Simulation and Testing of a Platooning Cooperative Longitudinal Controller

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Abstract. Previous studies have shown that the ITS solution called ***platooning*** allows the autonomous collaborative driving and can improve traffic safety and throughput. Traffic flow is optimized by Cooperative Adaptive Cruise Control (CACC), which allows for the automatic short-distance vehicle following, using inter-vehicle wireless communication in addition to onboard sensors. This paper presents the platooning vehicle longitudinal controller evaluation using simulation environment. The employed controller uses IEEE 802.11p technology for vehicle-to-vehicle (V2V) communications on Vehicular Ad hoc Network (VANET). To evaluate the CACC the Veins simulation framework was used and the complete simulation setup is described in this paper. The presented analysis expound the methodology to verify controller safety and stability characteristics within the different traffic scenarios and platooning maneuvers using the simulation.

Keywords: VANET Simulation · ITS · IVC · CACC · Platooning · Cooperative driving · IEEE 802.11p.

1 Introduction

As the statistics show, the majority of the road fatal accidents occurs on high speed roads [Eurostat], and that makes focusing on improving vehicles and infrastructure safety for the high-speed traffic an important issue. In addition, the traffic congestion problem, caused by the increased number of vehicles, affects the efficiency of the road transportation system. To help solve these problems, a more efficient use of currently available means of transportation is needed. Therefore, the set of Intelligent Transportation Systems (ITS) solutions is proposed, that contributes to improving traffic flow stability and safety. One promising ITS application that deals with traffic congestion, safety and fuel saving, is called *platooning*. The highway traffic is organized into groups of close-following vehicles: platoons. Platooning enables the vehicles to drive in groups at a small distance, autonomously and safely, following the leader vehicle, driven by a professional driver, that is able to lead the platoon [?,?,?]. This is a complex ITS application that is composed of two different parts, i.e. the vehicle control system and Inter-Vehicular Communication (IVC) system. The vehicle control, which allows for the automatic short-distance vehicle follow, is carried out by the Cooperative Adaptive Cruise Control (CACC) system. The CACC technology uses wireless communication in addition to onboard sensors to improve system reactivity. The focus in this paper is the CACC longitudinal control system that automatically regulates the vehicle acceleration to guarantee the desired distance to the preceding vehicle. Regarding communication technologies, short range DSRC and vehicular LTE are currently both presented as a possible common solution for ITS applications. Eventually combined into hybrid communication system. Nevertheless, the current paper focus on IEEE 802.11p Vehicle-to-Vehicle (V2V) communications technology for Vehicular Ad hoc Network (VANET).

2 Related work

The research community presents several versions of a vehicle longitudinal controller, which exploits wireless communication. This section provides a brief overview of available publications that cover the subjects related to V2X applications, with special attention to advanced applications (e.g. Platooning and CACC).

The use of feedback control systems on vehicles is covered on R. Rajamani *Vehicle Dynamics and Control* [2] book. It is intended to serve as a useful resource to researchers who work on the development of such control systems. Also, this book provides a comprehensive coverage of vehicle control systems and the dynamic models used in the development of these control systems.

Ploeg et al. [4,5] describe the design and practical validation of a CACC system. Focusing on the feasibility of implementation, a decentralized controller design with a limited communication structure is proposed (a wireless communication link with the preceding vehicle only). A necessary and sufficient condition for string stability is derived. For a velocity-dependent inter-vehicle spacing policy, it is shown that the wireless communication link enables driving at small inter-vehicle distances, whereas string stability is guaranteed.

This paper widely uses the work presented in Segata Ph.D. thesis [1,6]. Its first contribution is the design of PLEXE, an extension for the vehicular simulation framework Veins that enables research studies on various platooning aspects, including design and evaluation of control algorithms, communication protocols, and applications. The same work presents a platooning control algorithm that can be adapted to network conditions. Also, this work proposes a set of undirected information broadcasting (beaconing) protocols that specifically take into account the application requirements.

Amoozadeh et al. [3] present a developed platoon management protocol for CACC vehicles based on wireless communication through VANET. The validity and effectiveness approach is shown by means of simulations, using different platooning setting. The idea of organizing traffic in platoons is originally proposed in [9] by PATH for Intelligent Vehicle Highway System (IVHS) and was successfully demonstrated by National Automated Highway Systems Consortium (NAHSC) using real cars in 1997. They propose a system architecture where control tasks are arranged in a five-layer hierarchy. Physical, regulation and coordination layers are distributed among controllers on each vehicle, whereas link and network layer control groups of vehicles.

The CACC approach presented by Gehring et al.[10] is based on distance measurement between the vehicles and on a vehicle to vehicle communication but does not need road infrastructure. A two layered control structure is proposed. Therefore, a robust platoon controller is introduced for the outer control loop by use of sliding mode control design. Practical results of a platoon consisting of 7 trucks show that by use of the proposed control concept string stability can be achieved.

Milanês et al. [11] describe the design, development, implementation and testing of a CACC system. The design of the system is based on controllers that determinate the maneuvers in the platoon [18]: the leader vehicle approaching maneuver and the car-following regulation maneuver. The solution aims to reduce significantly the gaps between the vehicles, taking advantage of information exchanged using DSRC wireless communication. Additionally, the CACC improved the response time and platoon stability, when in comparison to the ACC system, proving that the system may be able to improve traffic flow and capacity.

3 Control Theory

The automated vehicle control system can be divided into lateral (steering) and longitudinal (speed) controllers. In this paper we will discuss only the vehicle longitudinal controller. This system is able to maintain automatically the intended speed by sending a signal to the vehicle control unit that tells the engine to speed up or to slow down. In a platoon, the controller objective is to realize a desired distance to the preceding vehicle. This desired distance may be an increasing function of vehicle velocity in order to take safety aspects into account. The control system actuation is normally delayed due to the internal mechanical dynamic. When the controller advise the car to accelerate, it needs to send the signal to the engine control unit, that, in the end, accelerates the car. This process is clearly not immediate and is referred to as actuation lag. The typical actuation time is around $0.5s$ [1] and it includes the engine response delay, sensors/sampling delay, etc..

3.1 String Stability

String stability is a property of a cascaded system, characterizing the evolution of the effects of disturbances over the interconnected systems. Thereby, string stability is a fundamental platoon propriety used to analyze the car following control logic. The attenuation of disturbances across the vehicle string is an essential requirement for vehicle platooning control algorithm [2,3,5]. For a graphical demonstration of string stability consider Fig. 1, which shows the vehicles speed as a function of time, representing stable and unstable behaviour. Fig. 1(b) demonstrate that the rear vehicle can not attenuate disturbance induced by the vehicle in front, that leads to the unstable behaviour of the 2nd car. This instability (strong speed oscillation) may lead to vehicles collision. The controller string stability can be proved if any disturbance induced by the preceding vehicle is not amplified towards the end of the platoon.

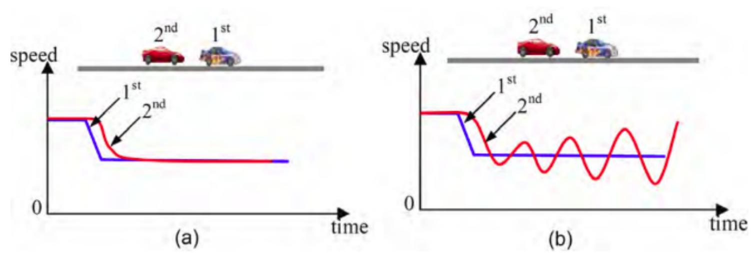


Fig. 1. String stability propriety: (a) stable (b) unstable [15]

3.2 Cooperative Adaptive Cruise Control

Automatic vehicle following based on data exchange by means of wireless communication, in addition to the data obtained by radar, is commonly referred to as *Cooperative Adaptive Cruise Control (CACC)*, illustrated in Fig. 2. The main idea is to share information such as acceleration, speed, position, etc., through wireless communication, to improve the reactivity of the longitudinal controller, by reducing the delay of the response to the preceding vehicle behaviour. The messages are transmitted several times per second using IEEE 802.11p technology. Due to this additional V2V communication CACC is able to achieve string stability at time gaps significantly smaller than 1 s. Furthermore, each vehicle can obtain information from the vehicles around using the wireless communication.

3.3 CACC logic

The used controller is a predictive controller employing a one-vehicle look-ahead communication topology. The longitudinal control algorithm is based on the work described in [5]. In brief: CACC employs wireless V2V communication, in addition to onboard sensors, to share real-time vehicle data that may improve controller reactivity and enable car-following at closer distances. The advantage here is gained by communicating the *desired* acceleration of the preceding vehicle instead of the actual one. The desired longitudinal acceleration represents the intention of the vehicle in front and can be determined based on driver's pedal signals or controller command. The reason for choosing this controller is the fact that the one-vehicle look-ahead topology is the easiest to understand and has the simplest possible communication structure. Thereby it has the highest probability of being implemented for the real world. According to [5], the control formula is defined as:

$$\Delta a = T_g^{-1}(-a_c + K_p(d - L - T_g V) + K_d(V_p - V - T_g a_r) + a_p)T_s \tag{1}$$

where K_p, K_d is the controller design parameters, d actual distance to preceding vehicle, L standstill distance, V_p velocity of the preceding car, a_r and V is the own vehicle acceleration and speed, a_p is the preceding vehicle acceleration, a_c is the own vehicle controller acceleration calculated on previous step, Δa delta acceleration, T_g pretended time headway and T_s is the controller execution period. Then, the indented vehicle acceleration is given by:

$$a = a_c + \Delta a \tag{2}$$

This model does not hold for limit situations, such as emergency braking, which are characterized by nonlinear behavior due to complex braking system dynamics. However, such situations can be handled with sending a specific message using other ITS solution like *collision avoidance system*.

4 Simulation setup

Simulation is a better solution to evaluate the performance of the designed vehicle control system before starting implementing the real prototype. Every test on simulation can be easily accomplished and repeated for posterior analysis. PLEXE [6,8] allows the simulation of automated car-following systems (i.e. platooning). It provides realistic vehicle dynamics and several cruise control models.

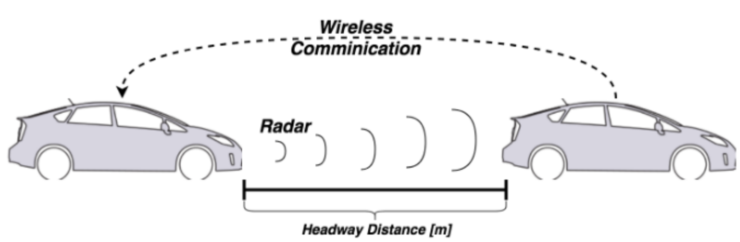


Fig. 2. Schematically depicted CACC system concept

This framework enables a detailed simulation of wireless communication among the vehicles, together with realistic mobility. PLEXE is Veins-based [12], also coupling the OMNeT++ network simulator with the SUMO road traffic simulator, meaning that users can benefit from a fully detailed IEEE 802.11p and IEEE 1609.4 DSCR/WAVE network stack for realistic simulation of vehicular networks. Moreover, it extends SUMO by implementing several cruise control models and realistic engine dynamics. Due to these benefits, PLEXE framework was chosen to perform all the following simulation tests. We adopt the common beacon format and the standard message dissemination procedure used on PLEXE. *Beacons* in ITS application are single-hop periodic broadcast messages, transmitted by every vehicle. The information received by means of this beacons (i.e. acceleration, position, speed, etc..) is then used to feed automated controller.

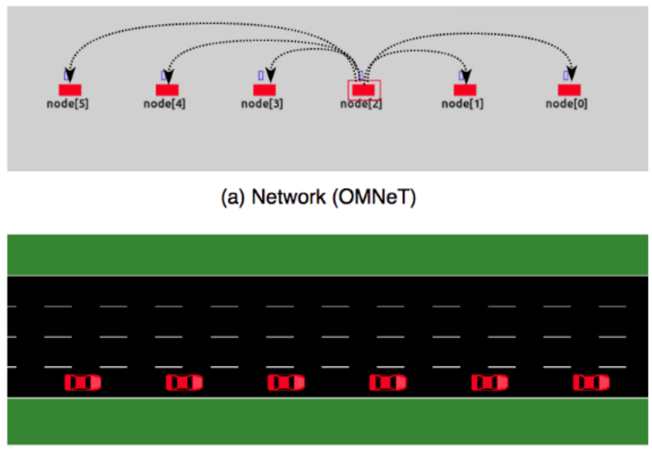
To perform the evaluation of the vehicle cooperative longitudinal controller, an highway simulation scenario was chosen. CACC is supposed to be used mostly outside the city roads, thus the urban scenarios are not covered in this paper. This simple use case represents four lines straight highway road with unidirectional traffic flow. Fig. 3 shows a part of the highway with a platoon of six vehicles. Each vehicle has an assigned ID, where platoon leader ID is equal to 0, first follower vehicle has ID equal to 1, and so on. A homogeneous platoon was assumed for this study, assuming that all vehicles in the string show identical dynamic behaviour and implements the same engine model.

The OMNeT++ network simulator represents vehicles in the form of communication nodes, as shown in Fig. 3 (a). All nodes send periodic beacons to perform information exchange. Each node has the same position as the vehicle in the traffic simulation. This is achieved by means of TraCI server provided by SUMO. On every simulation step OMNeT++ node pass received beacon data to the SUMO. Then, SUMO uses this information as input for the CACC controller to calculate velocity and acceleration. The resulting values are used to estimate the position of the vehicle. SUMO returns this position to OMNeT, which moves its nodes accordingly.

In this simulation setup, the free-space path loss model and Nakagami-m distributed fading model is considered. The beacon message work on top of the IEEE 802.11p (PHY) / IEEE 1609.4 (MAC) models provided by Veins and send beacons on Control Channel (CH) only. The channel central frequency is 5.89 GHz with data rate of 6 Mbit/s and transmission power of 100 mW. Other configuration parameters are listed in Table 1. The vehicles inside the platoon should follow the preceding vehicle at predefined time-gap spacing. Larger platoon sizes can increase maximum road utilization, but also affect platoon flexibility and traffic flow stability. There is no exact size limit defined, although some researches [11,7] recommends a maximum platoon size up to 10 to 20 vehicles.

5 Controller Evaluation

This section presents controller tests in a simulation environment. Analyzing controller behavior in different scenarios allows verifying its stability, safety and



(a) Network (OMNeT)

(b) Traffic (SUMO)

Fig. 3. Screenshot of network (a) and traffic (b) simulation environment

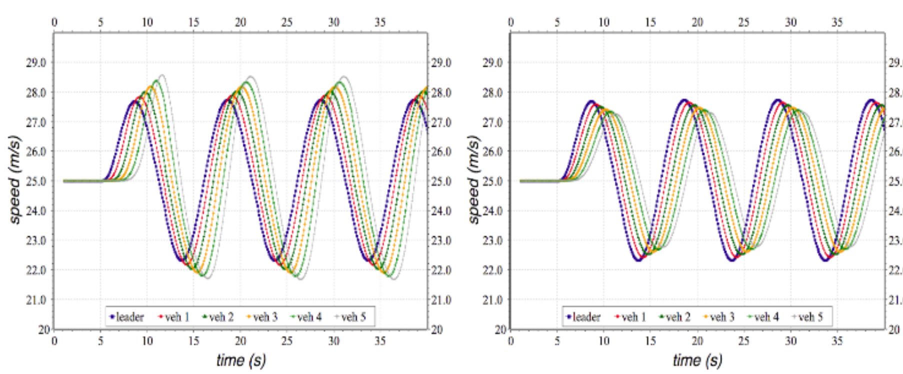
Table 1 - Default simulation settings

	Parameter	**Value**
Communication	Free space path loss model (α)	2.0
	PHY/MAC model	IEEE 802.11p/1609.4
	Frequency	5.89 GHz (CCH)
	Bitrate	6 *Mbit/s*
	Access category	AC_VI
	Beacon size	150 *B*
	Beacon frequency	10 *Hz*
	Transmit power	20 *dBm*
	Sensitivity	–94 *dBm*
	Thermal noise	–95 *dBm*
	CCA-threshold	–65 *dBm*
Mobility	Platoon size	6
	Car length	4 *m*
	Intra-platoon time-gap	0.5 *s*
	Max Speed	150 *km/h*
	Max acceleration	2.5 m/s^2
	Max deceleration	6 m/s^2
CACC	Kp	0.2
	Kd	0.7
	Ks	0.4
	Reaction Time (τ)	0.5 *s*
	Standstill distance	2 *m*
	Operating frequency	100 *Hz*

performance characteristics. Simulation permits fast controller analysis using different configuration parameters during the tests. However, the simulation may reduce the system realism due to the use of simplified models. For this basic tests an ideal wireless communication is considered (i.e. no packet losses). The leader introduces all movement disturbance and the followers should correctly react to these changes.

5.1 Comparison with ACC

The longitudinal controller is tested against Adaptive Cruise Control (ACC) system provided by PLEXE framework. ACC is an optional cruise control system, that uses the additional devices (radar or LIDAR) and automatically adjusts the vehicle speed to maintain a safe distance from vehicles ahead. The controllers are compared by looking at the velocity profiles as a function of time using the same time-gap spacing for both. Fig. 4 shows the vehicles speed over the time, illustrating the benefits of IVC-based controller against a purely sensor-based system. ACC controlled vehicles have increased disturbance introduced by the leader. This means that under these conditions ACC control system is not string-stable and make cause vehicle collision. The additional information received via wireless communication ensures CACC controller string stability on small spacing.



(a) ACC (b) CACC

Fig. 4. Comparison between ACC and CACC showing string stable (b) and string unstable (a) behavior

5.2 String stability properties

String stability is an essential requirement of the vehicle-following control systems. Using the standard approach to analyze string stability, the implemented simulation scenario continuously changes the leader speed in sinusoidal mode. A constant headway time policy is used to calculate the desired inter-vehicle distance, which is related to the vehicle speed. Sinusoidal disturbance frequency is set to 0.1 Hz with 10 km/h of oscillation amplitude. The controller string-stability evaluation was provided using different headway times, see Fig. 5. It clearly shows a tradeoff between selected headway time and attenuation capabilities of the controller. A tracking lag can be observed by looking at how the velocity of one vehicle is out of phase with its predecessor.

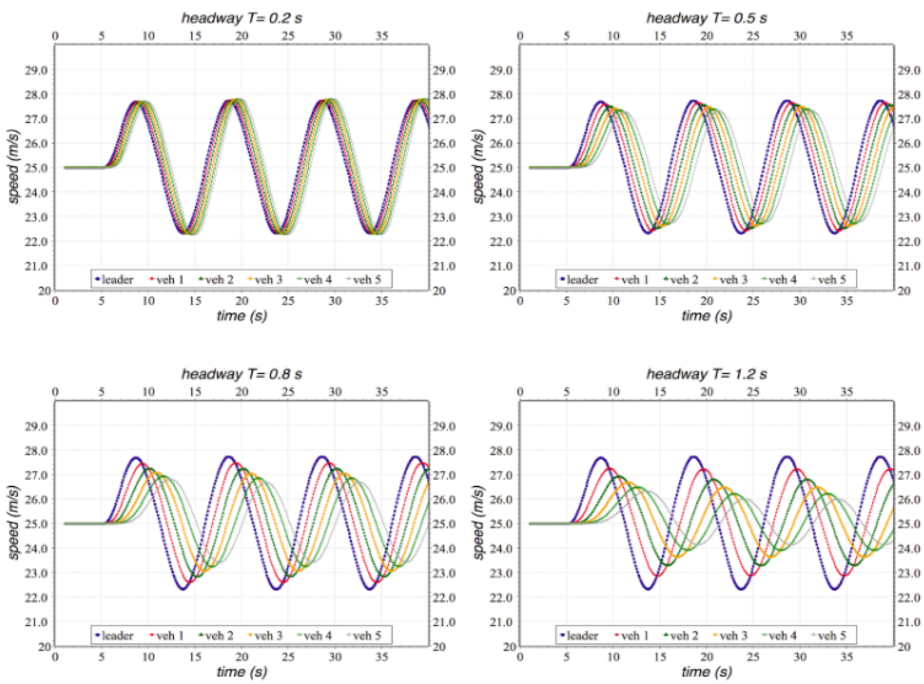
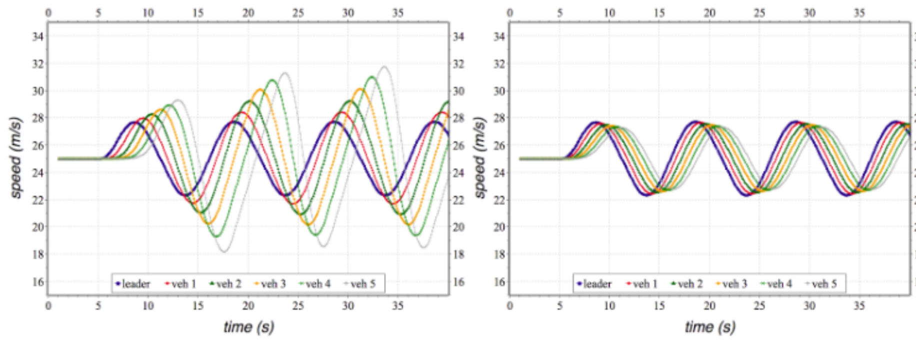


Fig. 5. Vehicles speed for different headway time, illustrating string-stability properties

5.3 Desired vs Real acceleration

Using wireless communication, the CACC can also obtain the *desired* acceleration of the front vehicle to control the external input. Unlike *real* acceleration, the desired acceleration represent future information about the intended vehicle behavior. Using the desired acceleration instead of the actual one gives an advantage in term of system reactivity. Clearly, this information cannot be measured by any sensor. Fig. 6 compares behavior of the resulting platoon when preceding vehicle sends the actual and desired acceleration using the same headway time. Then it was analyzed with respect to string stability, from which it appears that sharing the desired acceleration increases the performance in terms of minimizing the inter-vehicle distance while guaranteeing string stability.



(a) actual acceleration (b) desired acceleration

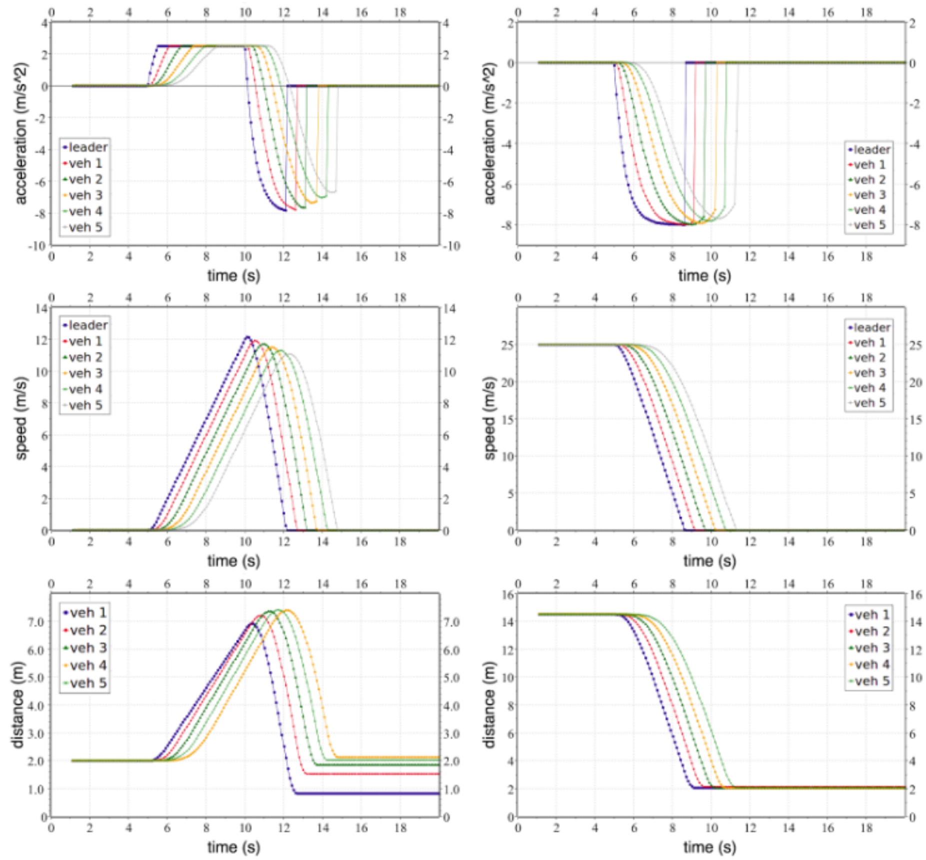
Fig. 6. Speed profile when sending actual (a) and desired (b) acceleration

5.4 Basic Analysis

It has been shown that CACC is string stable for time-gaps smaller than T=1 s, besides the other simulation experiments must be performed to validate the longitudinal controller. There are numerous possible traffic scenarios that can be implemented, so this work is focused on extreme situations, like sudden braking or fast acceleration. By analyzing the behaviour of the controller in extreme maneuvers the performance can be tested in terms of stability and robustness. Fig. 7 shows the result obtained for these scenarios that represent acceleration, speed and distance profiles of a platoon with five vehicles and a leader.

Fig. 7 (a) shows the *Accelerate and Brake* scenario, where all platoon vehicles depart from the rest position. The leader vehicle continuously accelerates for 5s and then brakes until complete stop, using the maximum possible deceleration. The initial inter-vehicle distance is 2 m. The leader accelerates from the standstill with the constant acceleration of 2.5 m/s^2 and all the followers attempt to reach the desired distance and speed. After 5s the leader achieves the velocity of about 45 km/h and applies maximum deceleration (-8 m/s^2) until full stop is reached. This particular scenario is pretty demonstrative, since after maximum acceleration it comes to the maximum deceleration and all vehicles come to a stop safely.

Fig. 7 (b) shows the second example, the platoon travels on the freeway with the constant speed of 90 km/h. The leader performs a sudden break, constantly decelerating (-8 m/s^2) until full stop. The followers correctly track its behavior without causing any collision. All the vehicles were able to come to a full stop and converge at the predefined standstill distance of 2m. In both scenarios a tracking lag can be observed, in spite of it, every platoon vehicle can safely track leader motion in short distance following.



(a) accelerate and brake scenario (b) braking scenario

Fig. 7. Simulation experiments to validate the longitudinal controller

5.5 CACC Maneuvering

So far, it has been demonstrated that the CACC is able to maintain platoon string stable behaviour if choosing an appropriate headway time. Intra-platton distance depends on platoon cruise speed: the higher the speed the larger the distance. However, a platoon needs to be modified during its course, therefore, it should support basic platoon maneuvers (e.g. vehicle join, vehicle leave, lane change, etc..). Moreover, a platoon needs interact with other vehicles on the road. For these reasons, CACC equipped vehicle must be able to maintain the desired fixed distance to the preceding vehicle and the longitudinal controller must provide those capabilities.

To support these features the original controller was extended introducing a new input variable and a new configuration parameter to the controller logic. This new input variable on the control loop represents the desired distance to the front vehicle. The new configuration parameter was called *Gain(G)* characterizes the internal controller dynamics, i.e. define how fast the vehicle reaches the desired distance. Basically the controller need to transform the desired distance into the time-gap indicated in seconds on every execution step. The simple transformation algorithm is represented in the following:

if $d_i > 0$ **and** $V_p > 0$ **then**
  if $d_i > d$ **then**
    $H \leftarrow (d + G)/V_p$
  else
    $H \leftarrow d_i/V_p$
  end if
end if

.

where d_i is the pretended distance in meters, d is the actual distance to the preceding vehicle, V_p is the preceding vehicle speed, G is the defined gain parameter and H is the required headway time. Fig. 8 provides a simple example of platooning join by side maneuver and the Fig. 9 shows the acceleration, distance and speed profiles of the platoon vehicles. The vehicle on the side wants to join the platoon, so in order to make the lane change possible, the vehicle in the middle of platoon must create enough space at the front of the preceding vehicle. Here, the main task of the longitudinal controller is to guarantee the desired fixed distance to the front vehicle, independently of the leader behaviour. The CACC of the other followers, which are already platoon members, does not change the operation state and just maintain headway distance. When G=10 , see Fig. 9(a) the controller responds faster and conclude the maneuver at around 20 s. The fast maneuver CACC-settings leads to undesirable oscillations and might result in an uncomfortable driving for the passengers. Fig. 9(b) shows a successful longitudinal maneuver when G=1. After 35s vehicle 2 creates the required gap to let the joiner enter the platoon. The gain parameter (G) manage the controller reactivity. It is clear that G must be tuned to meet a good trade-off between convergence time and driving comfort.

6 Conclusion and Future Work

The CACC system may improve car-following performance using the additional data (e.g. acceleration) exchanged between the vehicles through a wireless communication link. Consequently, the controller can react faster to the behaviour of the vehicle in front. This paper describes the process of CACC testing using the simulation environment. It was possible to conclude that the used longitudinal controller is able to work safely and efficiently, ensures a vehicle following at a close distance, together with traffic flow stability. Finally, the performance of the longitudinal controller employed for basic platoon operations was demon-

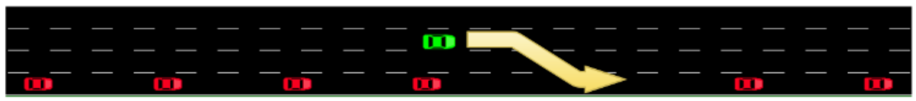


Fig. 8. Graphical representation of platooning join by side maneuver

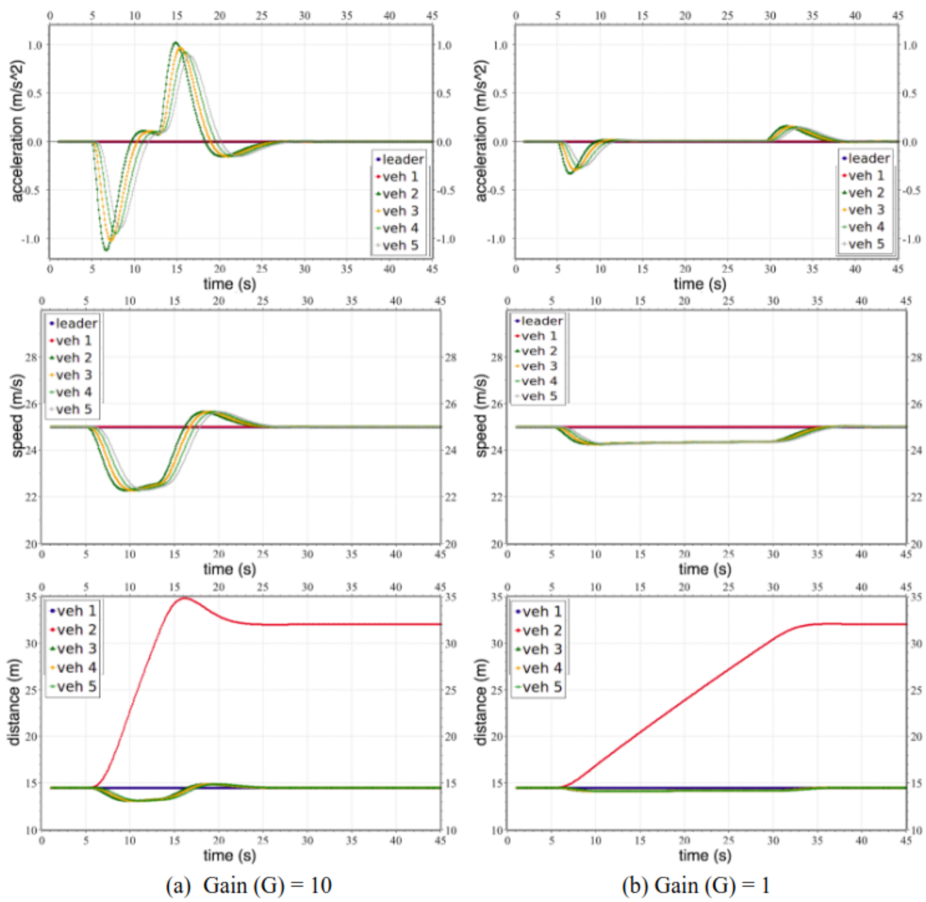


Fig. 9. Platoon vehicles behaviour for different CACC parametrization. Controller reaching the desired distance faster (a) and slowly (b).

strated. The presented results allow determining the parameters under witch CACC confirms its string stability and robustness.

The future work could be extended by improving the CACC in order to take into account the existence of road gradient and bend, since all the simulation testes was realized on the straight road. The implemented controller uses the information received from the directly preceding vehicle only. However, recently proposed CACC solutions have introduced multi-vehicle communication topology to improve the controller performance. This additional information from the other platoon vehicles may improve controller robustness against communication impairments. The controller evolution section provides the basic controller tests in simulation environment. Nevertheless, the other traffic scenarios should be also analyzed. The simulation scenario could be improved using the real road topologies, rather than straight road. Furthermore, stimulation may take into account heterogeneous traffic (i.e., vehicles with possibly different dynamic characteristics).

The CACC performance strongly depends on the availability of communicated information of the preceding vehicle. However, IEEE 802.11p wireless communication is not flawless i.e. collisions on the shared wireless medium may cause packet loss. Therefore the impact of communication impairments, such as transmission delays and packet losses, should be investigated. The presented simulation setup uses only the strictly periodic beaconing approach, however the dynamic beaconing strategy can be tested for the future work. For example, the beaconing frequency may vary according to the vehicle speed variation. Further research on the impact of communication losses on CACC performance is needed. Moreover, the increased network traffic also requires a careful analysis.

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