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Generation of tests for safety assessment of V2V platooning trucks

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Abstract

Large steps are being taken by the industry and R&D organizations in automated driving technology development, as well as in setting up appropriate methods for safety assessment of cooperative automated driving functions. An important component of safety assessment is scenario-based testing. In this paper, we will focus on the generation of scenario-based tests for a very specific group of vehicles: trucks in a platoon enabled by vehicle-to-vehicle (V2V) communication. The basis is formed by previously proposed scenario-based assessment methods for individual automated driving vehicles. These methods however do not consider the inter-vehicle communication component. It is discussed how V2V communication interconnects vehicles in a system-of-systems, and how to include V2V communication in the scenario description. By means of practical application, it is shown how V2V communication influences the description of tests for the individual trucks in a platoon, to make assessment of safe deployment of multi-brand platoons on the public road possible.

Keywords: PLATOONING, SCENARIO-BASED TESTING, V2V COMMUNICATION

Introduction

The effort that is put into the development of automated vehicles by the industry is unmistakably very high. In the automation challenge, we distinguish between performance of perception, how well does the sensor system detect, identify, track and predict behaviour of objects possibly interfering with the ego vehicle, and between the performance of control and decision logic, how well is the ego vehicle capable of anticipating on this behaviour as early as possible in the best possible way. Of course, if proper perception of the sensor system fails, then anticipation becomes very difficult or even impossible. The development of a fair and reliable safety assessment framework is important for the safe deployment of automated vehicles on the public road, i.e. to test performance of perception and performance of control and decision logic. Results are important for authorities to monitor the safety of vehicles that they allow on the road and to steer policy with regard to implementation of automated vehicles, and for the industry, to get an understanding how their automated vehicle performs in terms of safety on the road, as early as in the development phase.

Safety assessment frameworks that are based on real-world scenarios are considered to be a structured way of dealing with the infinite different situations that an automated vehicle needs to be able to deal with in a safe way when deployed on the public road [1, 2, 3, 4]. So far, safety assessment frameworks consider single automated vehicles that base their responses on their view at the surrounding traffic and their environment. Sensor systems based on radar, lidar and/or camera techniques collect that view, where sensor fusion on board of each individual automated vehicle is used to build a single world model. The world model is the most important input to the automated vehicle's decision and control logic, in order for the vehicle to provide an appropriate response.

An important technology to enable higher levels of automation is V2X communication (where X represents "everything"), which considers both the information exchange between vehicles and the infrastructure (V2I) and the information exchange between vehicles through V2V communication. The latter, V2V communication, is an indispensable technology to enable safe platooning of trucks. Platooning of long-haul trucks is expected to show large benefits regarding reductions in fuel consumption [5], improvements of traffic throughput as a result of more efficient utilization of road capacity, and improved road safety by decreasing the role of the human in controlling the vehicle [6]. Regarding fuel consumption and traffic throughput, results improve with decreasing time-headway (THW[*]) between the trucks in the platoon. Conventional Advanced Cruise Control (ACC) systems, measuring relative speed and distance with respect to the preceding vehicle in the platoon using sensors such as camera, radar and/or lidar, are not able to assure string stability in the platoon unless relatively large intervehicle distances are chosen [7]. With V2V communication, string stability in the platoon can be achieved even for short following distances [7].

In the European Horizon 2020 project ENSEMBLE [8], technology is developed to demonstrate heterogeneous multi-brand truck platooning enabled by V2V communication. As current frameworks for safety assessment of (highly) automated vehicles do not consider inter-vehicle communication (V2V) or more generic V2X, it is not possible to simply apply such a safety assessment framework to the use case of truck platooning. The European Horizon 2020 project HEADSTART [9] aims to define testing and validation procedures of Connected and Automated Driving (CAD) functions and in this way supports the safety assessment of the truck platooning solutions developed in ENSEMBLE. This paper shows how the definition of the concept 'scenario' [10] is extended for applications making use of V2V communication and how test cases are described. With a practical example, it is shown how this works out in practice, e.g. in model-in-the-loop or hardware-in-the-loop simulations.

Approach

To study the impact of V2V communication in the description of scenarios and the generation of test cases, the truck platooning use case from the H2020 ENSEMBLE project [12] has been selected. Reason to focus on a specific use case is that in the generation of test cases based on real-world scenarios, the operational design domain (ODD according to SAE J3016 [11]) plays an important role.

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[*] THW is defined as the distance between the rear of the preceding truck and the front of the following truck, divided by the speed of the following truck.

The ODD is used to select those scenarios and those parameter ranges that are relevant for the function-under-test. In a truck platoon, trucks follow each other at a short distance, in order to reduce fuel consumption and make more efficient use of the roads and infrastructure. The smaller the time-headway (THW), the larger the potential fuel consumption reduction. Trials have been performed with a THW between platooning trucks as small as 0.8 sec., whereas in normal traffic a THW of 2 sec. between vehicles is considered safe.

Truck platooning enhanced by V2V communication

To allow trucks to cooperate in a platoon with a THW << 2 sec., communication between the trucks is introduced. So far, the first truck in the platoon is driven by a normal truck driver. All actions taken by the driver to manoeuvre through traffic is communicated in an instant to the following trucks, with Platoon Control Messages (PCMs). The following trucks have an automated platooning system on board to establish and maintain the distance to the preceding truck when possible. The automated system uses a camera and a radar to continuously measure the speed and the distance to the preceding truck and its own position on the road. With the communicated information on acceleration or deceleration, the following trucks can act simultaneously without significant delays, maintaining a short distance. When platooning at a low THW, safety might be compromised, e.g. by failing communication between the trucks or by the occurrence of unexpected events on the road. Before deployment of the functionality, it needs to be tested in order to determine whether the function and its implementation is safe to be deployed on the road.

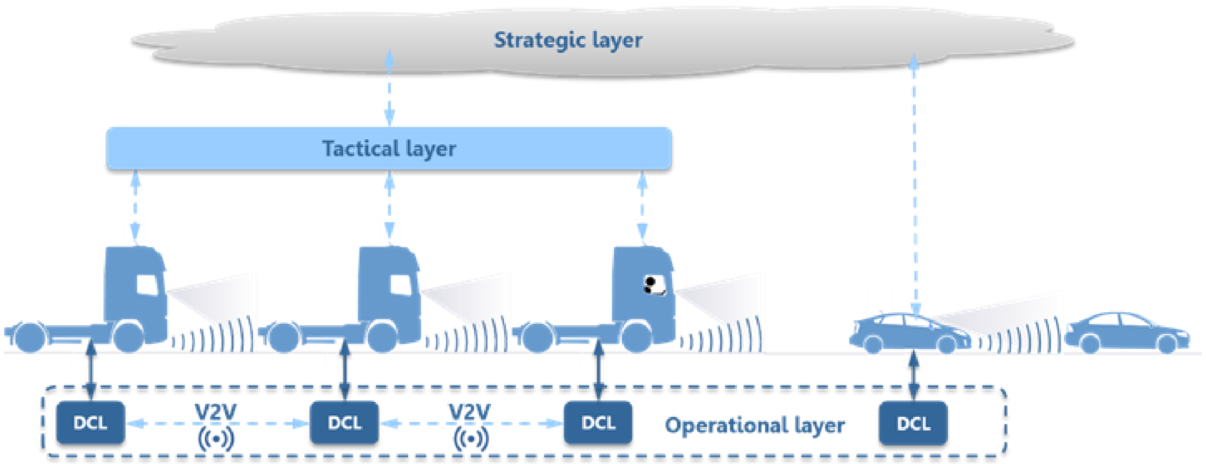

Figure 1 Different layers for V2V communication (DCL refers to the Decision and Control Logic on board of each truck) according to the ENSEMBLE project [8]

Definition of the system-under-test

A fundamental choice needs to be made for the safety assessment of platooning trucks as there are essentially two possibilities to draw the system boundary for the system-under-test:

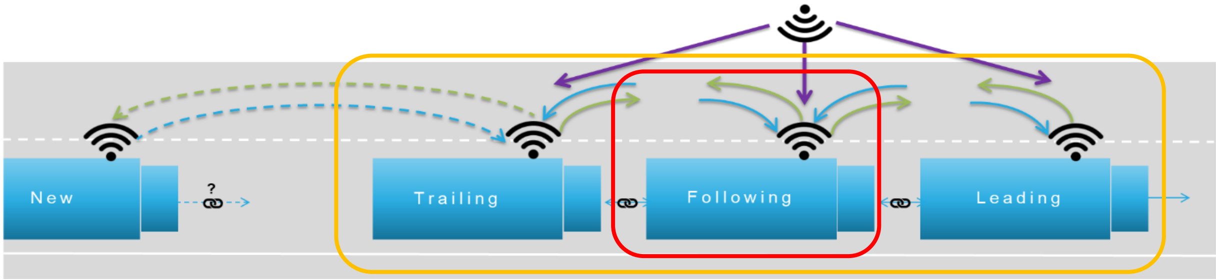

Figure 2 Two essentially different ways of considering system boundaries for the platooning use case.

A. Assessment of the platoon as a system-of-vehicles

In the system-of-vehicles, the vehicles are cooperating following agreed rules on the use of V2X messages (the platooning protocol). This is the system boundary indicated by the orange bounding box in Figure 2:

- Vehicles are able to receive messages from other vehicles in the platoon (V2V) and from the environment (I2V) and interpret these, like sensors that make an image of the environment as input to the decision and control of the vehicle.
- Transmission of messages is considered similar to the use of the actuators, such as steering, braking or gas pedal actuation. Input to the actuators is received from the decision and control algorithms. A transmitted V2V message is intended as input to the decision and control of one other vehicle in the platoon.
- The only communication crossing the system boundary considers messages received from or transmitted to the infrastructure.

B. Assessment of the response of the individual vehicle

In case individual vehicles are assessed, it is important to consider that the vehicles are part of a platoon, and that the vehicles also respond to input received by V2V communication[†] (system boundary indicated by the red bounding box in Figure 2):

- Information is received from the vehicle in front and from the vehicle to the rear (V2V) for interpretation of decision and control software (similar to a sensor).
- Moreover, a different type of information is received from the infrastructure, e.g., information on speed limit, desired THW given the traffic situation or road layout, etc.
- Input from the decision and control software in the truck is used for the actuators and to transmit operational messages. The transmitted operational messages are used by the vehicle to the rear for operational control (e.g., longitudinal vehicle following). This is typically part of the operational layer and has a real-time nature. So, this V2V communication is intended to have a low latency

[†] The communication protocol described here results from the ENSEMBLE project; it describes in generic terms how trucks are agreed to communicate and interact. The platooning communication protocol is not standardized yet, but this work contributes to ETSI TR 103 298: ITS; Platooning; Pre-standardization Study.

and high update rates. The messages for platoon management are of a more tactical nature, so less time stringent, but of interest for all platoon members (upstream and downstream) to share status and coordinate platoon manoeuvres.

- The information crossing the system boundary considers tactical and/or strategic layer information received from or transmitted to the infrastructure, and the messages received from the preceding and following truck. Additionally, the messages generated by the individual truck as a result of decision and control (similar to actuation) cross the system boundary. These outgoing messages only target the preceding truck or the following truck.

Although one might expect a result regarding the safety of a platoon as a whole when assessing the platooning use case, it is more meaningful to address the safety of an individual vehicle in the platoon. For Platooning as an ***active support function*** [12], each individual vehicle remains responsible to behave safely, also as part of the platoon. Another fundamental argument results from the fact that we consider multi-brand platooning, which means that for each individual vehicle that has platooning functionality on board, the safety of this functionality needs to be assessed. Consequently, we choose for assessing individual vehicles regarding its platooning functionality. The assessment needs to consider the different roles that a vehicle can have in a platoon (leader, follower, trailing), as its function changes with that role.

If we only would consider the platoon as a whole, then we would need to find a solution for the fact that platoons might have different compositions, with a different number of trucks, cooperation between different type of trucks and a different order of trucks in the platoon. In that case, safety assessment needs to be performed on all possible platoon configurations, which is simply not feasible. As an example, consider a three-truck platoon. In case each truck in the platoon is manufactured by one of six European truck manufacturers, there are 216 (6 × 6 × 6) possible platoon configurations. In case assessment is performed for each truck separately, taking its role in a platoon into account, then only 18 (6 brands × 3 possible roles) configurations need to be considered.

Definition of Operational Design Domain, Scenarios and Test cases

Before addressing the description of scenarios and test cases for use as input in scenario-based safety assessment for a truck in a V2V enhanced platoon, we first need to provide definitions:

<u>Operational Design Domain (ODD)</u>

The ODD is a description of the operations for which the vehicle is designed, including a description of the functionality. SAE automotive standard J3016 [11] defines an ODD as “operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics.”

Scenario

A scenario is used to describe the situations and conditions that any vehicle may encounter on the road during its lifetime. More formally, a scenario is a quantitative description of the relevant characteristics and activities and/or goals of the ego vehicle(s), the static environment, the dynamic environment, and all events that are relevant to the ego vehicle(s) within the time interval between the first and the last relevant event [13]. As depicted in Figure 3 this includes:

- Dynamic environment: the manoeuvres of other actors such as vehicles and pedestrians;
- Static environment: the type of infrastructure, roads and road furniture;
- Conditions such as lighting and weather conditions under which the scenario occurred.

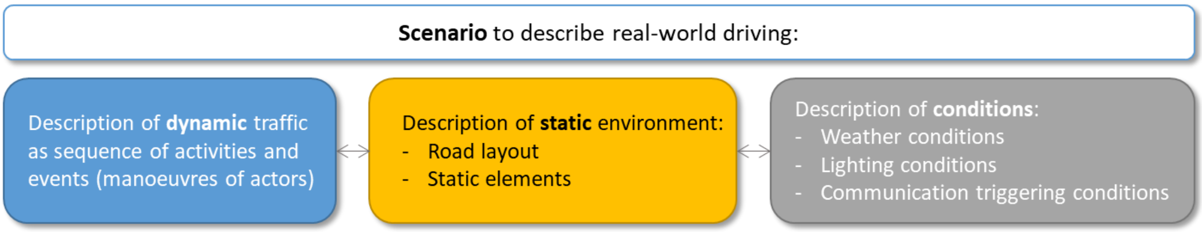

Figure 3 Schematic view on components that describe a real-world scenario

Test case

According to Stellet et al. [14], a test is an evaluation of a statement on the system-under-test (test criteria), under a set of specified conditions (test case) using quantitative measures (metrics) and a reference of what would be the acceptable outcome (reference).

In the next sections, first V2V communication will be discussed in more detail. Thereafter, the definitions introduced here for the system-under-test, ODD, scenario and test case, using the considerations related to V2V communication, will be used to show how to extend the scenario and test case description [15] to include relevant information related to V2V communication. Consequently, this will show how to describe tests that consider V2V to enhance the platooning functionality as well.

V2V communication between transmitter and receiver

V2V communication, a wireless information exchange between the vehicles in a platoon, mainly takes place in the operational layer, near the decision and control logic of the Automated Driving System (ADS) of the individual vehicle. To enable communication, each vehicle has a radio system with a transmitter for sending messages and a receiver for receiving messages, as indicated in Figure 4. The transmitting function communicates for example the vehicle's braking intention to the following vehicle. Like a sensor, the receiving function acquires information through communication as input for the control and decision logic in the ADS.

The added value of scenario-based testing lies in the possibility to assess the impact that the course of events and activities in a scenario has on the quality of interpretation of the received messages by the receiver. In an ideal situation, the receiver receives the exact messages transmitted by the transmitter with only a negligible delay. Under influence of a scenario, there might be changes in the environment (e.g., driving through a tunnel) or differences in the line of sight between transmitter and receiver (e.g., as the platoon drives through a bend in the road), that influence the quality of information exchange between transmitter and receiver. In this paper, we assume that the quality of the transmitted signal is not influenced by the various scenarios. Any deterioration of the V2V communication signal (delay, package loss, signal loss) is attributed to disturbances that act on the signal between transmitter and receiver, resulting in a signal of lower quality that is received by the receiver compared to the signal that is transmitted, see Figure 4.

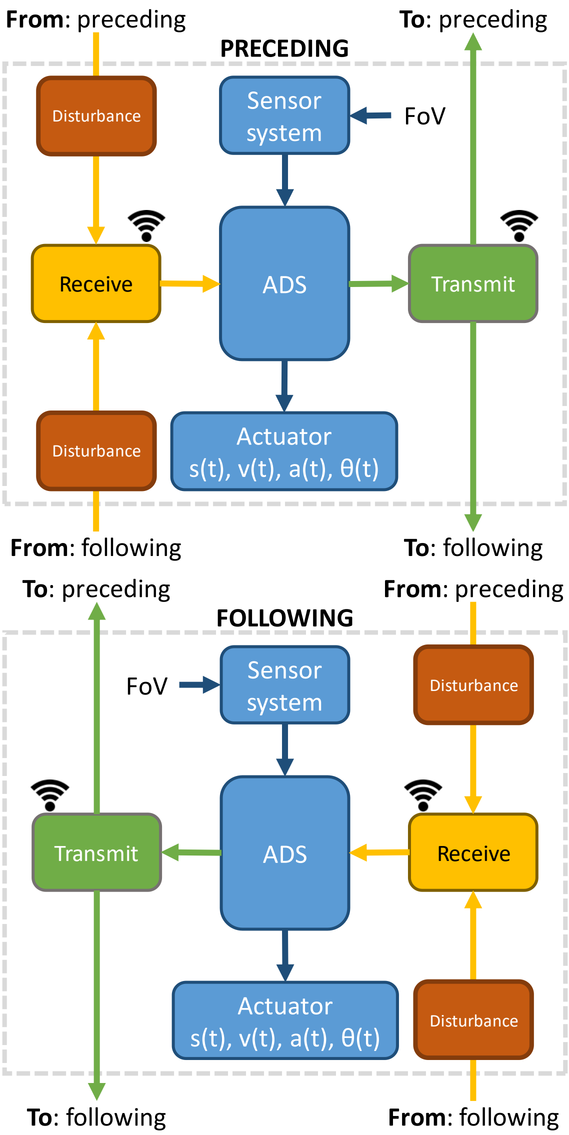

Figure 4 Input-output scheme for two communicating vehicles in a platoon where ADS is the automated driving system and FoV is the field of view of the sensor system onboard each vehicle.

Scenario description and test case generation for V2V functions

When V2V communication is part of the use case, such as for truck platooning functions, it has to be determined how to describe scenarios to include relevant information related to such communication, or how to describe potential deterioration of the communication quality in relation to the scenario.

For each scenario that is relevant for a truck in a platoon, it is determined which activities or events in the scenario are potentially influencing the quality of V2V communication. In analogy with the SOTIF standard ISO 21448:2019 [16], we call these triggering conditions. Triggering conditions are considered to be potential causes for disturbances that decrease the quality of the received communication signal. In the same way that a weather condition, such as fog, can cause a camera to be less capable of distinguishing other traffic participants around the ego vehicle, triggering conditions may cause disturbances in the V2V communication channel and exchanged V2V messages. Examples of triggering conditions are:

- Multi-path reflections: the receiver receives multiple times the same signal due to reflections on objects in the dynamic and static environment, e.g., when driving through a tunnel.
- Loosing line-of-sight: the direct line-of-sight between the transmitter (on a target vehicle) and the receiver (on the ego vehicle) is lost due to a reconfiguration of the target with respect to the ego vehicle, e.g., when a platoon drives in a bend of the road.
- Availability and performance of the communication channel: this can depend on the environment, the communication system itself, usage of the channel (congestion, overload). This has impact on experiencing message delay, messages being lost/dropped, or worst-case complete failure of the V2V communication function.

These examples of triggering conditions show that there is a direct relation between the course of events and activities in the scenario (SOTIF: operational situation) and a triggering condition for communication. Both the scenario and the triggering conditions are required to determine the effect on the quality of the received communication signal. The triggering conditions for communication are added to the scenario description of Figure 3 as communication triggering conditions, in a similar way as for lighting and weather conditions.

The description of the scenarios including V2V communication is complemented by indicating the type of V2V communication messages that are exchanged, considering the platooning communication protocol that is defined for the H2020 ENSEMBLE project [17]. From the different type of messages presented in the protocol, we learn that Platoon Control Message (PCM) is a message set for the operational layer of the platoon, exchanging control information at 20 Hz between the vehicles in the platoon. A PCM contains all necessary data for controlling the vehicle both longitudinally as well as laterally to enable safe platooning. Since these messages are active in the operational control layer of the individual vehicles in the platoon, these messages (or the loss of PCM communication) are potentially safety critical.

As mainly the exchanges of PCMs has a real-time influence on the control and operation of individual vehicles in the platoon, we will consider how to relate PCMs to scenario descriptions. In other words, for scenario-based testing, where we test the safety performance of vehicles, we include that part of communication that is potentially safety critical and for which the quality of message transfer can depend on the scenario.

Instead of quantifying the triggering conditions as part of scenario descriptions, it suffices to know what levels of deterioration in communication (the received information or messages) can be expected in the real world. Typical parameters describing the deterioration would be:

- The encountered communication delay at any moment in time. Usually, the communication delay is in the order of 2 – 4 [ms], but occasionally this may rise to 6 – 8 [ms];
- The number of PCMs lost over the different instances that message loss occurs (given a certain message frequency, here we consider an exchange rate of 20 [Hz]).
- The moments in time that communication loss is detected (the number of messages lost increases over a pre-defined threshold), and the level of the threshold.

In the generation of scenario-based tests, there are two options to include deterioration of V2V communication at the level of PCMs, e.g., as a disturbance to an ideally transmitted PCM situation at the side of the receiver, according to Figure 4:

A. By stochastically sampling the deterioration parameters independent of the scenarios that are simultaneously occurring.
B. By relating the deterioration parameters to the scenarios, for those scenarios that have shown to influence signal quality as a result of triggering conditions, e.g., driving through a bend, through a tunnel or over a steel bridge.

Field tests are required to identify and characterize the communication signal deteriorations, to provide input to both options A. and B. In the methodology, option A. is preferred as to test the effect of deteriorations of communication in any type of scenario, independent of the source of the deteriorations.

Example

As an example of the method proposed in this paper, we will derive test cases for one specific scenario out of the many possible relevant highway scenarios for truck platooning. We consider a scenario that frequently occurs on highways: a lead vehicle braking (an overview -and incomplete list- of possible scenarios is found in [15]). This scenario is relevant for each of the roles that a truck can have in a platoon, so we will focus on the roles *leading*, *following*, and *trailing*.

The scenario happens on a two-lane one-directional road. The ego vehicle is driving on the right lane (in right-hand traffic). The road is (nearly) straight without any intersections. The ego vehicle (either *leading*, *following*, or *trailing*), is initially driving at a constant speed. Another vehicle drives in front of the ego vehicle at initially the same speed as the ego vehicle. This lead vehicle reduces speed. If the ego vehicle is the platoon *leading* vehicle, this other lead vehicle is not part of the platoon. On the other hand, if the ego vehicle is the *following* or *trailing* vehicle in the platoon, the lead vehicle is part of the platoon as well. In case of the latter, it is assumed that the lead vehicle correctly transmits its PCMs.

Table 1 lists the possible test cases for the scenario category lead vehicle braking in which different V2V-related triggering conditions are considered. Note that for each listed test case condition, some variations are possible. For example, in case of loss of PCMs, this could be several messages over a longer time, five consecutive messages, etc. In case of loss of communication, the moment at which this loss of communication occurs could vary. For example, the communication could be lost just before the vehicle in front starts braking or during the braking action of the predecessor.

Table 1 Different test case conditions for the scenario category lead vehicle braking.

	Role of ego-vehicle	Preceding braking vehicle	Communication from lead vehicle
1	Leading	Not part of the platoon	N.A.
2	Following	Part of the platoon	Communication delay of 6 to 8 ms
3			1 to 5 PCMs are lost
4			Communication is lost
5	Trailing	Part of the platoon	Communication delay of 6 to 8 ms
6			1 to 5 PCMs are lost
7			Communication is lost

To complete the test description, the test criteria (What do we want to test?), metrics (How do we quantify the performance with respect to a test criterion?) and references (When is the test criterion met?) are listed in Table 2. For the references, parameters are used, such that is more convenient to change the actual values of these references if similar references are shared among different test cases.

Table 2 Test criteria, metrics and references to test V2V in a lead vehicle braking scenario in which Δ_{lon} is a safe minimum longitudinal distance and f_{com} is the known PCM communication frequency

Test criterion	Metric(s)	Reference(s)
Ego vehicle avoids collision with lead vehicle	1. Distance to lead vehicle 2. THW	1. $> \Delta_{\text{lon}}$ 2. $> \text{THW}_{\text{min}}$
Ego vehicle remains sufficiently close to the leading *truck*	THW	$< \text{THW}_{\text{max}}$
Ego vehicle communicates intended deceleration to *following truck*	Communication frequency	$= f_{\text{com}}$

Conclusion and Outlook

The example shows how a scenario translates into input to the automated driving system (ADS), by the sensor system, by V2V communication, and by the driver (for the leading truck, as well as by the safety driver in the other trucks in the platoon). The decision and control logic of the ADS on-board each vehicle in the platoon interprets the incoming signals and continuously provides a response. This response results in control of the actuators, the transmission of information across the platoon, and possibly information on an HMI to the driver. A scenario for a given truck in the platoon is described by indicating the intention of the truck (based on its role), the (dynamic) behaviour of the road users in the direct environment of the truck (which obviously includes the behaviour of the other truck(s) in the platoon whenever relevant) as monitored by the sensor system, the received information through V2V communication and the weather, lighting and communication triggering conditions. For the safety assessment of a truck in a platoon, this would lead to at least the following tests regarding V2V communication:

Communication system tests: tests, similar to sensor perception tests, where the basic functionality of the transmitter and receiver in each truck is tested. Are the correct messages transmitted at the intended points in time, in relation to the output to the actuators by the ADS? Such tests are not necessarily scenario-based, and consequently, these tests are out of scope for this paper.

Scenario-based tests: tests are conducted for each role of the truck in the platoon separately. Tests for different scenarios are provided, where the presence of V2V communication leads to additional variations as disturbances to a situation with ideally transmitted PCMs at the side of the receiver. The disturbances follow characteristic deteriorations of communication signals that are characterized in field tests, similar to the characterization of scenarios in field tests.

Both type of tests can be conducted in virtual simulation, in a hardware-in-the-loop environment and on a proving ground.

The methodology that is proposed and demonstrated in this paper, will be applied to the truck platooning use case as developed in the ENSEMBLE project [8]. Triggering conditions as well as levels of disturbances to PCM communication in the platoon's operational layer need to be observed and characterized in order to provide realistic and relevant communication tests. Before setting up testing equipment for testing on the proving ground, tests will be conducted in a hardware-in-the-loop (HiL) setup, to check feasibility of the proving ground tests. Moreover, HiL test will be conducted to determine which tests need to be repeated in real life on the proving ground.

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