Platooning of IVC-Enabled Autonomous Vehicles: Information and Positioning Management Algorithms, for High Traffic Capacity and Urban Mobility Improvement

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To my lovely wife

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Abstract

Urban traffic congestion is one of the major problems our cities face nowadays. The main challenge is to improve road capacity and avoid traffic congestion, under high vehicle density. This thesis aims to contribute for urban mobility improvement, using platooning of IVC-enabled autonomous vehicles. This way, new intraplatoon information management strategies to deal with safe and stable operation are proposed, as well as inter- and intraplatoon positioning management strategies with cooperative behavior to improve the efficiency of an advanced traffic management system.

New algorithms to mitigate communication delays are presented, and Matlab/Simulink-based simulation results are reported. We argue that using anticipatory information from both the platoon's leader and the followers significantly impacts on platoon string stability. The obtained simulation results suggest that the effects of communication delays may be almost completely canceled out. The platoon presents a very stable behavior, even when subjected to strong acceleration patterns.

When the communication channel is subjected to a strong load, proper algorithms may be selected, lowering network load and maintaining string stability. Upon emergency occurrences, the platoon timely response may be ensured by dynamically increasing the weight of the platoons' leaders data over the behavior of their followers. The simulation results suggest that the algorithms are robust under several demanding scenarios.

To assess if current intervehicle communication technology can cope with the proposed information-updating schemes, a research of its operation was conducted through a network simulator.

Inter- and intraplatoon positioning management strategies with cooperative behavior are also addressed, to improve the efficiency of an advanced traffic management system. Novel algorithms to ensure high traffic capacity are presented, and Matlab/Simulink-based simulation results are reported.

Using underneath the new proposed algorithms to mitigate communication delays with anticipatory information, we consider a constant spacing between platoons' leaders as a fundamental condition to attain high traffic capacity. As such, new algorithms to maintain interplatoons' leaders constant spacing are proposed, as well as novel algorithms allowing vehicles to enter the main track cooperatively. Furthermore, a new set of algorithms to improve safety is also presented.

A novel architecture was developed, where each vehicle consists of two distinct modules: a leader and a follower. Based on Matlab/Simulink simulations of several scenarios, the new algorithms were assessed and the simulation results presented, confirming that the proposed algorithms ensure high traffic capacity and vehicle density, and avoid traffic congestion. These features were validated through simulations performed on a novel SUMO-based simulation platform.

The simulation results proved that the proposed algorithms lead to a clear benefit of a platooning system when compared to bus and light rail-based transit systems.

Keywords: Advanced traffic management systems, anticipatory information, autonomous vehicles, cooperative behavior, high traffic capacity, intervehicle communications, network simulation, platoon positioning management, platooning, platoons' leaders constant spacing, safety improvement, simulation, traffic information management, traffic simulation.

Resumo

O congestionamento de tráfego urbano é um dos problemas mais prementes que as nossas cidades enfrentam atualmente. O maior desafio que se coloca consiste em melhorar a capacidade das vias e evitar os congestionamentos, na presença de alta densidade de veículos. Esta tese procura contribuir para a melhoria da mobilidade urbana, com a utilização de *platoons* de veículos autónomos com comunicações entre veículos. Assim, são propostas novas estratégias de gestão de informação dentro dos *platoons* para manter uma operação segura e estável, bem como estratégias de gestão de posicionamento de veículos com comportamento cooperativo entre e dentro de *platoons* com o intuito de melhorar a eficiência de um sistema avançado de gestão de tráfego.

São apresentados novos algoritmos para mitigar os atrasos das comunicações, bem como resultados de simulações efetuadas em Matlab/Simulink. Afirmamos que a utilização de informação antecipada, tanto por parte do líder do *platoon* como dos seus seguidores, produz uma melhoria muito significativa na estabilidade da cadeia de veículos de um *platoon*. Os resultados obtidos através de simulações indicam que os efeitos dos atrasos das comunicações podem ser quase completamente anulados. O *platoon* apresenta um comportamento muito estável, mesmo quando sujeito a fortes acelerações.

Quando o canal de comunicação está muito ocupado, podem ainda ser selecionados algoritmos adequados, para atenuar a carga do canal de comunicação e manter a estabilidade da cadeia de veículos. Na hipótese de ocorrerem situações de emergência, a resposta pronta do *platoon* pode ser assegurada pelo aumento do peso da informação dos líderes dos *platoons* sobre os respetivos seguidores, efetuada de forma dinâmica. Os resultados de simulação sugerem que os algoritmos são robustos em diversos cenários exigentes.

Para proceder à avaliação da capacidade das atuais tecnologias de comunicação entre veículos de lidarem com os esquemas de atualização de informação propostos, foram também efectuadas simulações num simulador de redes.

Nesta tese são também apresentadas estratégias de gestão de posicionamento de veículos com comportamento cooperativo, entre e dentro de *platoons*, para melhorar a eficiência de um sistema avançado de gestão de tráfego. São apresentados novos algoritmos para garantir elevada capacidade de tráfego, e são relatados resultados de simulações efetuadas em Matlab/Simulink.

Com a utilização nas camadas inferiores do sistema dos novos algoritmos propostos para mitigar os atrasos das comunicações através de informação antecipada, consideramos como condição fundamental para a obtenção de elevada capacidade de tráfego o espaçamento constante entre os líderes dos *platoons*. Para tal, são propostos novos algoritmos para manter um espaçamento constante entre os líderes dos *platoons*, bem como novos algoritmos para permitir aos veículos a sua entrada na via de forma cooperativa. Além disso, também é apresentado um novo conjunto de algoritmos para aumentar a segurança. Foi desenvolvida uma nova arquitetura, onde cada veículo é composto por dois módulos: um líder e um seguidor. Os novos algoritmos foram avaliados através de simulações de vários cenários efetuadas em Matlab/Simulink e os resultados apresentados confirmam que os algoritmos propostos garantem elevada capacidade de tráfego e alta densidade de veículos, e evitam congestionamentos. Estas caraterísticas foram validadas através de simulações efetuadas numa nova plataforma de simulação baseada no simulador de tráfego SUMO.

Os resultados das simulações demonstraram que os algoritmos propostos conferem ao sistema de *platoons* uma evidente vantagem, quando comparado com sistemas de transporte baseados em autocarros e metros de superfície.

Palavras-chave: Antecipação de informação, aumento da segurança, comportamento cooperativo, comunicações entre veículos, elevada capacidade de tráfego, espaçamento constante entre líderes de *platoons*, gestão de informação de tráfego, gestão de posicionamento de *platoons*, simulação, simulação de redes, simulação de tráfego, sistemas avançados de gestão de tráfego, veículos autónomos.

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List of Abbreviations

3GPP	3rd Generation Partnership Project
4G	4th Generation Cellular Networks (e.g., LTE Advanced)
AC	Access Category (e.g., voice: AC_VO)
ACC	Adaptive Cruise Control
ACK	Acknowledgment (e.g., ACK packet)
ADAMS	ADAMS, Multibody Dynamics Simulation. ©MSC Software
AEV	Autonomous Electric Vehicle
AHS	Automated Highway System
AIFS	Arbitration Interframe Space
AIFSN	Arbitration Interframe Space Number
AIM	Autonomous Intersection Management
ATMS	Advanced Traffic Management System
CACC	Cooperative Adaptive Cruise Control
CALM	Communications Access for Land Mobiles (formerly: Communication Air Interface Long and Medium Range)
CAM	Cooperative Awareness Message
CASS	Cooperative Active Safety System
CCA	Cooperative Collision Avoidance
CCH	Control Channel (DSRC)
CEN	European Committee for Standardization (Comité Européen de Normalization)
CH	Channel

CICA	Cooperative Intersection Collision Avoidance
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access/Collision Detection
CW	Contention Window
DCF	Distributed Coordination Function
DGPS	Differential Global Positioning System
DIFS	Distributed Coordination Function Interframe Space
DSRC	Dedicated Short Range Communication
E1	E1-Type Simulated Loop Detector in SUMO
EDCA	Enhanced Distributed Channel Access
EMSG	Number of Extra Meters for Safety Gap
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FA	Follower Agent
FCD	Floating Car Data
GI	Guard Interval
GPS	Global Positioning System
HDM	Human Driver Driver (car following) Model
IDM	Intelligent Driver (car following) Model
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organization for Standardization
ITS	Intelligent Transportation Systems

IVC	Intervehicle Communications
IVHS	Intelligent Vehicle and Highway Systems
IVT	Intervehicle Time
LA	Leader Agent
LOS	Line-of-Sight Communications
LPT	Leader Positioning Time
LTE	Long Term Evolution
LTE-Advanced	Long Term Evolution Advanced (4G)
MAC	Medium Access Control
MAS	Multi-Agent Systems
MATLAB	MATLAB, The Language of Technical Computing. ©Mathworks
MSCFModel	Microscopic Simulation Car Following Model (SUMO)
MT	Meter Time
NAV	Network Allocation Vector
NLOS	Non-Line-of-Sight Communications
NS-2	NS-2 Network Simulator
NS-3	NS-3 Network Simulator
NVB	Number of Vehicles Positioned Before P that Left the Main Track
OBU	On-Board Unit (vehicle communications)
P	Previous Position in the Platoon of the Last Vehicle that Remained in the Main Track
PATH	California Partners for Advanced Transit and Highways
PHY	Physical Layer

PRT	Personal Rapid Transit
QoS	Quality of Service
RMPC	Robust Model Predictive Control
RSU	Roadside Unit (infrastructure communications)
RTF	Recovering Time Factor
RTS/CTS	Ready to Send/Clear to Send
SCH	Service Channel (DSRC)
SIFS	Short Interframe Space
SIMULINK	Simulink, Simulation and Model-Based Design. ©Mathworks
ST	Slot Time (DSRC)
STDMA	Self-configuring Time Division Multiple Access
SUMO	Simulation of Urban MObility Traffic Simulator
TC	Token Cycle
TCP	Transport Control Protocol
TCP/IP	Transport Control Protocol/Internet Protocol
TDMA	Time Division Multiple Access
TS	Time Slot
TW	Time to Wait
UC	Updating Cycle
UDP	User Datagram Protocol
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator Coordinate System
V2I	Vehicle to Infrastructure Communications

V2V	Vehicle to Vehicle Communications
V2X	Vehicle to Vehicle/Infrastructure Communications
VAM	Vehicle Actuation Moment
VANET	Vehicular Ad-hoc Network
VO	Voice access category (AC_VO)
WAVE	Wireless Access in Vehicular Environments
WGS84	World Geodetic System Standard for Use in Cartography (e.g., GPS)

Part I

Presentation

Chapter 1

Introduction

This thesis' research addresses urban traffic congestion, proposing a novel approach to improve mobility. The main challenge of our research is to maintain high traffic capacity and avoid traffic congestion, even when operating under high vehicle density.

Since human driven vehicles present traffic flow limits very difficult to surpass (see Fig. 4.2, in page 30), it was decided to use platoons with a constant spacing policy between vehicles, to allow a considerable increase of lane capacity, even when conservative values for vehicle speed are used. However this choice presented some constraints: the timings involved in the constant spacing platooning were not compatible to human drivers; communications did not present enough performance to allow such system to operate safely, due both to delays and reliability issues; safety operation of the system had to be ensured; system scalability should be possible, otherwise the system would be useless; vehicle autonomy had to be addressed, since fully automated vehicles controlled by a centralized system was unlikely to be successfully implemented; autonomous vehicles' interaction with conventional traffic had to be avoided; non-stop travels from origin-to-destination had to be addressed.

With these premises in mind, a comprehensible system is proposed in this thesis. The main problems were tackled from a bottom-up approach, dealing first with fundamental issues, such as communication delays and its reliability and, from that base and upon it, methods to deal with traffic congestion avoidance, high traffic capacity and safety were proposed. So, firstly we considered only IVC-enabled autonomous vehicles, to allow the use of more demanding spacing policies between vehicles, namely constant spacing policy. Then, we used the platooning approach, to increase maximum traffic flow. This way, it was possible to considerably increase the capacity of the track where vehicles evolve, while maintaining safety system operation. However, communication delays did not allow proper platoon string stability. So, we proposed new communication and information-updating algorithms to improve communication performance and mitigate communication delays' effects over platoon string stability. Afterwards, we addressed the urban traffic congestion problem, proposing algorithms to ensure that the proposed traffic system features could enable high traffic capacity and avoid traffic congestion. Moreover, safety concerns were always present, leading to new algorithms aiming to increase safe system operation. Finally, all system components were subjected to thorough simulation tests, to assess their correctness and appropriateness. For that purpose, three different simulators were used: Matlab/Simulink, the network simulator NS-3 and the Simulation of Urban MObility (SUMO) traffic simulator.

In this thesis we consider autonomous vehicles in the following context: all vehicles' devices used to acquire data (lidar, radar, communications, etc.) gather information that may be used by the vehicle to undertake actions following its own rules. This way, throughout this thesis, communications are not considered as a mean to remotely control each vehicle, but as a way to improve vehicle's information about its situation in the system, enabling it to act accordingly to the best information available.

1.1 Research Goals

Our main goals were:

- **Improve urban mobility.** Although many valid approaches could be undertaken, we have chosen the use of driverless vehicles using IVC with a high degree of vehicles' autonomy, since this approach could provide very high traffic flow values. So, new communication and information-updating algorithms were proposed, aiming to improve urban mobility.
- **Avoid traffic congestion.** One major problem when operating under very high vehicle density is due to speed variations, since it can cause traffic congestion. The use of IVC-enabled autonomous vehicles does not automatically ensure traffic congestion avoidance. So, new rules and new algorithms were proposed, aiming to enable safe and congestion-free traffic within urban areas.

To address the aforementioned goals, this research was conducted under the following specific goals:

- **Mitigate communication delays.** Under the demanding scenarios of vehicles' platooning using a constant spacing policy, IVC performance was a key issue. Our main concern was the unavoidable presence of communication delays and its impact on string stability. So, we proposed new communication and information-updating algorithms that could mitigate communication delays under the proposed platooning scenarios.

- **Improve traffic safety.** Vehicles evolving very close to each other rise concerns with respect to safe operation. To address this problem, we proposed algorithms to increase safe vehicle operation.
- **Achieve high traffic capacity.** This is a very important goal, since urban mobility improvement closely depends on its achievement. So, we presented new algorithms, aiming to enable high traffic capacity under high vehicle density.

To achieve our goals, it was necessary to promote the gathered use of several different fields of knowledge, such as traffic, communications, simulation, control, autonomous vehicles and energy (see Table. 4.1, in page 26). Since several problems had to be tackled, our work encompassed different fields of knowledge to achieve results that could enable new contributions for traffic mobility improvement.

1.2 Key contributions

Our key contributions are listed bellow, which correspond to the upper six layers of Fig. 1.1 and 2.1.

- **Communication Algorithms.** Intervehicle communications (IVC) are promising technologies to foster widespread implementation and use of ITS components. DSRC is a prominent ITS communication technology. So, we decided to verify if DSRC was able to operate under our novel information-updating algorithms. To improve DSRC performance under the platooning scenario, we proposed and implemented DSRC high-level modifications, using time slots, aiming to avoid packet collisions within vehicle platoons, and transmitting both in broadcast and in unicast. To assess DSRC behavior, a simulation scenario was then developed with NS-3 simulator [Fernandes 2012].
- **Information Management Algorithms.** Communication delays are commonly unavoidable. However, very small communication delays may have a significant impact on a vehicle platoon string stability. So, if we were going to use a platooning system with a constant spacing policy, communication delays had to be addressed and its effects over platoon string stability mitigated. To achieve this goal, new

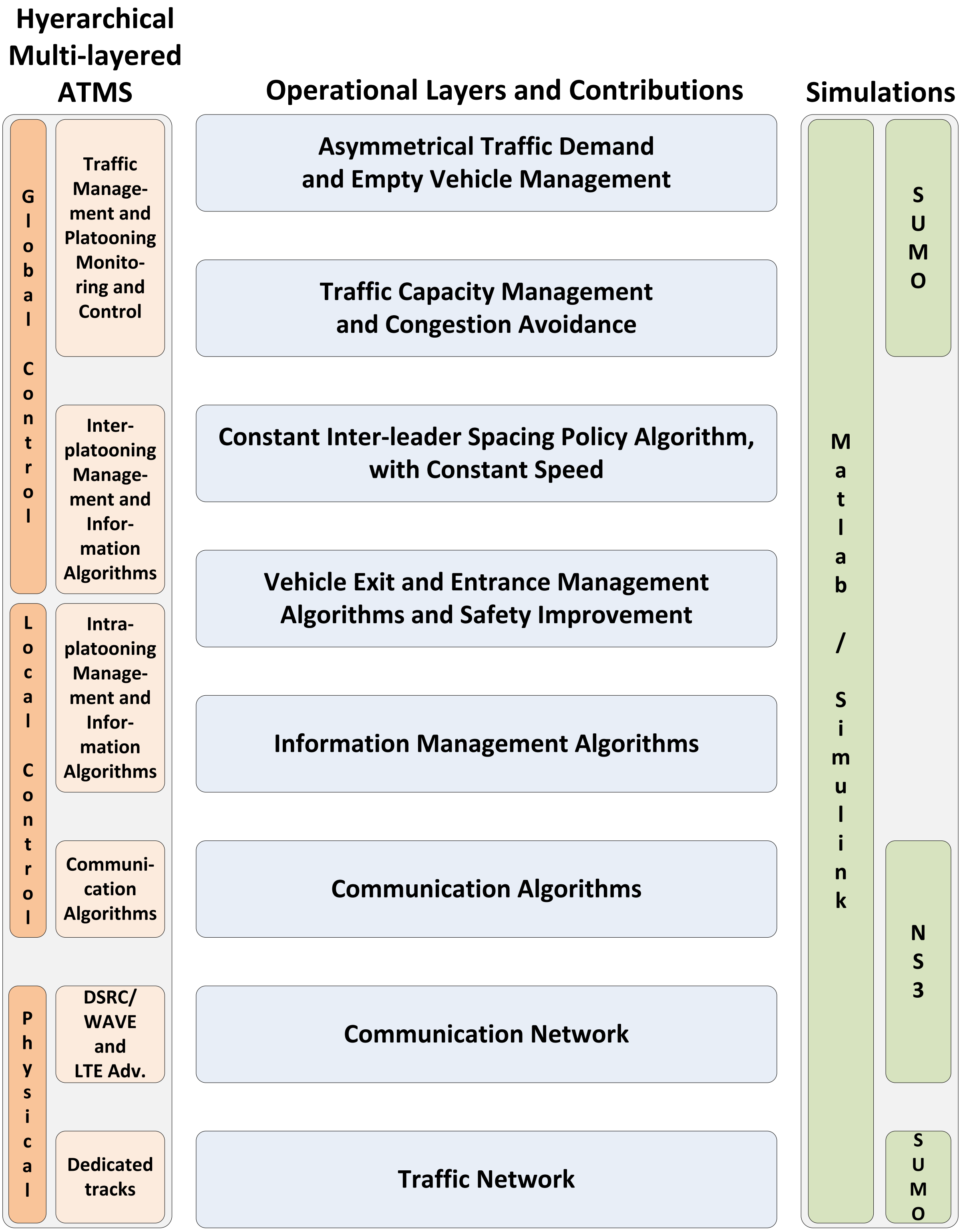

Figure 1.1: Thesis contributions

algorithms using anticipatory information were proposed and assessed. The results proved that the new information-updating algorithms could mitigate communication delays, avoiding their effects on platoon string stability [Fernandes 2012].

- **Constant Interleader Spacing Policy Algorithm, with Constant Speed.** Using driverless vehicles is not, by itself, a guaranty that traffic congestion will not occur. And high traffic density does worsen the situation. So, we proposed new algorithms, aiming to enable traffic congestion avoidance while maintaining a high traffic capacity. For that purpose, we developed new platoon positioning management algorithms, using agent-based concepts to achieve our goals [Fernandes sbmt].

- **Vehicle Exit and Entrance Management Algorithms and Safety Improvement.** We addressed the problem of vehicles exiting the main track. We presented new algorithms to perform exit maneuvers safely [Fernandes sbmt]. Another problem that we addressed was related to the entrance of vehicles in the main track, and the platoon formation. So, we presented new algorithms to allow vehicles to enter the main track cooperatively, by communicating and coordinating their entrance with the vehicles evolving on the track [Fernandes sbmt]. Additionally, the subsequent platoon formation was also addressed. Since exiting and entrance maneuvers may rise safety concerns, new algorithms to improve vehicles' safety when performing those maneuvers in a platoon, were also developed, presented and assessed [Fernandes sbmt].

- **Traffic Capacity Management and Congestion Avoidance.** We developed a new simulation scenario, with a complete platooning system using off-line stations, in SUMO traffic simulator [Fernandes sbmt], to validate traffic capacity improvement and congestion avoidance of the simulated platooning system.

- **Asymmetrical Traffic Demand and Empty Vehicle Management.** With the aforementioned scenario, an asymmetrical traffic demand with empty vehicle management was implemented and assessed [Fernandes sbmt].

- **Simulations.** Simulations are of most importance to assess new systems, as the one proposed, since its real implementation for testing purposes is not usually viable. However, to allow appropriate system assessment, simulators must be reliable and validated. Since there are no simulators prepared to simultaneously assess all problems under study, we selected the appropriate simulator for each scenario under testing. So, the following simulators were used:

- **Matlab/Simulink.**

  Matlab/Simulink are probably the most known software tools to simulate and test a variety of research fields. That is why we chose these tools to assess the main algorithms proposed in this work. To do so, we developed new models [Fernandes 2012] to test the information-updating algorithms, and further developed those models with agent-based concepts [Fernandes sbmt] to implement and assess platoon positioning management algorithms, algorithms for cooperatively vehicle's entrance and exiting, algorithms for platoon formation, as well as algorithms for safety improvement.
- **NS-3.** NS-3, and the former NS-2, are probably the most known open source communication network simulators in use by the research community. We used NS-3 to put DSRC to test, although the DSRC protocol is neither completely implemented in NS-3 nor in NS-2. So we had to proceed with the necessary adjustments to ensure that the scenario implementation was reliable and the results realistic. To achieve these goals, new features were added to the NS-3 simulator [Fernandes 2012].
- **SUMO.** SUMO is a well known project of an open source microscopic traffic simulator. Its development exists for over a decade, and most of its functionalities are already validated by several research projects. However, all scenarios and assumptions are based on human driven vehicles, since SUMO uses only human-based car following models. As such, we implemented and tested a new car following model in SUMO, to simulate platoons of autonomous vehicles under a constant spacing policy [Fernandes 2010]. Moreover, that improvement enabled us to assess traffic capacity assumptions using platoons. Additionally, we developed a new simulation scenario, with a complete platooning system using off-line stations [Fernandes sbmt]. With this scenario, an asymmetrical traffic demand with empty vehicle management was implemented and assessed.

CHAPTER 2

Background and Research Approach

This thesis is based in a thorough research involving diverse fields of knowledge (see Table 4.1, in page 26), and started four and half years ago. The main research goals, urban mobility improvement and traffic congestion avoidance, were always present, leading the path to several research lines, as described in Sections 2.1 and 2.2. A comprehensive map of the thesis is also presented in Section 2.3.

2.1 Research Lines Encompassing Several Fields of Knowledge

Communications were one of the first themes to be addressed. IVC, particularly DSRC/WAVE [IEEE 2010c], [IEEE 2010a], [IEEE 2010b], were analyzed in a throughout way, and a literature review was conducted [Fernandes 2007]. Meanwhile, traffic and network simulators were also subject of research. Several traffic simulators were analyzed, such as FreeSim [Miller 2007], Open-Source Microscopic Traffic Simulator [Treiber 2010], Transims [Transims 2012], and SUMO [Krajzewicz 2006], as well as network simulators, such as NS-2 [NS-2 2012], NS-3 [NS-3 2012], JiST/Swans [Barr 2011], OMNeT++ [Omnet 2012] and NCTuns [Wang 2007]. Methods to link these two type of simulators were also investigated. Among them, IWIS [Jarupan 2008], Veins [Sommer 2011] (which linked OMNeT++ and SUMO) and TraNS [Piorkowski 2008] (which used TraCI [Wegener 2008] to link NS-2 to SUMO) were analyzed. However, these approaches revealed relatively low performance levels.

Another followed line of research was related to multi-agent systems (MAS). This approach is considered very promising on the study, assessment and implementation of novel traffic management systems [Wang 2005], and traffic simulation systems [Chen 2010]. So, a vast literature review of MAS systems in general, and multi-agent based traffic simulator systems in particular, was performed. Several agent-based platforms were also tested (Jade [Bellifemine 2003], Jadex [Pokahr 2003], Jack [AOS 2012], Prometeus [Padgham 2005]) and a new architecture proposed [Fernandes 2008]. However, it was found that some of the MAS approaches applied to traffic simulation presented some issues concerning scalability. Nevertheless, we continued to analyze agent-based simulators to use in traffic. One promising agent-based traffic simulator was proposed by Ferreira *et al.* [Ferreira 2008]: MAS-T^{2}er Lab framework. This simulator was able to support collaborative simulation and different perspective analysis of the complex and dynamic application domain of traffic and transportation in major urban areas. Another agent-based simulator, Matsim [Rieser 2007], also revealed its potential as a promising approach for traffic simulation. To test Matsim behavior, maps of the city of Coimbra, Portugal, were converted from OpenStreetMaps [OpenStreetMaps 2012]. Moreover, we made a small contribution to Matsim code, consisting of the conversion of the geographical projection of Coimbra from WGS84 to UTM. Some experiments were implemented in the area of Polo II campus of the University of Coimbra, and the results visualized in Google Earth.

Additionally, we addressed some further scenarios and a new information management architecture. A considered scenario consisted of agents that represented each driver's profile (e.g., risk aversion [Illenberger 2011]), and used communication systems to find the best route as a negotiated compromise to all drivers' interests. Moreover, we also considered drivers' response to information, a subject that was thoroughly analyzed by Chorus [Chorus 2007]. One of the premises of our approach was that reliability of drivers' perception of information should be as higher as possible. Otherwise, drivers' compliance levels of each agent's suggestions would decrease, compromising the whole system's usefulness. However, one of the main goals remained unanswered: How to achieve high traffic capacity with human driven vehicles? Even with the best information available, traffic flow of vehicles with human drivers presents some limits difficult to surpass (about 2200 vehicles per hour per lane). We considered these limits too low to be a viable solution to a significant urban mobility improvement. And common traffic, which is usually modeled by constant time headway policy, could not cope with such objectives (see Section 4.3 on page 28).

2.2 Research Approach

Platooning of IVC-enabled autonomous vehicles was then considered, since its use along with constant spacing policy could ensure considerably higher lane capacities [Varaiya 1993]. Rajamani [Rajamani 2006] stated that a system using a constant spacing policy could not be implemented with autonomous control, and that IVC use was mandatory to ensure string stability. We proposed and implemented a simulation setup to assess a traffic system using a constant spacing policy and IVC [Fernandes 2010]. However, the effects of communication delays on platoons' string stability remained a safety concern. So, our next step consisted of developing and assessing algorithms to mitigate communication delays' effects on platoon string stability. To achieve our goal, the new proposed algorithms presented in this thesis used innovative methods, such as anticipatory information [Fernandes 2012].

Some other challenges remained: How should platoon formation be addressed? What would happen if front platoon vehicles exited the lane? How to ensure vehicle entrance in the lane cooperatively? How could safety operation be ensured and improved? Would high traffic capacity be achieved? These and other related problems were addressed by the proposal and assessment of new algorithms presented in this thesis, namely inter- and intraplatoon positioning management and cooperative behavior algorithms for high traffic capacity and safety improvement [Fernandes 2011], [Fernandes sbmt].

2.3 Thesis Map

This thesis core is based on two journal articles: [Fernandes 2012], published in *IEEE Transactions on Intelligent Transportation Systems*, and [Fernandes sbmt], submitted to *IEEE Transactions on Intelligent Transportation Systems* for third round of review. Thus, some topics may eventually overlap, namely in the "Introduction", and "Related Work" of chapters 4 and 5. Moreover, for the sake of figures and formulas repetition avoidance in Chapter 5, a figure of Section 5.4 (on page 74) was replaced by a reference to Fig. 4.1, of Section 4.3 (on page 26), and two formulas of Section 5.3.1 (on page 68) were replaced by references pointing to Chapter 4, Section 4.3 (on page 28).

Fig. 2.1 shows the involved research topics along the chapters and sections of this thesis, and clarifies that all research contributions and results presented in chapter 5 use underneath the contributions and results of chapter 4.

- **Chapter 1.** Introduction of the thesis work is presented and discussed.
- **Chapter 2.** Background and the research approach is presented and discussed.
- **Chapter 3.** Related work is presented.
- **Chapter 4.** The novel algorithms to mitigate communication delays are presented and assessed. Moreover, the DSRC technology is tested through simulation.

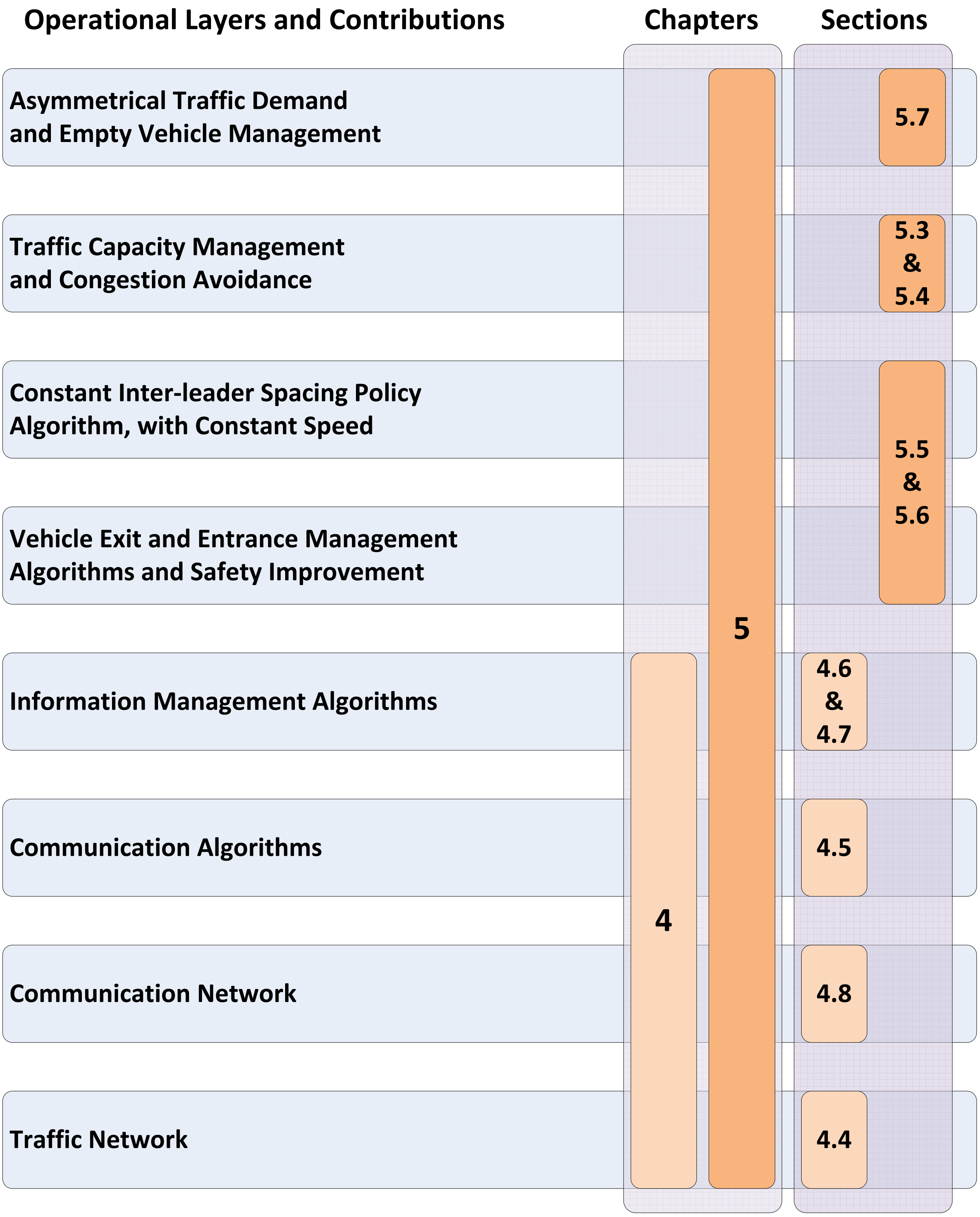

Figure 2.1: Map of thesis core. Chapters' columns cover the layers that are essential to the concepts and models presented in each chapter. Sections' columns present the specific topics of new contributions related to the covered layers.

  - **Section 4.3.** Traffic limits are discussed and proposals to surpass them are presented.
  - **Section 4.4.** The car following model used is presented.
  - **Section 4.5.** The new communication methods, using time slots, are presented.
  - **Section 4.6.** The novel information-updating algorithms to mitigate communication delays are presented.
  - **Section 4.7.** The results of the assessment of the information-updating algorithms through Matlab/Simulink simulations are presented.
  - **Section 4.8.** The new communication methods, using time slots, are simulated through NS-3 simulator.

- **Chapter 5.** The novel algorithms ensuring a constant spacing between platoons' leaders are presented and assessed. Moreover, new algorithms to ensure seamless exit and entrance of autonomous vehicles in the main track are presented and assessed. Additionally, safety improvements are proposed. Finally, a complete simulation scenario in SUMO traffic simulator is presented.
  - **Section 5.3.** Traffic congestion avoidance approaches, under high vehicle density, are discussed, and rules to ensure high traffic capacity are proposed.
  - **Section 5.4.** An ATMS hierarchical multilayered ATMS is proposed.
  - **Section 5.5.** Positioning Management Algorithms are proposed.
  - **Section 5.6.** Positioning Management Algorithms are assessed through Matlab/Simulink simulations.
  - **Section 5.7.** Simulation of a complete platooning system is presented.

- **Chapter 6.** Conclusion, summary of research, and future work, are presented.

Chapter 3

Related Work

In Chapter 2, Section 2.1 we reported some examples of the thorough analysis of published research works. In this chapter, we present related work on the several fields of knowledge considered important to this research (see Table 4.1, in page 26). Since thousands of research works encompassing many scientific fields were analyzed, it would be impractical to mention every relevant authors' works. Therefore, the references presented in this chapter consist solely of the combined references of Chapters 4 and 5, which compose this thesis' core (see thesis map in Section 2.3).

3.1 Related Fields of Knowledge

Traffic theory: Traffic theory is a fundamental scientific field of intelligent transportation systems (ITS) [Gazis 2002], [Immers 2002]. In [Lint 2012], Hans van Lint presents an insightful explanation of traffic behavior under high density.

Intelligent Transportation Systems (ITS) fields: Important fields related to ITS have been the subject of research studies and their results have been published in the last years. Many of them are related with cybercars [Parent 2007], autonomous vehicles [Milanés 2011a], adaptive cruise control (ACC) [Xiao 2011], cooperative adaptive cruise control (CACC) [van Arem 2006], [Kesting 2010], cooperative active safety system (CASS) [Huang 2011], on-ramp merging systems [Wang 2010b], [Milanés 2011b], among other research topics. The European Commission recently delivered a white paper [EU 2012], where clear goals and deadlines are defined, throughout a roadmap of forty initiatives to build a competitive transport system that will improve mobility. Among these initiatives, electric vehicles (EV) and new intelligent transportation systems (ITS) are key issues.

Intelligent Vehicle and Highway Systems (IVHS): In [Shladover 2007], Shladover reviewed the history of the founding of the California Partners for Advanced Transit and

Highways (PATH) program, and of the national intelligent transportation system program in the U.S., providing perspective on the changes that have occurred during the past 20 years. In [Varaiya 1993], Varaiya discussed key issues related to a highly automated intelligent vehicle and highway system (IVHS) and proposed a IVHS control system architecture. Swaroop *et al.* [Swaroop 1994], [Swaroop 1999] investigated various platooning control strategies. Alvarez and Horowitz [Alvarez 1997] researched the conditions to achieve safe platooning under normal mode of operation. Horowitz and Varaiya described in [Horowitz 2000] a five-layer automated highway system control architecture, involving the infrastructure and the vehicles. Kato *et al.* [Kato 2002] described the technologies of the cooperative driving with automated vehicles and IVCs in the Demo 2000 cooperative driving. Global control strategies for vehicle platooning systems are addressed in [Bom 2005].

Personal Rapid Transit (PRT): The concept of Personal Rapid Transit (PRT) has been analyzed in the scientific community for quite a while. Among a large number of researchers that published on the subject, Anderson's book [Anderson 1978], as well as the book from Irving *et al.* [Irving 1978], paved the fundamental concepts of such a futuristic mode of transportation, at least at that time. More recently, Anderson [Anderson 2009] published updated issues about the PRT concept. PRT experimental testing and field applications have been reported [Vectus 2012], [ULTra 2012]. However, the benefits of such system with regard to light rail or conventional cars are yet to be clearly demonstrated. Simulators more focused on PRT systems have been proposed [Xithalis 2012, iTS 2012]. However, it is not clear how they model both communications and cooperation.

Autonomous Vehicles: Kolodko *et al.* [Kolodko 2003] completed what is believed to be the first on-road demonstration of autonomous passenger vehicles performing cooperative passing and traversal of unsignalized intersections. In [Baber 2005], Baber *et al.* presented the Griffith University's Intelligent Control Systems Laboratory (ICSL) platform, and the successful tests of ICSL's cooperative autonomous driving algorithms. In [Furda 2011], Furda *et al.* addressed the topic of real-time decision making for autonomous city vehicles, i.e., the autonomous vehicles' ability to make appropriate driving decisions in city road traffic situations. Naranjo *et al.* [Naranjo 2009] developed a control architecture that can manage automatic driving of two cars, CyCabs, and automated mass-produced cars, as part of European Union CyberCars2 Project [Cybercars2 2009]. Recently [Broggi 2010], Broggi's team completed a 3-month journey of 13000 km, with four autonomous EVs equipped to drive in leader-follower configuration.

Advanced Traffic Management System (ATMS): A full scale automated system managed by an ATMS may rise some concerns with respect to computation limits, if using a centralized approach. As such, a distributed and hierarchical ATMS is considered more appropriate and scalable. Hallé and Chaib-draa [Hallé 2005] proposed a hierarchical driving agent architecture based on three layers (guidance layer, management layer and traffic control layer), to achieve collaborative driving in ITS context, making use of communications to autonomously guide cooperative vehicles on an AHS. Wang [Wang 2005] proposed a three-level hierarchical architecture, applying concepts of agent-based control to networked traffic and transportation systems. In [Wang 2010a], he also presented an overview of the background, concepts, basic methods, major issues, and current applications of parallel transportation management systems. Dold and Stursberg [Dold 2009] proposed an approach to robust model predictive control for distributed systems with chain structure, which includes a scheme for communicating predicted control trajectories between the subsystems. Wang and Pham [Wang 2008] developed an high-fidelity cosimulation platform to study the motion and control of a vehicle platooning system, in MSC ADAMS and Matlab/Simulink [MathWorks 2012].

Intervehicle Communications (IVC): Intervehicle communication (IVC) [Hartenstein 2010] is emerging as a prominent ITS field for helping in reducing traffic congestion. Dedicated short-range communications (DSRC) [IEEE 2010c], [IEEE 2010a], [IEEE 2010b], [Morgan 2010] and long-term evolution advanced (LTE-Advanced) [3GPP 2012], infrared [ISO 2006], and visible light communications (VLC) [IEEE 2011] are some of the promising IVC technologies.

Safety-based IVC is crucial for appropriate platooning operation. However, DSRC broadcasting performance does not present enough reliability to ensure safe vehicle operation in such scenarios. Several proposals have recently been made, aiming to improve its features. In this context, Yu and Biswas [Yu 2007] presented a novel medium access control (MAC) protocol for IVC using DSRC, which consists of a self-configuring time division multiple-access protocol with short and deterministic delay bound capabilities. Torrent-Moreno *et al.* [Torrent-Moreno 2009] proposed a distributed transmit power control method to control the load of periodic messages on the channel. Bi *et al.* [Bi 2010] presented a cross-layer broadcast protocol to allow efficient and reliable message dissemination in IVC systems. Palazzi *et al.* [Palazzi 2010] proposed a novel IVC architecture that adapts its functionalities to efficiently serve applications by quickly propagating their messages over a vehicular network. Tabatabaei *et al.* [Tabatabaei 2011] presented an improvement on simpler propagation models for simulations by augmenting ray-tracing-derived models of wireless propagation. However, there are few approaches concerning the analysis of DSRC use in a constant spacing platooning environment, presenting specific problems to deal with.

3.2 Relation to our Work

Communication delays: The effects of communication delays on the string stability of platoons were researched by Mahal [Mahal 2000]. The main conclusion was that string stability of platoons is compromised in the presence of communication delays. A simple method to deal with string instability due to communication delays was proposed in [Liu 2001]. The solution consisted of a simultaneous update of all vehicles' controllers with the delayed information. However, it did not deal with anticipatory information from the leaders or the followers.

Platooning: Rajamani *et al.* [Rajamani 2006] developed a controller of platoons with constant spacing, concluding that autonomous control is not enough to ensure string stability. He found that only with IVC is the string stability of vehicle platoons achieved. The method was experimentally evaluated in field tests [Rajamani 2000].

In this research work, the use of a constant spacing policy by intraplatoon vehicles, and by interplatoon leaders, is considered a key issue to obtain considerable higher capacity values with platooning of IVC-enabled autonomous vehicles. However, we did not find relevant simulation studies using this policy under the aforementioned scenarios in the literature. Most of the published studies consider a constant time headway for the spacing policy between consecutive vehicles, and others use moving blocks which is a concept based on a similar principle where the safety gap is proportional to speed. The constant time headway spacing policy presents a major drawback: the spacing between vehicles increases for higher speed values, lowering vehicle density and consequently limiting the capacity of the system.

To assess IVC performance, network simulators are used. Among them, the open source NS-3 [NS-3 2012] network simulator is one of the most used by the communication research community. The implementation of accuracy enhancements of the 802.11 model and EDCA QoS extensions in NS-3 was reported in [Bingmann 2009]. In this thesis, DSRC high level modifications are proposed and implemented, using time slots, aiming to avoid packet collisions within vehicle platoons, and transmitting both in broadcast and in unicast [Fernandes 2012]. Then, using these modifications, a simulation scenario is developed in NS-3 simulator to assess DSRC's behavior.

Moreover, new algorithms to mitigate communication delays on platoons of IVC-enabled autonomous vehicles are proposed in this thesis. Using anticipatory information, both from the platoon's leader and the followers, platoon string stability is improved [Fernandes 2012]. The novel algorithms are assessed through Matlab/Simulink simulations. To our best knowledge, there are no published research works proposing similar algorithms, which are extremely favorable on the improvement of platoons' behavior and safety.

Among the myriad of traffic simulators, the Simulation of Urban MObility (SUMO) [Krajzewicz 2006] is one of the most known and used open source traffic simulator by the research community. Although SUMO primarily uses the Krauß car-following model [Krauß 1998], the intelligent driver model (IDM) [Treiber 2000] is also implemented in SUMO. Other car following models have been proposed, such as the Intelligent Driver Model (IDM) [Kesting 2008]. In [Fernandes 2010] we addressed the implementation of IVC-enabled autonomous vehicle platooning capabilities in the SUMO traffic simulator, through the addition of a new car following model to SUMO. The modified SUMO simulator was used to validate the traffic flow assumptions made in [Fernandes 2011], where were also proposed the base rules for interplatoon positioning management strategies, by maintaining a constant spacing between platoons' leaders.

In this thesis positioning management algorithms for safe and efficient ATMS operation are proposed and assessed, to ensure high traffic capacity and vehicle density, while avoiding traffic congestion [Fernandes sbmt]. Matlab/Simulink simulations are performed to assess the proposed novel algorithms. Moreover, a complete new simulation scenario setup is also implemented in SUMO traffic simulator, consisting of a complete multi-platooning system of IVC-enabled autonomous vehicles with off-line stations, performing cooperatively [Fernandes sbmt]. Then, SUMO simulation comparing the novel proposed system toward the conventional transit systems are performed.

To our best knowledge, there are still no traffic simulators with the new presented features, such as: the simulation of a large number of platoons of constant spaced autonomous vehicles; vehicles exiting to stations and entering the main track from stations cooperatively; the permanent measuring of the traffic flow, capacity, occupancy and vehicle density; and the avoidance of congestion operating at very high flow and density values.

Part II

Platooning with IVC-enabled Autonomous Vehicles

Chapter 4

Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow

P. Fernandes, and U. Nunes, "Platooning with IVC-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow," *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 1, pp. 91-106, March 2012.

Abstract

Intraplatoon information management strategies for dealing with safe and stable operation are proposed in this paper. New algorithms to mitigate communication delays are presented, and Matlab/Simulink-based simulation results are reported. We argue that using anticipatory information from both the platoon's leader and the followers significantly impacts platoon string stability. The obtained simulation results suggest that the effects of communication delays may be almost completely canceled out. The platoon presents a very stable behavior, even when subjected to strong acceleration patterns. When the communication channel is subjected to a strong load, proper algorithms may be selected, lowering network load and maintaining string stability. Upon emergency occurrences, the platoon's timely response may be ensured by dynamically increasing the weight of the platoons' leaders data over the behavior of their followers. The simulation results suggest that the algorithms are robust under several demanding scenarios. To assess if current intervehicle communication technology can cope with the proposed information-updating schemes, research of its operation was conducted through a network simulator.

4.1 Introduction

Urban traffic congestion is becoming an unmanageable problem. Its consequences span from economics, public health, and energy consumption to pollution, among others. Traffic regulation through dynamic tolls may temporarily mitigate its impact, but new long-term solutions are required.

As concerns urban transportation, it seems likely that demand tends to always surpass supply. Nevertheless, mobility of urban inhabitants and goods should be granted and improved. However, more road network construction is not always viable and might not even ensure sound benefits. The problem to tackle resides on how to improve road capacity while reducing both travel time and traffic congestion. Platooning may help to improve lane capacity, if constant spacing is used [Swaroop 1994], [Swaroop 1999], [Rajamani 2006]. However, to be effective with respect to traffic flow, platooning should be performed with vehicles evolving on dedicated tracks and operating on a nonstop basis from origin to destination [Anderson 2009]. As such, by eliminating the stop-and-go problem of common car and transit systems, platooning could contribute to a faster and more comfortable mobility with higher energy efficiency.

Intervehicle communication (IVC) is emerging as a prominent technology for helping in reducing traffic congestion. Recent technological advances on communications, such as dedicated short-range communications (DSRC) [IEEE 2010c], [IEEE 2010a], [IEEE 2010b] and long-term evolution advanced (LTE-Advanced) [3GPP 2012], as well as on cooperative adaptive cruise control (CACC) [Kesting 2010], personal rapid transit (PRT) [Anderson 2009], and autonomous vehicles, such as cybercars [Parent 2007], are opening new research avenues which might show the usefulness of platooning in urban mobility improvement, when applied to automated vehicles. Moreover, since the vehicles in platooning are expected to be allowed to move very close to each other, a considerable reduction on energy consumption might be possible [Anderson 2009], once each follower vehicle would benefit from a reduced air drag due to their precedent vehicle.

In the present stage of our research, some assumptions are made. First, only longitudinal control of vehicles is assumed. Second, we consider only autonomous vehicles platooning. Third, we consider a platoon dimension up to 31m long (a maximum of 8 vehicles 3 m long and 1 m apart). Next, line-of-sight (LOS) communication between each leader and its followers is assumed. Then, our communication algorithm uses time slots, aiming to avoid intraplatoon packet collisions. Finally, the vehicles' dynamics are considered identical. These assumptions aim to isolate the effects of communication delays on the platoon's behavior. However, they must be assessed to find if they are acceptable with respect to communication constraints. For that purpose, the NS-3 [NS-3 2012] network simulator is used in testing several demanding platoon scenarios.

Among others, the following problem can be formulated: How can platoon stability be ensured under the negative effects of communication delays? Control methods for ensuring platoon string stability exist [Rajamani 2006], however, under the assumption of the use of IVC without delays. This is not a realistic assumption, and communication delays are known to create hardly manageable string instability [Mahal 2000]. Intraplatoon information management strategies to deal with this problem are proposed in this paper. Our main goal is to ensure platoon string stability under the unavoidable presence of communication delays. To achieve our goal, we aim to enclose the communication, computation and actuation delays within an upper bound delay, which is managed at a higher level in a way that presents no significant effect on platoon string stability.

An appropriate scenario for a platoon-based mobility system consists in its implementation with autonomous electric vehicles (EVs) in a network of dedicated tracks with offline stations and nonstop trips from origin to destination, managed by a hierarchical multilayered advanced traffic management system (ATMS) [Fernandes 2011], [Fernandes sbmt]. As such, traffic of conventional vehicles is not considered in this scenario. Figure 4.1 shows a partial view of the proposed ATMS. This study focuses on the appropriate operation of each platoon, dealing with its string stability when facing communication delays. Nevertheless, this work is part of a more vast research, where other important problems are also subject of study, such as the rules to construct a platoon and leaders' election. For a more detailed description, see [Fernandes 2011] and [Fernandes sbmt]. A brief summary of those rules follows: All leaders are elected by an upper level of the ATMS, receiving from it their acceleration patterns in predetermined time periods; a vehicle is only allowed to enter the track to evolve isolated, if it will occupy a leader's vacant location at precise positioning, and it will perform as leader; a set of up to eight vehicles may be admitted to the track, despite not joining other vehicles evolving in the track, as long as the first vehicle occupies a leader's vacant position and performs as leader, whereas the remaining vehicles perform as followers, under the control law (4.6) of Section 4.4; an isolated vehicle, or a set of vehicles, may enter the track just behind other evolving vehicles, performing as follower(s), if the total number of vehicles is ≤ 8; when a leader leaves the track, the lead vehicle of the platoon's remaining vehicles must assume leadership; should some unforeseeable event occur, leaders are allowed to perform emergency stops, under the information-updating algorithms described in Section 4.6.

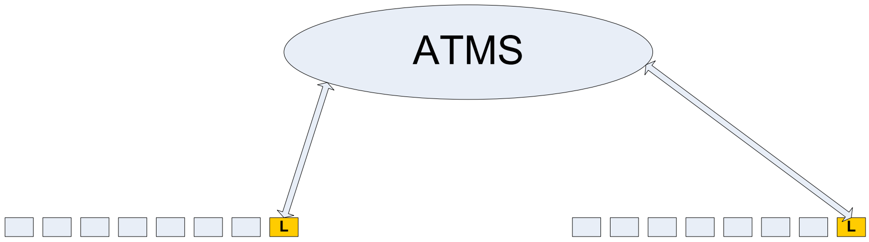

Figure 4.1: Hierarchical ATMS (partial view).

Table 4.1: Fields of Knowledge to Consider

Field	**Some relevant topics**
Traffic	Theory, fundamental diagram, traffic flow
Communications	DSRC/WAVE, LTE-Advanced (4G)
Simulation	Traffic and communication networks
Control	Constant spacing platooning, string stability
Autonomous vehicles	Communicant, cooperative
Computer Science	C++, Python, Java, application architecture
Energy	Consumption, efficiency, EV's

The upper levels of the proposed ATMS should control the whole system, including platoon leaders' appropriate operation and admission of vehicles into the system, to avoid congestion, even when operating close to its maximum capacity. The management of free vehicles to deal with asymmetrical transportation demand should also be ensured by the ATMS.

Since communication failures are of considerable importance in such scenarios, we further explore communication algorithms that might ensure that communication errors do not occur or are minimized. For that purpose, network simulations were performed with NS-3, and results are reported.

In the succeeding sections, we present the applied platoon control models, communication and information-updating schemes, and simulation models and results.

4.2 Related Work

This research encompasses several fields of knowledge (as shown in Table 4.1). A great number of research studies and results have been published in the last years, concerning the aforementioned fields. Many of them are related with autonomous vehicles [Milanés 2011a], adaptive cruise control (ACC) [Xiao 2011], CACC [Kesting 2010], cooperative active safety system [Huang 2011], among other research topics.

In [Shladover 2007], Shladover reviewed the history of the founding of the California Partners for Advanced Transit and Highways (PATH) program, and of the national intelligent transportation system program in the U.S., providing perspective on the changes that have occurred during the past 20 years. In [Varaiya 1993], Varaiya discussed key issues related to a highly automated intelligent vehicle and highway system (IVHS) and proposed a IVHS control system architecture. Swaroop *et al.* [Swaroop 1994], [Swaroop 1999] investigated various platooning control strategies. Alvarez and Horowitz [Alvarez 1997] researched the conditions to achieve safe platooning under normal mode of operation. Horowitz and Varaiya described in [Horowitz 2000] a five-layer automated highway system control architecture, involving the infrastructure and the vehicles. Rajamani *et al.* [Rajamani 2000] developed a controller of platoons with constant spacing, concluding that autonomous control is not enough to ensure string stability. He found that only with IVC is the string stability of vehicle platoons achieved. The method was experimentally evaluated in field tests. Kato *et al.* [Kato 2002] described the technologies of the cooperative driving with automated vehicles and IVCs in the Demo 2000 cooperative driving. Global control strategies for vehicle platooning systems are addressed in [Bom 2005]. Recently [Broggi 2010], Broggi's team completed a 3-month journey of 13000 km, with four autonomous EVs equipped to drive in leader-follower configuration.

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In [Fernandes 2010] we addressed the implementation of IVC-enabled autonomous vehicle platooning capabilities in the Simulation of Urban MObility (SUMO) traffic simulator [Krajzewicz 2006]. Dold and Stursberg [Dold 2009] proposed an approach to robust model predictive control for distributed systems with chain structure, which includes a scheme for communicating predicted control trajectories between the subsystems. Wang and Pham [Wang 2008] developed an high-fidelity cosimulation platform to study the motion and control of a vehicle platooning system, in MSC ADAMS and Matlab/Simulink.

Safety-based IVC is crucial for appropriate platooning operation. However, DSRC broadcasting performance does not present enough reliability to ensure safe vehicle operation in such scenarios. Several proposals have recently been made, aiming to improve its features. In this context, Yu and Biswas [Yu 2007] presented a novel medium access control (MAC) protocol for IVC using DSRC, which consists of a self-configuring time division multiple-access protocol with short and deterministic delay bound capabilities. Torrent-Moreno *et al.* [Torrent-Moreno 2009] proposed a distributed transmit power control method to control the load of periodic messages on the channel. Bi *et al.* [Bi 2010] presented a cross-layer broadcast protocol to allow efficient and reliable message dissemination in IVC systems. Palazzi *et al.* [Palazzi 2010] proposed a novel IVC architecture that adapts its functionalities to efficiently serve applications by quickly propagating their messages over a vehicular network. Tabatabaei *et al.* [Tabatabaei 2011] presented an improvement on simpler propagation models for simulations by augmenting ray-tracing-derived models of wireless propagation. However, there are few approaches concerning the analysis of DSRC use in a constant spacing platooning environment, presenting specific problems with which to deal.

4.3 Traffic Flow Limits

Maintaining a desired intervehicle spacing in platoons demands a tight control of each vehicle. In case of human-driven vehicles, intervehicle spacing is defined through a constant time headway, which means that increasing speed implies increased spacing. According to [Kesting 2008], the "desired minimum gap" s^* between two vehicles under the intelligent driver model (IDM) [Treiber 2000], is given by

$$s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \tag{4.1}$$

with $\Delta v := v_\alpha - v_{\alpha-1}$, where α denotes the follower vehicle and $\alpha - 1$ denotes the leading vehicle, s_0 is the minimum distance in congested traffic, a is the maximum acceleration and b is the "comfortable deceleration". The last term of (4.1) is only significant in non-stationary traffic, when $\Delta v \neq 0$. Term vT is the most relevant one to the resultant spacing in stationary traffic, where T denotes the "safety time gap". When speed increases, s^* proportionally increases, which means that the road vehicle density decreases. With

Table 4.2: Lane Capacity Using Platoons

v	n	d (m)	D (m)	C (ve/h)	SUMO	k (veh/km)
36 km/h	1	–	15	2000	2400	55
	5	1	30	3674	3675	102
	8	1	30	4721	4730	131
	15	1	30	6067	6070	169
	20	1	30	6606	6600	183
72 km/h	1	–	25	2571	2800	36
	5	1	30	7347	7340	102
	8	1	30	9443	9450	131
	15	1	30	12135	12140	169
	20	1	30	13211	13210	183

human drivers, it is not possible to avoid this performance pattern, even with IVC, because human reaction time is the main reason for the need of the safety gap proportional to the vehicle speed. That reaction time of about 1 s leads to the lack of string stability in vehicle platooning. This means that, if the lead vehicle decelerates, the spacing between vehicles may decrease toward the end of the platoon, leading to possible collisions.

According to [Varaiya 1993], road capacity may be increased by using platoons with tightly spaced vehicles. The formulation to determine road capacity is given as follows:

$$C = v\,\frac{n}{ns + (n-1)d + D} \tag{4.2}$$

where C represents the number of vehicles (in vehicles per second), d is the intraplatoon spacing (in meters), D is the interplatoon spacing (m), s the vehicle length (in meters), v the steady-state speed (in meters per second), and n is the number of cars in each platoon.

Based on (4.2), Table 4.2 presents lane capacity values for $s = 3$ m, and velocities of 36 and 72 km/h. The parameter k represents the vehicle density in vehicles per kilometer. The spacing of free vehicles ($n = 1$) is consistent with the minimum gap obtained from the IDM model (4.1), in which human drivers, presenting reaction times of approximately 1 s, need about 15 m of safety gap at a speed of 36 km/h. Note the significant improvement of lane capacity with platoons of 8 vehicles each, when compared with the free vehicle case, even with an interplatoon spacing of 30 m, which is double the spacing of individual vehicles (15 m). It is also worth mentioning, that for the free vehicle case, the values were

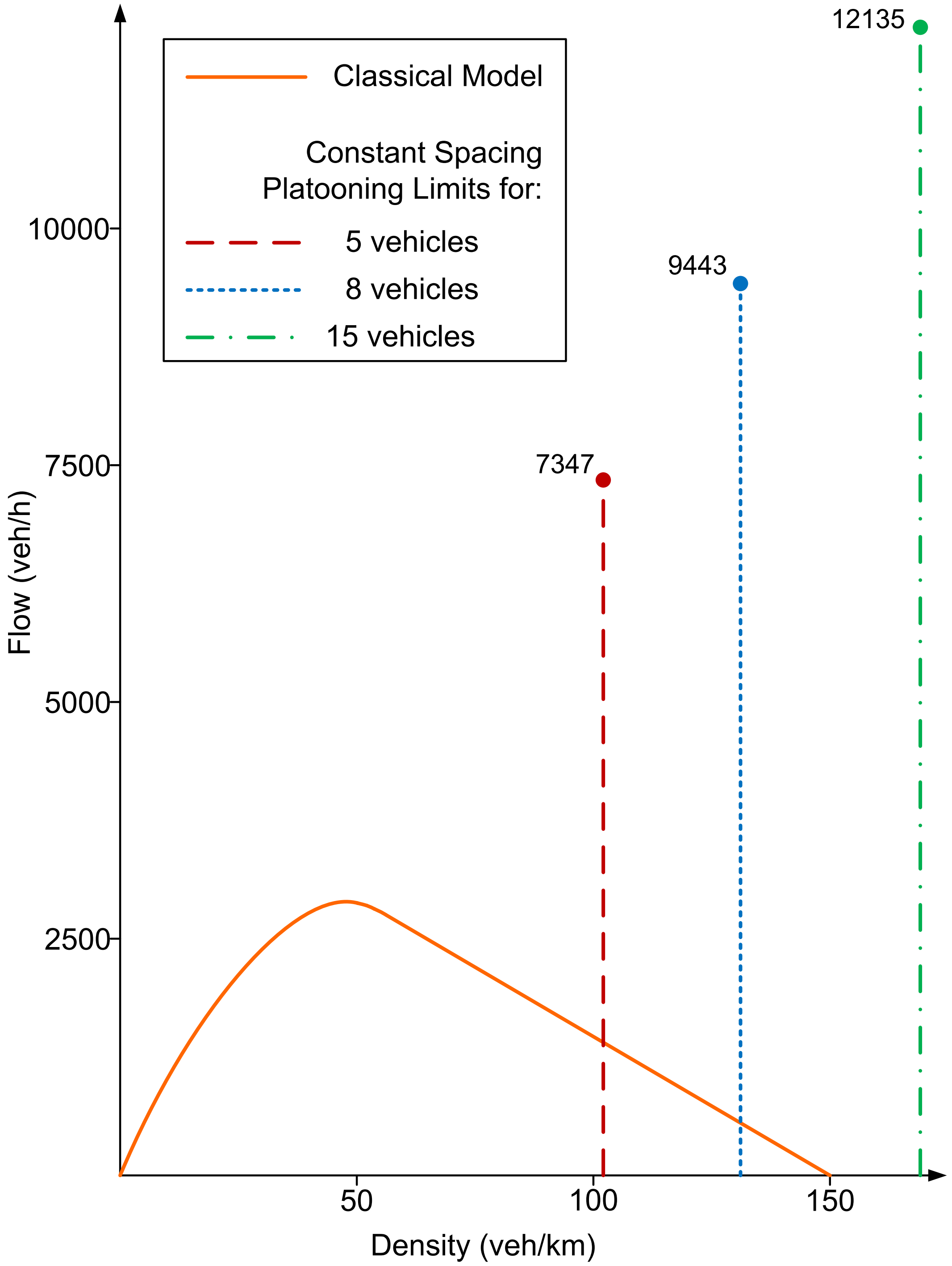


Figure 4.2: Fundamental Diagram of Traffic Flow. Limits for platoons of five, eight, and 15 vehicles each, separated by 30 m, with vehicles 3 m-long and 1 m apart from each other, are depicted in dashed lines, with upper values for the speed of 72 km/h.

obtained under ideal conditions, i.e., without traffic lights, intersections or other obstacles usually present in an urban environment. Doubling the velocity in Table 4.2 leads to a slight improvement of the lane capacity (28.5%) in the case of free vehicles. However, the capacity doubles with platoons of 8 vehicles, when compared with the analogous case at the speed of 36 km/h, resulting in more than three times the capacity of the lane with free vehicles, the same speed considered. Table 4.2 also presents the traffic flow results of simulations of constant speed platoons, performed on the SUMO traffic simulator. In Table 4.2, SUMO results for $n = 1$ were obtained using the Krauß car-following model [Krauß 1998]. The platooning results ($n \geq 5$) were obtained with the modified SUMO reported in our previous work [Fernandes 2010], which consists in a novel car-following implementation allowing to simulate platooning of autonomous vehicles with constant spacing. The simulation scenario consisted of a several-kilometers-long straight lane, where a large sequence of platoons evolved in formation. At some defined points of the lane, E1-type loop detectors were installed in SUMO, allowing to obtain the aggregate results of traffic flow. Although slightly higher in the case of free vehicles, these results are consistent with those theoretically drawn from (4.2).

In Fig. 4.2 we represent the fundamental diagram of traffic flow [Gazis 2002]. By the fundamental relation of traffic flow theory

$$q = u \times k \tag{4.3}$$

where q represents traffic flow (in vehicles per hour), u the vehicle speed (in kilometers per hour), and k the vehicle density (in vehicles per kilometer). The classical model states that, above a critical density k_c (approximately 50 veh/km in Fig. 4.2), the traffic state begins to enter in a congestion phase, where vehicles are closer to each other and moving slower, until traffic comes to a full stop, at a jam density k_j, at about 150 veh/km. The data obtained with SUMO for the conventional traffic are consistent with the continuous line. In Fig. 4.2 we further represent three upper limits of density values, by vertical dashed lines, for the cases of platoons with 5, 8, and 15 vehicles each, corresponding to the following values of k: 102, 131, and 169 veh/km, respectively. These are the upper bounds at which a constant spacing platooning system could operate. Once the platoons' formation is already in place, lane capacity is proportional to the speed. The flow is equal to lane capacity, if the vehicle density is maintained. The top of each dashed line is the theoretical flow limit with respect to a given density and speed values. For example, 9443 veh/h is the lane capacity for the case of a density of 131 veh/km, with a platoon

Table 4.3: Nomenclature of Mathematical Formulations

Symbol	**Description**
$\ddot{x}_{i\_des}$	desired acceleration of the ith vehicle
$\ddot{x}_{i-1}$	acceleration of the vehicle preceding the ith vehicle
$\ddot{x}_l$	acceleration of the vehicle leader of the platoon
V_i	velocity of the ith vehicle
V_l	velocity of the vehicle leader of the platoon
C_1	control gain used in longitudinal controller (weight factor of the leader with respect to the preceding vehicle, with values $0 \leq C_1 < 1$)
ξ	damping ratio (equal to 1 for critical damping)
ω_n	bandwidth of the controller

featuring $v = 72$ km/h, $n = 8$, $d = 1$ m, and $D = 30$ m (see Table 4.2). However, for a traffic system to operate with a traffic flow close to 9443 veh/h (under the aforementioned conditions), the admittance of vehicles should be limited, to ensure that the correspondent maximum density of 131 veh/km would never be surpassed. Otherwise, congestion would occur, lowering the traffic flow value. Moreover, such traffic system should be based on constant spacing platooning of autonomous vehicles and managed by an ATMS. Based on Table 4.2, we find $n = 8$ as the best compromise between traffic flow improvement and platoons' dimension.

4.4 Base Model of Vehicle Control

It becomes clear that one way to effectively improve road capacity consists of the use of vehicle platoons with constant spacing. However, constant spacing platooning requires string stability, which means that the spacing errors do not amplify down the platoon from vehicle to vehicle. To ensure string stability between vehicles in a constant spacing platoon, IVC is required [Swaroop 1994], [Rajamani 2006].

According to Fig. 4.3 and considering the desired i th-vehicle position defined by

$$x_{i\_des} = x_{i-1} - L_i \tag{4.4}$$

where $L_i = l_{i-1} + g_{i\_des}$, with l_{i-1} being the length of the preceding vehicle and g_{i_des} the

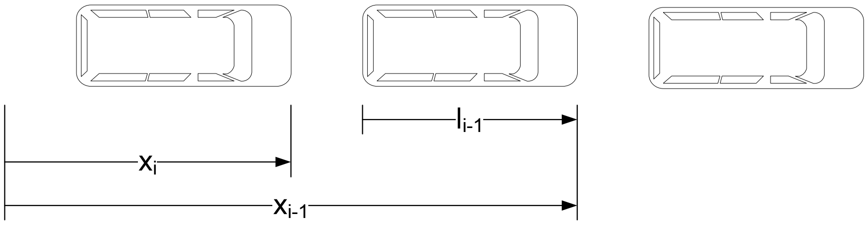


Figure 4.3: String of platoon vehicles.

intervehicle desired gap, the spacing error is defined as

$$\varepsilon_i = x_i - x_{i-1} + L_i \tag{4.5}$$

Using a sliding mode approach, Rajamani [Rajamani 2006] designed a controller with vehicles' desired acceleration expressed as

$$\begin{aligned} \ddot{x}_{i\_des} &= (1 - C_1)\ddot{x}_{i-1} + C_1\ddot{x}_l \\ &\quad -(2\xi - C_1(\xi + \sqrt{\xi^2 - 1}))\omega_n\dot{\varepsilon}_i \\ &\quad -(\xi + \sqrt{\xi^2 - 1})\omega_n C_1(V_i - V_l) - \omega_n^2\varepsilon_i \end{aligned} \tag{4.6}$$

The parameters of (4.6) are described in Table 4.3. With this control method, spacing error will converge to zero, and the system is string stable, under the conditions $\xi \geq 1$ and $C_1 < 1$ [Rajamani 2006]. To each follower in a platoon of vehicles, parameter C_1 represents the weight factor of the leader's information with respect to the preceding vehicle. When $C_1 = 0$, the following second-order system is attained:

$$\ddot{x}_{i\_des} = \ddot{x}_{i-1} - 2\xi\omega_n\dot{\varepsilon}_i - \omega_n^2\varepsilon_i \tag{4.7}$$

and only the precedent vehicle's information becomes relevant to each vehicle behavior. From (4.6), we can conclude that, to determine the desired acceleration of each vehicle, wireless communications are needed to allow each vehicle to receive the speed and acceleration values from both the preceding vehicle and the platoon leader. It is assumed that vehicles have precise self-position information in real time, whether obtained from Global Positioning System (GPS)/differential GPS, or from other sensing means. Moreover, the distance from each vehicle to its precedent is assumed to be determined by the use of a lidar or radar installed in each vehicle. Additionally, it is assumed that platoon formation and leader's election are dealt with by the ATMS at a higher level [Fernandes 2011],

Table 4.4: Information Updating Schemes' Parameters

Algorithm	**Anticipation**	**C_1**	**Apparent Delay (leader, followers)**	**Updating Cycle** uc
I	none	static	$100\,ms$, $100\,ms$	$100\,ms$
II	leader	static	$0\,ms$, $100\,ms$	$100\,ms$
III	leader	dynamic	$0\,ms$, $100\,ms$	$100\,ms$
IV	all	static	$0\,ms$, $0\,ms$	$100\,ms$
V	all	static	$0\,ms$, $0\,ms$	$800\,ms$

[Fernandes sbmt]. The control model does not integrate air drag nor the coefficient of friction effects. As such, the focus of this research is on communication delay effects over an identical set of vehicles and strategies to mitigate them.

4.5 Communications

We consider IVC supported by wireless communications from the leader to all followers and from each vehicle to its immediate follower and the leader. The communication scheme uses time-division multiple access with token passing [Liu 2001]. All vehicles transmit their data at each token cycle tc, in their respective time slot ts. For that purpose, $tc = 10 \times ts_j$, $j = 1, ..., 10$. We also consider $tc = 100\,ms$ and $ts = 10\,ms$ as appropriate reference values.

4.6 Information Management Algorithms

To exchange information between vehicles, allowing an appropriate platoon behavior, five information-updating schemes are proposed.

Table 4.5 presents the parameters of the information-updating schemes. The delay bounds used in these algorithms are much higher than those obtained through simulation, with respect to packet transmission delays. The idea of these algorithms is to operate under an upper bound delay while continuing to ensure a stable platoon behavior. Consequently, lower delay effects over string stability may then be mitigated or even almost canceled out. Additionally, by managing information at an upper level, with anticipatory information, delays perceived by receivers may be canceled out (null apparent delays), as presented in Table 4.5, and explained throughout the next sections, where the proposed information-updating schemes are described. All of them use the platoon's information

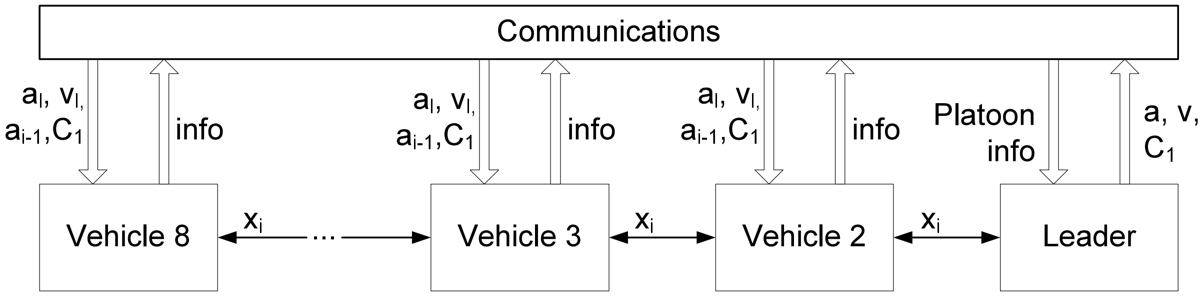


Figure 4.4: Platoon's information flow diagram.

Table 4.5: Algorithm Parameters

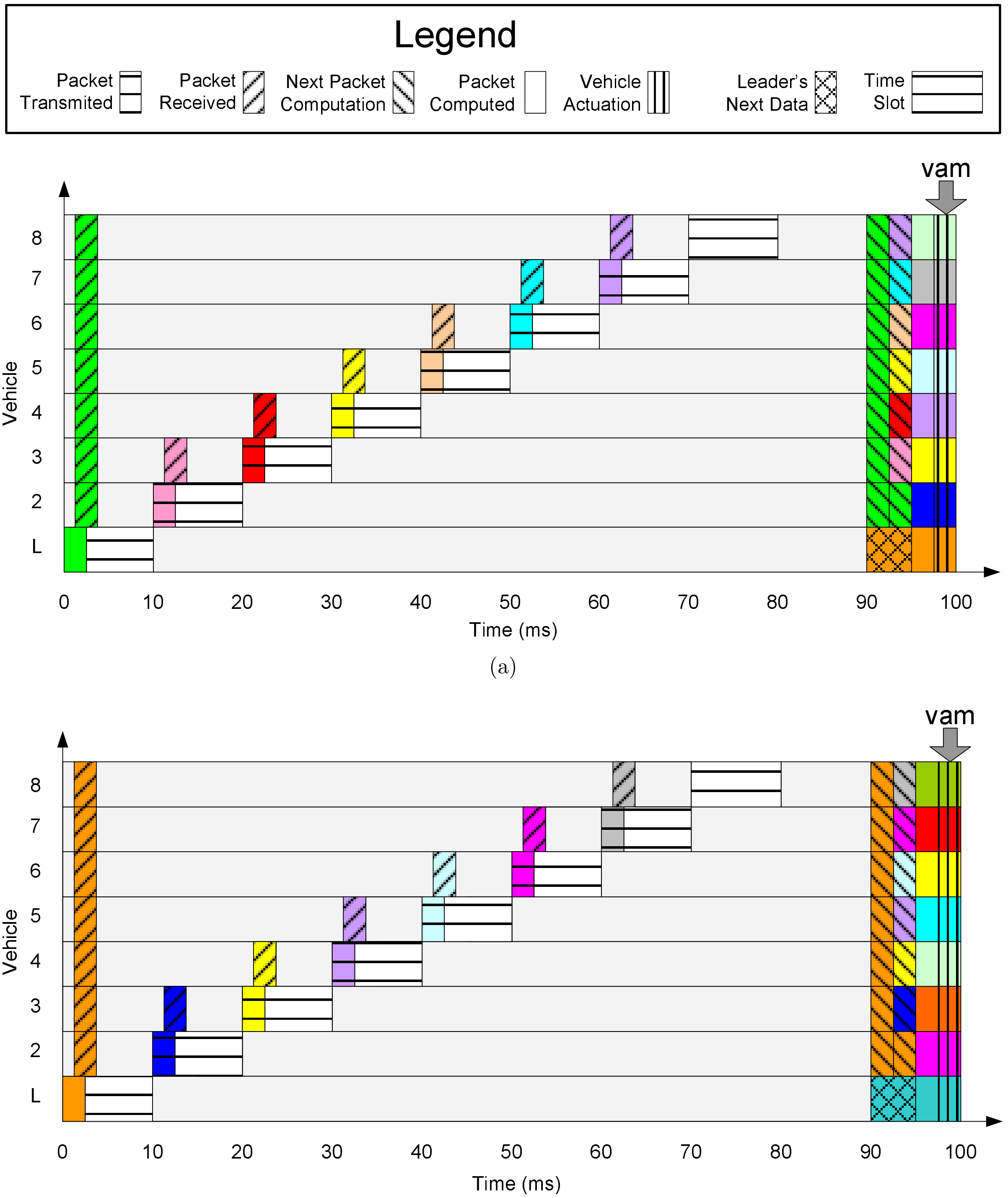
Parameter	**Definition**
uc_i	updating cycle i
ts_j	time slot j
a_c	current acceleration
a_n	next acceleration
v_c	current speed
v_p	predicted speed
vam	vehicle actuation moment

flow architecture, which diagram is shown in Fig. 4.4.

4.6.1 Information-Updating Scheme I

This first scheme is presented as a work base, to which the other proposed schemes II, III, IV and V will be compared with. Moreover, it also makes possible the study of the influence that C_1 parameter presents over the platoon stability. The platoon's leader transmits its data to all followers in its time slot ts_1. Each vehicle j, in sequence, transmits its data to the respective follower, in each ts_j, in sequence. After all vehicles have obtained the data, they proceed to the computation of the next acceleration they must apply through their actuators. However, all vehicles are synchronized and simultaneously update their operation parameters at the end of each information-updating cycle uc to improve platoon stability [Liu 2001]. We will designate that instant by vehicle actuation moment vam. We adopt an updating cycle $uc = 100$ ms. With n being the number of vehicles per platoon, with $1 \leq n \leq 8$, and $ts = 10$ ms, condition $uc \geq n \times ts$ is verified.

Fig. 4.5 shows a temporal diagram of the packet data exchange between the platoon vehicles in two consecutive 100-ms time frames. Different colors represent different data



(a)

(b)

Figure 4.5: Algorithm I: Without anticipatory information. (a) First 100-ms time frame. (b) Second 100-ms time frame.

content. First, the leader broadcasts its present data to all followers. Each of them, in turn and in their respective time slot, transmits the acceleration computed in the previous 100-ms time frame. At the end of the frame, all vehicles compute their next acceleration, based on the measured distance to the respective precedent vehicle, and the data received from that vehicle and the leader. At the same time, the leader computes the acceleration value to apply in the next frame. Then, all vehicles simultaneously perform the actuation of the obtained data in each vehicle. The information of the leader and also of all vehicles to each of their followers is 100 ms old.

Table 4.5 defines the parameters used in the following algorithms:

Algorithm 1 Leader in Information-Updating Scheme I

```
for all $uc_i$ do
    At $ts_1$, leader broadcasts its current acceleration $a_c$ and speed $v_c$
    At $ts_{10}$, leader gets from ATMS or compute its next acceleration $a_n$
    At $vam$, leader actuates with $a_n$
end for
```

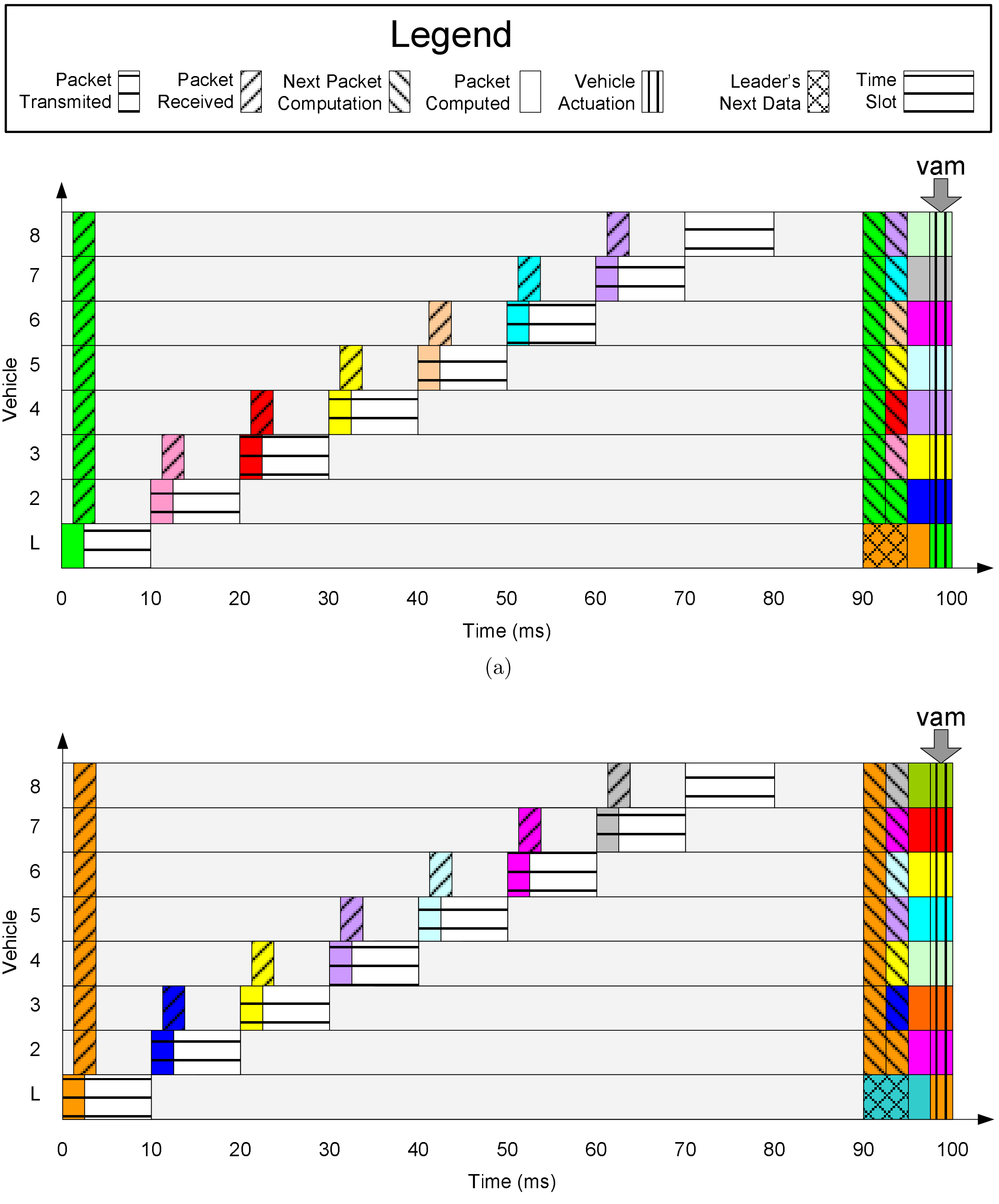
Algorithm 2 Follower in Information-Updating Scheme I

```
for all $uc_i$ do
    At $ts_1$, vehicle $v_j$ receives the acceleration and speed from the leader
    At $ts_{j-1}$, vehicle $v_j$ receives the acceleration from its precedent vehicle
    At $ts_j$, vehicle $v_j$ transmits its current acceleration $a_c$ to its follower
    At $ts_{10}$, vehicle $v_j$ compute its next acceleration $a_n$ under the control law of (4.6)
    At $vam$, vehicle $j$ actuates with $a_n$
end for
```

Algorithm 1 presents the leader's behavior in this information-updating scheme, whereas Algorithm 2 presents the behavior of a follower, both represented in pseudocode.

4.6.2 Information-Updating Scheme II

In this information-updating scheme, the platoon's leader announces the plan for the next frame at each tc, in its ts_1, but waits before actuating with the computed values to allow the followers to be able to update their data before their own actuation. This waiting step is a key feature to improve platoon stability and may be interpreted as an "anticipatory information" that all vehicles receive from the leader to allow them timely and simultaneous actuation, at the vehicle actuation moment vam. The information that each follower emits to the subsequent vehicle is 100 ms old, as in the Scheme I. Each updating cycle is $uc = tc = 100$ ms.



(a)

(b)

Figure 4.6: Algorithm II: With leader's anticipatory information, using the vehicle actuation moment *vam*. (a) First 100-ms time frame. (b) Second 100-ms time frame.

Fig. 4.6 shows a temporal diagram of the packet data exchange between the platoon vehicles in two consecutive 100-ms time frames. First, the leader broadcasts the data to all their followers. However, differently from the previous scheme, the information broadcasted by the leader has not yet been applied to the vehicle. Instead, the leader waits until all the remaining vehicles receive and transmit their data. Each vehicle, in turn and in the respective time slot, transmits its actual acceleration (which was computed in the previous 100-ms time frame, considering the leader's anticipatory information). With this updating scheme, it is possible, at the cost of an increase of 100 ms in the reaction time of the leader, to considerably improve the platoon stability, in the direct proportion of the leader's information weight, as represented by parameter C_1 in (4.6).

Algorithm 3 Leader in Information-Updating Scheme II

```
for all $uc_i$ do
    At $ts_1$, leader compute its predicted speed $v_p$ at vam, based on its current acceleration $a_c$
    At $ts_1$, leader broadcasts its next acceleration $a_n$ and predicted speed $v_p$
    At $ts_{10}$, leader gets from ATMS or compute the next acceleration to use at the next updating cycle $uc_{i+1}$
    At $vam$, leader actuates with $a_n$
end for
```

Algorithm 3 presents the leader's behavior in this information-updating scheme, whereas the behavior of a follower is the same as in Scheme I (Algorithm 2). The main differences from Algorithm 1 are presented in italic text.

4.6.3 Information-Updating Scheme III

All vehicles in the platoon receive information from the leader at all *uc*, as in Scheme II. Parameter C_1 in (4.6), which represents the weight of leader's data, is dynamically changed to cope with some potential dangerous conditions (e.g., in the presence of a unexpected strong deceleration of the leader). In such cases, the leader warns its followers to increase their C_1. We introduce here a new parameter C_2 that will serve as a base value, whereas the C_1 parameter will dynamically vary, which we will designate by $C_{1_{dyn}}$, where $C_1 = C_{1_{dyn}}$, with $C_2 \leq C_{1_{dyn}} < 1$. This parameter is used when strong accelerations (both positive or negative) are determined by the leader. In these cases, $C_{1_{dyn}}$ immediately assume a value close to 1 (without reaching it, since string stability requires that $C_1 < 1$ [Rajamani 2006]), for a very short period of time, after which, the value rapidly decays to the C_2 base value again. Nevertheless, all vehicles use the same

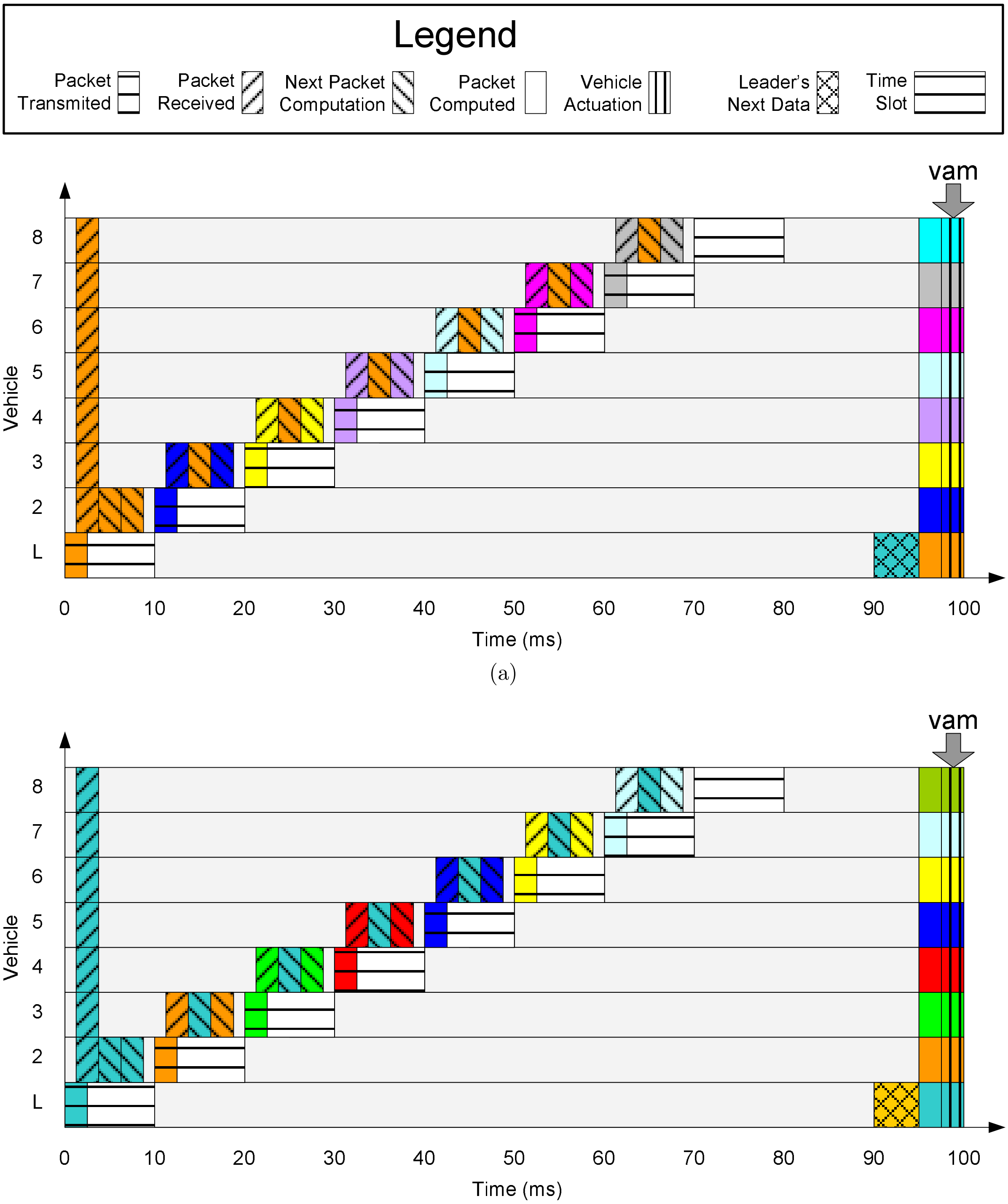
C_1 value in each *uc*. With this algorithm, very conservative C_2 values may be maintained, whereas a very stable platoon behavior is achieved. As we will see in the results (Section 4.7.3), the behavior of the platoon is even better than the obtained behavior with a fixed $C_1 = 0.9$.

4.6.4 Information-Updating Scheme IV

This information-updating scheme extends the key feature of Scheme II (anticipatory information) from the leader to all vehicles. The platoon leader announces the plan for the next frame at each tc, in its ts_1. Each follower, in sequence, determines its own plan for the next tc and transmits it to their respective follower, in their own time slot. As such, at each tc, both the leader and each of the followers, in sequence, transmit their data. Each vehicle j transmits in its time slot ts_j to allow all vehicles to transmit without packet collisions. It is important to note that, although both the leader and all the remaining platoon vehicles transmit their next acceleration value, they all hold their actuation, until all vehicles receive their information. Only then, all vehicles simultaneously update their operation parameters, at the vehicle actuation moment vam, in the end of each information-updating cycle uc. Each updating cycle $uc = 100$ ms. Since this updating scheme transmits data to use on the next uc, the platoon stability improves significantly in comparison with the other schemes. The timings at which this algorithm operates are appropriate to demanding dynamic operations, where vehicles are required to be more responsive and adaptive. However, it is very demanding with respect to both communication and timely computation of vehicle parameters.

Fig. 4.7 shows a temporal diagram of the packet data exchange between the platoon vehicles in a 100-ms time frame. This scheme consists of an evolution of the Scheme II. In this case, all vehicles in the platoon announce the acceleration value before the moment at which it will be used to act on the vehicle. For that purpose, a tight synchronization and very short timings must be ensured. Note in Fig. 4.7a that each vehicle has to compute its next acceleration value within the time it received the data of its precedent vehicle and the beginning of its own time slot, where it must be able to transmit the computed value to its own follower. In Fig. 4.7, we admit that less than one third of the time slot is used to receive the precedent vehicle's data, which leaves enough remaining time to perform the needed computations.

Algorithm 4 presents the follower's behavior in this information-updating scheme, whereas the behavior of a leader is the same as in Scheme II (Algorithm 3).



(b)

Figure 4.7: Algorithm IV: With all vehicles' anticipatory information, using the vehicle actuation moment *vam*. (a) First 100-ms time frame. (b) Second 100-ms time frame.

Algorithm 4 Follower in Information-Updating Scheme IV

```
for all $uc_i$ do
    At $ts_1$, vehicle $j$ receives the acceleration and speed from the leader
    At $ts_{j-1}$, vehicle $j$ receives the acceleration from its precedent vehicle
    At $ts_{j-1}$, vehicle $j$ compute its predicted speed $v_p$ at $vam$, based on its current acceleration $a_c$
    At $ts_{j-1}$, vehicle $j$ compute its next acceleration $a_n$ at $vam$, under the control law of (4.6)
    At $ts_j$, vehicle $j$ transmits its next acceleration $a_n$ to its follower
    At $vam$, vehicle $j$ actuates with $a_n$
end for
```

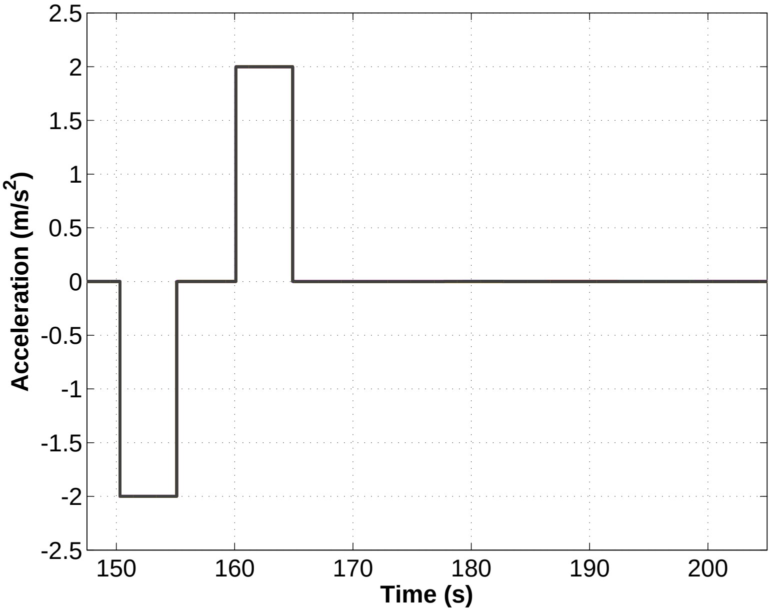
4.6.5 Information-Updating Scheme V

At the first *tc*, the leader transmits its data to the followers. At each subsequent *tc*, each of the followers, in sequence, transmits their data to the vehicle behind them. As on the Scheme IV, the vehicles hold their actuation, until all vehicles receive their information. Only then, all vehicles simultaneously update their operation parameters, at the vehicle actuation moment *vam*, in the end of each information-updating cycle *uc*. With a n-vehicle platoon, each *uc* should attain the condition $uc \geq n \times tc$. For an eight-vehicle platoon, with $tc = 100$ ms, $uc \geq 800$ ms. This updating scheme is proposed for a stable and foreseeable traffic state. Its major advantage consists of the significant low communication channel load it presents.

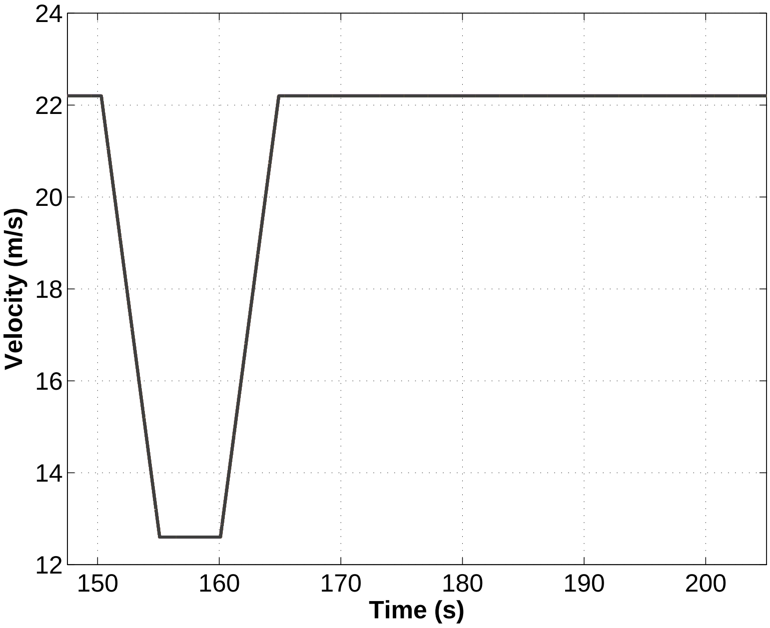
4.7 Results

To assess the appropriate operation of the proposed models, several simulations were carried out in Matlab/Simulink [MathWorks 2012]. All models include an eight-vehicle platoon of IVC-enabled autonomous vehicles, aiming to maintain a 1-m distance to their precedents. The operational part of the model is implemented in Simulink. Fig. 4.4 shows the platoon's information flow diagram. The applied acceleration profile and the resultant velocity are shown in Fig. 4.8. Table 4.6 presents the simulation parameters used in the Matlab/Simulink simulations.

In this section, we present the results obtained from simulations performed with Matlab/Simulink for the five information-updating schemes previously proposed.

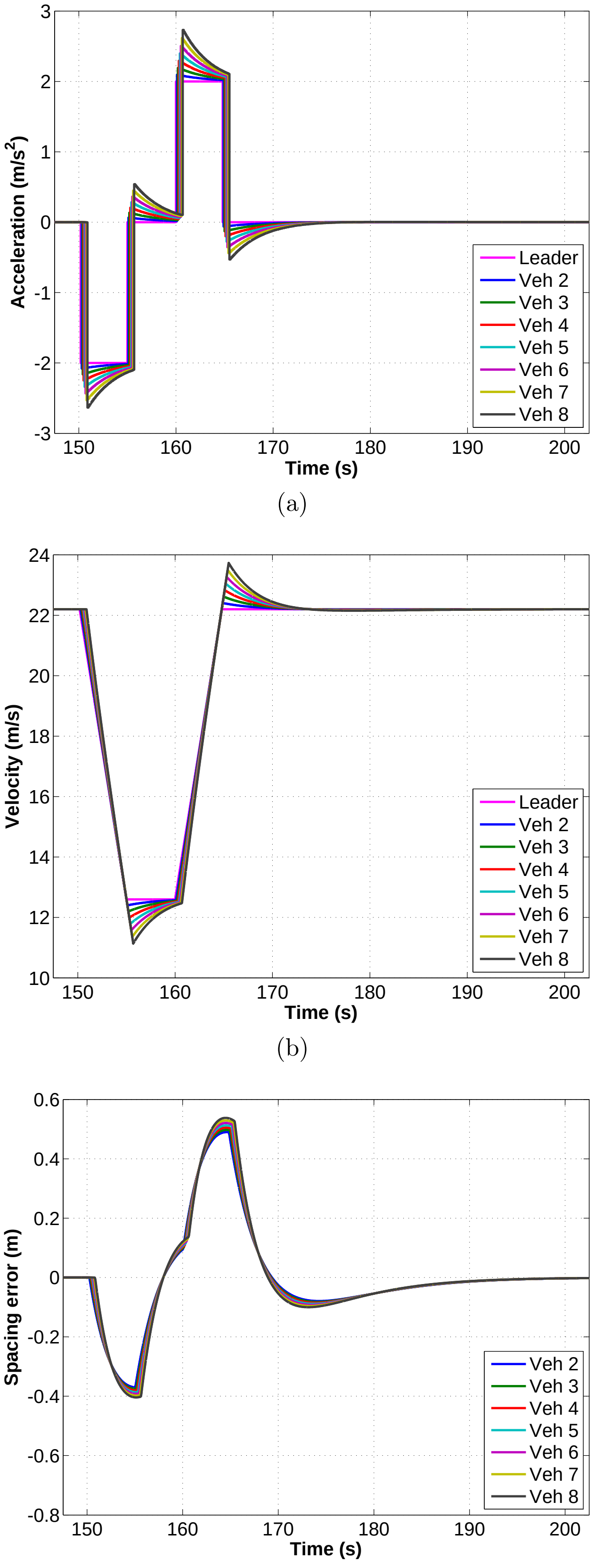


(a)



(b)

Figure 4.8: Leader's actuation. (a) Acceleration pattern. (b) Velocity pattern.



(a)

(b)

(c)

Figure 4.9: Algorithm I with $C_1 = 0$. (a) Acceleration of the platoon. (b) Velocity of the platoon. (c) Spacing error of the platoon.

Table 4.6: Parameters of the Simulation Model

Parameter	**Symbol**	**Value**
Time step	T_s	$1\,ms$
Bandwidth of the controller	ω_n	0.2
Damping ratio	ξ	1
Leader's weight (fixed)	C_1	$0 \leq C_1 < 1$
Leader's weight base value	C_2	$0 \leq C_2 < 1$
Leader's weight (dynamic)	$C_{1_{dyn}}$	$C_2 \leq C_{1_{dyn}} < 1$
Maximum acceleration	a_{max}	$3\,ms^{-2}$
Leader's acceleration	a_{upp}	$2\,ms^{-2}$
Leader's deceleration	a_{low}	$-2\,ms^{-2}$
Maximum deceleration	a_{min}	$-4\,ms^{-2}$
Communication time slot	ts	$10\,ms$
Communication token cycle	tc	$100\,ms$
Information updating cycle	uc	$100\,ms$, $800\,ms$

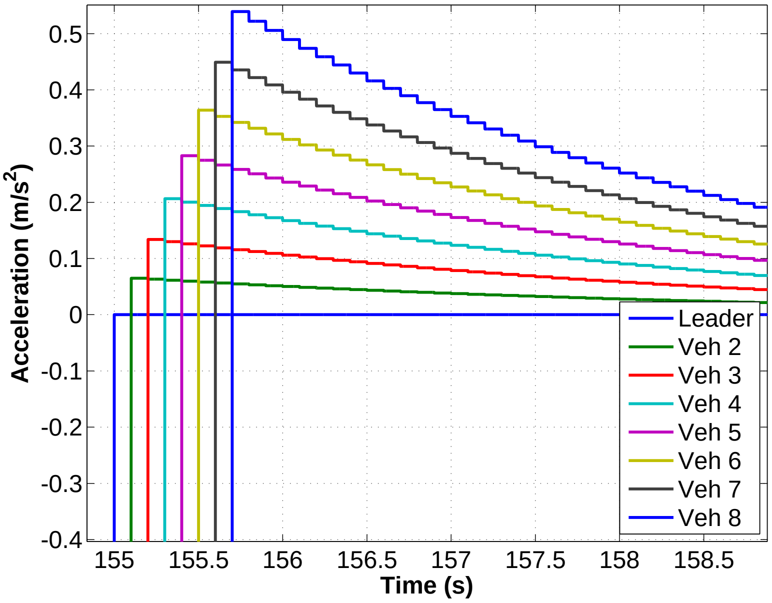
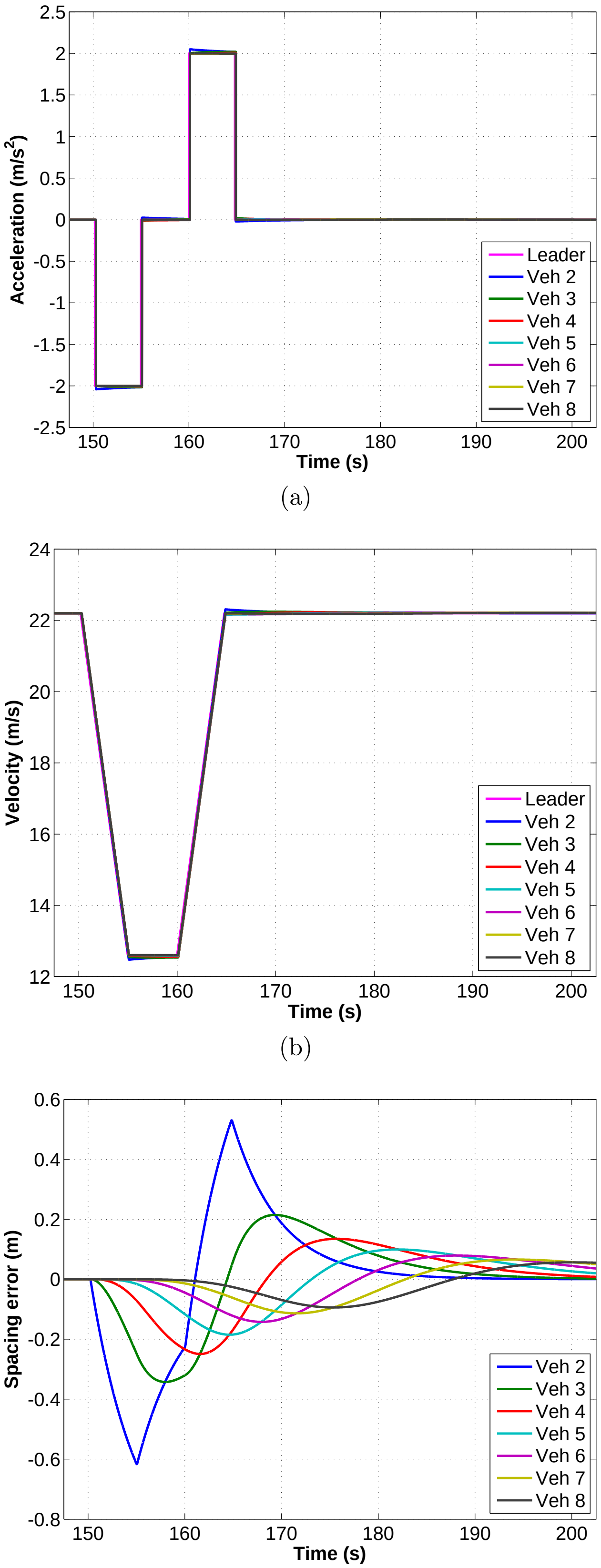


Figure 4.10: Acceleration of the platoon (zoomed)



(a)

(b)

(c)

Figure 4.11: Algorithm I with $C_1 = 0.999$. (a) Acceleration of the platoon. (b) Velocity of the platoon. (c) Spacing error of the platoon.

4.7.1 Information-Updating Scheme I

The first simulation corresponds to the Scheme I (Section 4.6.1). It is assumed that all vehicles operate with transmitted information 100 ms old. As such, their response will present a delay with respect to each precedent vehicle. In Fig. 4.9a, the increase in the absolute values of the followers' acceleration with respect to the leader is presented. Fig. 4.10 shows a detailed region of Fig. 4.9a, where we can observe the discrete values of the acceleration, with an 100-ms sample period. Fig. 4.9b shows the resultant velocity of each vehicle, with all of them approaching their precedent vehicle and subsequently falling behind it, as Fig. 4.9c clearly shows. All vehicles reach to a point (at about 155 s) where they are only 60 cm apart from the respective precedent vehicle. In this first simulation we used $C_1 = 0$, which means that the leader's information has no effect on the behavior of all the platoon followers, except on the second vehicle, since this is the leader's immediate follower.

A second simulation was performed using $C_1 = 0.999$. Fig. 4.11 shows the acceleration, velocity and spacing error of this case. Note that the second vehicle is noticeably affected by the 100-ms communication delay, presenting a worse response than that of the previous case. Equation (4.6) may enlighten this issue. When $C_1 = 0$, the computation of the next acceleration value does not consider the difference of the velocity values between the vehicle and the leader. However, as C_1 increases, that difference is used. Unfortunately, the second vehicle is using 100-ms-old information, from both the leader's acceleration and the velocity values. As such, the result is worse when compared with the case of $C_1 = 0$ since the spacing error in the later case was only caused by 100-ms-old acceleration value from the precedent vehicle (which is the leader in this case). The response is also more abrupt than before. Since the remaining vehicles receive the same information from the leader at the same time, the spacing error toward their precedent vehicles is softened. (It is worth remembering that they are operating with $C_1 = 0.999$.)

4.7.2 Information-Updating Scheme II

This scheme differs from the previous scheme by a feature that is of the most importance to the stability of the platoon: the transmission of leader's anticipatory information. As explained in Section 4.6.2, this is due to the leader's waiting step, until the vehicle actuation moment *vam* is reached, allowing its followers to timely use the transmitted information in their own next acceleration computation. The simulation of this scheme presents several relevant results: as we can observe from Fig. 4.12a, independently of the

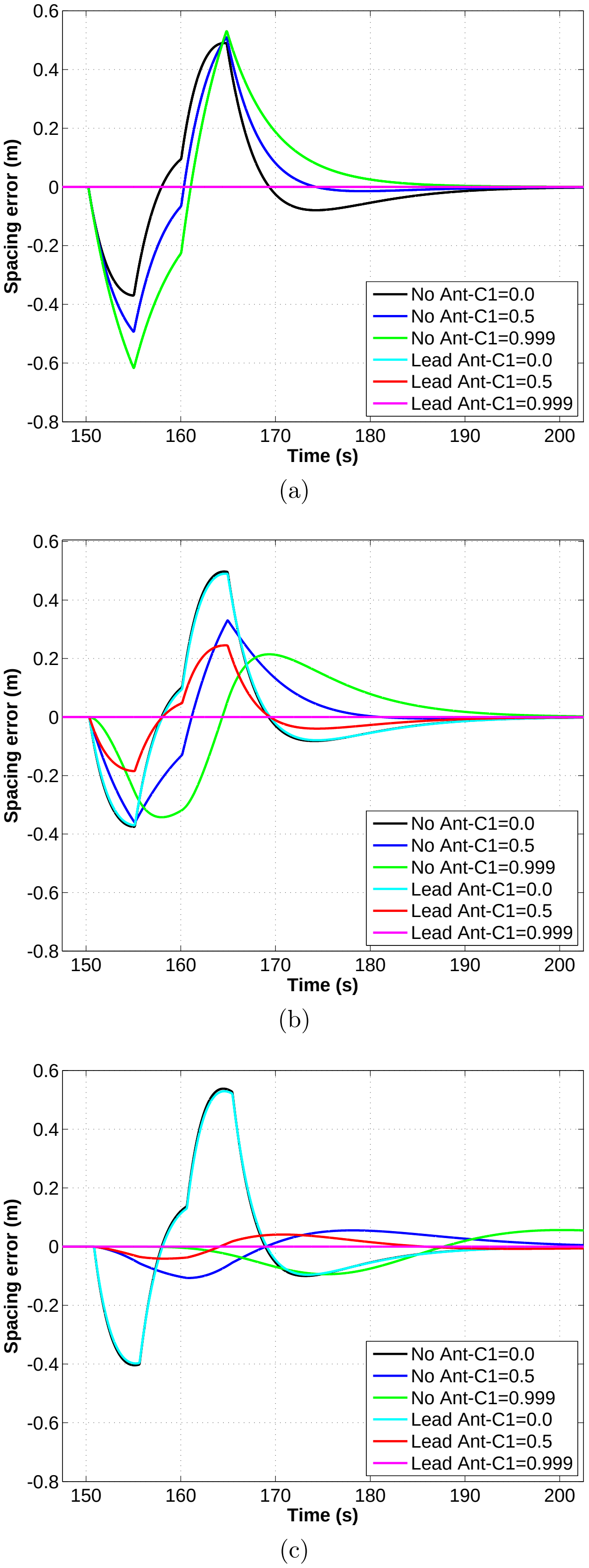
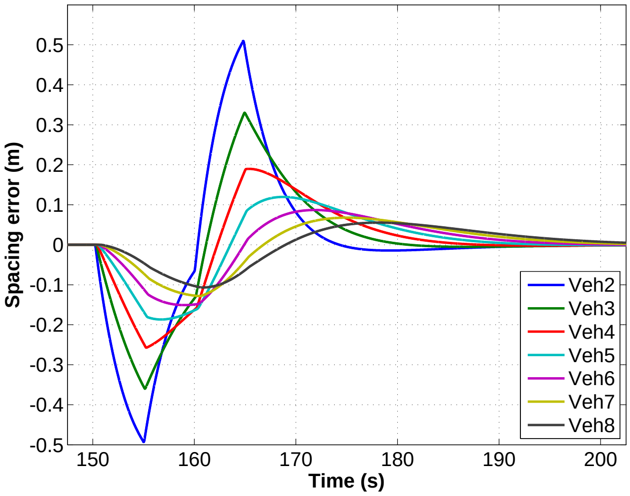
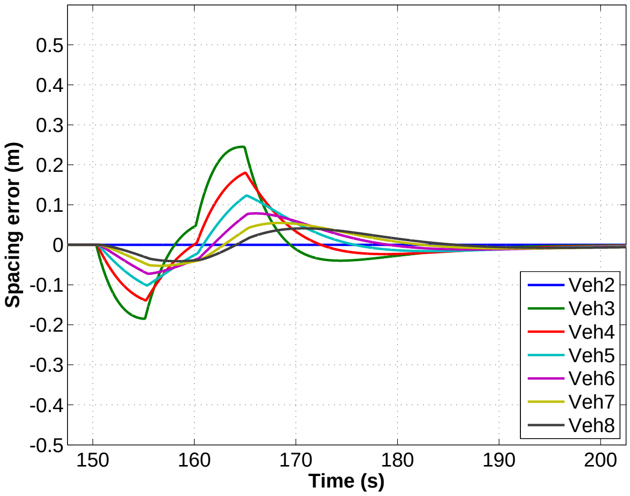


Figure 4.12: Algorithm II: Leader's anticipation. (a) Vehicle 2. (b) Vehicle 3. (c) Vehicle 8.



(a)



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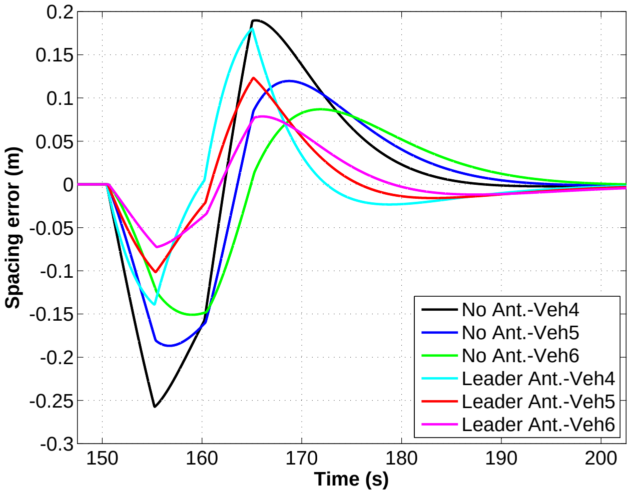


(c)

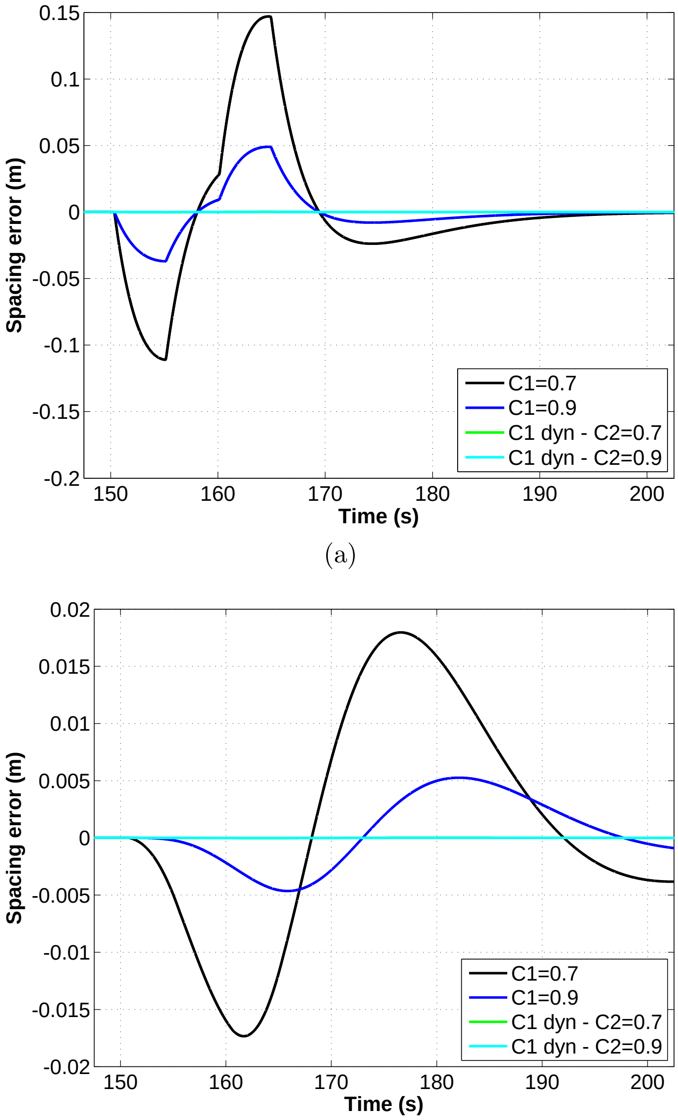
Figure 4.13: Analysis of the influence of $C_1 = 0.5$ on the platoon behavior. (a) No Anticipation with $C_1 = 0.5$. (b) Leader's Anticipation with $C_1 = 0.5$. (c) Vehicles 4, 5, and 6 comparison, with $C_1 = 0.5$.

Table 4.7: Influence of C_1 on the Spacing Error

Veh	**$C_1 = 0$**			**$C_1 = 0.5$**			**$C_1 = 0.9$**		
	NA	**LA**	**%**	**NA**	**LA**	**%**	**NA**	**LA**	**%**
2	**-0.370**	**0.000**	**100**	**-0.493**	**0.000**	**100**	**-0.592**	**0.000**	**100**
	0.490	0.000	100	0.509	0.000	100	0.526	0.000	100
3	**-0.375**	**-0.370**	**1**	**-0.360**	**-0.185**	**49**	**-0.327**	**-0.037**	**89**
	0.497	0.490	1	0.330	0.245	26	0.213	0.049	77
4	**-0.381**	**-0.375**	**2**	**-0.257**	**-0.139**	**46**	**-0.238**	**-0.020**	**91**
	0.505	0.497	2	0.190	0.180	5	0.131	0.026	80
5	**-0.386**	**-0.381**	**1**	**-0.187**	**-0.101**	**46**	**-0.177**	**-0.012**	**93**
	0.513	0.505	2	0.120	0.123	−3	0.095	0.015	85
6	**-0.392**	**-0.386**	**2**	**-0.151**	**-0.073**	**52**	**-0.135**	**-0.009**	**94**
	0.521	0.513	2	0.087	0.079	9	0.075	0.010	87
7	**-0.398**	**-0.392**	**2**	**-0.128**	**-0.052**	**59**	**-0.108**	**-0.006**	**94**
	0.529	0.521	2	0.068	0.055	19	0.062	0.007	89
8	**-0.404**	**-0.398**	**1**	**-0.107**	**-0.041**	**62**	**-0.089**	**-0.005**	**95**
	0.538	0.529	2	0.055	0.041	25	0.053	0.005	90

LEGEND: Veh - Vehicle position NA - No Anticipation
LA - Leader Anticipation % - Improvement

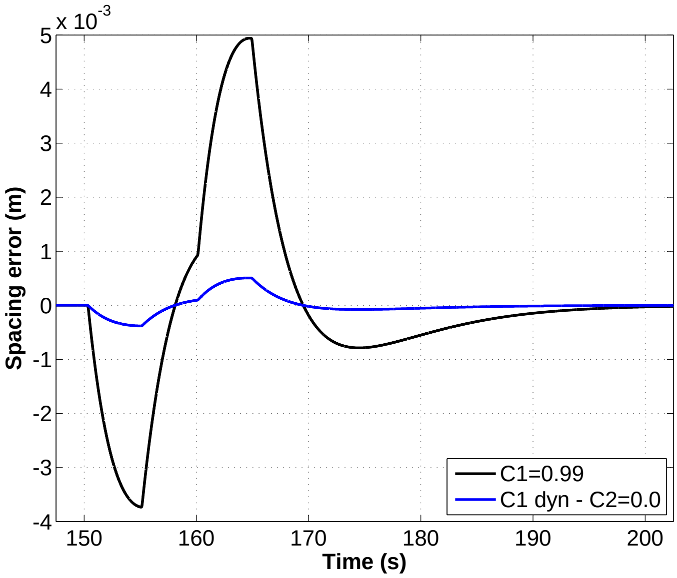
value of C_1, the second vehicle mimics the behavior of the leader, as it is also its precedent. The third vehicle response is shown in Fig. 4.12b. The response is identical of that of Scheme I when $C_1 = 0$, as expected. However, as C_1 increases, the vehicle's response is considerably improved. As C_1 approaches 1, the tracking error approaches zero. The same behavior is presented by all the remaining vehicles (the eighth vehicle's response is presented in Fig. 4.12c). These results show that leader's anticipatory information has a major impact on the platoon stability, and apart from the second vehicle, its effect is proportional to C_1. Ideally, platooning with this operating scheme and a very high C_1 value would assure a very stable platoon behavior. However, it would be also problematic in the long run, since vehicles would be considering the leader's data almost exclusively, which is neither secure nor reliable. As such, a scheme that could entangle a balance between stability and safety would be preferable. The platoon operating with a fixed C_1 value between 0.5 and 0.7 has shown to be an acceptable compromise. However, it is not adaptive.



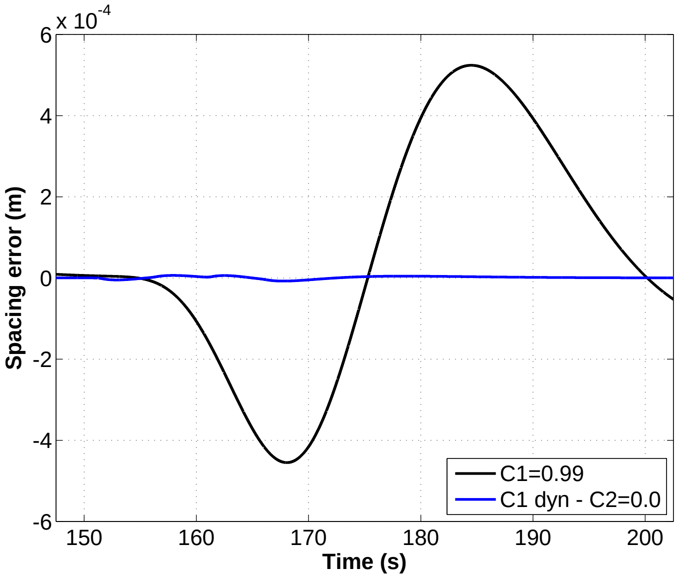
(a)

(b)

Figure 4.14: Algorithm III: Comparison of a fixed and a dynamic C_1. (a) Vehicle 3. (b) Vehicle 8.

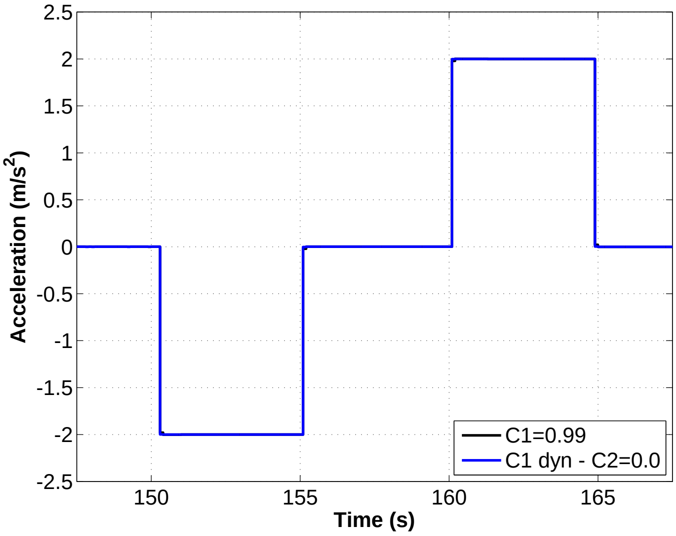


(a)

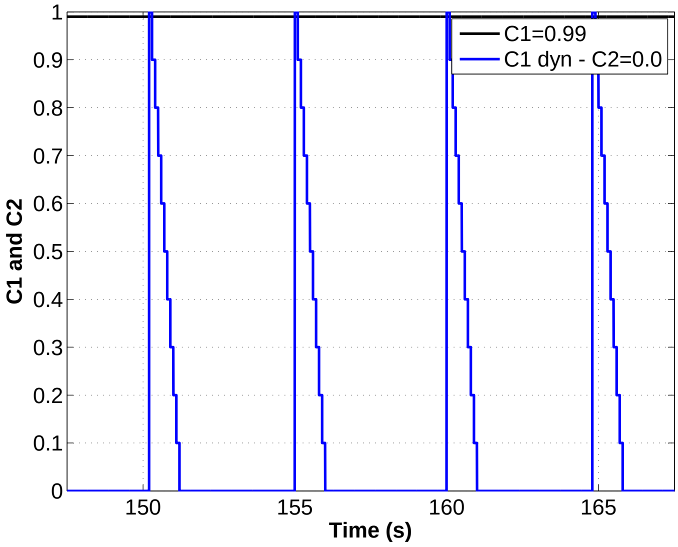


(b)

Figure 4.15: Algorithm III: High fixed versus dynamic C_1 with low C_2. (a) Vehicle 3. (b) Vehicle 8.



(a)



(b)

Figure 4.16: Algorithm III: Leader's acceleration and dynamic C_1. (a) Vehicle 3: Acceleration. (b) Vehicle 3: Dynamic C_1 with $C_2 = 0$.

4.7.3 Information-Updating Scheme III

In the simulation of this updating scheme, we analyze the adaptive value for the leader's information weight, $C_{1_{dyn}}$, discussing in detail the effects of this dynamic parameter on the platoon stability. Table 4.7 presents the spacing errors of algorithms I and II, when performed with several different C_1 parameter values. The lines in bold represent the spacing error values when the vehicles approach their precedent, with respect to the 1-m objective distance (negative error values), whereas the other lines represent the spacing error when the vehicles have fallen behind its 1-m objective (positive error values). We can observe that the C_1 value is crucial to platoon stable behavior.

When operating with $C_1 = 0.5$, the spacing error data of the vehicles in positions 4, 5, and 6 seem to be contradictory. Therefore, a more detailed analysis is required. In fact, these vehicles seem to present no behavior improvement from the leader's anticipatory information with respect to the case where no anticipation exists. In Fig. 4.13 we can see the behavior of the platoon with $C_1 = 0.5$. Fig. 4.13a shows the spacing error with no anticipatory information, whereas Fig. 4.13b shows the case when anticipation exists. We can observe that, in the later case, since the second vehicle mimics the behavior of the leader, the remaining vehicles are unable to so promptly respond when an acceleration occurs. Therefore, the response of the vehicles in positions 4, 5, and 6 is not so good as expected, resulting in similar values of the former case, in the absence of anticipatory information, as can be seen in Fig. 4.13c. However, it is important to notice that this only happens when vehicles accelerate. During braking maneuvers, the improvement is always above 45%, which assures a safe operation of the system.

Although higher values of C_1 prove to be generally beneficial in the presence of leader's anticipatory information, they should not be maintained for a long time. In fact, a high C_1 value is only required when a considerable difference of the acceleration, in absolute terms, occurs between consecutive *uc* intervals. When facing strong accelerations and/or decelerations, a prompt platoon response is required to maintain stability. However, as the acceleration stabilizes, C_1 may then be relaxed to a more conservative value. These are the premises of the present scheme. For this purpose, we introduced the aforementioned parameter C_2, representing the base value above which the dynamic C_1, which is represented by $C_{1_{dyn}}$, will vary, when strong accelerations are determined by the leader. Fig. 4.14 shows the comparison of the results for equal values of a fixed C_1 and a base value C_2 with dynamic $C_{1_{dyn}}$. We consider only fixed C_1 values of 0.7 and 0.9 since the difference of results using low fixed C_1 with respect to equally low C_2 with dynamic $C_{1_{dyn}}$ is so high that the resultant graph scale does not allow accurate visualization of the spacing errors corresponding to the $C_{1_{dyn}}$ values. Fig. 4.15 shows the spacing error results showing better response of dynamic $C_{1_{dyn}}$ with a base value C_2 of zero, when compared with fixed $C_1 = 0.99$. Note that this is one of the most unfavorable case for $C_{1_{dyn}}$ and an extremely favorable case for fixed C_1. Even so, the dynamic scheme presents a considerable stability improvement. Fig. 4.16 shows both the acceleration patterns of the third vehicle and the values of dynamic $C_{1_{dyn}}$ with a base value $C_2 = 0$, and a fixed $C_1 = 0.99$.

4.7.4 Information-Updating Scheme IV

The results of this scheme are extremely favorable. We already observed, in Scheme II, the beneficial results of the leader's anticipatory information over the platoon behavior, even operating with 1-uc-old information from precedent vehicles. However, with this Scheme IV, we took a step further with respect to information anticipation. In this scheme, all vehicles announce the acceleration value that they will use on the next updating cycle uc before their followers compute their own predictable values in an ordered chain of events. Then, all the platoon's vehicles simultaneously actuate at the vehicle actuation moment vam, resulting in a very stable behavior. In this updating scheme, C_1 may present a near zero value, as far as no communication failures occur. This happens because the leader's information is already incorporated into the precedent vehicles' own information, which is anticipatively received. The results of this algorithm, for different C_1 values, present a spacing error virtually null.

4.7.5 Information-Updating Scheme V

This scheme is analogous of the precedent, with one major difference: the uc is now of 800 ms, instead of 100 ms, as in the previous case. This means that only one vehicle transmits at each $tc = 100$ ms. This scheme is intended to be used in the presence of stable and foreseeable traffic conditions and is very benign in what concerns communication network load. Despite a uc value eight times greater than before, the results are very favorable. The results of this algorithm, for different C_1 values, present a spacing error virtually null, similarly to the previous scheme case.

Table 4.8: DSRC System Parameters

Parameter	**Value**
Frequency Spectrum	$5.9\,GHz$
Channel Size	$10\,MHz$
Max Range	$\leq\ 1\,Km$
Data Rate	$3\,Mbps$ to $27\,Mbps$
Latency	$\leq\ 50\,ms$
Slot Time ST	$16\,\mu s$
$SIFS$	$32\,\mu s$
$AIFS$	$64\,\mu s$

4.8 Network Simulations

Some of the information-updating schemes used in previous simulations are very benign where communication network load is concerned. However, the current IVC technologies and protocols rise some concerns of whether they can cope with the involved timings of the information-updating schemes, when all vehicles communicate within 100 ms. To assess current IVC operation in such scenarios, we chose to test DSRC since it is conceived to deal with high-mobility patterns, presenting very low latencies and large-enough range. However, its intrinsic operating characteristics require a more throughout analysis to assess its behavior when a large number of vehicles is involved. For that purpose, we used the NS-3 network simulator.

4.8.1 DSRC Operating Parameters

DSRC/Wireless Access in Vehicular Environments are defined in the IEEE 802.11p and 1609.x standards [IEEE 2010c], [IEEE 2010a], [IEEE 2010b], [Morgan 2010]. The lower layers are defined in IEEE 802.11p and its MAC protocol uses an improved version of the distributed coordination function, which is named enhanced distributed channel access (EDCA), with quality-of-service (QoS) capabilities. The DSRC system parameters are presented in Table 4.8.

4.8.2 NS-3 Simulation Setup and Parameters

A scenario of ten platoons of eight vehicles each was implemented in NS-3. Each platoon is separated by 30 m. Each vehicle is 3 m long and is separated from the precedent

Table 4.9: Parameters of the NS-3 Network Simulation

Parameter	**Value**
Number of nodes	80
Guard interval	4 ms
Time slot (leader)	11 ms
Time slot (follower)	5 ms
Node spacing (intraplatoon)	4 m
Node spacing (interplatoon)	33 m
Propagation delay model	Constant speed
Propagation loss model	Log distance
Data rate (leader)	3 $Mbps$
Data rate (follower)	27 $Mbps$
AC	3 (VO)
$AIFSN$	2
CW_{min}	3
CW_{max}	7

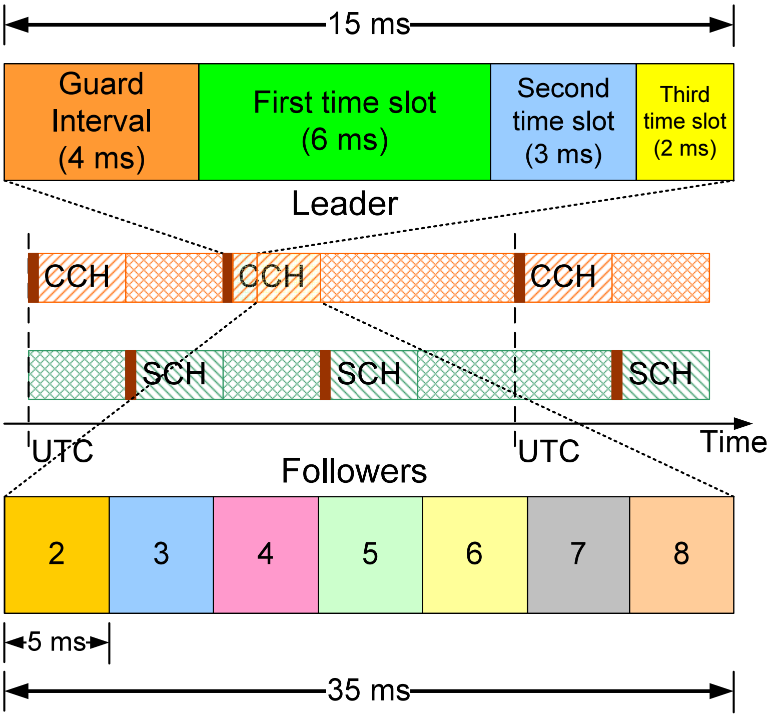


Figure 4.17: DSRC CCH leaders' and followers' time slots.

vehicle by 1 m. The antennas are defined at 1.5 m above the ground. The platoons' leaders broadcast messages to their followers at 3-Mb/s data rate and in LOS. Each follower communicates to its own follower using unicast at 27-Mb/s data rate. Each data packet has a 100-B payload, and explicit acknowledgement (ACK) packets have 10 B. The communication is performed through the DSRC control channel (CCH) since CCH is dedicated to safety and control messages, whereas service channels (SCH) are reserved for more general-information purposes. The CCH intervals are active for 50 ms of each 100-ms interval. A 4-ms guard interval (GI) was reserved at the beginning of each CCH to allow proper synchronization and channel switching of all vehicles [Hartenstein 2010]. Of the remaining 46 ms, we reserved a time slot of 11 ms for the leader and 5-ms time slots for each one of the seven followers. Fig. 4.17 shows the proposed logical division of the CCH, aiming to avoid packet collisions within each platoon. Nevertheless, data packets continue to contend for the transmission media access between each i -th vehicle of near platoons.

The main concern that this setup poses is related to proper reception of leaders' broadcasted messages by the vehicles in eighth position at each platoon. In fact, the distance to their respective leaders is 28 m, and the leaders of the platoons behind them are only 33 m apart (considering antenna-to-antenna distances). To assess proper communication flow, a ten-platoon setup of eight vehicles each was implemented. The main simulation parameters are presented in Table 4.9.

4.8.3 NS-3 Simulation Results

Several simulations were performed. In the beginning of each one, a warm-up process was conducted to proceed to the fulfillment of the MAC/Internet Protocol address association tables (among other actions). This procedure intends to avoid the overhead that such packet exchange would produce during the first superframe of data transmission. DSRC protocol defines that each CCH start time is synchronized with the coordinated universal time (UTC). Additionally, we divided each CCH in time slots, to avoid intraplatoon collisions. These two features could lead to an interplatoons transmission synchronism, which might increase first packet collisions in the beginning of each time slot, even when using the arbitration interframe space number (AIFSN) and contention window (CW) mechanisms, of the IEEE 802.11e EDCA QoS enhancements [Bingmann 2009]. In fact, when a node detects that the media is busy, a new CW is computed, and the corresponding

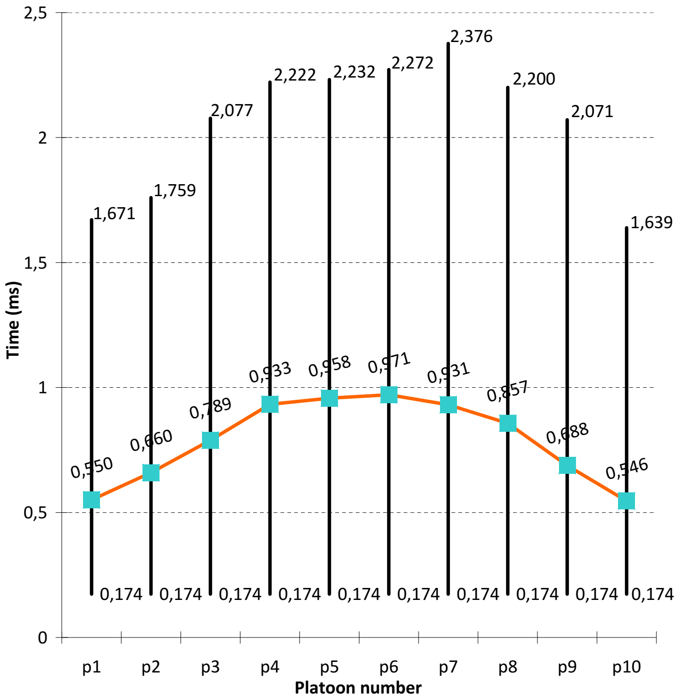


Figure 4.18: Platoons' followers reception delays of messages from their precedent vehicles, using unicast.

backoff time is applied, i.e.,

$$CW_{new} := min\{2 \times (CW_{old} + 1) - 1,\ CW_{max}\} \tag{4.8}$$

However, at the beginning of each time slot, only the $AIFS[AC]$ interval is used, with

$$AIFS[AC] = AIFSN[AC] \times ST + SIFS \tag{4.9}$$

with the access category $AC = 3(AC\_VO)$, the arbitration interframe space $AIFS[AC] = 64\,\mu$s, $AIFSN[AC] = 2$, DSRC slot time $ST = 16\,\mu$s, and the short interframe space $SIFS = 32\,\mu$s. Since all platoons' vehicles use this same value, collisions are prone to occur. To minimize the probability of these early collisions, an additional application-level random backoff between CW_{min} and CW_{max} was inserted.

The presented data of Figs. 4.18 and 4.19 were obtained from statistically noncorrelated simulations of 100 frames of 100 ms each.

Fig. 4.18 shows the aggregate data of average, minimum, and maximum values of reception delays from precedent vehicles, per platoon, using unicast. Higher average delay values are presented by the middle platoons. This results are in concordance with what

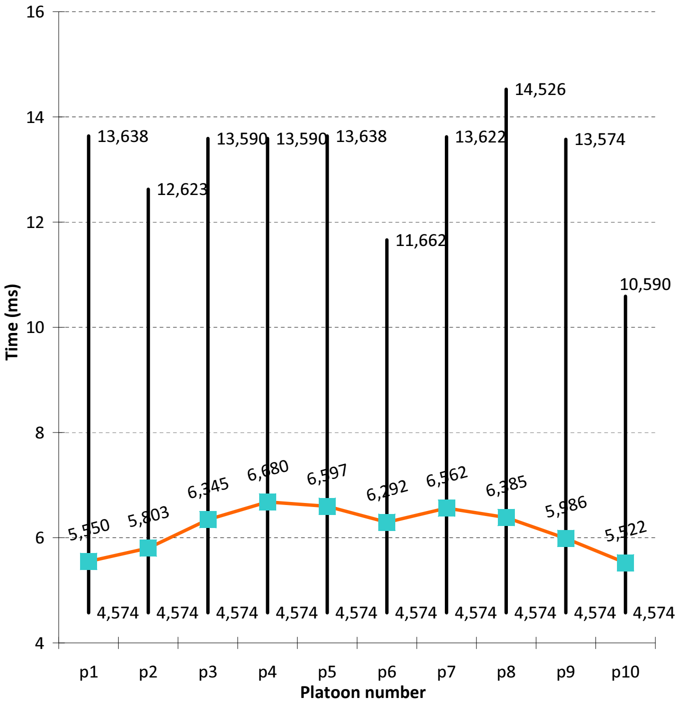


Figure 4.19: Platoons' followers reception delays of messages broadcasted by their leaders.

would be expected since these platoons receive transmissions from both the platoons upfront and the platoons behind. (The DSRC range limit may be higher than the length of a ten-platoon chain like this one.) We see that the average values are all under 1 ms, and no failures occurred over the entire simulation. Since the time slots of the followers are 5 ms long, they have enough remaining time to perform all the required computations, which validates the assumptions made when information-updating Scheme IV was presented and simulated (Subsections 4.6.4 and 4.7.4 respectively). Even the maximum detected delay of 2.376 ms is bellow half the time slot value.

Although unicast communication between followers is reliable, the broadcasted communication between the leaders and their followers is not very resilient. There is no packet delivery guarantee since the ACK mechanism does not exist in broadcasting. Moreover, even if a collision occurs, the broadcast emitter has no means of detecting it, since the MAC of IEEE 802.11p uses carrier sense multiple access with collision avoidance (CSMA/CA). Therefore, an explicit ACK mechanism had to be implemented to ensure proper reception of broadcasted messages from each platoon's leader to all its followers. Although several strategies to improve reliable broadcasting in vehicular environment have been proposed by the research community, this is a problem that has yet to be completely tackled. After several experimental simulations, we decided to implement a selective ACK mechanism. Since all performed simulations revealed that the vehicles in the eighth position had always failed to receive its message when transmissions failure occurred, we used those vehicles as referees for acknowledge successful platoons' leaders transmissions. As such, they became the sole followers to emit ACKs upon proper reception of their own leader's messages, in the right time slots. Using this scheme, several subdivisions of leader's time slots, and two or three transmissions were thoroughly tested. The most favorable results were obtained with the leader's time slot subdivision shown in Fig. 4.17. Considering the 4 ms of the GI, the first transmission occurs at 4 ms from the beginning of each CCH interval, at the beginning of the 11-ms leader's time slots, and is 6 ms long; the second one occurs at 10 ms, if necessary, and is 3 ms long; and the third one occurs at 13 ms, for 2 s long. The obtained results with this time slots subdivision, and the parameters presented in Table 4.9 suggest that this communication scheme is reliable.

Fig. 4.19 shows the aggregate results of the simulations performed, with the average, minimum, and maximum values of reception delays of the followers, from leaders' broadcasted messages, per platoon position. Higher average delay values are presented by the middle platoons, due to the same aforementioned reason. As such, the platoons at the top of the chain present better average delay results, around 5.5 ms, whereas the platoons in the middle present average delay results at about 6.7 ms. Simulation also showed that the first leaders' transmissions were mostly successful. When the corresponding ACK did not arrive in time, a second transmission took place. When the second transmission's ACK was not timely received by the leader, a third transmission occurred. Quantitatively, 89.4% of the first transmissions were successful; 9.8% reached their destiny at the second transmission; and only 0.8% required three transmissions to be properly received.

Since platoon leaders' time slots were augmented by 50% with respect to previous Matlab/Simulink simulations and followers' time slots were reduced to half its previous value, a new set of simulations were performed with these different timings. The results are similar to those obtained previously, confirming the appropriate performance of the proposed algorithms.

4.9 Conclusion

A simulation engine for platoons of IVC-enabled autonomous vehicles has been implemented in Matlab/Simulink. Several information-updating schemes have been proposed and assessed through simulation scenarios. The simulation results suggest that the proposed information-updating algorithms are appropriate to the problem under study.

To assess whether DSRC could cope with the tight time constraints of the simulation models, a set of simulations has been performed with the NS-3. The results suggest that the proposed algorithms may operate using the present technology, although some concerns remain with respect to broadcast performance of the DSRC protocol. Moreover, the selected Log Distance signal propagation model used in the NS-3 simulator may be simplistic. Other models (e.g. Three Log Distance, or Nakagami with different *m–parameter* values) might probably present less favorable results with respect to leaders' broadcasting since the reliability of this protocol is still an open issue in the research community. Thus, more demanding network scenarios with more complex mobility patterns should also be assessed.

Nevertheless, when using the information-updating Scheme IV proposed and simulated in sections 4.6.4 and 4.7.4 respectively, the leader's anticipatory information is already incorporated in the information that each vehicle receives from its precedent and transmits to its own follower, allowing a safe operation with parameter $C_1 = 0$. As such, an all-unicast intraplatooning transmission scheme is feasible, leaving broadcasting for leaders to communicate with other platoons and infrastructure. Moreover, unicast messages are resilient and timely delivered under the simulated scenarios.

Since constant spacing platooning may enable a considerable increase of traffic flow, more simulation results of IVC-enabled autonomous vehicles are required, aiming at the comprehension of new possible representations of the fundamental diagram of traffic flow applied to such scenarios.

Considering the favorable performance presented by the proposed information-updating algorithms in the very demanding scenario of constant spacing platoons, they might also allow important safety and efficiency improvements when applied to different scenarios involving other type of IVC-enabled vehicles.

Chapter 5

Inter- and Intraplatoon Positioning Management and Cooperative Behavior Algorithms for High Traffic Capacity

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P. Fernandes, and U. Nunes, “Platooning with IVC-enabled Autonomous Vehicles: Inter- and Intraplatoon Positioning Management and Cooperative Behavior Algorithms for High Traffic Capacity.” *IEEE Transactions on Intelligent Transportation Systems*. **Submitted for third round of review**. [1]

Abstract

Inter- and intraplatoon positioning management strategies with cooperative behavior are proposed in this paper, to improve the efficiency of an advanced traffic management system. Novel algorithms to ensure high traffic capacity are presented, and Matlab/Simulink-based simulation results are reported. Recently, we proposed new algorithms to mitigate communication delays using anticipatory information. In this paper, we consider a constant spacing between platoons' leaders as a fundamental condition to attain high traffic capacity. New algorithms to maintain interplatoons' leaders constant spacing are proposed, as well as novel algorithms allowing vehicles to enter the main track cooperatively. Furthermore, a new set of algorithms to improve safety is also presented. A novel architecture was developed, where each vehicle consists of two distinct modules: a leader and a follower. Based on Matlab/Simulink simulations of several scenarios, the new algorithms are assessed and the simulation results presented, confirming that the proposed

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[1] This chapter forms a revised and extended version of: P. Fernandes, and U. Nunes, “Algorithms for management of a multi-platooning system of IVC-enabled autonomous vehicles, with high traffic capacity,” *2011 14th Int. IEEE Conference on Intelligent Transportation Systems*, Washington DC, USA, October 5-7, 2011.

algorithms ensure high traffic capacity and vehicle density, and avoid traffic congestion. These features were validated through simulations performed on a novel SUMO-based simulation platform. The results proved that the proposed algorithms enable a clear benefit of a platooning system, when compared to bus and light rail-based transit systems.

5.1 Introduction

THIS research addresses urban traffic congestion, proposing a novel approach to improve mobility. The European Commission recently delivered a white paper [EU 2012], where clear goals and deadlines are defined, throughout a roadmap of forty initiatives to build a competitive transport system that will improve mobility. Among these initiatives, electric vehicles (EV) and new intelligent transportation systems (ITS) are key issues.

The main challenge is to improve road capacity and avoid traffic congestion. For common traffic, when vehicle density is high, perturbations may cause traffic jams [Treiber 2000]. Platooning may help to improve lane capacity, if constant intraplatoon spacing is used [Swaroop 1994], [Rajamani 2006]. In our previous work [Fernandes 2012], we proposed new information-updating algorithms to mitigate the effects of communication delays on platoon string stability. To achieve our goal, we aimed to enclose the communication, computation and actuation delays within an upper bound delay, managed by algorithms that avoid their impact on the platoon string stability. So, higher traffic capacity is achievable, since vehicles may evolve very close to each other in platoons [Fernandes 2012]. Moreover, using intervehicle communications (IVC), we also assessed the behavior of the dedicated short range communications (DSRC) [IEEE 2010c, IEEE 2010a, IEEE 2010b], through the NS-3 simulator [NS-3 2012], under the presented platooning scenarios [Fernandes 2012].

In this paper we propose new algorithms to ensure high traffic flow of a system operating at high traffic densities, while avoiding traffic congestion. A constant spacing between platoons' leaders is considered as a fundamental condition to attain high traffic capacity. This novel approach is grouped in four major algorithms: interplatoon positioning management algorithms; intraplatoon positioning management algorithms; platoon joining maneuvers management algorithms; and extra spacing for secure maneuvering improvement algorithms. Interplatoon positioning management algorithms aim to maintain a constant spacing between platoons' leaders, using novel repositioning maneuvers to lead each new platoon's leader to the position occupied by the previous leader. Intraplatoon positioning management algorithms aim to ensure that all platoons' followers are in place, evolving close behind their leaders, under a control loop as described in [Fernandes 2012]. Platoon joining maneuvers management algorithms aim to allow vehicles to enter the main track cooperatively, whether behind incomplete platoons or occupying vacant leader's positions. Extra spacing for secure maneuvering improvement algorithms aim to add extra spacing methods to improve safety when vehicles perform exiting maneuvers. So, we address the improvement of the lower layers of the hierarchical advanced traffic management system (ATMS) [Fernandes 2012] at a higher level, aiming to ensure high capacity operation of the traffic system, by avoiding speed variations of platoons, and keeping enough space available to permanently accommodate up to eight vehicles per platoon.

All the proposed algorithms were tested through several simulation scenarios, using an improved version of the novel model [Fernandes 2012] developed in Matlab/Simulink [MathWorks 2012], and the results are presented. These new algorithms were validated through simulations performed on a novel scenario implemented in the Simulation for Urban MObility (SUMO) traffic simulator [Krajzewicz 2006], consisting of a complete track with off-line stations and the new features that we added to SUMO [Fernandes 2010], enabling the use of platooning with constant spaced communicant autonomous vehicles. A performance comparison between the proposed platooning system and bus and light rail-based transit systems is presented.

5.2 Related Work

The concept of Personal Rapid Transit (PRT) has been analyzed in the scientific community for quite a while. Among a large number of researchers that published on the subject, Anderson's book [Anderson 1978], as well as the book from Irving *et al.* [Irving 1978], paved the fundamental concepts of such a futuristic mode of transportation, at least at that time. More recently, Anderson [Anderson 2009] published updated issues about the PRT concept. PRT experimental testing and field applications have been reported [Vectus 2012], [ULTra 2012]. However, the benefits of such system with regard to light rail or conventional cars, are yet to be clearly demonstrated. Simulators more focused on PRT systems have been proposed [Xithalis 2012, iTS 2012]. However, it is not clear how they model both communications and cooperation.

Other important fields related to ITS have been subject of research studies and their results have been published in the last years. Many of them are related with autonomous vehicles [Milanés 2011a], adaptive cruise control (ACC) [Xiao 2011], cooperative adaptive cruise control (CACC) [van Arem 2006], [Kesting 2010], cooperative active safety system (CASS) [Huang 2011], on-ramp merging systems [Wang 2010b], [Milanés 2011b], among other research topics. In [Shladover 2007], Shladover reviews the history of the founding of the California Partners for Advanced Transit and Highways (PATH) program, and of the national ITS program in the U.S., providing perspective on the changes that have occurred during the past twenty years. In [Varaiya 1993], Varaiya addressed key issues related to highly automated intelligent vehicle highway systems (IVHS). Swaroop *et al.* [Swaroop 1994], [Swaroop 1999] investigated various platooning control strategies. Alvarez and Horowitz [Alvarez 1997] researched the conditions to achieve safe platooning under normal mode of operation. Horowitz and Varaiya described in [Horowitz 2000] a five-layer automated highway system control architecture, involving the infrastructure and the vehicles. Kolodko *et al.* [Kolodko 2003] completed what is believed to be the first on-road demonstration of autonomous passenger vehicles performing cooperative passing and traversal of unsignalized intersections. In [Baber 2005], Baber *et al.* presented the Griffith University's Intelligent Control Systems Laboratory (ICSL) platform, and the successful tests of ICSL's cooperative autonomous driving algorithms. In [Furda 2011], Furda *et al.* addressed the topic of real-time decision making for autonomous city vehicles, i.e., the autonomous vehicles' ability to make appropriate driving decisions in city road traffic situations. Naranjo *et al.* [Naranjo 2009] developed a control architecture that can manage automatic driving of two cars, CyCabs, and automated mass-produced cars, as part of European Union CyberCars2 Project [Cybercars2 2009]. Recently [VisLab 2012], Broggi's team completed a three month journey, with four autonomous EVs equipped to drive in leader-follower configuration.

Rajamani presented in [Rajamani 2006] a controller of platoons with constant spacing, concluding that autonomous control is not enough to ensure string stability. He found that only with IVC is the string stability of vehicle platoons achieved. The method was experimentally evaluated in field tests [Rajamani 2000].

We consider the use of a constant spacing policy by intraplatoon vehicles, and by interplatoon leaders, as key issues to obtain considerable higher capacity values with platooning of IVC-enabled autonomous vehicles. However, we did not find relevant simulation studies using these policies under the aforementioned scenario in the literature. Most of the published studies consider a constant time headway for the spacing policy between consecutive vehicles, and others use moving blocks which is a concept based on a similar principle where the safety gap is proportional to speed. The constant time headway spacing policy presents a major drawback: the spacing between vehicles increases for higher speed values, lowering vehicle density and consequently limiting the capacity of the system.

Since platooning with a constant spacing policy is very sensitive to communication delays [Mahal 2000], in [Fernandes 2012] we proposed new algorithms to mitigate communication delays on platoons of IVC-enabled autonomous vehicles, using anticipatory information, both from the platoon's leader and the followers. The results obtained through Matlab/Simulink simulations showed a significant improvement on platoons string stability.

A full scale automated system managed by an ATMS may rise some concerns with respect to computation limits, if using a centralized approach. As such, a distributed and hierarchical ATMS is considered more appropriate and scalable. Hallé and Chaib-draa [Hallé 2005] proposed a hierarchical driving agent architecture based on three layers (guidance layer, management layer and traffic control layer), to achieve collaborative driving in ITS context, making use of communications to autonomously guide cooperative vehicles on an AHS. Wang [Wang 2005] proposed a three-level hierarchical architecture, applying concepts of agent-based control to networked traffic and transportation systems. In [Wang 2010a], he also presented an overview of the background, concepts, basic methods, major issues, and current applications of parallel transportation management systems.

In [Fernandes 2010] we addressed the implementation of autonomous vehicle platooning capabilities in SUMO traffic simulator. More recently, we used the modified SUMO simulator to validate traffic flow assumptions, as described in [Fernandes 2012], and we implemented new scenarios to assess the feasibility of a complete multi-platooning system of IVC-enabled autonomous vehicles with off-line stations, performing cooperatively. In [Fernandes 2011], we proposed the base rules for interplatoon positioning management strategies, by maintaining a constant spacing between platoons' leaders, for safe and efficient ATMS operation, to ensure high traffic capacity and vehicle density, while avoiding traffic congestion. To our best knowledge, there are still no traffic simulators with the new presented features in this paper, such as: the simulation of a large number of platoons of constant spaced autonomous vehicles; vehicles exiting to stations and entering the main track from stations cooperatively; the permanent measuring of the traffic flow, capacity, occupancy and vehicle density; and the avoidance of congestion operating at very high

Table 5.1: Lane Capacity using Platoons

v	n	d (m)	D (m)	C (veh/h)	SUMO	k (veh/km)
54 km/h	1	–	20	2348	2600	44
	5	1	30	5510	5510	102
	8	1	30	7082	7082	131
	15	1	30	9101	9100	169
	20	1	30	9908	9915	183

flow and density values.

5.3 Motivation

Platooning presents major advantages. However, maintaining a desired intervehicle spacing in platoons demands a tight control of each vehicle. For the case of human-driven vehicles, intervehicle spacing is defined through a constant time headway, which means that spacing is proportional to speed [Kesting 2008]. The human reaction time, typically around one second, leads to the lack of string stability in human-driven vehicle platooning. This means that the spacing between vehicles may decrease toward the end of the platoon when the lead vehicle decelerates, leading to possible collisions.

5.3.1 Traffic Flow Improvement

Lane capacity may be increased by using platoons with tightly constant spaced vehicles [Varaiya 1993]. The formulation to determine lane capacity is given by 4.2 (on page 29). Based on (4.2), Table 5.1 presents some values, for $s = 3\,m$ and $v = 54\,km/h$. This reference speed was chosen as a compromise between two conflicting objectives: ensuring safe operation by the use of a conservative speed value, and maintaining a favorable maximum traffic flow, using a high enough speed value. The spacing for the case of free vehicles ($n = 1$), shown in Table 5.1 is consistent with the minimum gap from the time headway model, for the typical human drivers' reaction time. For example, with platoons of 8 vehicles each, lane capacity is more than doubled ($5510\,veh/h$) when compared with the free vehicle case ($2348\,veh/h$), despite the use of an interplatoon spacing ($30\,m$) greater than the spacing of individual vehicles ($20\,m$). For higher velocities, there is a slight improvement of the lane capacity for the case of free vehicles, whereas the capacity

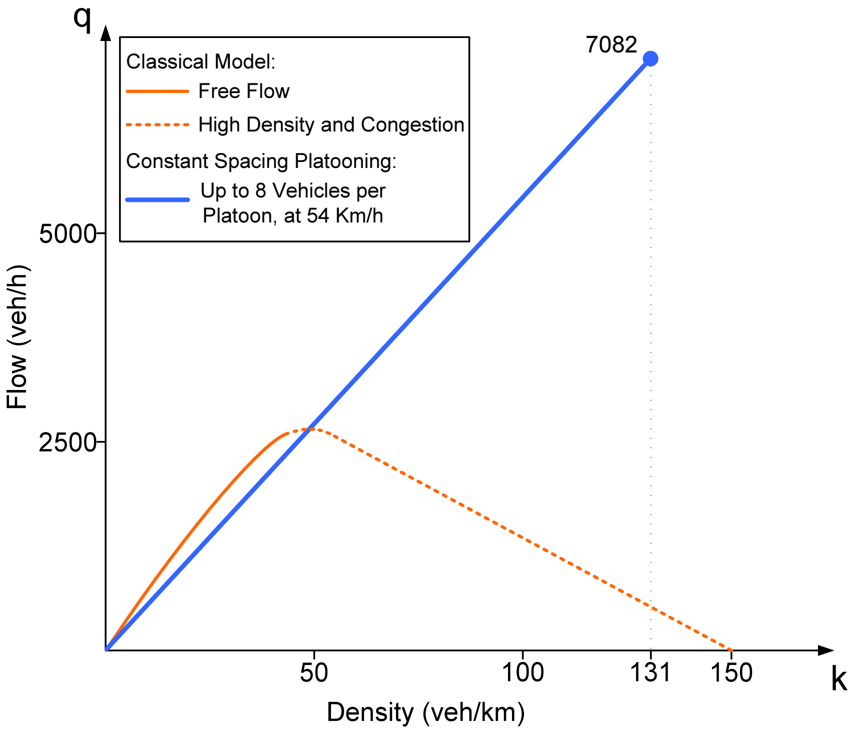


Figure 5.1: Diagram of Traffic Flow for conventional vehicles and platooning of autonomous vehicles (k-q diagram).

of platoons of 8 vehicles doubles, if the speed is also doubled [Fernandes 2012]. Since the data obtained from (4.2) could not be validated through a real constant spacing platooning system, the microscopic simulator SUMO was modified with the features described in [Fernandes 2010], and a complete new scenario was implemented (see Section 5.7 for further details). Several simulations were performed, to produce capacity results for all the cases under study. Table 5.1 presents the data obtained through SUMO simulations, which confirms the lane capacity values previously obtained theoretically.

The fundamental relation of traffic flow theory is given by 4.3 (on page 31). Fig. 5.1 shows the fundamental diagram of traffic flow [Gazis 2002], and the equivalent diagram for the case of constant spacing platooning of autonomous vehicles with constant interplatoons' leaders spacing. In the classical model, the data for conventional vehicles represented by a continuous line is related with the free flow case. The dotted line represents the case where the critical density k_c is attained, approximately at 50 veh/km, near the maximum flow value (lane capacity), around 2600 veh/h. Above this critical density, traffic state begins to enter in a congestion phase, where vehicles are closer to each other and moving slower, until traffic comes to a full stop, at a jam density k_j, typically about 150 veh/km. For the case of constant spacing platooning of autonomous vehicles, the

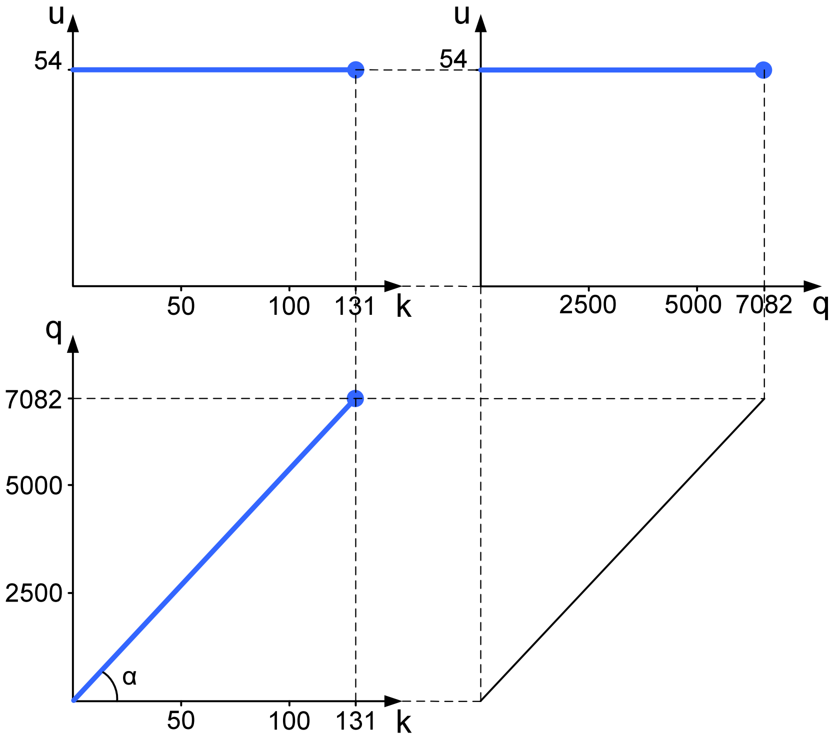


Figure 5.2: The three fundamental diagrams related with platooning of autonomous vehicles (k-u, q-u, and k-q diagrams).

data were obtained through several SUMO simulations, with a new complete scenario setup, using the new features added as described in [Fernandes 2010] (see Fig. 5.26 in Section 5.7). In Fig. 5.1, the flow values for platoons of up to 8 vehicles each, represent the case of intervehicle spacing of $1\,m$ within each platoon, and $30\,m$ of interplatoon distance for complete platoons, which leads to a distance between platoons' leaders of $61\,m$. We can see that a flow value of $7082\,veh/h$ is attainable, even with a limited velocity of $54\,km/h$. The top of the line is upper-bounded, since we establish the corresponding $131\,veh/km$ as the maximum vehicle density of the system. This way, the system always operates within the equivalent free flow zone of conventional traffic while presenting a very high capacity.

Fig. 5.2 represents the three related fundamental diagrams for platooning of autonomous vehicles (k-u, q-u, and k-q diagrams). The proposed ATMS system operates with an imposed constant speed to pertain to the equivalent free flow zone, avoiding congestion. Free flow speed u_f is given by $u_f = \tan(\alpha)$, which means that the slope of the straight line, $\tan(\alpha)$, corresponds to the value of free flow speed u_f, of $54\,km/h$. The represented values in the three diagrams of Fig. 5.2 were obtained through several simu-

Figure 5.3: Traffic flow for two different strategies of autonomous vehicles platooning, for a constant speed of 54 km/h.

lations, using the setup scenario described in Section 5.7. A closer look at the triangular model of the fundamental diagram [Immers 2002], which consists of a simplification of the classical fundamental diagrams, highlights many similarities with the obtained diagrams, if we consider only the free flow zones. However, beyond other more elaborate considerations, two clear differences can be immediately spotted: (i) the slope of the k-q diagram's straight line is generally higher than the presented case. This is due to the fact that the triangular k-q diagrams for common traffic, representing traffic evolving on highways, consider speed values around twice as much the values considered in the present study. As such, the presented straight line of the k-u diagram is longer, and the line of the k-q diagram is less steep; (ii) being simplified, the triangular diagram for common traffic does not represent accurately the fact that, for a given flow value of the k-q diagram, different speed and density values may be involved (when speed is higher, density is lower). However, in the presented case of autonomous vehicles, we are using and representing a constant speed of vehicles in platoons.

5.3.2 Rules to Ensure High System Capacity with Platoons

As we have seen in Subsection 5.3.1, even with a velocity limit of 54 km/h, a flow value of 7082 veh/h is attainable for platoons of 8 vehicles and 30 m apart. The data in Fig. 5.1 concerning leaders' constant spacing platooning, when platoons are incomplete, present lower vehicle densities than those we could obtain if the interplatoon spacing was constant and, consequently, lower flow values for the same platoon dimensions, as Fig. 5.3 clearly shows. For example, for the case of platoons with 5 vehicles each, and considering a constant speed of 54 km/h, with the interplatoon distance of 30 m, the resultant vehicle density should be of 102 veh/km, and the traffic flow of 5510 veh/h. With 5-vehicle platoons, when their leaders are 61 m apart, and for the same speed, the vehicle density presents a lower value of 83 veh/km, and the traffic flow is of 4426 veh/h. There is an important reason to use this approach. In fact, if constant interplatoon distance is used, congestion avoidance may not be ensured by the system. For example, consider a circular track where platoons with 5 vehicles each, with constant interplatoon distance of 30 m, evolve in formation. Consider also that it is necessary to use full system capacity, with platoons of 8-vehicle each. Subsequently, three more vehicles will be inserted just behind each platoon. When the first 5-vehicle platoon receives the three extra vehicles, the platoons immediately behind it will have to brake, in order to maintain the interplatoon distance of 30 m. Two different scenarios may now be considered, both with the same consequences: (i) the communication delays between platoons are mitigated and are not considered; (ii) the communication between platoons presents some delay. In (i), all platoons would brake simultaneously, including the platoon in front of the platoon receiving the three extra vehicles, in a continuous self-feeding process, leading to an eventual stop of the whole system. In (ii), the braking platoons would create a well known "shock wave" propagating upstream, in the opposite direction of the platoon movement, with a speed related to the involved communication delays. The number of completed platoons (from 5 to 8 vehicles) depends on the track length. However, as soon as the wave would reach the front of the completed platoons, it would continue to propagate more intensely, leading to an eventual congestion in a matter of time. Either way, it becomes clear that the track can not cope with these extra vehicles and simultaneously maintain the interplatoon distance of 30m, since there is not enough space available for all of them. (For an insightful explanation of traffic behavior under high density, see Hans van Lint flash lecture [Lint 2012]).

Instead of constant interplatoon spacing, the proposed constant spacing between platoons' leaders ensures that there is always enough space behind each platoon to accommodate as many vehicles as necessary to complete the platoon, when it is not complete (eight vehicles), without forcing the platoons behind to brake in order to maintain the interplatoon distance of 30 m. As such, the ATMS is able to maintain full system capacity. When traffic demand is lower, incomplete platoons will be spaced by more than

30 m, which benefits safety. One could also argue that a considerable higher density could be attained under the considered scenario, if the interplatoon spacing of 30 m was occupied by more vehicles, forming an almost continuous platoon. In this case, densities around 245 veh/km could be obtained. However, this assumption is not realistic or viable. Firstly, vehicles must be able to enter the main track which requires a safety gap. Secondly, vehicles must also be allowed to exit the main track, which may require extra spacing to execute exit maneuvers. Those maneuvers could impose speed variations on the platoons. However, in a system operating at such high traffic density, speed variations must be avoided, since they may induce congestion. The proposed ITS based on platooning of autonomous vehicles with constant spacing between platoons' leaders, and managed by a hierarchical multilayered ATMS, has safety concerns as a top priority.

5.3.3 Assumptions

In the present stage of our research, some assumptions are made: only longitudinal control of vehicles is assumed; only platoons of autonomous vehicles are considered; each considered platoon dimension is about 31 m long (8 vehicles 3 m long and 1 m apart); the vehicles' dynamics are considered identical; the vehicles use the control and communication methods described in [Fernandes 2012]; when emergency events occur, the platoons behind are alerted through direct interplatoon communications; the information-updating scheme IV proposed in [Fernandes 2012] is used, to ensure string stability of platoons; autonomous vehicles do not share the road with conventional vehicles; autonomous vehicles use dedicated tracks, operating on a nonstop basis from origin to destination, with off-line stations [Anderson 2009]; vehicles use on board track switching [Irving 1978]; autonomous vehicles' electric power source comes from the infrastructure; autonomous vehicles' batteries should be small and light, providing only enough energy to cope with power failures; autonomous vehicles should be lightweight; vehicles' maneuvers exiting the track to stations, as well as entering the track from stations, are performed cooperatively; the system is managed by a hierarchical multilayered ATMS. The ATMS should control: the platoons' leaders appropriate operation; the admission of vehicles into the system avoiding congestion even when operating close to its maximum capacity; and the management of empty vehicles to deal with asymmetrical transportation demand.

In this paper we consider autonomous vehicles in the following context: all vehicles' devices to acquire data (lidar, radar, communications, etc.) gather information that may be used by the vehicle to undertake actions under its own rules. This way, throughout this paper, communications are not considered as a mean to remotely control each vehicle, but as a way to improve vehicle's information about its situation in the system, enabling it to act accordingly to the best information available. For the proposed ATMS to be feasible, we consider that the platoon vehicles must present a prominent autonomous behavior, although complying to the system rules, like any other autonomous vehicles in other contexts.

5.4 Hierarchical Multilayered ATMS

Fig. 4.1 (on page 26), shows a partial view of ATMS that integrates zone agents responsible for controlling the platoon leaders. We intend to isolate this level from the platoon's management level, where each leader must control its platoon's followers. Vehicles leaving the platoon must perform the exiting maneuvers autonomously. When traffic demand is high, complete 8-vehicle platoons under the constant spacing policy between platoons' leaders, present leaders' spacing of 61 m, and interplatoons' spacing of 30 m. Lower traffic demand leads to incomplete platoons (seven vehicles or less). However, leaders' spacing will be maintained (61 m). Even when low traffic demand leads to the presence of isolated vehicles, they must occupy precise positions, separated by a multiple of the interplatoons' leaders defined distance ($61\,m$ in the present case), and perform as leaders. This rule may appear too restrictive in respect of the delay that may be imposed upon free vehicle's entrance in the main track. However, two arguments should be enough to justify it. Firstly, for a speed of $15\,m/s$ ($54\,km/h$), the maximum time overhead imposed to the vehicle entering the track is about 4 s only. Secondly and more important, this rule always ensures a deterministic safety gap between vehicles, allowing an appropriate management of new vehicle entrance, whether to evolve alone or to join another vehicle to form a platoon. Moreover, if incomplete platoons are already in place, there is always enough space behind them to insert vehicles, until a maximum of eight per platoon. As such, when a leader leaves the main track, the lead vehicle of the remaining vehicles of the platoon must assume leadership, while avoiding overloading the higher level of ATMS. Moreover, the new leader must accelerate to reach the position that previous leader would be occupying. The same reasoning applies to platoons' middle vehicles. When such a vehicle exits, its followers must autonomously close the gap it left, as soon as possible.

We define a rule stating that all vehicles join the platoon from behind. The main reason for this rule is to avoid the use of small gaps by vehicles joining a platoon in its middle positions, after the exit of its middle vehicles, since these maneuvers could

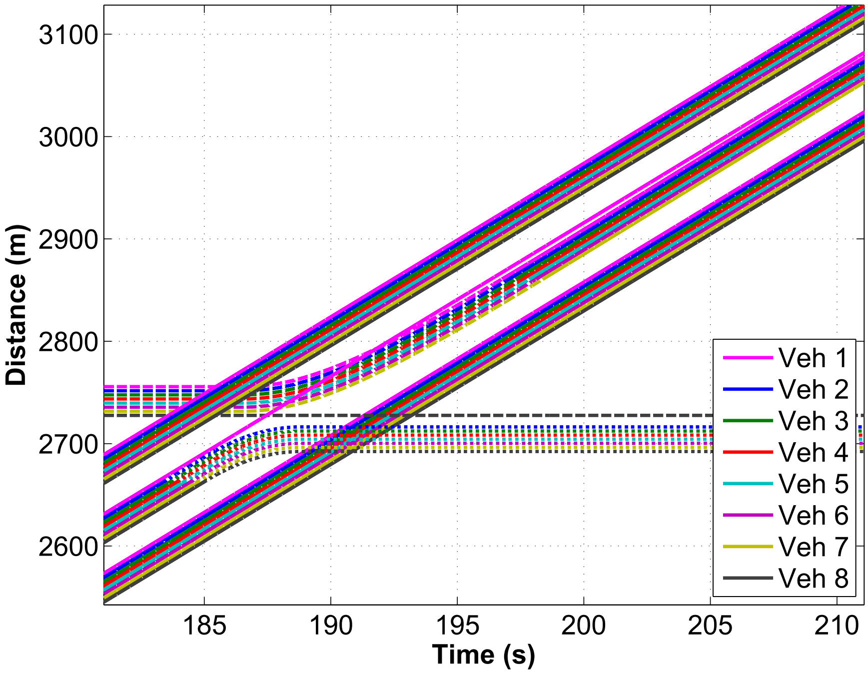


Figure 5.4: Seven tail vehicles exiting and seven vehicles joining a platoon at a station, with old leader maintaining its position.

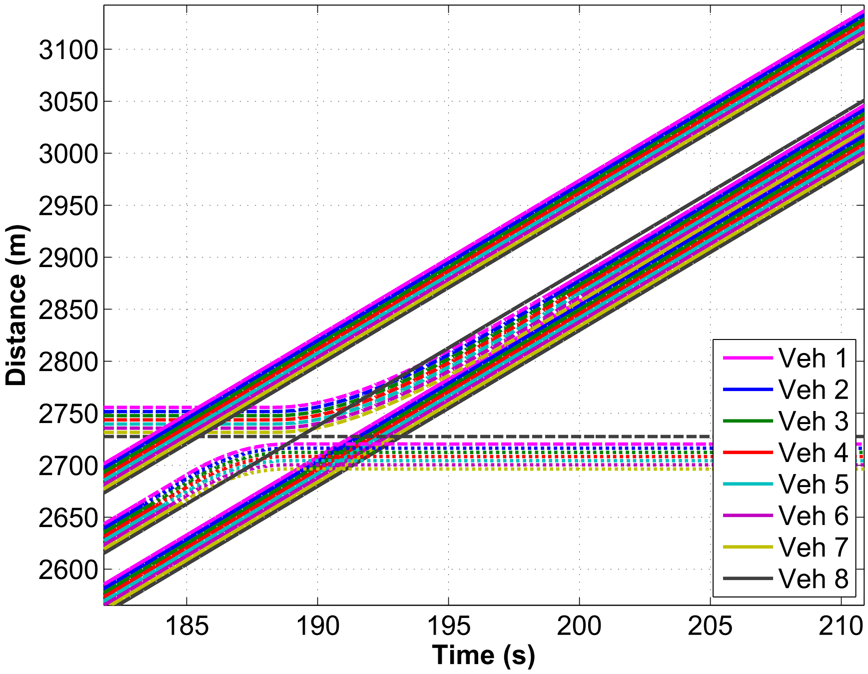


Figure 5.5: Seven front vehicles exiting and seven vehicles joining a platoon at a station, without new leader's repositioning maneuver.

compromise safety. Following the aforementioned rule, we present two limit scenarios: Fig. 5.4 presents the case when the last seven vehicles exit the platoon and no leaders' repositioning maneuver is performed. In this case up to new seven vehicles may join the platoon safely; Fig. 5.5 presents the case when the first seven vehicles exit the platoon and no new leaders' repositioning maneuver is performed. It is clear that, in this case, there is no space behind the eighth vehicle to accommodate all the seven entering vehicles. In fact, if the last of the seven entering vehicles could be accepted in the main track, it would collide with the leader of the platoon following behind. As such, to avoid collision, the following platoons would have to slow down, compromising the "no congestion" principle that the proposed ATMS aims to maintain. If the adopted rule was to accept vehicles at platoons' front, the same problem would arise, with the presented arguments in the reversed order. A solution to this problem is proposed in the next section.

Performing the splitting and joining maneuvers with a high level of autonomy and cooperatively, allows to isolate higher ATMS layers of dealing with platoon details, ensuring that leaders always occupy the right positions, and that platoons are always in close formation. Since the ATMS may transmit to all leaders their acceleration pattern, in time periods of the order of several seconds, the ATMS is able to manage a considerable amount of platoons simultaneously.

If vehicles were fully automated, the ATMS could fail to manage the whole system. Had the ATMS to deal with all vehicles' maneuvers and control, in a centralized manner, and the system would quickly fail to operate safely and efficiently. In fact, communication delays and computation overload would compromise system operation. That is the main reason for the proposal of a hierarchical multilayered ATMS. Higher ATMS levels deal mainly with platoon leaders, system capacity management and safety issues; platoons' leaders control each platoon behavior, particularly the interplatoon positioning management; all vehicles perform with a high level of maneuvering autonomy, although complying with established following rules (as human drivers, being fully autonomous, also comply to traffic signs and rules); vehicles' exiting maneuvers are performed autonomously; vehicles' entrance maneuvers are coordinated cooperatively with evolving vehicles on main track, and are subjected to ATMS clearance. Hence, ATMS has the availability needed to control the whole system, since the tasks are distributed among system components.

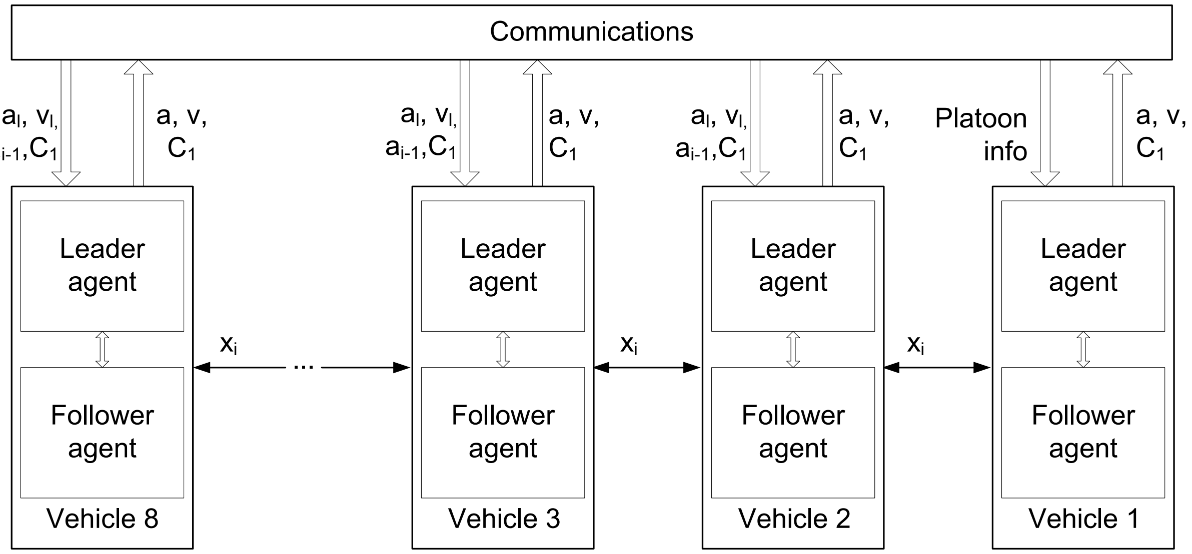


Figure 5.6: Information flow diagram of agent-based platoons.

5.5 Positioning Management Algorithms

To accomplish the task of vehicles' repositioning of new platoons' leaders, each vehicle consists in two modules, a leader agent and a follower agent, as depicted in Fig. 5.6. As such, every vehicle may assume leadership of a platoon, or follower behavior, depending on the circumstances. Moreover, the level of leadership is independent, whether is external (real) or internal (virtual), which means that a new real leader may externalize commands from its internal follower, and its internal follower, in turn, may follow its internal leader. These behavior patterns will be further clarified in the next subsections, where the proposed algorithms are described.

5.5.1 Interplatoon Positioning Management Algorithms

We propose a constant spacing policy between platoons' leaders, of $61\,m$ from each one's front bumper, for the reference speed of $15\,m/s$. Vehicles exiting from platoons' tail do not raise concerns. However, when a leader vehicle leaves the platoon, strategies must be implemented to avoid slowing down the platoons behind. The first one of the remaining vehicles of the platoon becomes the new platoon's leader. If it maintains its current interplatoon positioning while other vehicles join the platoon, constant speed of platoons that follow behind may be compromised. So, the new leader must accelerate within some conditions, to ensure large enough spacing behind the platoon to be occupied by new vehicles joining the platoon. As such, when a platoon leader leaves the track, a follower will take its place, becoming the new platoon's leader, with the following procedures, to ensure a constant spacing between platoons' leaders:

- initially, the leader uses its internal leader agent (LA) to command the platoon, and followers use their internal follower agents (FA);
- the leader transmits information about its current objectives to the new leader of the platoon;
- an eventual follower about to exit the platoon's front transmits that information to its own followers;
- the leader and eventually some of its followers leave the main track to a deceleration track;
- only after the last of the exiting vehicles has abandoned the main track, are those vehicles allowed to brake;
- the new leader of the platoon assumes external (real) leadership;
- internally, the new leader activates its internal LA, maintaining the internal FA activated;
- internal FA changes the objective value L_i of the tracking error of (5) in [Fernandes 2012], from $4\,m$ to $0\,m$;
- this action leads to an immediate increase of the spacing error ε_i of the new leader's FA of $0\,m$ to $n \times 4$, where n is the number of platoon's front vehicles that left the main track;
- the new leader's FA performs the required maneuvers to attain its internal LA position;
- followers of the new leader behave as usual, maintaining their objective value of tracking error;
- internal LA continues receiving commands from an upper level of the ATMS, changing its behavior accordingly;

- when the tracking error becomes lower than a predetermined threshold value, LA assumes the command of the platoon operations;
- this process is transparent to all remaining followers.

With this scheme, maximum capacity should be ensured, whereas congestion may be avoided.

5.5.2 Intraplatoon Positioning Management Algorithms

Vehicles exiting the main track to a station may also come from middle positions of a platoon. Such occurrences do not pose any problems to the relative platoon positioning with respect to its neighbors. However, those maneuvers must also be timely performed, and the space that exiting vehicles were occupying must be filled in by their followers, if any. For that purpose, the following procedures should be performed:

- each follower uses its internal follower agents (FA);
- a follower about to exit the platoon transmits that information to its own followers;
- the exiting followers pertaining to the case described in Subsection 5.5.1 are not considered in the present algorithm;
- two or more consecutive followers may leave the main track at once;
- as soon as a follower leaves the main track, its followers must accelerate to fill the left gap.

5.5.3 Platoon Joining Maneuvers Management Algorithms

Inter- and intraplatoon positioning management algorithms described in the two previous subsections, allow the vehicles to enter the main track safely after ATMS clearance, whether behind incomplete platoons or occupying vacant leader's positions, without slowing down platoons behind. To accomplish such task, vehicles entering the main track must act synchronously and cooperatively with the platoon's vehicles that remained in the track. In the case when all platoon's vehicles exited the track, the lead vehicle of the entering vehicles will occupy a leader's position, followed by any vehicles that enter behind, to a maximum of 8 vehicles per platoon. The following procedures describe the actions required to ensure safe and smooth vehicle entrance:

Table 5.2: Joining Maneuver Parameters

Parameter	**Description**
TW	Time to wait
LPT	Leader's positioning time
EMSG	Number of extra meters for safety gap
MT	Meter time
P	Previous position in the platoon of the last vehicle that remained in the main track
IVT	Intervehicle time
NVF	Number of vehicles positioned in front of P that left the main track to a station
RTF	Recovering time factor

- initially, the vehicles about to enter the main track are stopped at a station;
- if the track is empty on a leader's positioning spot, a maximum of 8 vehicles enter the main track, departing at an exact moment to achieve the right positioning timely;
- if a platoon passes by, track sensors detect how many vehicles exited the track to the station, how many vehicles remained, and what were their positions in the platoon;
- the information gathered as described in the previous item is confirmed through IVC;
- the departure of vehicles is determined through an algorithm that delays the moment the first vehicle starts to move, in a way that it reaches the main track with a predetermined safety gap to the vehicle it will follow;
- on the acceleration track, the first vehicle behaves as the leader of the remaining joining vehicles that follow it;
- the departure delay is computed as follows (see Table 5.2):

$$TW = LPT + EMSG \times MT + P \times IVT - NVF \times RTF \tag{5.1}$$

  - TW is proportional to the last vehicle's previous position in the platoon that remained in track, and inversely proportional to the number of vehicles that

  exited the track and were previously positioned in front the last vehicle that remained in track;
  - the values of the parameters presented in Table 5.2 are dependent of: the physical characteristics of each station; the considered speed; and the platoon dimension. So, in Section 5.6 (Results) they will be defined for the considered scenario (see Table 5.3);

- when the departure of vehicles about to enter the main track occurs, a communication channel between the last vehicle in the platoon and the leader of the entering vehicles is established;

- the leader of the entering vehicles behaves as a follower of the last vehicle of the platoon it will join;

- the behavior described in the two previous items ensures that the entering maneuver is performed cooperatively;

- the TW parameter is used mainly to avoid early departures, since the length of the acceleration track is finite and vehicles must be correctly positioned when entering the main track;

- the main reason for the previous restraint comes from the fact that the vehicles are evolving at around $15\,m/s$ in the final positioning maneuver;

- the leader of the vehicles joining the platoon enters the main track with a distance to the last platoon's vehicle of $1 + EMSG\,m$;

- as soon as the vehicles enter the main track, they must accelerate to fill the left aforementioned gap.

5.5.4 Extra Spacing for Secure Maneuvering Improvement Algorithms

For the sake of safety improvement, a further algorithm is proposed to increase the distance between some of the platoon's vehicles, just before exiting maneuvers are performed. As such, the spacing between exiting vehicles and vehicles that remain on the main track is increased to $1 + EMSG\,m$, under the following procedures:

- initially, the leader uses its internal leader agent (LA) to command the platoon, and followers use their internal follower agents (FA);

- a vehicle about to exit the platoon transmits that information to its own followers;

- two or more consecutive vehicles may leave the main track at once;

- before a follower leaves the track, it will increase its distance to its precedent, under the following conditions:

    - when a follower not about to exit receives indication from its precedent vehicle that it will leave the track, its internal FA changes the objective value L_i of the tracking error of (5) in [Fernandes 2012], from $4\,m$ to $5\,m$;
    - when a follower about to exit receives no indication from its precedent vehicle that it will leave the track, its internal FA changes the objective value L_i of the tracking error of (5) in [Fernandes 2012], from $4\,m$ to $5\,m$;
    - when a follower not about to exit receives no indication from its precedent vehicle that it will leave the track, it will keep its distance to its precedent;
    - when a follower about to exit receives indication from its precedent vehicle that it will leave the track, it will keep its distance to its precedent;
    - in summary, let PV be the precedent vehicle, and OV the own vehicle. Consider that those variables may assume two values: 1 representing an exiting maneuver, and 0 otherwise. So, if $PV \neq OV$, then OV brakes to create extra spacing to PV.

- the algorithm presented above avoids to create extra spacing between consecutive vehicles exiting the main track, as well as between consecutive vehicles remaining in track. Extra spacing is only added to the vehicle in front of an exiting convoy, and to the vehicle behind;

- the algorithm presented above may be performed synchronously, or asynchronously;

- as soon as the follower leaves the main track, its followers must accelerate to fill the left gap.

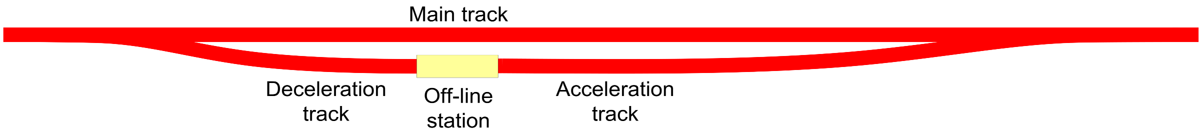


Figure 5.7: Station configuration used in simulations (the off-line station part of the figure is not represented to scale).

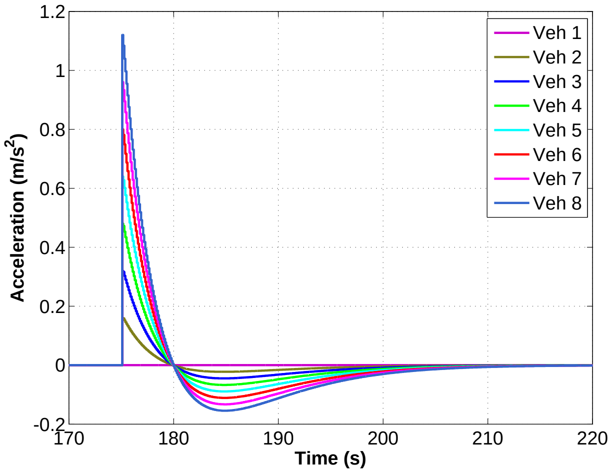
5.6 Results

To assess the appropriate operation of the proposed algorithms, several simulations were carried out in Matlab/Simulink. All models include eight-vehicle platoons with IVC-enabled autonomous vehicles. Each vehicle is simulated by a model consisting of two modules: a leader and a follower. Underneath this control system, the whole communication system reported in [Fernandes 2012] is used. The parameters used in the Matlab/Simulink simulations are defined in Table 4.6 (on page 45). Fig. 5.7 depicts the station configuration used in the performed simulations.

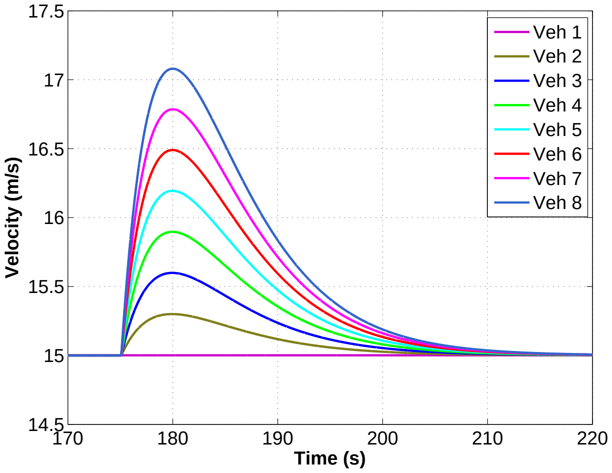
5.6.1 Interplatoon Positioning Management Algorithms

Fig. 5.8 presents aggregate results from the repositioning mechanism of the seven possible cases, without any perturbation. We can observe in Fig. 5.8a that, if only the previous leader vehicle exits the main track, the maximum acceleration applied to the new leader is of $0.16\, m/s^2$. If two vehicles exit, the third one, becoming the new leader, is accelerated to a maximum of $0.32\, m/s^2$. In the case of the fourth vehicle, the maximum applied acceleration is of $0.48\, m/s^2$. And so forth $(0.64; 0.8; 0.96)$, until the eight vehicle's case $(1.12\, m/s^2)$. As such, the acceleration is proportional to the previous position occupied by the new leader of the platoon. Consequently, speed increase is higher for the cases when vehicles in the tail of the platoon assume leadership (Fig. 5.8b). The spacing error (Fig. 5.8c) is equal to $n \times 4$, where n is the number of platoon's front vehicles that left the main track. After 30 s, the spacing error is below 1 m, independently of the case (1 to 7 front vehicles exiting). This means that the time needed to reach minimum tracking error does not depend significantly of the new leader's previous position.

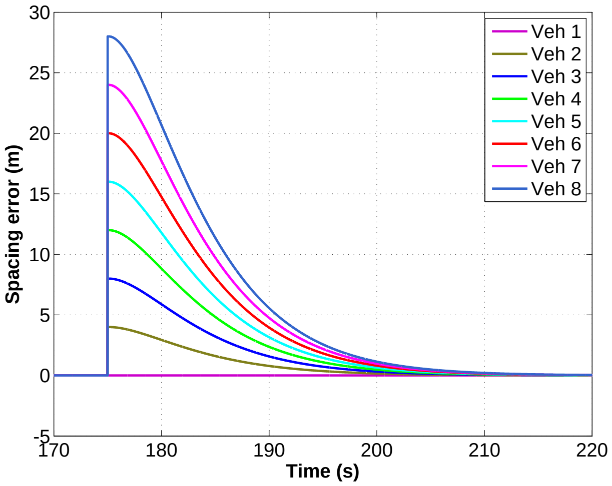
Fig. 5.9 depicts the platoon's behavior when five leading vehicles exit the main track. It is shown that the sixth vehicle, becoming the leader at 145 s, accelerates to reach previous leader's position, while being followed by vehicles close behind. The virtual trajectories of the vehicles that left the main track are depicted, to show that the remaining



(a) Acceleration



(b) Velocity



(c) Spacing error

Figure 5.8: Tracking of leader's positioning without perturbation.

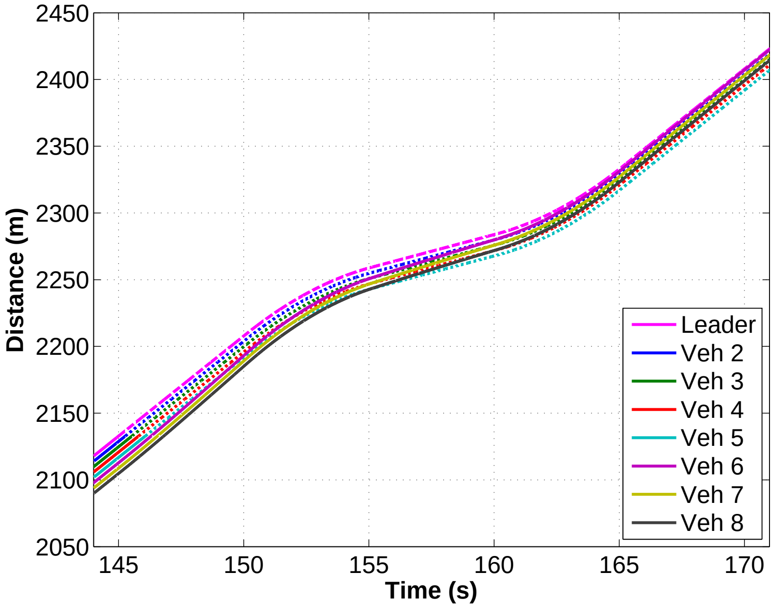


Figure 5.9: New leader reaching previous leader position, with representation of the virtual path that exiting vehicles would perform.

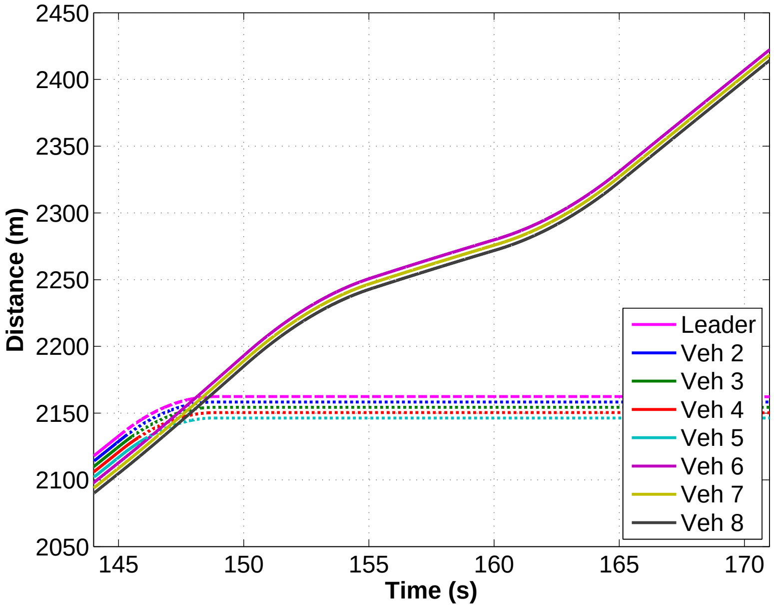


Figure 5.10: New leader reaching previous leader position, with a full stop of exiting vehicles to a station. The braking maneuvers are performed off-line.

vehicles perform repositioning maneuvers, as expected. Fig. 5.10 depicts what really happens, since the vehicles that left the main track brake on a deceleration track, and will come to a full stop when reaching an off-line station. It is important to acknowledge that when more than one vehicle exit the main track, the leader and the remaining vehicles of the exiting convoy only brake after the last vehicle's exit maneuver. As such, their speed reduction in the deceleration track does not affect the speed of the followers that remained in the main track.

To assess the robustness of the algorithms, a perturbation on the acceleration was applied (see dotted line in Fig. 5.11a), while the repositioning maneuver was taking place. The internal LA of the new leader, serving as a reference for the FA, applied the acceleration pattern, in spite of not being yet the real platoon's leader. Meanwhile, the FA continued trying to reach the virtual position of the previous leader, adapting its acceleration pattern accordingly. Even considering this perturbation, the resultant acceleration (Fig. 5.11a), and consequent velocity (Fig. 5.11b) are such that the spacing error profile is not affected (Fig. 5.11c).

5.6.2 Intraplatoon Positioning Management Algorithms

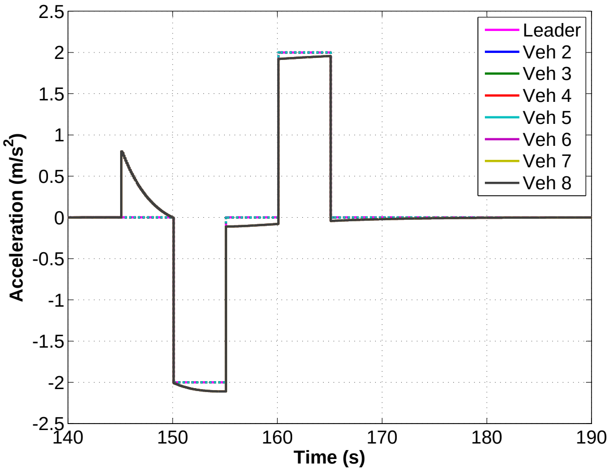
When a follower is about to exit the platoon at the next station, it announces its intention to its followers. Some of them, in turn, may also intend to exit at the same station. As such, several scenarios are possible:

- an isolated vehicle exits the track;
- several vehicles exit, but their immediate platoon neighbors remain in the track;
- several vehicles exit, in one or more convoys of two or more vehicles each.

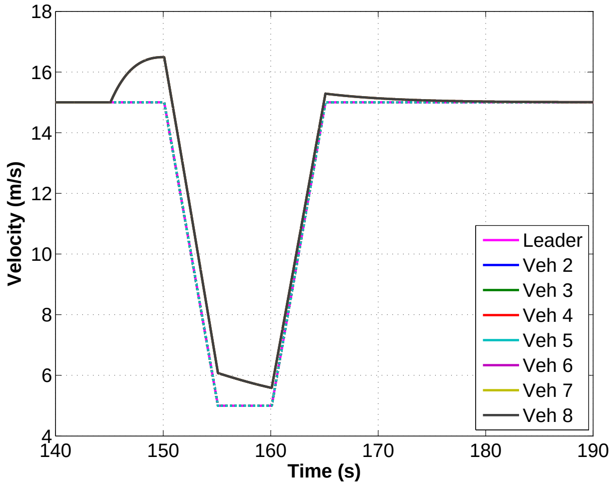
Examples of each of the aforementioned cases follow:

5.6.2.1 Exiting of an isolated vehicle

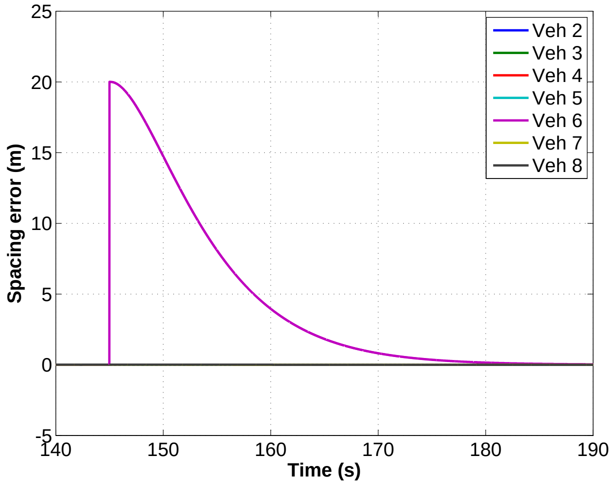
Fig. 5.12 presents the distance profile of the platoon, i.e., the relation between each vehicle's position (m) versus time (s), when the vehicle in fourth position exits the main track;



(a) Acceleration



(b) Velocity



(c) Spacing error

Figure 5.11: Acceleration profile, resultant speed and spacing error of the robustness assessment.

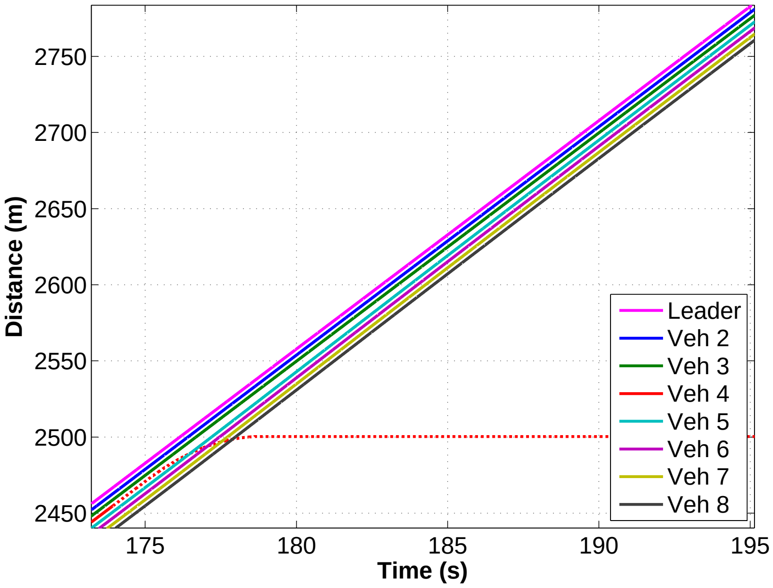


Figure 5.12: Follower in fourth position exits the main track to a station. Vehicles from fifth to eighth position accelerate to close the gap.

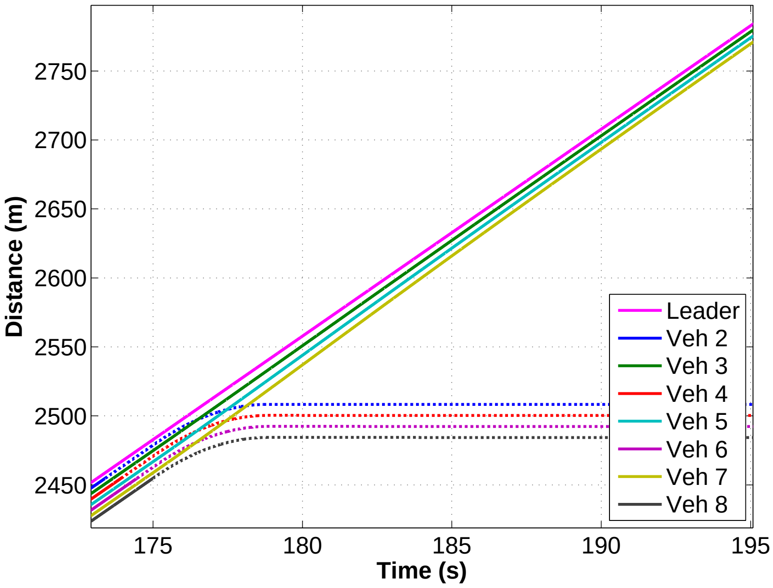


Figure 5.13: Followers in second, fourth, sixth, and eighth position exit the main track to a station. Vehicles in third, fifth, and seventh position accelerate to close the gaps.

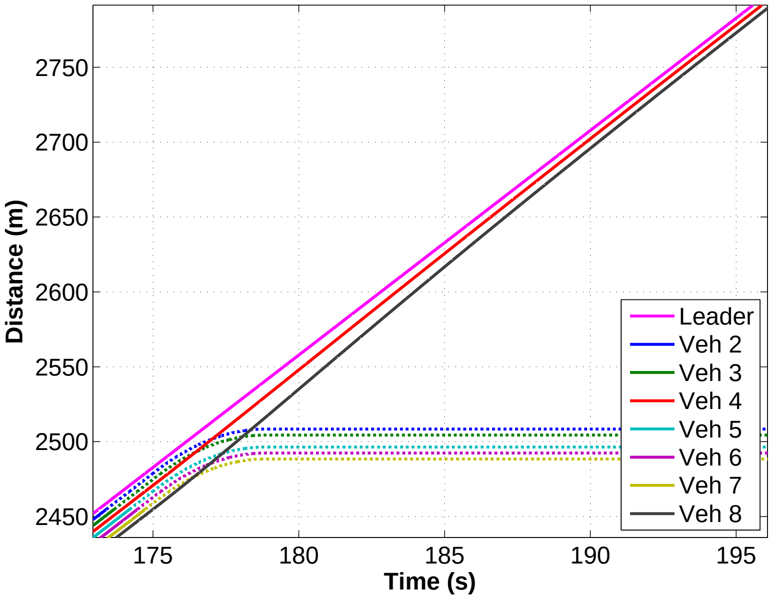


Figure 5.14: Followers in second, third, fifth, sixth, and seventh position exit the main track to a station. Vehicles in fourth, and eighth position accelerate to close the gaps.

5.6.2.2 Exiting of intercalated vehicles

Fig. 5.13 presents the distance profile of the platoon, for the case when the vehicles in second, fourth, sixth, and eighth platoon's position exit the main track;

5.6.2.3 Exiting of convoys of vehicles

Fig. 5.14 presents the distance profile of the platoon, for the case when two convoys leave the platoon: the first one consists of vehicles in second and third position; the second one, of vehicles in fifth, sixth, and seventh position. Vehicles in fourth and eighth position accelerate to close the left gaps.

5.6.3 Inter- and Intraplatoon Positioning Management Algorithms

Fig. 5.15 presents the distance profile of the platoon for the case when the first two vehicles exit the main track at the same time an isolated follower in fourth position along with a convoy of two vehicles in sixth and seventh position also exit. The vehicle in third position, becoming the new platoon leader, accelerates to occupy the position of the previous leader, whereas vehicles in fifth and eighth position accelerate to close the left gaps.

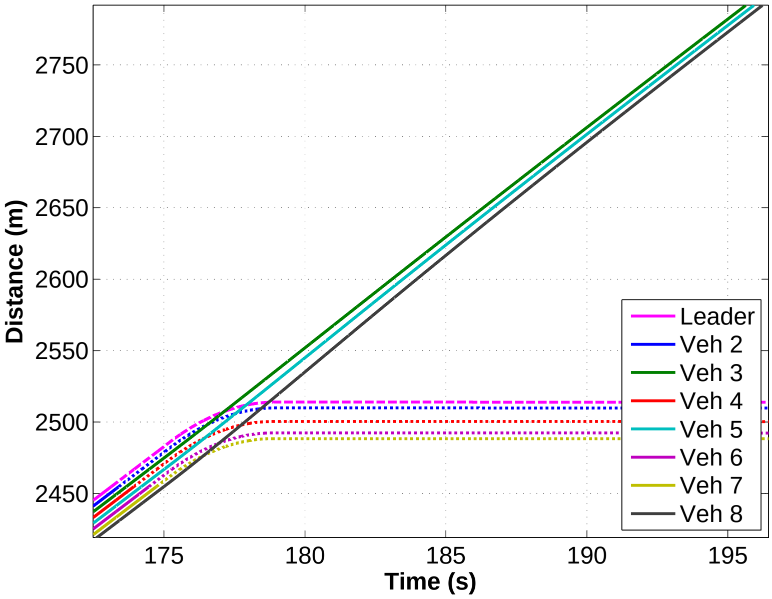


Figure 5.15: Leader and the vehicle in second position exit, along with followers in fourth, sixth, and seventh position. Vehicles in third, fifth, and eighth position accelerate to close the left gaps.

5.6.4 Platoon Joining Maneuvers Management Algorithms

The maneuvers of vehicles departing from a station to join incomplete platoons evolving on the main track are performed cooperatively, according to the algorithm (5.1) of Subsection 5.5.3. The simulation scenario includes a station with a configuration as depicted in Fig. 5.7, where the distance between the exit point from the main track and the entrance point to the main track is of 200 m. So, the vehicles performing the repositioning maneuvers recover more than two thirds of the gap to reach their new positions, from the exit point until the entrance point. Under this scenario, the values of the parameters of Table 5.2 are presented in Table 5.3.

Fig. 5.16 represents the case when seven vehicles of the platoon's front exit the main track to a station, whereas seven vehicles enter the track from the same station. The repositioning maneuver performed by the eighth vehicle that remained in the track allows all seven entering vehicles to join the platoon safely, under the algorithm (5.1), from Subsection 5.5.3, which solves the problem presented in Fig. 5.5 of Section 5.4. This algorithm ensures plenty of space available to safely perform the joining maneuver, without slowing down the platoons following behind. The joining maneuvers are performed cooperatively with the vehicles in the main track, using sensors and IVC. Fig. 5.17 shows the velocity patterns of the exiting and joining maneuvers presented in Fig. 5.16. The eighth vehicle

Table 5.3: Parameter Values Used for TW Computation

Parameter	**Value**
$TW = LPT + EMSG \times MT + P \times IVT - NVF \times RTF$	
LPT	0.9667 s
EMSG	2
MT	0.0667 s
P	Variable ($1 \le P \le 8$)
IVT	0.2667 s
NVF	Variable ($0 \le NVF \le P - 1$)
RTF	0.1233 s

of the first platoon, becoming the new leader, temporarily increases its speed to perform the repositioning maneuver, while the other seven vehicles brake simultaneously in the deceleration track, until reaching a full stop. The seven vehicles of the entering platoon initiate their departure maneuver in the acceleration track a short period of time after the last vehicle from the exiting platoon has passed through the exit point (TW parameter's value, computed accordingly to (5.1) and Table 5.3). The entering platoon reaches the entrance point of the main track at a speed similar to the speed of the vehicles it will join.

Fig. 5.18 represents the case when a complete platoon of eight vehicles exits the main track to a station, whereas eight vehicles enter the track from the same station. Fig. 5.19 shows the case when the first five vehicles of a complete platoon exit. The sixth vehicle, becoming the new leader, performs the repositioning maneuver, followed by the seventh and the eighth vehicles, increasing the space availability for the entrance of five vehicles at the same station. A zoomed view is shown in Fig. 5.20. Fig. 5.21 shows the case when vehicles exit from even positions of a complete platoon. Although in this case the leader does not have to perform a repositioning maneuver, all the remaining vehicles close the gaps, allowing the entrance of four vehicles at the same station. Fig. 5.22 shows how vehicles in third and sixth position perform the repositioning maneuvers after three pairs of vehicles have exited (in first, second, fourth, fifth, seventh, and eighth position). Subsequently, six vehicles join the incomplete platoon. Fig. 5.23 exemplifies how incomplete platoons could also be involved in exiting and entrance maneuvers at a station.

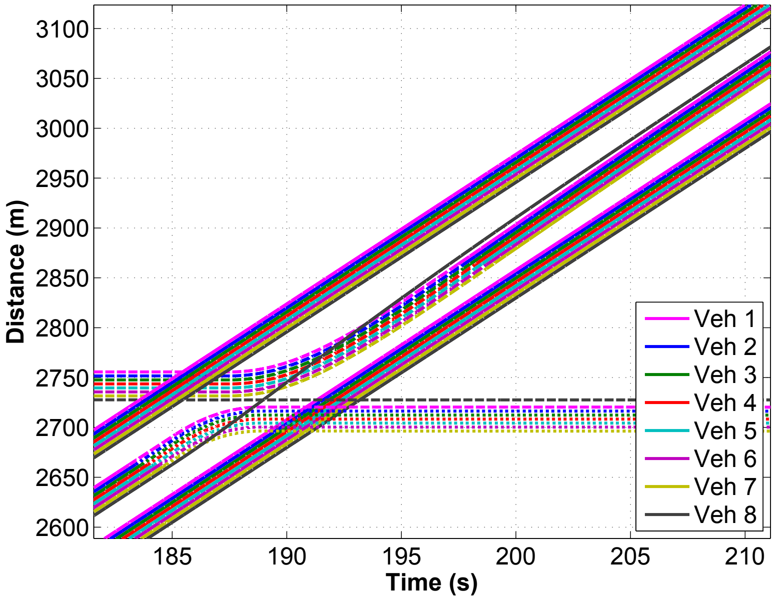


Figure 5.16: Seven vehicles exiting and seven vehicles joining a platoon at a station, with the new leader performing the repositioning maneuver.

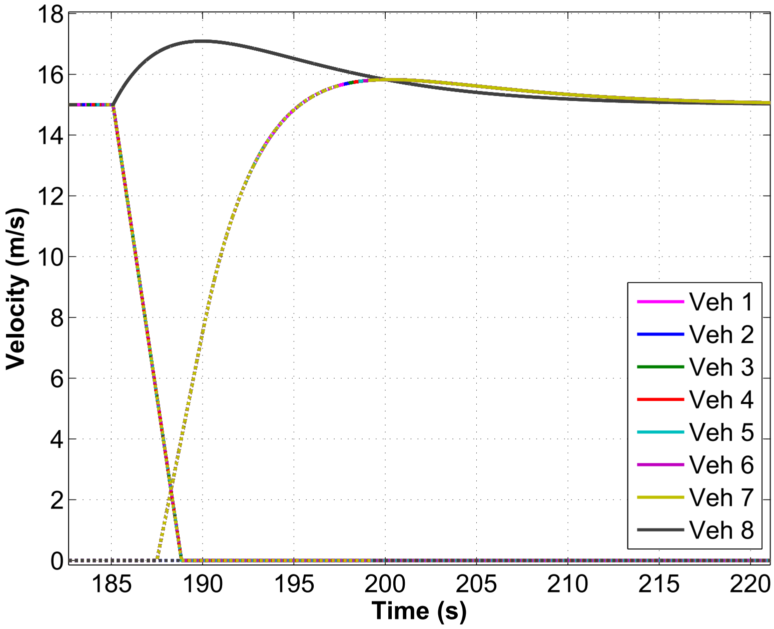


Figure 5.17: Velocity patterns of the seven exiting vehicles, and the new seven vehicles joining the platoon, while the eighth vehicle, becoming the new leader, performs the repositioning maneuver.

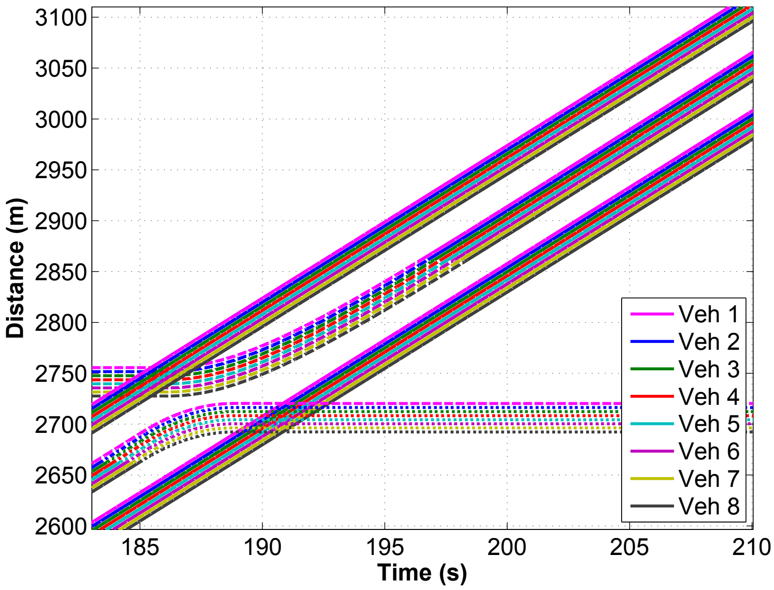


Figure 5.18: Eight vehicles exit and eight vehicles enter the main track at a station.

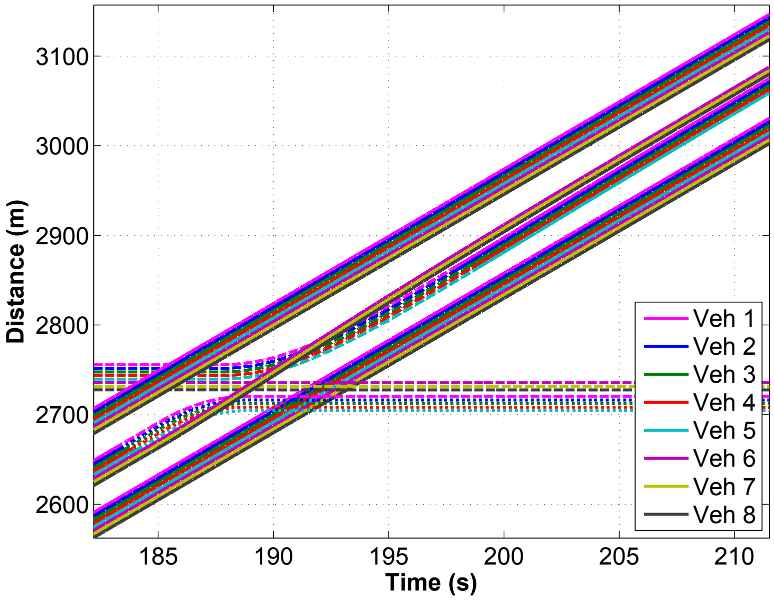


Figure 5.19: Five front vehicles of a platoon exit, and five vehicles join the platoon at a station after the repositioning maneuvers of the vehicles in the sixth (new leader), seventh and eighth position.

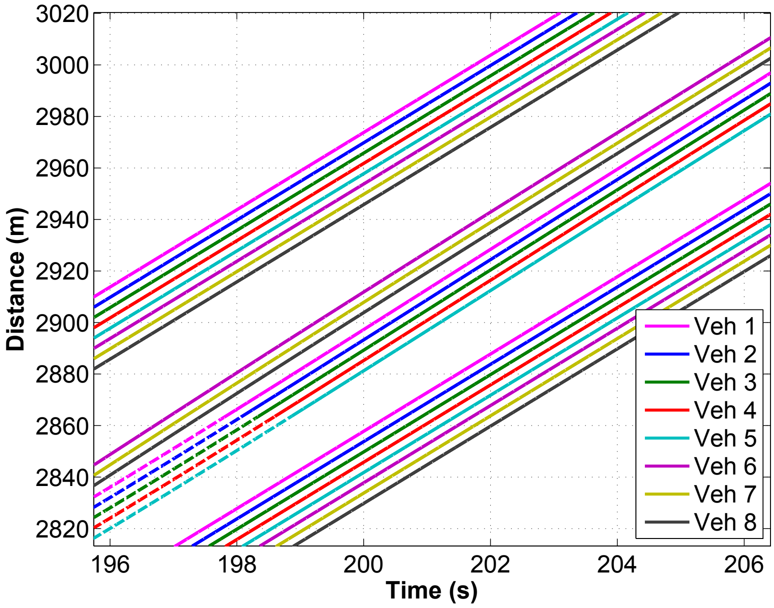


Figure 5.20: Zoomed view of Fig. 5.19, where smooth joining maneuvers are visible.

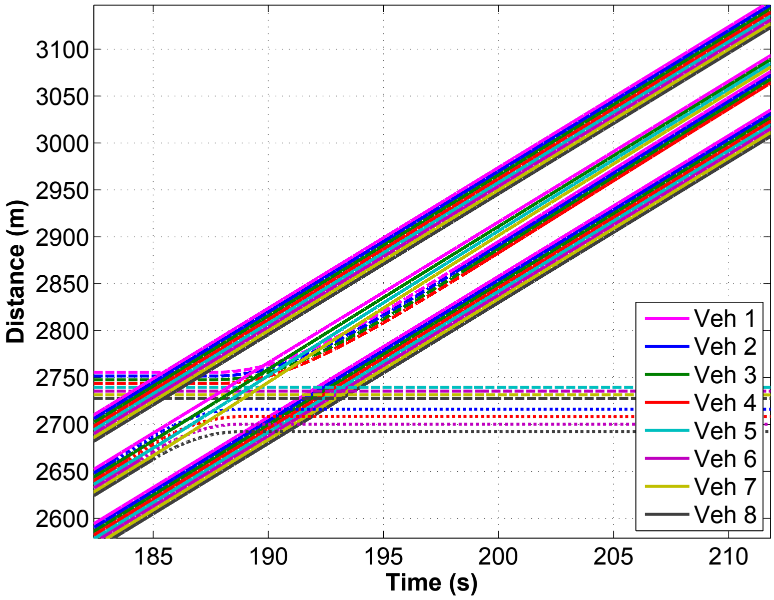


Figure 5.21: Four intercalated vehicles exit and four vehicles join the platoon at a station, with previous leader maintaining its position.

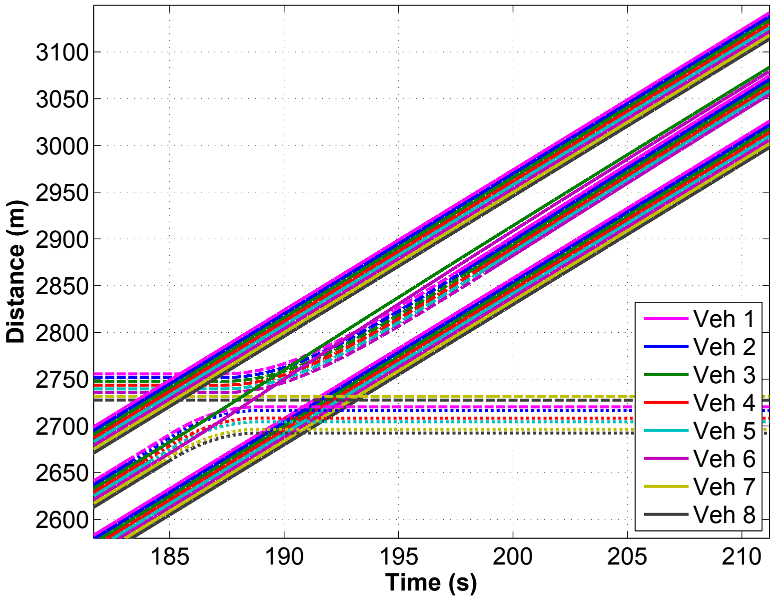


Figure 5.22: Six vehicles exit in pairs, and six vehicles join the platoon at a station, after the remaining vehicles have performed the repositioning maneuvers.

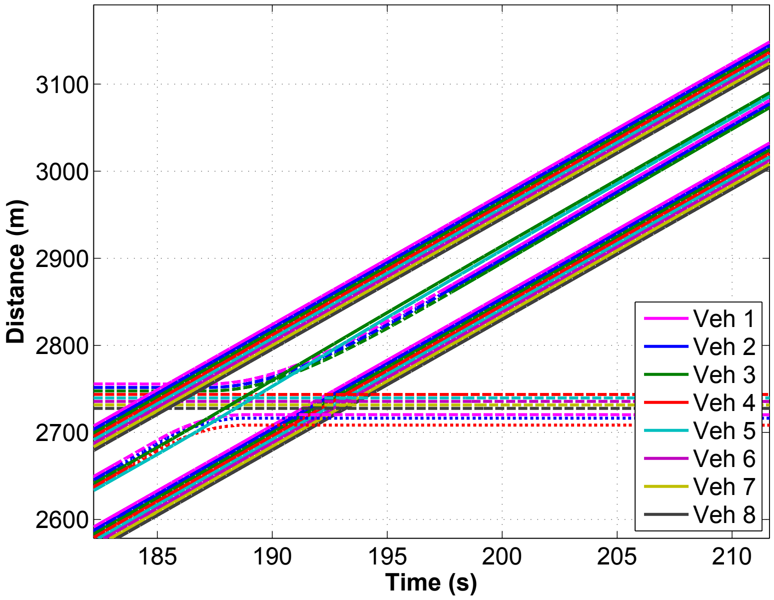


Figure 5.23: Three vehicles exit from an incomplete platoon, and three vehicles join it at a station, after the remaining vehicles have performed the repositioning maneuvers.

5.6.5 Extra Spacing for Secure Maneuvering Improvement

Until now, all exiting maneuvers were performed with platoons' vehicles at the nominal distance of one meter from each other. Onboard track switching mechanisms may enable such lane change seamlessly, at the reference speed used in the simulations. However, we considered advisable to perform simulation studies adding extra spacing between vehicles exiting the main track and those remaining there, a few seconds before vehicles perform those maneuvers. As such, several timings were assessed through simulations. The retained $10\,s$ as the reference value for the beginning of the braking maneuver, since it was considered a good compromise between timely maneuver execution and passengers' comfort. A value of $5\ s$ was also simulated, and the results showed that the deceleration value could be three times higher.

With respect of the braking maneuver two approaches were taken.

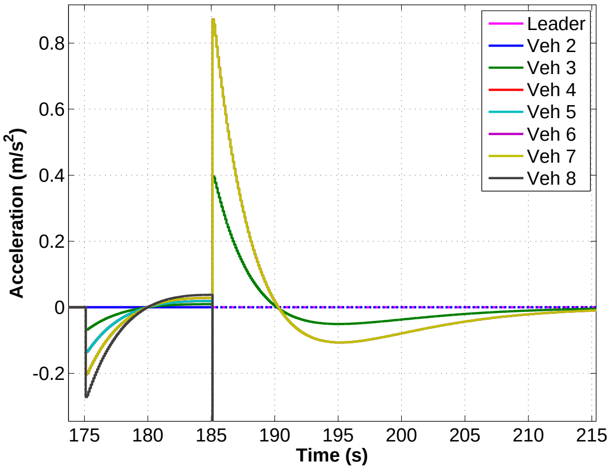
5.6.5.1 Synchronous Braking Maneuver

All vehicles involved in braking maneuver brake at the same time, under the algorithm of Subsection 5.5.4.

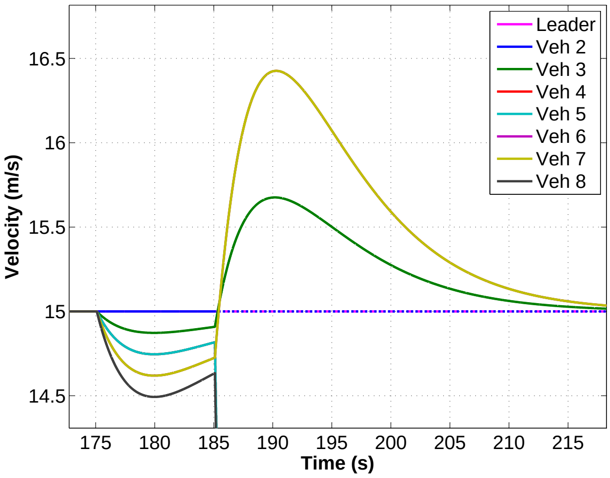
Fig. 5.24 shows the platoon's profiles of the acceleration, speed, and spacing error, when the braking maneuvers are performed simultaneously, before vehicles in first, second, fourth, fifth, and eighth position exit the main track. Fig. 5.25 shows the distance profile of the platoon, detailing the zone where the braking maneuvers take place. The increased spacing from 4 to 5 meters, in front of vehicles in third, fourth, sixth, and eighth position is visible.

5.6.5.2 Asynchronous Braking Maneuver

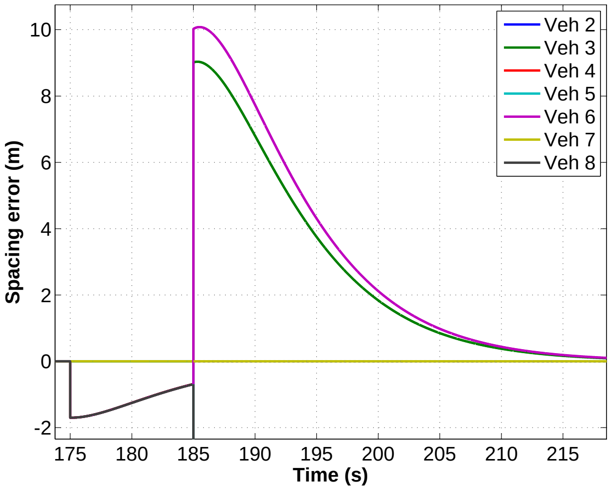
In the previous algorithm, the last vehicles in a platoon accumulate the deceleration of all braking vehicles at the exact moment that maneuver takes place. As such, their deceleration is higher than its precedent vehicles. This algorithm distributes the accumulation of the deceleration values along a short period of time. The simulation results proved that this scheme could present a slight decrease of last vehicles' deceleration, thus increasing passengers' comfort.



(a) Acceleration



(b) Velocity



(c) Spacing error

Figure 5.24: Braking maneuvers performed simultaneously, before vehicles in first, second, fourth, fifth, and eighth position exit the main track.

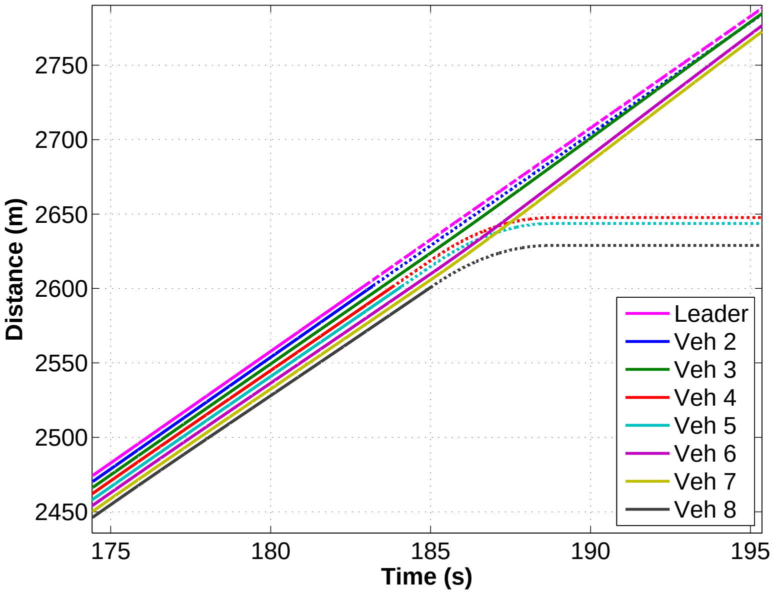


Figure 5.25: Vehicles in first, second, fourth, fifth, and eighth position exit the main track after the simultaneous braking maneuvers. The increased spacing, from 4 to 5 meters, in front of the vehicles in third, fourth, sixth, and eighth position is visible.

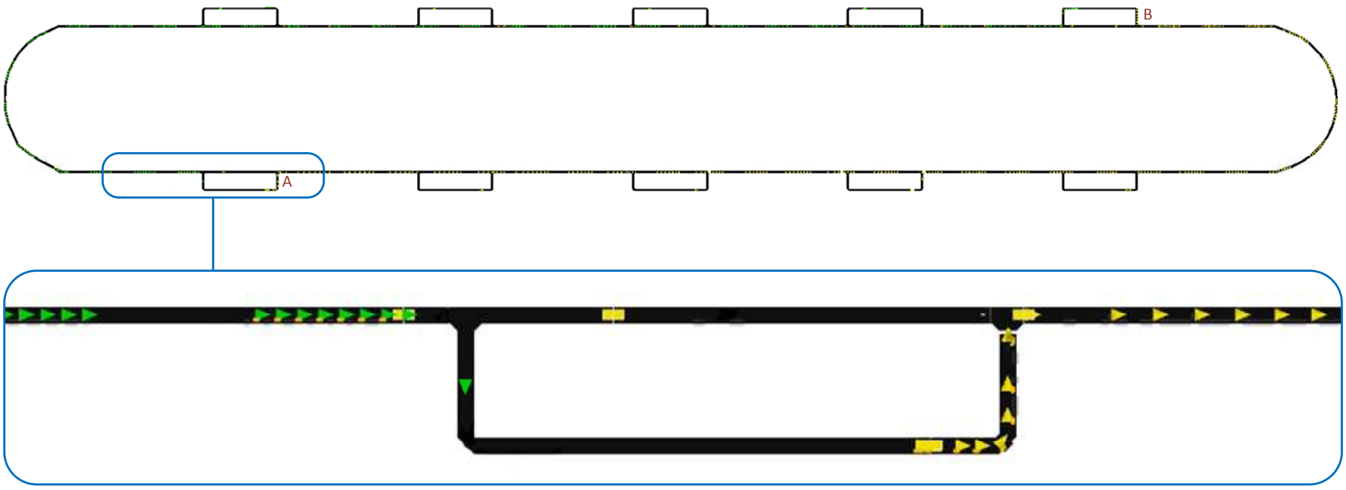


Figure 5.26: SUMO complete scenario setup of platoons of autonomous vehicles with off-line stations. In the zoomed view we can observe occupied vehicles evolving on the main track (in yellow) as well as free vehicles (in green) going to stations with more demand.

Table 5.4: SUMO Transportation Parameters

Transport System	**Length (m)**	**Max. Capacity (persons/veh)**
Platoon vehicle	3	4
Bus	15	67
Light rail	68	712

5.7 Simulation of a Complete Platooning System

To assess if the data theoretically obtained from (4.2) were realistic, a complete new simulation scenario setup was implemented in SUMO traffic simulator, using the new features added as described in [Fernandes 2010], and further modifications to provide cooperative behavior of evolving vehicles. The communications and information exchange among vehicles use the algorithms reported in [Fernandes 2012]. This simulation setup allowed to obtain the data values of SUMO presented in Table 5.1 and to confirm the analysis presented in Section 5.3. Furthermore, with the simulation setup depicted in Fig. 5.26, it was possible to perform throughout simulations under very high demand, stressing the traffic system to its full capacity.

5.7.1 Scenario Definition and Traffic Demand

To evaluate the impact of the constant spacing autonomous vehicles platoons' model on traffic flow improvement, the platooning system was implemented in SUMO traffic simulator, with the following scenario definition:

- the SUMO parameters are presented in Table 5.4;
- the scenario consists of a dedicated track 3965 m long with ten off-line stations, as shown in Fig. 5.26;
- the simulation of buses used the configuration of previous item, with a track consisting of a conventional lane;
- the light rail simulation also used the same configuration, with the stations defined over the main track;
- the maximum number of vehicles of each platoon is eight;

- the track can accommodate as much as 65 platoons for a total of 520 vehicles, if all platoons are complete;
- constant intraplatoon vehicles' spacing of 1 m is used;
- constant interplatoon leaders' spacing of 61 m is used;
- at a constant speed of 15.25 m/s, a platoon leader passes by some determined point every 4 seconds;
- followers abide by the control law (6) in [Fernandes 2012];
- maximum traffic demand is of 120 persons per minute;
- the passenger demand is mainly distributed asymmetrically from station **A** to station **B** (see Fig. 5.26), although the remaining stations are also used by passengers to enter or leave the transportation system;
- the main stations can accommodate at least 150 vehicles;
- several departure rates of bus and light rail are performed, and the results are compared with those obtained with platoons of up to eight autonomous vehicles each;
- the platooning transportation system uses a one-minute stop at each station;
- the bus and light rail transportation systems use a twenty-seconds stop at each station;
- the reallocation of empty vehicles to stations where they were most needed was performed.

A speed value of 15.25 m/s was used in SUMO, instead of the 15 m/s used in Matlab/Simulink simulations. This choice was made to solve computation accuracy issues of SUMO.

The entrance maneuvers of vehicles from stations to the main track are performed cooperatively in SUMO, using E1-type loop detectors deployed along predetermined points in the track (yellow rectangles in Fig. 5.26). Vehicles about to enter receive information from those sensors related with platoon dimension (how many vehicles may enter behind it) and its positioning (when to begin to accelerate in the acceleration track, in order to reach the main track just behind that platoon, at a speed almost equal to the platoon's

Table 5.5: Comparison of the Number of Transported Persons per Hour (p/h) and the Travel Time, for Three Types of Transportation.

Transport	**Frequency**	**Maximum capacity**	**Travel time (from A to B)**
Platoons	4 s	7 200 p/h	158 s
Bus	3 min	1 340 p/h	305 s
	2 min	2 010 p/h	
	1 min	4 020 p/h	
Light rail	10 min	4 272 p/h	413 s
	6 min	7 120 p/h	

one). The final stations' shape will be similar to the scheme presented in Fig. 5.7 of Section 5.6 (the off-line part, where vehicles stop for passengers to exit and enter, is not drawn to scale).

The simulations were performed separately. To ensure that the autonomous vehicles would not be in advantage, it was decided that each platoon's vehicle would transport only one passenger each, whereas bus and light rail systems were used at their full capacity. Moreover, the stop time at each station was defined as 20 s for the bus and light rail systems, whereas a stop time of 60 s was used for the case of platoons. As such, the bus and light rail systems are in advantage with respect to the capacity measured on passengers transported per hour.

5.7.2 SUMO Simulation Results

Table 5.5 presents the obtained results, through simulation, for the three modes of transportation, in what concerns persons per hour and travel time. The results suggest that the platooning of autonomous vehicles performs better in both capacity and travel time metrics. Even at its minimum vehicle occupancy, of one passenger per vehicle, the capacity would be of 7200 passengers per hour. Moreover, if we were to consider a more realistic scenario of an average of 1.5 passengers per vehicle for the platooning case, a value of 10 800 passengers per hour would be possible to attain. Furthermore, the platooning system could transport 28 800 passengers per hour at its maximum capacity. Since the values of both bus and light rail systems consider their full capacity, no improvements could be obtained by these types of transportation. In fact, the parameter that could be used for that purpose would be the departure rate of vehicles, by lowering the used time intervals. However, we already considered lower values than those found in the real world. As such, lowering those values even further could lead to unrealistic results and insecure modes of operation of such transportation systems. Additionally, the passengers' waiting time spent with bus and light rail transit systems is higher, in average, than the travel time presented in Table 5.5. In fact, since the capacity of both transportation systems is lower than the maximum passenger demand used in the simulation, queues of persons waiting for the next bus or train would form at the stations. Since the platooning system could ensure that no further waiting time would have to occur for the considered passenger demand, the advantage of this type of transportation would be even higher, in the case of the comparison of the complete journey times.

Another obtained value that is worth mentioning is the number of vehicles needed to maintain the platooning simulation at its maximum capacity: about 750 vehicles, considering a one-minute stop at origin or destination stations. This value was obtained performing the aforementioned empty vehicle management, by reallocating empty vehicles to stations where they were most needed (presented in green color in Fig. 5.26).

5.8 Key Points

We can outline the following points as concerns the proposed algorithms and the attained results:

- a multi-platoon system with intraplatoons' constant spacing benefits from using constant speed;
- a multi-platoon system with interplatoons' constant spacing leads to speed changes that may cause congestion and are uncomfortable to passengers;
- a multi-platoon system with interplatoons' leaders constant spacing ensures constant speed and safe operation, continuing to allow high system capacity achievement;
- to ensure interplatoon leaders' constant spacing, vehicles evolving alone must occupy precise positions, whose distance is multiple of the interplatoons' leaders spacing;
- if demand is low, some of the positions mentioned in the previous item may be empty;

- vehicles entering the main track behind incomplete platoons must join those platoons as soon as possible;
- no vehicle is admitted in the main track behind a complete platoon;
- if a platoon's leader exits the main track, the new leader vehicle of the remaining platoon's vehicles must perform the actions described in Subsection 5.5.1, to achieve previous leader's position;
- if a follower exits the main track, its followers that remained in track must perform the actions described in Subsection 5.5.2, to close the left gaps;
- the departure of vehicles from a station to join a platoon is performed under the rule (5.1) of Subsection 5.5.3;
- if extra spacing is to be used, the vehicles that perform the braking maneuvers are determined by the rules presented in Subsection 5.5.4.

5.9 Conclusion

In this paper we present novel algorithms to maintain platoons' leaders constant spacing using repositioning strategies, as well as to allow joining maneuvers of vehicles departing from stations to join incomplete platoons cooperatively, and to increase intervehicle spacing to undertake exiting maneuvers safely. The aforementioned algorithms were tested through a new simulation model for platoons of IVC-enabled autonomous vehicles implemented in Matlab/Simulink. This novel simulation setup was designed over the new model presented in [Fernandes 2012], which includes the platoons' vehicles control and IVC implementation, using new algorithms to mitigate the effects of communication delays over string stability of the platoons. The new leaders' repositioning maneuvers presented a very stable behavior, even when subjected to significant acceleration patterns. These algorithms work together aiming to ensure the efficient operation of a hierarchical multilayered ATMS when managing a platoon-based traffic system. The novel repositioning strategies proved to be effective on ensuring high traffic capacity and congestion avoidance. The joining maneuvers, using a novel algorithm, ensured that vehicles enter the main track cooperatively and safely. Exiting maneuvers used a new algorithm that ensures safety improvement.

To assess the usefulness of the proposed algorithms and to validate them, a novel simulation engine for platoons of communicant autonomous vehicles was implemented in the SUMO traffic simulator, using a modified version of SUMO simulator, to operate with a new car following model that we had previously developed [Fernandes 2010]. Therefore, this simulator presents novel key features enabling the study of constant spacing platooning systems. Further modifications were conducted on SUMO, to provide cooperative behavior of evolving vehicles, and a new simulation scenario defined. The simulation results of the platooning system using the novel proposed algorithms proved that high traffic capacity values are achieved, and congestion is avoided. A comparison of the simulation results of the platooning system with the simulation results of bus and light rail systems showed a clear advantage of the novel proposed system toward these conventional transit systems. Thus, a platoon-based system using the rules proposed in this paper may be a viable alternative to mass transit systems in urban areas. The results also seem to suggest that it is possible to envisage the practical implementation of a similar system in the midterm.

Future work will address the study of more complex traffic networks, and the improvement of communication reliability using simultaneously DSRC and other communication technologies, such as infrared and visible light communications.

Part III

Conclusions

Chapter 6

Conclusion, Summary of Contributions and Future Research

6.1 Conclusion

The main challenge of our research was to improve lane capacity and avoid traffic congestion, even when operating under high vehicle density. Hence, our research showed that urban mobility improvement is achievable.

This thesis approach consisted of the use of platoons of IVC-enabled autonomous vehicles, under a constant spacing policy. This approach was found promising to enable significant traffic flow improvement. However, communication delays presented a negative impact on platoon string stability, compromising the appropriate system operation and its safety. So, we addressed that problem proposing novel information-updating algorithms to mitigate communication delays. We developed new Matlab/Simulink models, to fully assess the algorithms appropriate operation. The results proved that communication delays were avoided, ensuring high platoon string stability. We consider this achievement of major importance for enabling such systems to deliver all their potential benefits.

Since DSRC is a current IVC prominent technology, we proposed some high level modifications, using time slots, aiming to avoid packet collisions within vehicle platoons, and transmitting both in broadcast as in unicast. The NS-3 simulation results suggested that the information-updating algorithms could be implemented with current technology.

Using the aforementioned information-updating algorithms, we were able to further develop the higher layers of the considered traffic system, aiming to enable high traffic capacity and traffic congestion avoidance, under high vehicle density and safe operation. To accomplish these goals, we proposed new platoon positioning management algorithms. These algorithms present two complementary counterparts: one operating at the interplatooning level, aiming to maintain a constant interleader spacing; other operating at the intraplatooning level, aiming to maintain safe operation when vehicles perform exit and entrance maneuvers. Moreover, these two operating levels were used together in the algorithms, allowing vehicles to enter the main track cooperatively, communicating and coordinating their entrance with the vehicles evolving on the main track. To enable the assessment of the proposed algorithms, we improved our Matlab/Simulink model, using novel agent-based features. The results proved that the algorithms could significantly improve traffic capacity, avoid traffic congestion and ensure safe platoon operation.

Moreover, a complete scenario using platoons on dedicated tracks and off-line stations was developed and assessed in SUMO traffic simulator.

6.2 Summary of Contributions

A summary of our key contributions are listed bellow.

- **Communication Algorithms.** We proposed high level modifications on the DSRC operation, using time slots for broadcast and unicast data transmission, implementing and assessing them through NS-3 simulations. The results showed to be promising. However, some reliability concerns remain with respect to DSRC broadcast performance under the demanding scenarios of constant spacing platooning, suggesting that further research is required on this subject.

- **Information Management Algorithms.** New information-updating algorithms using anticipatory information were proposed. These are of most importance, since communication delays were a major drawback to proper operation of platooning of communicant vehicles using a constant spacing policy, due to their negative impact on platoon string stability. With the new proposed algorithms, we were able to mitigate communication delays and we managed to significantly improve string stability. The Matlab/Simulink simulation results proved that the new information-updating algorithms were effective and appropriate.

- **Constant Interleader Spacing Policy Algorithm, with Constant Speed.** We proposed new platoon positioning management algorithms to ensure constant interleader spacing, aiming to avoid traffic congestion and ensure high traffic capacity. New Matlab/Simulink model improvements, using agent-based concepts, enabled us to assess these algorithms' proper operation. The results proved that high traffic capacity could be maintained, and traffic congestion avoided.

- **Vehicle Exit and Entrance Management Algorithms and Safety Improvement.** We addressed the problem of vehicles exiting the main track, presenting new algorithms to perform exit maneuvers safely, by increasing the spacing between vehicles involved in those maneuvers. The Matlab/Simulink results showed that the algorithms did improve vehicles' safe operation. We also addressed the entrance of vehicles in the main track, along with platoon formation. So, we presented new algorithms to enable the entrance of vehicles in the main track cooperatively, by communicating and coordinating their maneuvers with the vehicles evolving on the main track and, subsequently, performing platoon formation. The Matlab/Simuling results proved that the proposed algorithms perform appropriately under all considered cases.

- **Traffic Capacity Management and Congestion Avoidance.** We developed a new simulation scenario, with a complete platooning system using off-line stations and non-stop travels from origin to destination, in SUMO traffic simulator. Although some of the aforementioned algorithms were not fully implemented in SUMO, due to differences between our approaches and the SUMO operational assumptions, it was possible to validate traffic capacity improvement and congestion avoidance of the simulated platooning system.

- **Asymmetrical Traffic Demand and Empty Vehicle Management.** With the aforementioned scenario, an asymmetrical traffic demand with empty vehicle management was implemented and assessed. The SUMO results showed a significant decrease of the total number of vehicles needed to maintain the platooning system operating at its full capacity.

- **Simulations.** Throughout this research work, we used three different simulators: Matlab/Simulink, NS-3 and SUMO. Each of them was used on the study and assessment of specific algorithms, at different phases of this work.

  - **Matlab/Simulink.** Matlab/Simulink was used for the assessment of all the proposed algorithms, using novel agent-based models that we developed. The results proved that the algorithms under testing were appropriate.
  - **NS-3.** We contributed to NS-3 with new high level DSRC operational methods, to assess the DSRC protocol performance and reliability under the considered scenarios. Although NS-3 does not completely implement the DSRC protocol, we modified its operational parameters to ensure that the obtained results were reliable. Nevertheless, NS-3 could still benefit from further devel-

opments in this field, as well as from the implementation of new radio signal propagation models.

- **SUMO.** We implemented and tested a new car following model in SUMO, to simulate platoons of autonomous vehicles under a constant spacing policy [Fernandes 2010]. However, almost all previous SUMO scenarios and assumptions are based on human driven vehicles, since SUMO only use human-based car following models. Our contribution enabled us to assess traffic capacity assumptions using platoons. Additionally, we developed a new simulation scenario, with a complete platooning system using off-line stations and non-stop travels from origin to destination. Despite SUMO does not integrate all our proposed algorithms, it was still possible to validate traffic capacity improvement and traffic congestion avoidance, and implement and assess an asymmetrical traffic demand with empty vehicle management.

6.3 Future Research

The algorithms we proposed in this thesis proved to bring sound benefits to traffic systems based on platooning of IVC-enabled autonomous vehicles. Our main concern was to evaluate the impact of communication delays' effects on platoon string stability, and find solutions to avoid them. Moreover, all subsequent work was based on this concept, proving that by solving the communication delays' problem, we could envisage systems presenting higher traffic capacity and safe operation. The proposed novel information-updating algorithms may also allow important efficiency and safety improvements when applied to different scenarios involving other type of IVC-enabled vehicles, such as CACC scenarios. Communication technology could also benefit from further research on the methods to ensure safe data transmission, under high vehicle density scenarios. We find this topic significantly important to enable the implementation of real systems, using cooperative vehicles and presenting high traffic capacity. Further studies on the simultaneously use of more than one communication technology, such as infrared [ISO 2006], visible light communications (VLC) [IEEE 2011] and DSRC, are considered promising, aiming to unburden DSRC from performing a considerable amount of periodic and direct communications between intraplatoons' vehicles. The study of more complex traffic networks of platoons of IVC-enabled autonomous vehicles with leaders' constant spacing policy, evolving on several interconnected tracks, e.g., for previous space reservation for platoons at merging points, will also be subject of future research.

Part IV

Appendices

Appendix A

Simulation Frameworks

In this work, three simulation packages were used: Matlab/simulink, NS-3, and SUMO/TraCI.

The main components of the frameworks developed on each of the aforementioned packages follows.

A.1 Matlab/Simulink Simulation Framework

The Matlab/Simulink framework developed in this work is depicted in Fig. A.1. It spans over all main ATMS layers, dealing with communication and information updating management using anticipatory information, as well as vehicle role and positioning management. Traffic and leaders' monitoring and management are also addressed.

A.2 NS-3 Simulation Framework

The contribution for the DSRC model in NS-3 simulator was as follows: first, each CCH was modified to work with time slots, on a TDMA basis, as presented in Fig. 4.17 on page 57; second, explicit ACK packets were implemented in the leaders' broadcasting, using the eight vehicle of the platoon as a referee; third, a retransmission scheme was implemented, to ensure that broadcasted transmissions were properly delivered; finally, a backoff mechanism was introduced at the beginning of each time slot, using an additional application-level random backoff between CW_{min} and CW_{max}, as described on page 59.

A.3 SUMO/TraCI Simulation Framework

The SUMO framework used in this work is depicted in Fig. A.2 (adapted from [Wegener 2008]). The main contribution for the SUMO simulator was the development and integration of one more car following model: MSCFModel_Rajamani, as depicted in Fig. A.3.

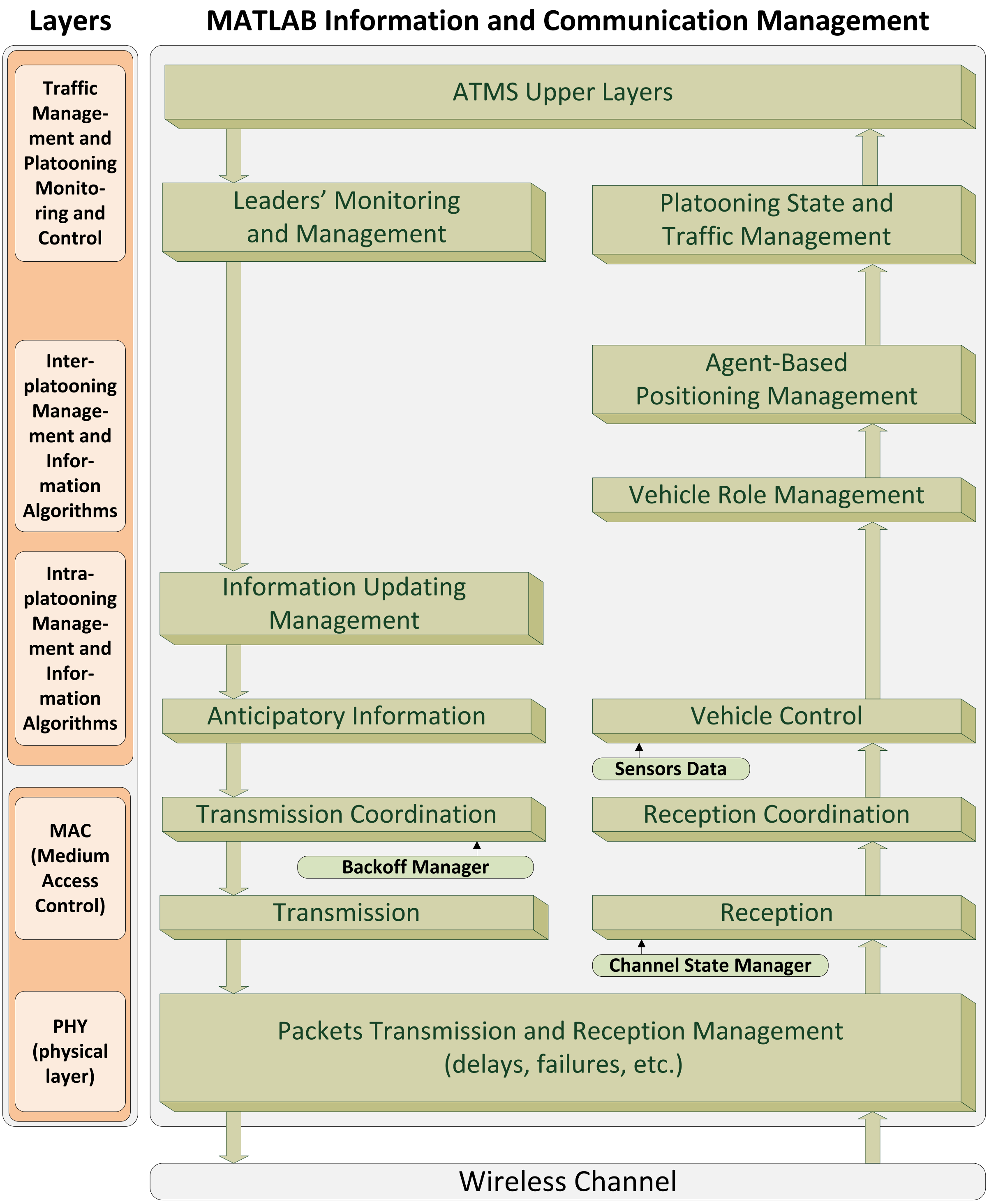


Figure A.1: Matlab/Simulink Framework.

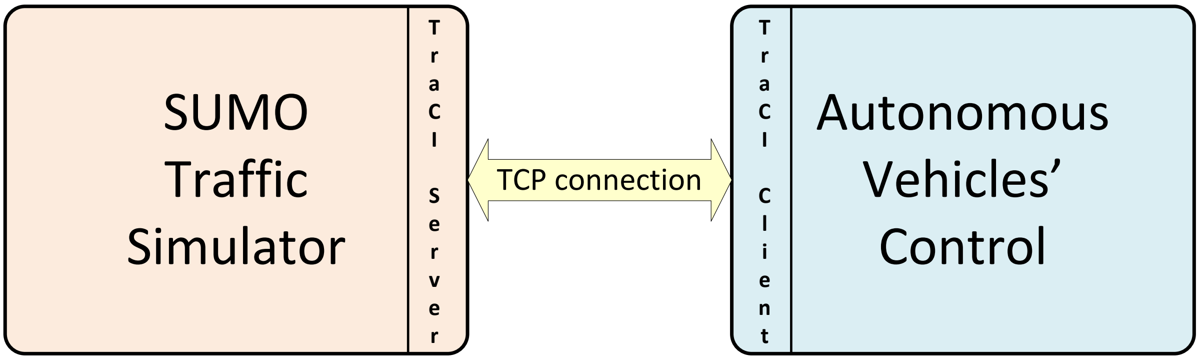


Figure A.2: SUMO/TraCI Framework.

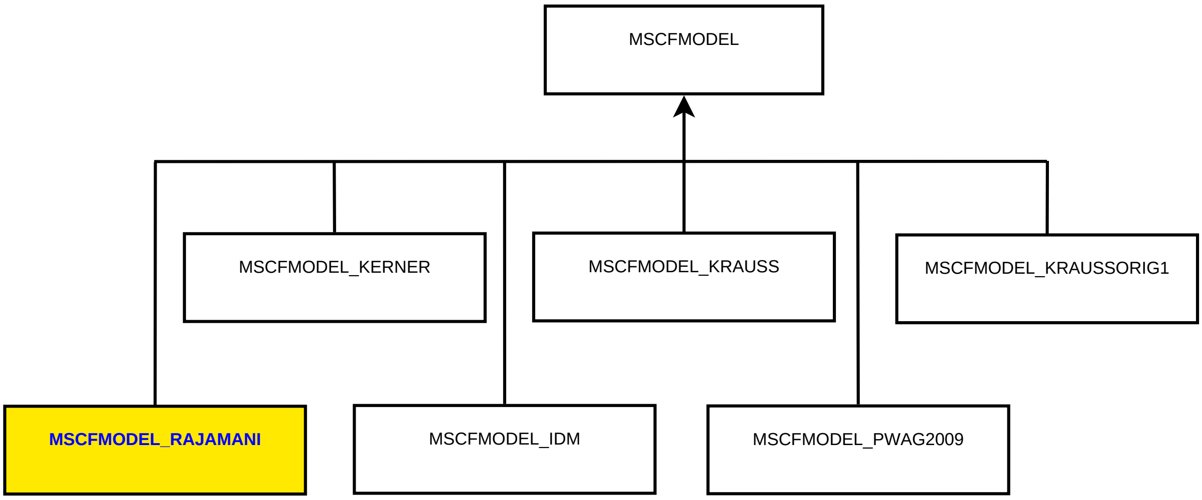


Figure A.3: Car following model added to SUMO.

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