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# Impact of radio channel characteristics on the longitudinal behaviour of truck platoons in critical car-following situations

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**Abstract:** Truck platooning is an application of cooperative adaptive cruise control (CACC) which relies on vehicle-to-vehicle communications facilitated by vehicle ad-hoc networks. Communication uncertainties can affect the performance of a CACC controller. Previous research has not considered the full spectrum of possible car-following scenarios needed to understand how the longitudinal behaviour of truck platoons would be affected by changes in the communication network. In this paper, we investigate the impact of radio channel parameters on the string stability and collision avoidance capabilities of a CACC controller governing the longitudinal behaviour of truck platoons in a majority of critical car-following situations. We develop and use a novel, sophisticated and open-source VANET simulator OTS-Artery, which brings microscopic traffic simulation, network simulation, and psychological concepts in a single environment, for our investigations. Our results indicate that string stability and safety of truck platoons are mostly affected in car-following situations where truck platoons accelerate from the standstill to the maximum speed and decelerate from the maximum speed down to the standstill. The findings suggest that string stability can be improved by increasing transmission power and lowering receiver sensitivity. However, the safety of truck platoons seems to be sensitive to the choice of the path loos model.

**Keywords:** Truck platoons, cooperative adaptive cruise control, V2V, VANET, radio channel,

# 1 Introduction

Truck platooning is a promising technology that is expected to generate fuel savings, emission reduction, and safer operations. It is an application of cooperative adaptive cruise control (CACC), where multiple trucks are organized into a group of close-following vehicles. The key technology behind CACC is vehicle-to-vehicle (V2V) communication facilitated by vehicular ad-hoc networks (VANETs). It enables participating vehicles to exchange relevant information (e.g., position, speed, acceleration) with each other over a self-organized wireless communication network [1]. Previous research has shown that uncertainties in V2V communications, arising from highly dynamic conditions of the wireless channel, can significantly impact the performance of a CACC controller [2,3]. However, these studies only look at one of the following critical car-following situations: stop-and-go [2] and deceleration to a slower speed [3]. Since trucks are heavy and long vehicles, it is vital to verify the performance of a CACC controller governing their longitudinal behaviour (i.e., string stability and collision-avoidance capabilities) in a majority of critical car-following situations that might arise in real traffic conditions.

Rapidly changing vehicular channels rely on a physical layer to enable the exchange of information. However, previous research has simplified the modelling of the physical layer regarding radio channels [4]. Therefore, a detailed sensitivity analysis is required to understand the impacts of the radio channel characteristics on the string stability and collision-avoidance capabilities of trucks in a platoon. In this regard, simulation-based investigations of VANET applications have gained momentum due to their cost-effectiveness and are critical to configure the operations of VANET systems [4]. This paper presents OTS-Artery, a novel and open-source VANET simulator, which brings microscopic traffic simulation (OpenTrafficSim (OTS) [5]), network simulation (Artery [6]), and psychological concepts [7] in a single environment to simulate next-generation traffic operations.

Consequently, the aim of this paper is to investigate the impact of radio channel characteristics on the longitudinal behaviour of truck platoons in critical car-following situations using a VANET simulator. The rest of the paper is structured as follows: The CACC controller for truck platoons is presented in section 2. The OTS-Artery VANET simulator is outlined in section 3. The experimental setup including communication and traffic scenarios is discussed in section 4 and its results are explained in section 5.

# 2 CACC Controller for Truck Platoons

We use a modified version of the CACC controller developed by Faber et al. [8] in this paper by removing redundancy. An ego truck is a CACC-equipped truck. Let $r$, $v$ and $r_{\text{standstill}}$ be its current headway spacing from its predecessor, its current speed, and minimum spacing at standstill (3 m), respectively. Let $v_p$ and $a_p$ be speed and acceleration of the predecessor of the ego truck, respectively. $r_{\text{CACC}}^{\text{safe}}$ is the safe following distance required for the ego truck. The target time gap $t_{\text{CACC}}$ is set to 0.5 s.

$$r_{\text{CACC}}^{\text{safe}} = t_{\text{CACC}} \cdot v + r_{\text{standstill}} \tag{1}$$

The ego truck responds to the acceleration of the predecessor, deviations between its desired and current speed, and the deviation between the current distance headway and the desired headway (see Equation 2).

$$a_{\text{CACC}} = k_a \cdot a_p + k_v \cdot \left(v_p - v\right) + k_d \cdot \left(r - r_{\text{CACC}}^{\text{safe}}\right) \tag{2}$$

where $a_{\text{CACC}}$ is bounded by the ego truck's minimum (-3 m/s$^2$) and maximum acceleration (2 m/s$^2$) capabilities. $k$, $k_a$, $k_d$, and $k_v$ are chosen as 0.3, 1.0, 0.1, and 0.58, respectively to provide a smooth acceleration response by minimizing overshoot and oscillations.

## 3 OTS-Artery

OTS-Artery is a novel and open-source VANET simulator. OTS incorporates human factors and social interactions in a microscopic simulation framework to model driving behavior. Whereas ARTERY is able to simulate the ETSI ITS-G5 protocol stack used in European VANETs. OTS-Artery couples the OTS with Artery via the Sim0MQ middleware that is based on the high-performance asynchronous ZeroMQ library. To simulate truck platoons, Artery is extended with a GtuProxyService that uses the plain single-hop broadcast mode of GeoNetworking. Each truck in Artery is equipped with the GtuProxyService which facilitates the exchange of relevant information between a leader-follower pair of the truck platoon. As shown in Fig. 1, the leader transmits the payload (sender GTU id, receiver GTU id, signal strength, time stamp, speed, and acceleration) to the Artery OTS core. The follower then calls the core upon message reception and receives the payload if the follower id matches the receiver GTU id in the payload. A new payload is transmitted every 100 ms. More information about OTS-Artery is available at: https://github.com/salilrsharma/OTS-Artery.

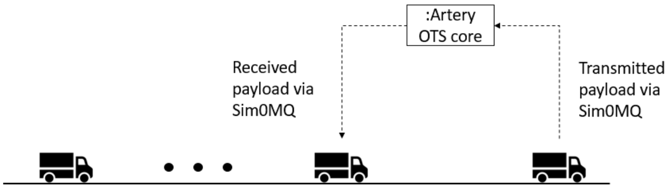


Figure 1: OTS-Artery architecture showing information exchange between a leader-

## 4 Experimental Setup

### 4.1 Communication Scenarios

1. Ideal: The V2V communication is handled idealistically within the traffic simulator OTS.
2. Realistic: A default radio channel is created based on IEEE 802.11p with OTS-Artery. The fixed and variable parameters of OMNET++ are presented in Table 1 where bold-faced values refer to the default channel. Transmission power (TP), receiver sensitivity (RS), and type of path loss model are varied to assess the impact of radio channel characteristics on the string stability and collision avoidance capabilities of truck platoons.

Table 1: OMNET++ parameters for radio channel based on IEEE 802.11p

| **Fixed parameters** | |
|---|---|
| Channel number | **180** |
| Carrier Frequency | **5.9 GHz** |
| Receiver Energy Detection | **-85 dBm** |
| Receiver SNIR Threshold | **4 dB** |
| | |
| **Variable parameters for sensitivity analysis** | |
| Transmission power (TP) | {50 mW, **200 mW**, 2000 mW} |
| Receiver Sensitivity (RS) | {**-85 dBm**, -96 dBm} |
| Path-loss model | {**VanetNakagamiFading** [9], Two-ray interference } |

### 4.2 Traffic Scenarios

The platoon topology consists of five identical trucks moving on a single-lane straight road section devoid of any other traffic. We consider the following three critical car-following situations.

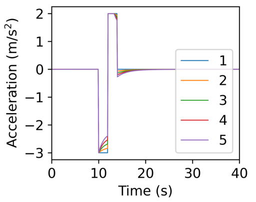
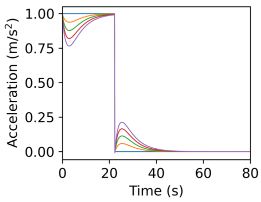
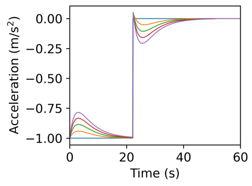
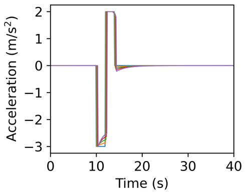
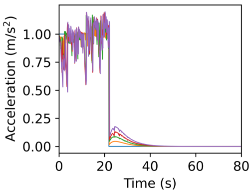
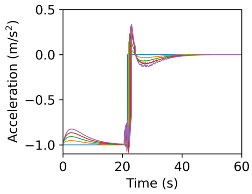
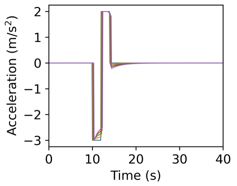
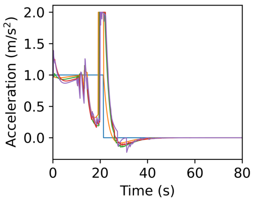
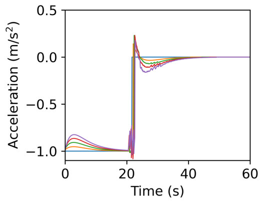
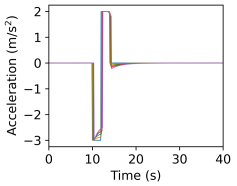
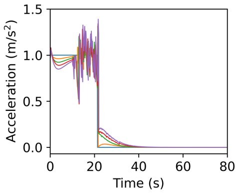
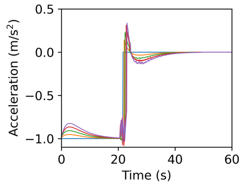
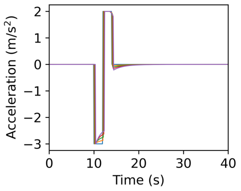
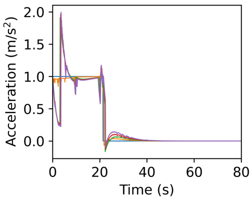
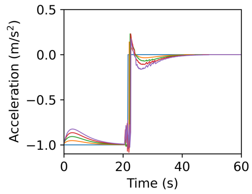
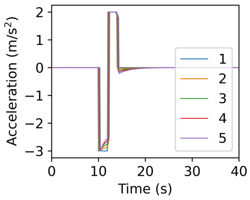
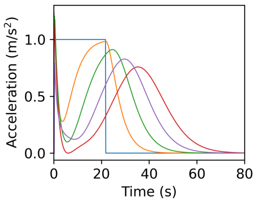
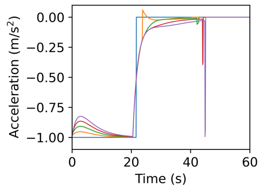
1. Stop-and-go: The platoon has an initial speed of 80 km/h (i.e., maximum allowed speed). The leader decides to decelerate at 10 s with 3 m/s$^2$ for the next 2 s. Then, the leader accelerates with 2 m/s$^2$ from 12-14 s. From 14 s onwards, the leader moves with a constant speed of 72.80 km/h.
2. Acceleration from zero to the maximum speed: The platoon has an initial speed of 0 km/h. The leader accelerates with 1 m/s$^2$ to reach the final maximum speed of 80 km/h at 22.22 s.
3. Decelerating from the maximum speed to the standstill: The platoon has an initial speed of 80 km/h. The leader decelerates with 1 m/s$^2$ to reach the standstill situation at 22.22 s.

## 5 Results

In the OTS scenario, the CACC controller results in a string stable behaviour where acceleration errors do not amplify when propagated upstream (see Table 2). This is attributed to the fact that communications are robust and do not include any delay. In the OTS-Artery scenario, we set up a more realistic radio channel to handle V2V communications. For situations involving stop-and-go, we observe a delayed yet string stable acceleration response from the follower trucks in the platoon.

When we change the values of RS, TP, and type of path-loss model, the acceleration responses observed in the stop-and-go situation are similar to that of the default radio channel. When the leader of a platoon accelerates from the standstill to the maximum speed, the acceleration of followers significantly fluctuates and might be fuel-inefficient. These fluctuations are reduced if we decrease the RS and increase the TP. Over and undershoots are observed; however, these do not amplify upstream. Large under and overshoots which stabilize until 80 seconds are observed when the path-loss model is changed to a deterministic one. Similarly, when the leader of a platoon decelerates to standstill, string stability is affected only in the case of the two-ray interference path loss model. Consequently, safety also gets worsened as the last two trucks of the platoon collide with each other in the same scenario.

Table 2: Acceleration profiles of truck platoons for traffic and communication scenarios

| **Communication scenarios** | **Traffic scenarios** | | |
|---|---|---|---|
| | **Stop-and-go** | **Accelerating to the max speed** | **Decelerating to standstill** |
| Ideal (OTS) |  |  |  |
| Realistic (default radio channel) |  |  |  |
| Realistic (RS = -96 dBm) |  |  |  |
| Realistic (TP = 50 mW) |  |  |  |
| Realistic (TP = 2000 mW) |  |  |  |
| Realistic (Path loss model = Two-ray interference) |  |  |  |

## 6 Conclusions

In this paper, the impact of radio channel characteristics on the longitudinal behaviour of truck platoons in critical car-following situations is studied. Our main conclusions are as follows.

1. An open-source simulator OTS-Artery is developed to evaluate VANET applications.
2. Short-term changes in the acceleration behaviour of the followers of a platoon (e.g., stop-and-go) are not significantly affected by the radio channel characteristics.
3. Situations involving truck platoons to accelerate to the maximum speed or decelerate down to the standstill require most of the attention while assessing the impact of radio channel characteristics and designing a robust CACC controller.
4. Path loss models can significantly affect safety in a truck platoon configuration.

A promising research direction can be to test the impact of the radio channel in other critical car-following situations such as emergency braking and gap-closing. Further, the impact of competing V2X services can also be studied. Another possibility is to test the impact of radio channels on the lane-changing behaviour of truck platoons. Afterward, large-scale VANET simulations can be conducted to assess the traffic and safety impacts of truck platoons on surrounding traffic in real traffic situations.

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