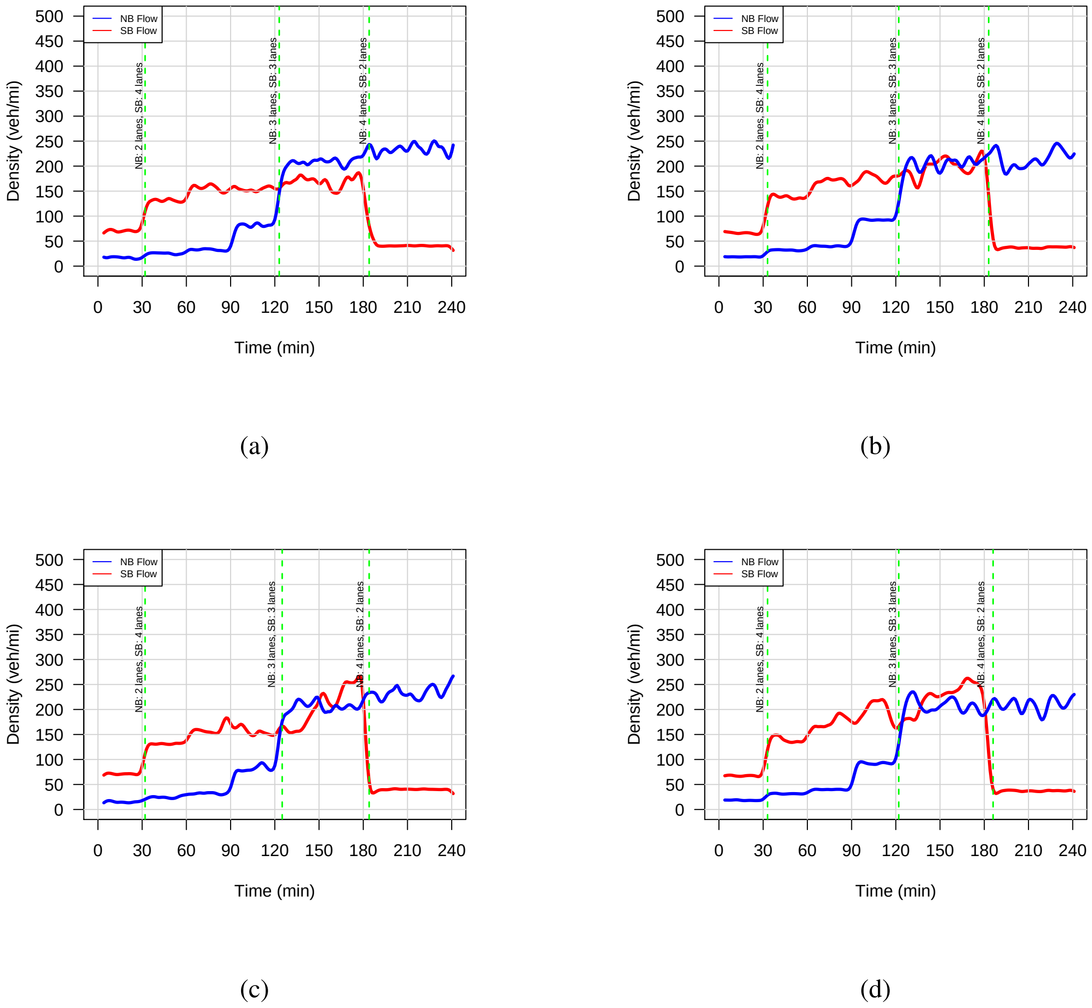


(d) Flow-density diagram (e) Flow-speed diagram (f) Speed-density diagram

Figure 4.11: Flow-density-speed diagrams for Control Scenario 4 with the flatbed controller. (a)–(c) NB traffic direction. (d)–(f) SB traffic direction.

with high vehicle's speeds and low road densities. By comparing the Figures 4.7e and 4.10e a slight differentiation can be observed. Specifically, in Figure 4.10e more dots are scattered at relative lower speed, hinting that the performance of the Flatbed platoon controller was slightly inferior compared with the proposed one of this thesis. The same behaviour can be described for the Figures 4.9e and 4.11e.

Figure 4.12 provides a better view about the performance of the RLS for the four control



(a)

(b)

(c)

(d)

Figure 4.12: Traffic densities and RLS operation with platooning control. (a) Control Scenario 1 with inductive-loop detector data, (b) Control Scenario 2 with RSU data, (c) Control Scenario 3 with inductive-loop detector data, (d) Control Scenario 4 with RSU data,

scenarios. Comparing the first two images, a small differentiation can be observed for the density of each flow, due to the data extraction method. As it was described before, Control Scenario 1 utilizes induction loop detectors to calculate the traffic density, while in contrast Control Scenario 2 utilizes an RSU. Both methods provide a good approximation of the road density in order for the RLS to operate. This can be described by the similar operation and decision times for the RLS. Specifically, Control Scenario 2 shows a slight faster response time for operation as it can calculate faster and more accurate the road density variations. The latest two figures shows a similar behaviour as the previous ones.

A further insight, about the performance of each Control Scenario, can be observed by the simulation statistics that are presented in Table 4.1. Concerning the Average Travel Time (ATT) for each scenario, which implies the average time needed from a vehicle to exit the simulation, it

Table 4.1: Simulation statistics.

Control Scenario	Average Travel Time (sec)	Average Travel Distance (m)	Average Speed (mi/h)	Total Simulated Vehicles
Control Scenario 0 without Platoons	233.2	2356.1	22.6	34657
Control Scenario 0 with Platoons	172.1 ↓ 26%	2354.6	30.6	35367
Control Scenario 1 without Platoons	216.4	2358.8	24.4	34895
Control Scenario 1 with Platoons	147.7 ↓ 14%	2355.3	35.7	35442
Control Scenario 2 without Platoons	215.2	2357.2	24.5	34981
Control Scenario 2 with Platoons	146.6 ↓ 1%	2355.7	35.9	35453
Control Scenario 3 flatbed Controller	149.1 ↑ 2%	2357.4	35.4	35440
Control Scenario 4 flatbed Controller	148.3 ↓ 1%	2357.8	35.6	35448

is obvious that by implementing platoons inside the traffic can greatly reduce the travel time need for the vehicles to pass the A38M. As was explained before, this is caused due to the reduction of road congestion, which allows vehicles to move more freely with higher speeds. The percentages around the ATT values shows the enhancement of traffic flow, compering with the previous Control Scenario that includes platoons. The green arrow represent a beneficial reduction of the travel time, while red represents an increase. The blue arrow compares the two traffic scenarios (platoons or no platoons) of Control Scenario 0, resulting in a 26% reduction of the ATT, only by inducing platoons inside the traffic. An additional huge reduction around 14%, can be observed by just simply enabling the RLS. Furthermore, as expected, the introduction of the RLS further enhance the traffic performance. Control Scenario 1 and Control Scenario 2 shows almost identical results, with the latest one providing a slight improvement to the ATT. Moving on, the Average Travel Distance (ATD) varies slightly for each simulation, due to the randomness of route selection for each vehicle. Moreover, by dividing the ATT with the ATD, the Average Travel Speed (ATS) can be acquired. The results are presented in mi/h in order to be compered with the above diagrams. Additionally, the differentiation of the Total Simulated Vehicles (TSV) for each simulation is caused due to the traffic congestion, which prevented the simulation to inject all the vehicles until its end.

4.4 Summary

In this chapter the simulation results were presented. Several cases were performed comparing simulations between human-driven cars and mix traffic scenarios that included platoons. Furthermore, a comparison between a non active and active Reversible Lane System was presented, proving that such systems as the RLS can greatly enhance the road performance. Additionally, the two data acquiring methods, which refers to the Inductive-Loop Detector method and the Road Side Unit, for the RLS were also simulated, providing almost similar results. In order to acquire a valid result for the proposed platooning control, an additional comparison with a well-know platooning control algorithm was also performed. The results showed that both controllers work very similar, generating almost identical results.

Chapter 5

Conclusion

The main objective of this thesis was the development, implementation, and evaluation of a platooning control algorithm, in a highway traffic scenario, combined with a Reversible Lane System (RLS) and a Road Side Unit (RSU). The implementation has included a full communication layer via the IEEE.802.11p protocol to allow automated vehicles to exchange information with the RSU and then decisions to be taken by the RLS.

The implementation of the platooning control algorithm was based on data provided by the platoon leader and the preceding vehicles. This was done to ensure string stability throughout the formation. Furthermore, the controller was based on the Constant Time Headway Policy combined with the leader's acceleration, in order to provide a constant space between each vehicle of the platoon. The design of the control algorithm was completed in a traffic free scenario with a sinusoidal input as the leader's acceleration. Numerous simulations were performed in order to optimize the gains of the algorithm. Additionally, in order to check the safety of the platoon controller, a second analysis was performed to simulate an emergency braking scenario. The results from both type of simulations led to the final parameter values of the controller.

Besides the implementation of the platooning control algorithm, an RLS was integrated for the A38(M) Aston Expressway motorway located in Birmingham, United Kingdom. The main objective was to evaluate the traffic performance by introducing platoons inside the simulations. The results showed that integration of the RLS greatly enhance the traffic conditions. Furthermore, when platoons were also involved a complete road congestion elimination was detected, allowing for the vehicles to move freely.

Finally, in this thesis an RSU was implemented, in order to evaluate the RLS performance, by utilizing data from connected vehicles. The main goal of this was to exploit the ability of vehicles to transmit data and provide an accurate estimation of the road density, in order to inform the RLS. After the result's analysis, the case scenario which introduced the RSU seemed to slightly enhance the traffic performance. This implementation was chosen as the advantages and capabilities of this technology is thought to be very important. Such technologies serves not only for traffic densities estimation, but also for road condition alerts, collisions and route alteration, on and off ramp guidance for an increased traffic performance etc.

In this thesis, several topics were not entirely covered, as the work and complexity of those would be immense. Most of them refers to the communication networks involved in a road traffic infused with platoons. The first part concerns the safety and privacy of the data transmitted by the connected vehicles. A simple communication protocol was introduced in this thesis to achieve data transmission between the RSU, without taking account the safety procedures required between a proper communication hand shake. Robust and efficient protocols for vehicle and infrastructure communications are required, in order for such technologies to be available in the future, ensuring safety and privacy for each user.

The second part concerns a further enhancement of the data acquiring method for the densities of the road. Multi-hop protocols involving data dissemination might be an ideal technology concerning an RLS. The development of a multi-hop protocol that will disseminate through the entire highway, can achieve an accurate estimation of the entire road density, without being limited by the range of the V2V or V2I communication.

Finally, the formation and breaking of platoons during the RLS area should be investigated thoroughly. It is very essential to understand the impact to the performance of the RLS with a dynamic formation of platoons and how such behaviour can compromise the safety of the passengers. Whether vehicles will be allowed or not to enter or leave a platoon during an RLS area or even create a completely new one, should be investigated.

Appendix A

OMNeT++

One of the most important aspects of this thesis was involved around *vehicular ad-hoc networks* (VANETS). In order to incorporate the vehicular communications to this work, the *OMNeT++ Discrete Event Simulator* was chosen [49]. The main focus of this simulators is to realistically simulate vehicular nodes and communications, providing additionally a well established compatibility with the traffic simulator SUMO. Furthermore, additional two software extensions where used. The first one refers to Veins, which is an open source vehicular network simulation framework [43]. By utilizing Veins, a bidirectional coupling between SUMO and OMNeT++ is easily achievable and extendable to incorporate vehicular networks and applications [44]. Furthermore, the platooning extension for Veins, known as Plexe [39] , was also utilized in order to implement platoons inside the simulation. Plexe offers an already established suite of platoon controllers, realistic networks and vehicle dynamics simulations. Following, two codes of this thesis concerning the vehicular networks, are presented.

A.1 RSU Application Layer

```
//Function that handles the WAVE Short Messages and beacons
RSU::WSM () {
    //If statement that checks if the message is intended for
   the RSU
    if (PSID==10){
        Getting Vehicles data from the transmitted message,
        like the vehicles id, speed, lane and edge of the road;
        //If statement for checking the direction of the vehicle
        if (Veh_Road_ID==SB_Road_ID) {
            Computes the total received number of vehicles
            that have communicated with the RSU for the SB;
        } else if (Veh_Road_ID=NB_Road_ID){
```

```
            Computes the total received number of vehicles
            that have communicated with the RSU for the NB;
        }
    }
}//Function that handles all the RSU computations
RSU::SelfMsg() {
    //If statement that sends the RSU beacons every beacon
   interval
    if (message=="Send Beacons"){
        Create and send down the beacon for every
        receiver with a PSID=11;
        Gathering the vehicle counts every beacon time
        interval for an average density;
        Also resets all the counters for the next iteration;
        Schedules a self message for the next beacon time event;
    }//Else if statement that handles the data passing for the
   RLS
    else (message=="Send RLS") {
        Pass density data for each flow to the appropriate ned
   variable,
        in order for the Manager to be able to access it;
        Writing down the data collected from the RSU;
        Resetting all the variable for the next iteration;
        Scheduling a self message for the next data passing
   iteration;
    }
}
```

A.2 Connected Vehicle's Application Layer

```
//Function that is responsible for receiving the beacons
AppLayer::WSM() {
    //If statement that checks if the received message comes
    //from RSU (with a PSID=11)
    if (PSID==11) {
      Schedules a self message with the default 0.5 second delay
    plus
      with the further random delay from 0 up to 2 seconds;
    }
```

```
}//Function that is responsible for the transmission of the
   vehicles data
AppLayer::SelfMsg() {
    Fills and send down the message with the necessary
   information
    like the vehicles Id, PSID, speed, lane and edge of the road
        }
```

Appendix B

SUMO

The microscopic road traffic simulator SUMO (Simulation of Urban MObility) was chosen in this thesis to incorporate traffic simulations [30]. This simulator is widely established in the scientific community, allowing for it to be easily extended with a wide variety of traffic scenarios [20]. Additionally, SUMO is already compatible with the discrete event simulator OMNeT++, which is responsible for the vehicular communication simulations. Furthermore, several platoon control algorithms are already included in the official software, allowing for an easy access and extension to the platoon models.

In order to simulate the Reversible Lane System inside SUMO, two different edges, concerning each road flow, were overlapped at the point of the buffer. Specifically, only one lane from each edge was overlapped in order for the buffer lane to be operated from both directions. Following, the Induction Loop Detector and Reversible Lane code is presented. Although both of these codes handles data and commands through SUMO, for simplicity reasons they were implemented from the Veins side, in order for the wireless data to be more easily accessible.

B.1 Reversible lane system

```
TraCIScenarioManager::RLS() {
    Access density data either from the induction loops or the
   RSU;

    //Decision making if statement
    if ($\rho_A$ >$\gamma\rho_{crit}$ and $\rho_B$ <=$\gamma^r\rho^r_{crit}$ and T_interval==true) {
        Closes the buffer and the median lane of the opposite
   current;
        Registers the time decision;
    } else if ($\rho_B$>$\gamma\rho_{crit}$and $\rho_A$<=$\gamma^r\rho^r_{crit}$  and T_interval==true) {
```

```
     Closes the buffer and the median lane of the opposite
current;
     Registers the time decision;
 }

 //Closing buffer lane when its not needed
 if ($\rho_A<\gamma^r\rho^r_{crit}$ and T_interval==true) {
     Closes the buffer lane when the A flow is below the
critical;
     Registers the time decision;
 } else if ($\rho_B<\gamma^r\rho^r_{crit}$ and T_interval==true) {
     Closes the buffer lane when the B flow is below the
critical;
     Registers the time decision;
 } else if ($\rho_A>\gamma\rho_{crit}$) and $\rho_B>\gamma\rho_{crit}$and T_interval==true) {
     Closes the buffer lane when both flows density are
     above the critical;
     Registers the time decision;
 }

 //Calculation of buffer lane occupancy
 if (Buffer lane is about to open for either the flows) {
     Checks if the buffer lane is empty;
     if (Buffer lane is about to open for A) {
        Checks if the B flows median lane is empty;
     } else if (Buffer lane is about to open for A) {
        Checks if the A flows median lane is empty
     }
 }

 //Flow check and Buffer lane activation
 if (Buffer lane is about to open for A and Buffer lane is
empty and B Median lane is empty) {
     Opens buffer lane for A;
 } else if (Buffer lane is about to open for B and Buffer
lane is empty and A Median lane is empty) {
     Opens buffer lane for B;
 }

 //If statement that handles when the RLS can make a decision
 depending on the T_optimal (10min;)
```

```
    if (simulationTime>=Decision Time + T_optimal) {
        T_interval=true;
    } else if (simulationTime<Decision Time + T_optimal) {
        T_interval=false;
    }
```

B.2 Implementation of inductive loop detectors

```
//Function that is responsible for the data gathering of the
   induction loop detectors
TraCIScenarioManager::LoopDetectors() {
    Calculates the total number of vehicle that have passed over
    the induction loop detectors;
    if (time==Induction_interval) {
        Pass the calculated data to the RLS, every Induction
        time interval (e.g. 1 minute);
        Reset all parameters;
   }
}
```

Bibliography

[1] ACEA. ACEA Report Vehicles in use Europe 2018. *European Automobile Manufacturers Association*, pages 1–19, 2018.

[2] M. Al-qutwani and X. Wang. Smart traffic lights over vehicular named data networking. *Information*, 10(3), 2019.

[3] M. S. U. Alam, S. Iqbal, M. Zulkernine, and C. Liem. Securing vehicle ecu communications and stored data. In *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, pages 1–6, 2019.

[4] A. Ali, G. Garcia, and P. Martinet. The flatbed platoon towing model for safe and dense platooning on highways. *IEEE Intelligent Transportation Systems Magazine*, 7(1):58–68, 2015.

[5] A. A. Ali. *CPS Security: Vehicle Platooning System Identifying & Modelling Cyber-Attacks*. PhD thesis, School of Computing Science, Newcastle University, 10 2016.

[6] K. Ampountolas, J. A. Dos Santos, and R. C. Carlson. Motorway Tidal Flow Lane Control. *IEEE Transactions on Intelligent Transportation Systems*, 21(4):1687–1696, 2020.

[7] A. Balador, C. Bai, and F. Sedighi. A comparison of decentralized congestion control algorithms for multiplatooning communications. In *2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, pages 674–680, 2019.

[8] R. H. R. H. Barnard. *Road vehicle aerodynamic design : an introduction / R.H. Barnard.* MechAero, St Albans, 2nd ed. edition, 2001.

[9] C. Bergenhem, S. Shladover, E. Coelingh, C. Englund, and S. Tsugawa. Overview of platooning systems. *Proceedings of the 19th ITS World Congress, Oct 22-26, Vienna, Austria (2012)*, 01 2012.

[10] K. Bhasin. A review paper on anti-lock braking system (abs) and its future scope. *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, 7:372–375, 08 2019.

[11] E. Chan. *SARTRE Automated Platooning Vehicles*, pages 137–150. Wiley, 06 2016.

[12] R. Chen, W. Jin, and A. Regan. Broadcasting safety information in vehicular networks: issues and approaches. *IEEE Network*, 24(1):20–25, 2010.

[13] X. Cheng, L. Yang, and X. Shen. D2d for intelligent transportation systems: A feasibility study. *IEEE Transactions on Intelligent Transportation Systems*, 16(4):1784–1793, 2015.

[14] S. Darbha and J. Hedrick. Constant spacing strategies for platooning in automated highway systems. *Journal of Dynamic Systems Measurement and Control-transactions of The ASME*, 121, 09 1999.

[15] S. Darbha, J. Hedrick, C. Chien, and P. Ioannou. A comparision of spacing and headway control laws for automatically controlled vehicles1. *Vehicle System Dynamics*, 23:597–625, 1994.

[16] S. Darbha, S. Konduri, and P. R. Pagilla. Benefits of v2v communication for autonomous and connected vehicles. *IEEE Transactions on Intelligent Transportation Systems*, 20(5):1954–1963, 2019.

[17] S. Darbha and C. Transportation. String stability of interconnected systems : an application to platooning in automated highway systems /. *Institute of Transportation Studies, UC Berkeley, Institute of Transportation Studies, Research Reports, Working Papers, Proceedings*, 01 1997.

[18] A. Davila, E. Dios, E. Aramburu, and A. Freixas. Environmental benefits of vehicle platooning. *Symposium on International Automotive Technology 2013*, 5, 01 2013.

[19] M. Dikmen and C. Burns. Trust in autonomous vehicles: The case of tesla autopilot and summon. In *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 1093–1098, 2017.

[20] J. Erdmann. Lane-changing model in sumo. *Proceedings of the SUMO2014 Modeling Mobility with Open Data*, 24, 05 2014.

[21] A. Eskandarian. *Handbook of Intelligent Vehicles*, pages 491–535. Springer, 01 2012.

[22] C. European. A European Strategy for Low-Emission Mobility. *European Commission (EC)*, 2016.

[23] Eurostat. Road accident fatalities - statistics by type of vehicle. *Statistics explained*, 2018.

[24] M. Guiggiani. *The Science of Vehicle Dynamics*. Springer, 01 2014.

[25] L. Hobert. A study on platoon formations and reliable communication in vehicle platoons, 08 2012.

[26] S. International. Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. In *Recommended Practice J3016*, 2016.

[27] D. P. I. I. Ismail and M. H. F. Ja'afar. Mobile ad hoc network overview. In *2007 Asia-Pacific Conference on Applied Electromagnetics*, pages 1–8, 2007.

[28] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil. Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions. *IEEE Communications Surveys Tutorials*, 13(4):584–616, 2011.

[29] P. Kavathekar and Y. Chen. Vehicle platooning: A brief survey and categorization. *Proc. of the ASME Design Engineering Technical Conference*, 3, 2011.

[30] D. Krajzewicz, G. Hertkorn, C. Feld, and P. Wagner. Sumo (simulation of urban mobility); an open-source traffic simulation. *4th Middle East Symposium on Simulation and Modelling (MESM2002)*, pages 183–187, 01 2002.

[31] G. Naus, R. Vugts, J. Ploeg, M. Molengraft, and M. Steinbuch. String-stable cacc design and experimental validation: A frequency-domain approach. *Vehicular Technology, IEEE Transactions on*, 59:4268 – 4279, 12 2010.

[32] L. Peppard. String stability of relative-motion pid vehicle control systems. *IEEE Transactions on Automatic Control*, 19(5):579–581, 1974.

[33] J. Ploeg, B. T. M. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer. Design and experimental evaluation of cooperative adaptive cruise control. In *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, pages 260–265, 2011.

[34] J. Ploeg, D. P. Shukla, N. van de Wouw, and H. Nijmeijer. Controller synthesis for string stability of vehicle platoons. *IEEE Transactions on Intelligent Transportation Systems*, 15(2):854–865, 2014.

[35] R. Rajamani. *Vehicle Dynamics and Control*. Springer, Boston, MA, 2nd edition, 2012.

[36] A. C. Regan and R. Chen. *Vehicular ad hoc networks*. Elsevier Ltd, 2015.

[37] M. Sauter. *Long Term Evolution (LTE) and LTE-Advanced*, pages 235–326. Wiley, 2014.

[38] I. Savage. Comparing the fatality risks in united states transportation across modes and over time. *Research in Transportation Economics*, 43(1):9–22, 2013.

[39] M. Segata, S. Joerer, B. Bloessl, C. Sommer, F. Dressler, and R. L. Cigno. Plexe: A platooning extension for Veins. In *2014 IEEE Vehicular Networking Conference (VNC)*, pages 53–60, 2014.

[40] S. A. A. Shah, E. Ahmed, M. Imran, and S. Zeadally. 5g for vehicular communications. *IEEE Communications Magazine*, 56(1):111–117, 2018.

[41] S. Sheikholeslam and C. Desoer. Longitudinal control of a platoon of vehicles with no communication of lead vehicle information: a system level study. *IEEE Transactions on Vehicular Technology*, 42:546–554, 1993.

[42] S. E. Shladover. Path at 20—history and major milestones. *IEEE Transactions on Intelligent Transportation Systems*, 8(4):584–592, 2007.

[43] C. Sommer, D. Eckhoff, A. Brummer, D. S. Buse, F. Hagenauer, S. Joerer, and M. Segata. Veins – The open source vehicular network simulation framework. In A. Virdis and M. Kirsche, editors, *Recent Advances in Network Simulation*. Springer, 2019.

[44] C. Sommer, R. German, and F. Dressler. Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis. *IEEE Transactions on Mobile Computing*, 10(1):3–15, 01 2011.

[45] M. Soyturk, K. N. Muhammad, M. Avcil, B. Kantarci, and J. Matthews. Chapter 8 - from vehicular networks to vehicular clouds in smart cities. In M. S. Obaidat and P. Nicopolitidis, editors, *Smart Cities and Homes*, pages 149–171. Morgan Kaufmann, Boston, 2016.

[46] A. Stamatellos. Οδηγός του μαϑήματος: Μηχανές Εσωτερική Καύσης. *title* = Οδηγός του μαϑήματος*:* Μηχανές Εσωτερική Καύσης, 02 1994.

[47] S. Tsugawa, S. Kato, and K. Aoki. An automated truck platoon for energy saving. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4109–4114, 2011.

[48] P. Varaiya. Smart cars on smart roads: problems of control. *IEEE Transactions on Automatic Control*, 38(2):195–207, 1993.

[49] A. Varga. The OMNET++ discrete event simulation system. *Proc. of the European Simulation Multiconference (ESM'2001)*, 9, 01 2001.

[50] S. Velupillai and L. Guvenc. Laser scanners for driver-assistance systems in intelligent vehicles [applications of control]. *IEEE Control Systems Magazine*, 29(2):17–19, 2009.

[51] Z. Wang, G. Wu, and M. J. Barth. A review on cooperative adaptive cruise control (cacc) systems: Architectures, controls, and applications. In *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, pages 2884–2891, 2018.

[52] B. Wolshon and L. Lambert. Reversible lane systems: Synthesis of practice. *Journal of Transportation Engineering*, 132(12):933–944, 2006.

[53] J. Wu, H. Sun, Z.-Y. Gao, and H. Zhang. Reversible lane-based traffic network optimization with an advanced traveller information system. *Engineering Optimization*, 41:87–97, 01 2009.

[54] B. Zhu, S. Yan, J. Zhao, and W. Deng. Personalized lane-change assistance system with driver behavior identification. *IEEE Transactions on Vehicular Technology*, 67(11):10293–10306, 2018.