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Research On Alternative Diversity Aspects foR Trucks

REPORT ON REQUIREMENT SPECIFICATION AND SYSTEM ARCHITECTURE CACC

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1 Introduction

1.1 Background

This document is the result of a deliverable for the ROADART project. This project aims to evaluate diversity techniques and antenna concepts in order to develop an in-vehicle platform for cooperative ITS systems for trucks and heavy duty vehicles in the Horizon 2020 call MG-3.5a-2014 “Cooperative ITS for safe, congestion-free and sustainable mobility.”

The ROADART project is defined by means of 9 work packages (WPs):
WP1 Requirements and Design
WP2 Channel Measurements, Characterization and Modelling
WP3 T2X Communication Techniques
WP4 Development of the ITS communication platform
WP5 Robust Cooperative Adaptive Cruise Control
WP6 Integration
WP7 Test, Demonstration and Evaluation
WP8 Dissemination and exploitation
WP9 Project Management

This deliverable is part of WP5: Robust Cooperative Adaptive Cruise Control.
The project and the objectives will be further explained in section 1.1.1 and 1.1.2.

1.1.1 The project

The main objective of ROADART is to investigate and optimise the integration of ITS communication units into trucks. Due to the size of a truck-trailer combination the architecture approaches investigated for passenger cars are not applicable. New architecture concepts have to be developed and evaluated in order to assure a sufficient Quality of Service (QoS) for trucks and heavy duty vehicles. An example of a specific use case is the platooning of several trucks driving close behind each other through tunnels with walls close to the antennas that support the communication systems. Due to the importance of tunnel safety, significant research effort is needed in order to check the behaviour of the antenna pattern, diversity algorithms and ray tracing models especially for trucks passing through tunnels. V2V and V2I systems specified from the C2C Communication Consortium are focussing on road safety applications. The ROADART project aims to demonstrate especially the road safety applications for T2T and T2I systems under critical conditions in a real environment, like tunnels and platooning of several trucks driving close behind each other. Besides that traffic flow optimization and therefore reducing Greenhouse Gas emissions are positive outcomes of the use cases demonstrated in this project. Demonstration and Evaluation of the use cases will be performed by simulation and by practical experiments on several levels. Besides evaluation on component and system level, the complete system will be evaluated in practice.

1.1.2 Objectives

The ROADART project aims to evaluate diversity techniques and antenna concepts in order to develop an in-vehicle platform for cooperative ITS systems for trucks and heavy duty vehicles in the Horizon 2020 call MG-3.5a-2014 “Cooperative ITS for safe, congestion-free and sustainable mobility.”

1.2 The objective of this deliverable

The objectives of WP5 are:

- To design and implement a safety framework for time-critical cooperative-driving applications, focussing on the application layer, in order to obtain robustness against wireless communication impairments, in particular packet loss and (time-varying) latency. To this end, Cooperative Adaptive Cruise Control (CACC) is chosen as the cooperative driving application of interest, being both time-critical and safety-critical.
- To design a CACC control system (on a simulation level) and to specify the implementation thereof on a truck, which serves as a test bench for experimental evaluation of the aforementioned safety framework, as well as for experimental evaluation of communication technology aspects as addressed in the other work packages.
- Investigation and evaluation of localization algorithms for the cases where the GNSS is not available (e.g. tunnels).
- To evaluate the theoretical results achieved on both the communication layer (WP3 and WP4) and the application layer by means of CACC.

To reach these objectives, several tasks are defined:

Task 5.1: CACC design (nominal functionality)

Task 5.2: Fault-tolerant cooperative driving

Task 5.3: Fail-safe cooperative driving

This deliverable aims to contribute to task 5.1 and describes the CACC requirements and architecture for the nominal functionality and for a set of safety aspects. The safety aspects which will be taken into account focus on communication impairments in combination with braking of the lead truck.

1.3 Structure of the document

The document is structured as follows.

First the nominal CACC system is explained in section 2, then safety with respect to wireless communication impairments is discussed in section 3. A literature review on the state of the art network induced imperfections and possible solutions is presented in section 4. The evaluation of the proposed controllers will be based on key performance indicators, which are proposed in section 5. The software architecture for the evaluation on simulation level and for the implementation in practise is proposed in section 6. Also the hardware architecture for the CACC application is described in this section. Finally, the conclusions are presented in section 7.

2 Nominal requirement specification of CACC

In this chapter the stakeholder and operational requirements for CACC will be introduced. Also the CACC objective will be presented. Further, the normal operational use of this system will be expressed in a step by step way. This chapter will assume nominal operation and will not yet focus on the safety challenges, which will be presented in the next chapter.

2.1 Stakeholder requirements

The stakeholder in the field of mobility, and related to the ROADART project are fleet owners, truck OEMs and government. The stakeholder requirements are:

- Fuel reduction, which directly leads to cost reduction
- Increase throughput, which leads to more efficient use of road capacity, thereby reducing traffic jams and thus loss-hours
- Safety, the above requirements should not lead to damage or danger to personnel.

A possible solution for the above requirements is the use of Cooperative Adaptive Cruise Control (CACC).

The benefits of CACC can be further exploited in combination with lateral vehicle automation, as shown in Figure 1. However, lateral vehicle automation is out of scope of this project.

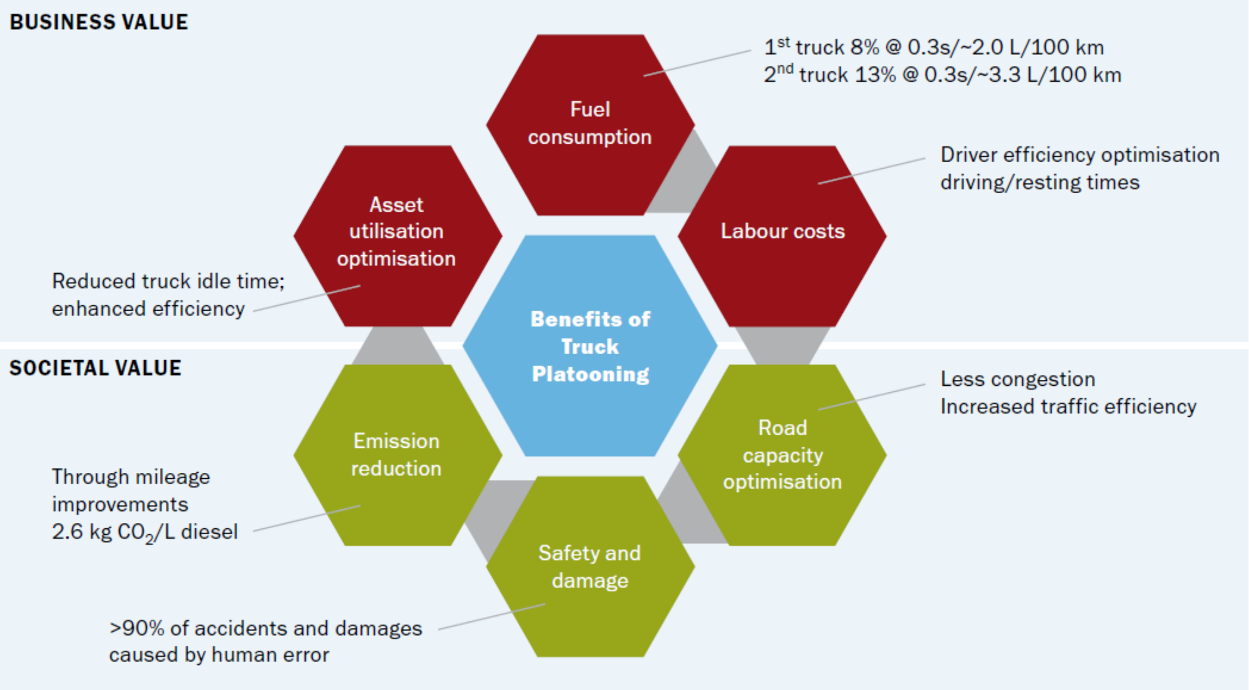


Figure 1: Benefits of platooning for business and societal values.

2.2 Operational requirements

The requirements for the environment are:

- Weather conditions must be good enough: no slippery road.
- Highway: e.g. A270
- Curvature > 125m (ISO ACC)
- There may be no cut in and emergency brake of the cut-in vehicle (such a situation would with a normal driver also lead to a collision).

2.3 Operational Concept Description

A truck will be equipped with longitudinal control. The desired time gap can be chosen by the user (via an HMI), but can never be lower than a minimum headway required for safety*. Also a cruise-speed is chosen by the user (via HMI). The system will not exceed this cruise-speed. In case there is no predecessor cruise control functionality is chosen, and the truck will aim for driving the defined cruise speed.

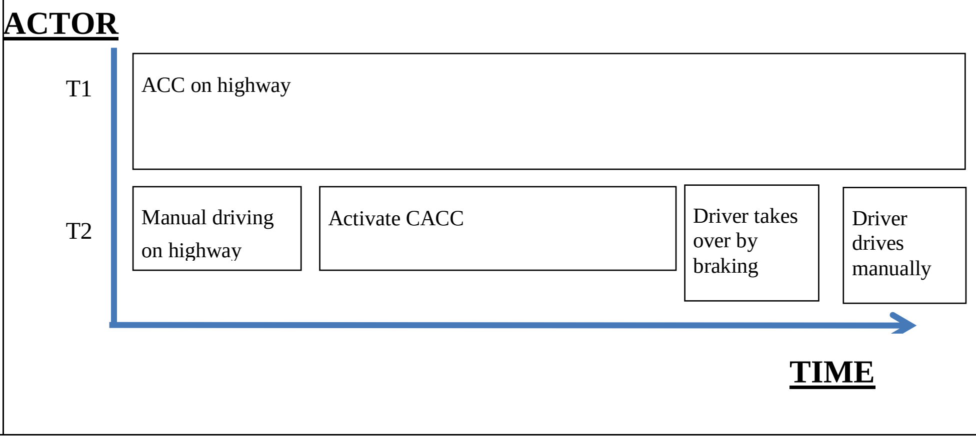
The driver must enable the system by pressing a button. He/she can take over the system (longitudinal control) in several ways; by braking or by pressing an emergency button.

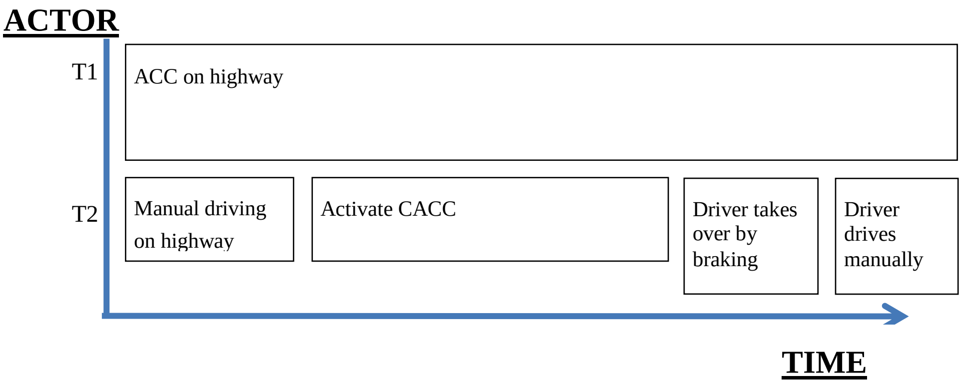
Step by step:

1. Driver starts the truck
2. Driver switches the system on
3. Driver sets the desired cruise speed and headway time.
4. Driver drives manually to the highway, following another communicating truck.
5. At the highway, the driver activates the CACC system at a distance of the communicating truck between approximately 10 – 50 m. There shall be no car in between these trucks.
6. The longitudinal control takes over, the driver only steers.
7. The system will be disabled by braking (after truck 1 confirms a safe traffic situation – no sudden brake actions to be expected). Now all control is back to the driver.
8. At the destination, the driver switches the system off, then shuts down the engine of the truck.

* depends on the state; all sensors/communication available, desired acceleration available,…

2.4 Operational Scenarios

ID	**UC_1**	
Name	**CACC on one lane on highway**	
Use case description	Automated truck follows other automated truck on the highway, on one lane, with a velocity of 80 km/h and in mixed traffic.	
Background attributes	Area type	Highway; A270
	Road segment	Detectable lane markings
	Environmental conditions	Weather is such that lane markings can be well detected by the on-board camera. Mixed traffic.
	Speed range	70-90 km/h
Participant 1 attributes (T1)	Type of participant	Truck which communicates its desired acceleration
	Start of position	Driving at the beginning of a highway (80 km/h)
	Manoeuvre	Manual driving and manual steering.
Participant 2 attributes (T2)	Type of participant	Truck equipped with (robust) CACC
	Start of position	Driving (between 15 to 200m) behind Automated truck 1.
	Manoeuvre	Follow truck 1 longitudinal on a headway time between 0.3s and 0.6s.
Sketch		
Sequence diagram		

ID	**UC_2**	
Name	**CACC on one lane in tunnel**	
Use case description	Automated truck follows other automated truck on the highway, on one lane, with a velocity of 80 km/h and in mixed traffic.	
Background attributes	Area type	Road which allows a velocity of 80 km/h, through a tunnel.
	Road segment	Detectable lane markings
	Environmental conditions	Tunnel of at least 400m, mixed traffic.
	Speed range	70-90 km/h
Participant 1 attributes (T1)	Type of participant	Truck which communicates its desired acceleration
	Start of position	Driving 80 km/h, 200m before the tunnel.
	Manoeuvre	Manual driving and manual steering.
Participant 2 attributes (T2)	Type of participant	Truck equipped with (robust) CACC
	Start of position	Driving (between 15 to 200m) behind Automated truck 1.
	Manoeuvre	Follow truck 1 longitudinal on a headway time between 0.3s and 0.6s.
Sketch		
Sequence diagram		

3 Safety

Fail-Safe and Fault Tolerant CACC

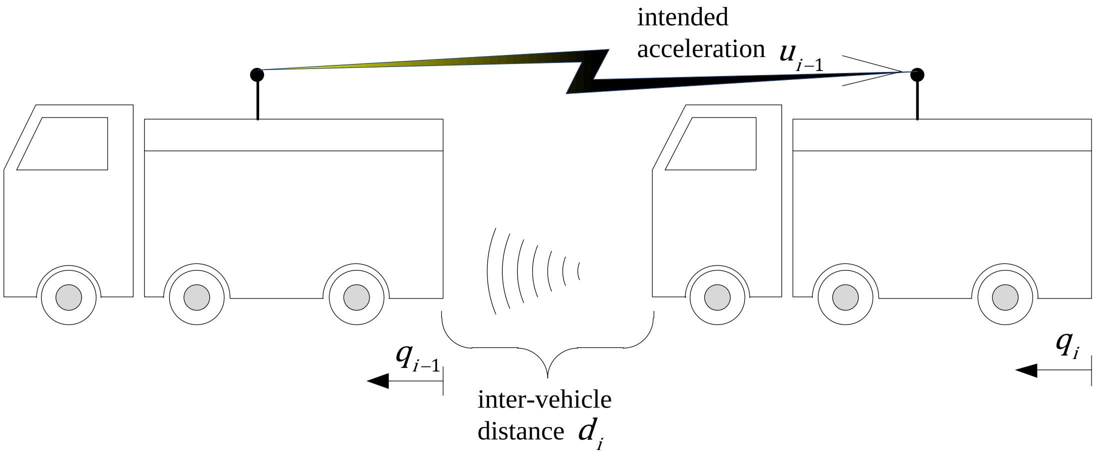
The quality of the wireless communication between the trucks has a direct effect on either the performance and/or the safety of the CACC operation. In the latter case, as explain below, the disruption of wireless communication becomes a safety hazard especially when combined with particular braking maneuvers by the leading truck.

There is a need for two separate strategies to cope with wireless communication problems:

- a strategy for safety-related scenarios: fail-safety; where the main aim is to prevent harm to personnel)
- a strategy for fault-tolerance (performance) , where the main aim is to maintain the functionality (CACC). With this strategy the system availability increases.

Safety related scenarios

Consider again the two-truck platooning framework shown below:



If the CACC controller is used to keep an inter-vehicle distance equal to the minimum headway for safety, then the wireless communication link becomes a single-point-of-failure safety hazard when combined with abrupt decelerations of the leading vehicle. More specifically, if during a period of lost communication, the leading vehicle performs a braking maneuver that reduces the inter-vehicle distance, d_i, below the minimum headway for safety before the following truck notices and reacts to it, then an accident may occur.

In order to ameliorate this hazard, assuming a packet-based communication protocol, the following trucks could implement the following (heuristic) strategy:

> If n consecutive communication packages are dropped consecutively, then disengage the CACC controller and perform collision avoidance.

In the context of safety, reconfiguration of the CACC controller is not necessary, since the goal is only to avoid collisions (control reconfiguration requires time, during which an accident can occur).

The specific value of n depends on several factors. For instance, it is a function of the minimum headway for safety, the current inter-vehicle distance, the current speed of both trucks, and the current leading truck's intended acceleration. The latter, when it is smooth enough, could be modeled on-line and predicted to replace the information in lost packets, increasing the value of n. A high value of n implies a less critical situation.

Once decided that the truck's state is no longer safe, collision avoidance is activated. The exact nature of the collision avoidance algorithm must be investigated.

Fault-tolerant scenarios

If the CACC controller is used to keep an inter-vehicle distance greater than the minimum required for safety, then the CACC controller can be adapted dynamically to cope with wireless communication problems. The latter are due to interference caused by, for example, an increased separation between trucks, a large number of communicating vehicles, an obstruction (i.e., another vehicle) between sender and receiver, or signal reflections in infrastructure (e.g., tunnels). These disruptions in turn lead to the following issues:

- Packet loss
- Time-varying delayed packet arrivals
- Out-of-order packet arrivals
- Packet duplications

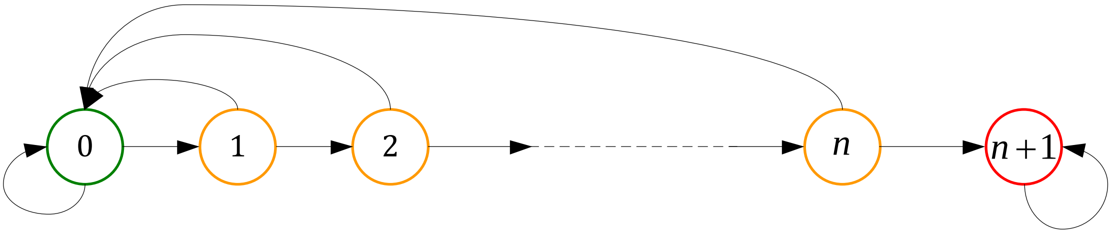
The use of adequate communication protocols can ameliorate most of these issues. For instance out-of-order packets can be re-ordered or just ignored, duplicates can be ignored, etc. From an automatic control perspective, the effect of these disruptions and correction mechanisms over the communication network can be characterized by two properties:

- Average packet latency: average time between the moment a packet is first transmitted and the moment when it is correctly received
- Packet loss rate: proportion of packets that are not correctly communicated

For the stated two-trucks scenario, the communication period (a communication frequency of 25 Hz leads to 40ms communication period) is comparatively large with respect to the inter-vehicle packet transmission time (about 2ms of transmission time plus some extra delay introduced by the communication electronics, but these are still in the same order of magnitude as the transmission time). Thus, packet latencies can be disregarded.

Packet loss, on the other hand, are more significant. The CACC design should aim for robustness against packet loss (and thereby still optimizing short following distances). In order to evaluate and design a CACC controller, models of packet loss are needed. Although this phenomena can be studied from a physical point of view using electromagnetic transmission models, it is generally simpler, and more appropriate for control purposes, to use phenomenological models. Such models describe the effects of the communication disruptions only, but not their underlying mechanisms.

As an example of such a phenomenological model, the packet arrival process at the following truck could be described with a Markov chain model that captures the statistics of the packet arrivals. Consider a situation in which communication packets could be lost in short bursts. Further suppose that a maximum of n consecutive packets can be tolerated before assuming the communication channel to be no longer functional. Since the following truck only checks its reception buffer periodically, say every T_r seconds, the packet reception process in the following truck could be represented by a discrete-time Markov chain, $\theta(l)$, with associated state diagram:



where $l = 0,1, \dots$ is the reception period counter, state “0” denotes “next packet in the sequence received”, state “i” with i$= 1, \dots, n$ denotes “i consecutive packets dropped”, and state “$n+1$” denotes that communication is assumed to be lost. (The transition probabilities are not shown in this diagram.) A particular sample path of this process is shown in the figure below.

The state of the Markov chain could then be used to determine the actions of the CACC controller. Based on the above state diagram, the controller could take one of 3 actions: nominal control ($\theta(l) = 0$), control plus data memory/forecast (to replace dropped data) ($\theta(l) = 1, \dots, n$), failed communication control ($\theta(l) = n + 1$).

This interaction between the Markov chain and the control system leads to a mathematical representation known as Markov jump systems (MJSs) that, in its more general form can be expressed as follows:

$$\begin{aligned} x_i(k+1) &= f_{\hat{q}(k)}(x_i(k), u_{i-1}(k), d_i(k)) \\ u_i(k) &= g_{\hat{q}(k)}(x_i(k)) \end{aligned},$$

Where $k = 0,1, \dots$ denotes the control system sample period counter (the sample period is denoted by T), $x_i(k)$ denotes the state of the (following truck’s) closed loop system (including the CACC controller), $u_{i-1}(k)$ is the leading truck’s intended acceleration at sample time kT, $d_i(k)$ is the inter-vehicle distance, $f_{\hat{\theta}(k)}$ and $g_{\hat{\theta}(k)}$ denote a family of state transition and output functions (one per state of $\hat{\theta}(k)$), and $\hat{\theta}(k) = \theta(l)$ for $k = lm, lm + 1, \dots, lm + m - 1$, where $m > 0$ is an integer such that $T_r = mT$ (that is, the reception period is an integer multiple of the control system sample period).

The derivation of the packet loss model will be based on experimental data. An example of 2 packet losses is presented in a sequence diagram in Figure 2. This could be one of the scenarios which will be investigated for fault-tolerance and fail-safety. These scenarios will be further specified in section 5.

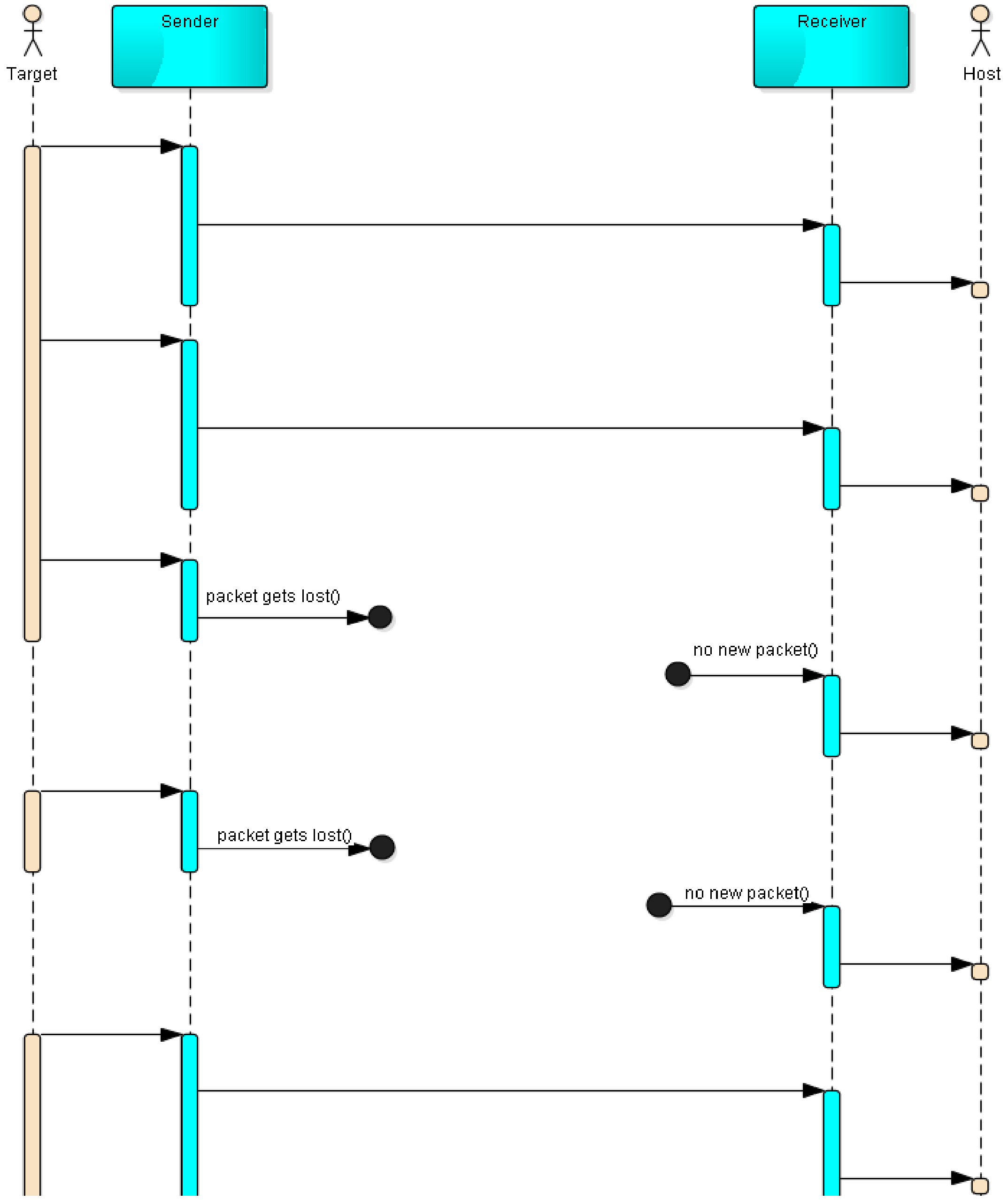


Figure 2: An example of 2 packet losses between target (lead truck; sender) and host (follower truck; receiver).

4 State-of-Art

The general objective of vehicular platooning can be summarized as packing the driving vehicles together as tightly as possible in order to achieve an increase in the traffic throughput, in addition to preventing amplification of disturbances throughout the vehicle string, the latter of which is known as string instability [1,2]. These are two conflicting objectives when conventional ACC is considered, since reducing inter-vehicle distances creates shockwaves which adversely affect the global traffic flow. Cooperative Adaptive Cruise Control (CACC) technology can overcome the drawbacks of ACC systems by making use of information exchange between vehicles (even with those which may be occluded from direct line of sight). Vehicle-to-Vehicle (V2V) wireless communication can therewith increase traffic flow by reducing inter-vehicle distances, improving the ride quality [3] and preventing amplifications of disturbances along the vehicle string.

A CACC system as illustrated in Figure 3 utilizes information exchange between vehicles through wireless communication besides local sensor measurements that are available in an ACC system. With this additional information, a CACC-equipped vehicle is able to react faster to the behaviour of the surrounding vehicles and, therewith, achieves a better synchronised traffic flow while avoiding string instability at smaller inter-vehicle distances. Besides the obvious increase in traffic throughput that is achieved by densely packing driving vehicles, another major benefit of CACC is the ability to attenuate the propagation of disturbances throughout the vehicle string. Such amplifications not only result in excessive acceleration/braking but also impair the traffic flow in general. Altogether, CACC is able to increase traffic flow, improve ride comfort, reduce travel times and achieve improved fuel economy.

The benefit in terms of fuel economy is especially apparent for heavy-duty trucks due to the fact that the aerodynamic drag of a truck is high due to the flat frontal surface. Therefore, close distance driving will result in a significant fuel reduction [4,5,6, 7]. Experimental results have shown that fuel reduction for both the follower and the leading truck can be achieved, respectively, as much as 20% and 6% [8]. In [9], the inter-vehicle distance between two heavy-duty trucks is varied between 3-10 m resulting in a fuel reduction of 10-12% for the following truck and a fuel reduction of 5-10% for the leading truck.

Recently, proof-of-concept demonstrations with CACC vehicles were performed with homogeneous vehicle strings [10] and also with heterogeneous vehicle strings in a multi-vendor setting [11, 12]. These implementations have shown the feasibility of CACC implementations and that significant improvements over existing ACC technology can be achieved already with relatively simple control algorithms and communication structures. However, given the safety-critical nature of the application, implementation for real traffic conditions requires consideration of the constraints imposed by the wireless communication needed to implement CACC.

On the one hand, control over a wireless communication network is the enabling technology that makes CACC realizable; on the other hand, very few studies consider the imperfections that are introduced by the network [13]. This is mainly due to the fact that systematic analysis and design tools for NCS arose relatively recently. In [13], a continuous-time transfer function based analysis of the effects of constant time delays on string stability was carried out. In [14,15,16,17], a Networked Control Systems (NCS) approach is adopted for the analysis of string stability properties of CACC systems which takes into account the effect of network-induced imperfections. In [14], a discretisation-based NCS modelling and analysis approach is adopted which also incorporates the effects of the sampling and the zero-order-hold in addition to constant wireless communication delays. These results have been extended in [16] with experiments. In [15], string stability conditions are provided on the uncertain and time-varying sampling/transmission intervals, delays, and scheduling constraints (requiring network protocols) induced by the wireless communication between vehicles. Another alternative of realizing robustness against wireless communications could be found in gracefull degradation means, of which a few approaches are presented in [18, 19]. A brief overview of research in the field of NCS, relevant in the scope of vehicular platooning, will be presented next.

Networked Control Systems

In the field of NCS, one considers the control of systems over a communication network. Communication and control over a shared network has received an increasing attention over the recent years, see e.g., the overview papers [20, 21, 22, 23]. Such control systems, in which the sensor data and control commands are transmitted over a wired or wireless network, are called Networked Control Systems (NCSs). A typical example of a network employed in the scope of control is the widely used Controller Area Network (CAN) in the automotive industry [24]. Compared to a traditional control system, which uses end-to-end wired connections between the sensors, actuators and controllers, NCSs make use of a shared medium to exchange information.

A particular benefit of employing wireless networks is avoiding the need for wired connections, which are infeasible in many situations including vehicular platooning applications for obvious reasons. However, the usage of (wireless) networked communication introduces new challenges related to the occurrence of time-varying sampling intervals, delays, and communication constraints. The impact of such network-induced effects on the control system requires a careful analysis and tradeoffs need to be made between control properties, such as stability and performance, and network-related properties such as delays, scheduling, bandwidth limitations etc. [25].

Network-induced Imperfections

The use of a communication network in the control loop makes the analysis and design of an NCS more complicated than a traditional (non-networked) control loop. Next to the presence of constraints and uncertainties, disturbances, and measurement noise, which already occur in traditional control loops, in NCSs, additional challenges arise that must be overcome before the advantages NCSs offer can be fully exploited. In particular, the design of an NCS has to deal with network-induced communication imperfections and constraints, which can be categorized into five types [25]:

i) Variable sampling/transmission intervals. If there is no synchronised clock for all nodes, the sampling/transmission intervals are uncertain and time varying. This phenomenon is also known as clock jitter in the literature [26].

ii) Variable transmission delays. In NCSs, transmission of data over a network takes a finite amount of time. Furthermore, if multiple nodes share a network, the network might be occupied for an uncertain period before the current nodes can send their data; this effect causes so-called contention delays. Therefore, the transmission delays are often uncertain and time varying.

iii) Communication constraints. NCSs have multiple sensors and actuators, which are grouped into nodes which all communicate over a shared network. Due to a shared communication medium, it is not possible that all these nodes transmit their data simultaneously. Therefore, a scheduling protocol is needed which orchestrates access of these nodes to the network for transmitting their data.

iv) Packet dropouts. Another difference between NCSs and a traditional plant-controller setup (in which end-to-end communication is employed) is the occurrence of packet dropouts, i.e., the possibility that data is lost during transmissions. Packet dropouts can result from collisions, unreliability of the network channel or congestion.

v) Sampling effects. In any practical implementation, the control system is implemented in a digital environment and can only transmit data that are digitized by using sampling.

The RoadArt project aims to:

- Investigate tradeoffs between wireless network specifications and headway policies in terms of their influence on string stability and safety.
- To demonstrate the validity of the analysis results by real experiments with Cooperative Adaptive Cruise Controller (CACC)-equipped trucks.

Network-aware string stability and safety analysis: The network-aware CACC model will be extended with analysis tools for string stability and safety in the presence of network effects. These analyses can provide the designer with guidelines for making multidisciplinary tradeoffs between control and network specifications and support the design of CACC systems that are robust to uncertainties introduced by wireless communication. Using these analysis tools, the dependency of string stability and safety on network-induced effects will be studied.

Experimental validation/demonstration: Moreover, the validity of the presented analysis framework will be inspected via experiments performed with CACC-equipped prototype vehicles in a homogeneous string.

Modelling CACC as a Networked Control System:

The interconnection between two trucks that operate within a CACC platoon is depicted in Figure 3Fig. X

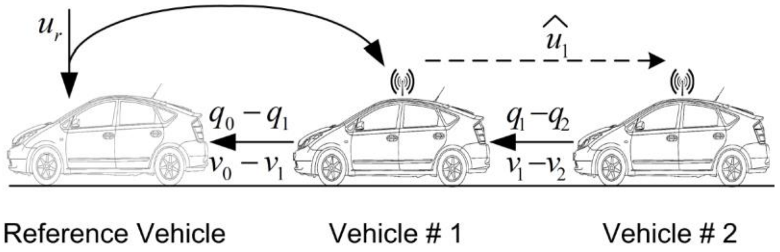


Figure 3: Schematic representation of CACC vehicle string.

In this platoon, the longitudinal dynamics of each truck (with index *i*) in the platoon together with its dynamic coupling to its predecessor can be expressed in the following form:

$$\dot{x}_i = A_{i,i}x_i + A_{i,i-1}x_{i-1} + \underbrace{B_{s,i}u_i}_{ACC} + \underbrace{B_{c,i}\hat{u}_{i-1}}_{CACC},$$
$$u_i = K_{i,i}x_i + K_{i,i-1}x_{i-1}$$

Where x_i represents the longitudinal vehicle dynamics states, $A_{i,j}$ describes the interconnection between the vehicle states i and j respectively. $B_{s,i}$ is the input vector corresponding to the ACC control input (u_i) to vehicle i and $B_{c,i}$, is the input vector for the additional CACC input ($\hat{u}_{i-1}$), which is sent to the i-th vehicle through the wireless network and is therefore subject to network effects. Further, $K_{i,j}$ represents the control law. For further details on a possible control choice the reader is referred to [14-17].

In this model, the control inputs for ACC and CACC functionality are written separately. This separation allows us to inspect the effects of these control inputs arising from different sensor sets (i.e. local and transmitted via V2V).

CACC NCS Model:

The model for a two-vehicle platoon as depicted in Figure 3 with a reference vehicle (i=0) can be written by using (XX) for *i=1,2* as:

$$\begin{aligned} \dot{x}_0 &= A_0 x_0 + B_{s,r} u_r \,, \\ \dot{x}_1 &= A_{1,1} x_1 + A_{1,0} x_0 + B_{s,1} u_1 + B_{c,1} u_r \,, \\ \dot{x}_2 &= A_{2,2} x_1 + A_{2,1} x_0 + B_{s,2} u_2 + B_{c,2} \hat{u}_1 \,, \end{aligned}$$

Next, by collecting all vehicle states as $\bar{x} = [x_0^T \; x_1^T \; x_2^T]^T$, this platoon model can be written in a compact form where the underlying ACC coupling and CACC dynamic coupling are separated

$$\begin{aligned} \dot{\bar{x}} &= (\bar{A} + \bar{B}_s \bar{K})\bar{x} + \bar{B}_c \hat{\bar{u}} + B_r u_r, \\ &= A^{ACC} \bar{x} + \bar{B}_c \hat{\bar{u}} + B_r u_r \end{aligned}$$

The control structure block diagram schematic representation of the interconnection of such a platoon can be seen in the NCS model as shown in Fig. 4.

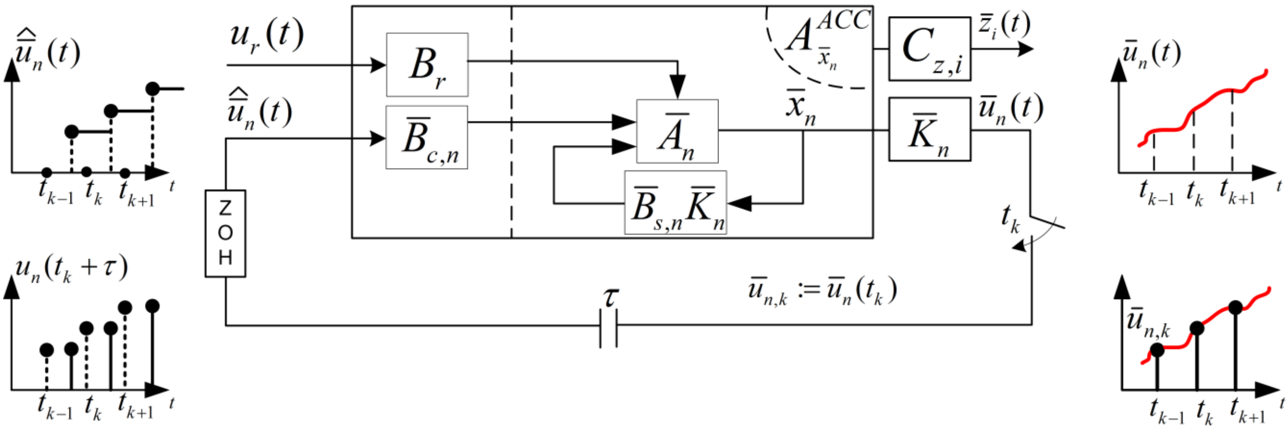


Figure 4: NCS modelling of the C-ACC interconnected platoon.

In Figure 4, the effects of the nature of wireless communication is shown. The wirelessly transmitted CACC input ($\bar{u}_n$(t)) is subject to:

- Sampling with interval (t_k): $\bar{u}_{n,k} \coloneqq \bar{u}_n(t_k)$,
- Transmission delays (τ),
- Zero Order Hold implementation at the receiving side.

Such a model is used in [14-17] show the effects of wireless communication impairments on string stability. String stability although a good measure for safety, is not by itself sufficient. For this reason, this modelling approach will be extended to include safety measures, such as the inter-vehicle distance, as a result of wireless communication losses and we will focus on the analysis of such impairments from a safety perspective.

5 Key performance indicators

This chapter aims to specify the control objectives by means of key performance indicators. Satisfying the key performance indicators may require the use of different controllers for different operating conditions. The problem formulation will summarize the goal of the different controllers. The key performance indicators will be determined based on a simulation study which evaluates a large set of test cases, which is also shortly described below.

Problem formulation

To summarize, this work package aims for:

1. Controller design for operational wireless situation (no packet loss, i.e. nominal scenario)
2. Controller design for wireless communication with packet loss (fault tolerant scenario)
3. Collision avoidance controller design (fail-safety scenario)

Possibly, these controllers can be combined into one or two controllers (e.g. with different settings).

Key Performance Indicators

The key performance indicators which will be used to evaluate the controllers are split into three categories:

- i. Safety:
    - a. The amount of test cases (described below) which would lead to a collision. This should be as low as possible.
    - b. The impact velocity in case a collision would occur. This could be a tuning parameter, which e.g. determines the minimum time gap.
- ii. Stability:
    - a. For controllers 1 and 2: String stability margin: number of vehicles for which the controller is still stable, as defined in [27].
    - b. For all controllers: internal stability.
    - c. Switching behaviour between controllers 1 and 2 should not lead to instability.
- iii. System availability:
    - a. For controllers 1 and 2: Fault Tolerant (FT)-time: the maximum duration of a wireless failure for which the system can avoid a collision (assuming a given set of acceptable braking patterns by the leading vehicle) and still maintains the following functionality.
    - b. The amount of test cases (described below) which the controllers (1 and 2) can handle without a collision.
    - c. The minimum acceleration over time of the host truck, to evaluate “false-positive” behaviour, i.e. severe braking in case this is not needed to avoid a collision. This aspect aims to favor less conservative controllers.

This evaluation will be based on a simulation study.

Simulation study

To evaluate the KPIs a large set of test cases needs to be defined. Therefore, a simulation setup is required. The simulation model will consist of the following components:

- Two truck models; only the longitudinal behaviour will be investigated. Although it is expected that both trucks are similar, there may be some slight variations in parameters (such as the actuator delay, time constant, or minimum acceleration). These variations will be taken into account as well.
- Controllers as mentioned above.
- Communication model as described in section 3.

- Simple sensor models which are required as input for the controllers (such as velocity, range, range rate, etc).

The simulation model will be implemented in Matlab Simulink such that the software can later on be easily compiled on a real-time platform in a truck.

The simulation study will focus on the following inputs, which defines the total set of test cases:

1. Variable sampling/transmission intervals $t_k - t_{k-1}$:
$$0 < t_k - t_{k-1} < \Delta t$$
    a. In which Δt represents the sample time of the receiving and sending communication units. For the simulation study a limited number of test cases within this interval will be chosen.
2. Packet loss:
As defined in Figure 4 and in section 3, a model for packet loss will be derived from experimental data.
3. Lead truck acceleration profiles: several profiles will be chosen, from worst-case braking action to no braking at all (to investigate “false-positive” behavior).
4. Timing of the braking action of the lead truck. The timing with respect to packet loss can lead to different situations.

The simulation will then derive the following parameters which identify the key performance indicators:

i. Safety:
    a. Inter-vehicle distance, to derive whether or not there will be a collision.
    b. Impact velocity, in case a collision would occur.
ii. Stability:
    a. For similar truck models, the number of trucks for which the control error does not amplify over the string of vehicles.
    b. For each controller: external perturbation should not lead to an amplification of control errors.
iii. System availability:
    a. FT-time: the maximum duration of a wireless failure for which the system can avoid a collision and still maintain the following functionality.
    b. The amount of test cases for which the controllers (1 and 2) can handle the situation without a collision.
    c. the minimum acceleration of the following truck,

6 Architecture

6.1 Software architecture

The software used in this work package serves two goals:

1. To evaluate the controllers on simulation level for fault-tolerance and fail-safety, based on KPIs described in section 5.
2. To be used for the real-time implementation on a truck for evaluation in practise.

The software will be written in MATLAB Simulink and the architecture will be chosen such that the above mentioned goals can be easily combined.

For the first goal the architecture presented in Figure 5 will be used. Here, the RT Control system will be equal to the software which is used for the real-time implementation in practise (second goal). Further, a simulation model of a vehicle is required, simple sensor models and a packet loss model.

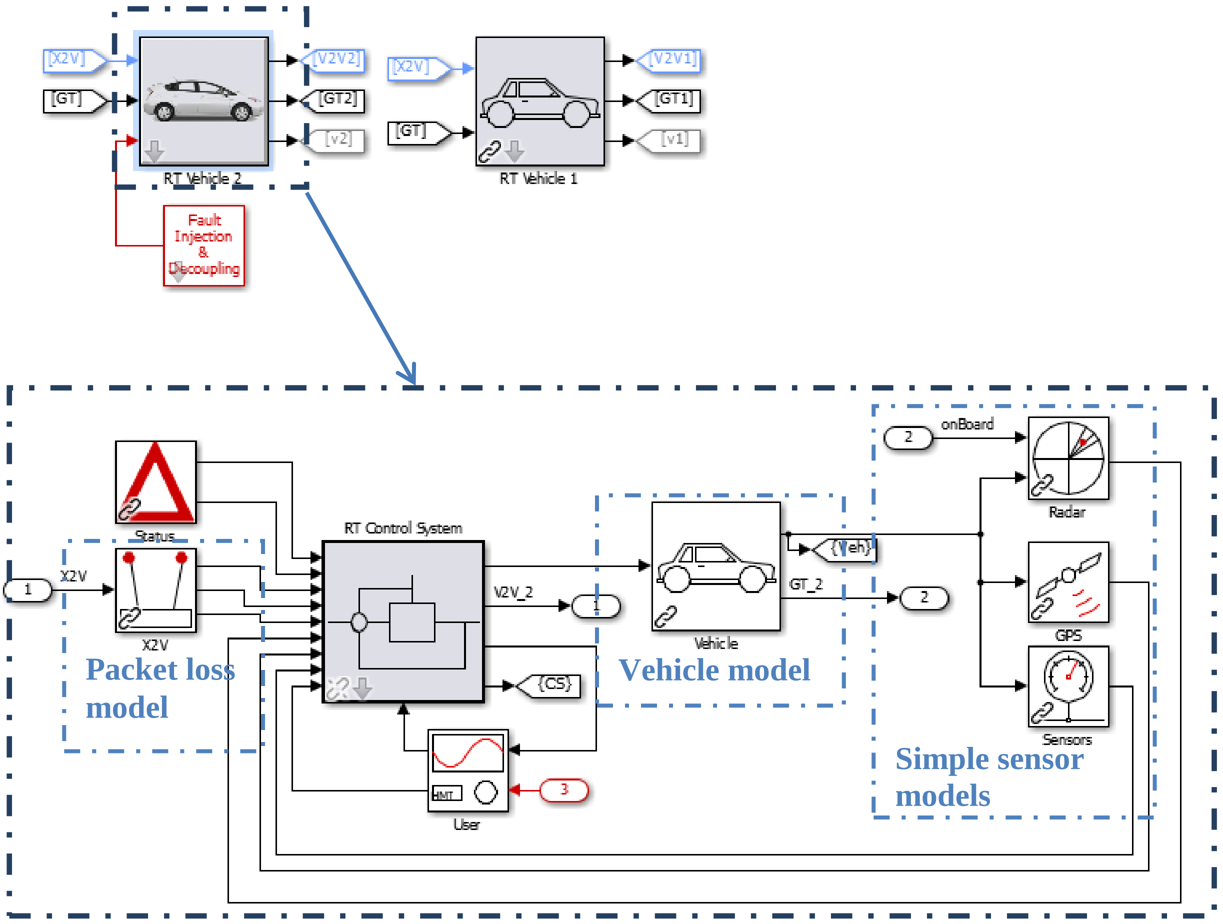


Figure 5: Software architecture which will be used to evaluate the RT Control system.

The functions required for the RT Control System are:

- Target tracking, fuses the on-board measurements of the radar with the communicated message. The target tracking provides the states of the target, which are defined as: distance, range rate, (absolute) acceleration, intended (absolute) acceleration.
- Host tracking, to determine the host global position, which is used to improve the GPS positions. This improved position will be broadcasted. Also, the global host position is required to calculate the relative position of the communicated message of the target, such that this message can be fused with the on-board measurements (in the target tracking algorithm).
- Control, (including nominal, fault-tolerant and fail-safety), there are possibly more types of controllers, these will be implemented in the control-block.
- Supervisor, the main task of the supervisor is to decide on which controller should be active and which settings should be used for the controller. Here, safety measures might be needed for evaluating the criticality of a situation.

The relations between these functions are shown in Figure 6.

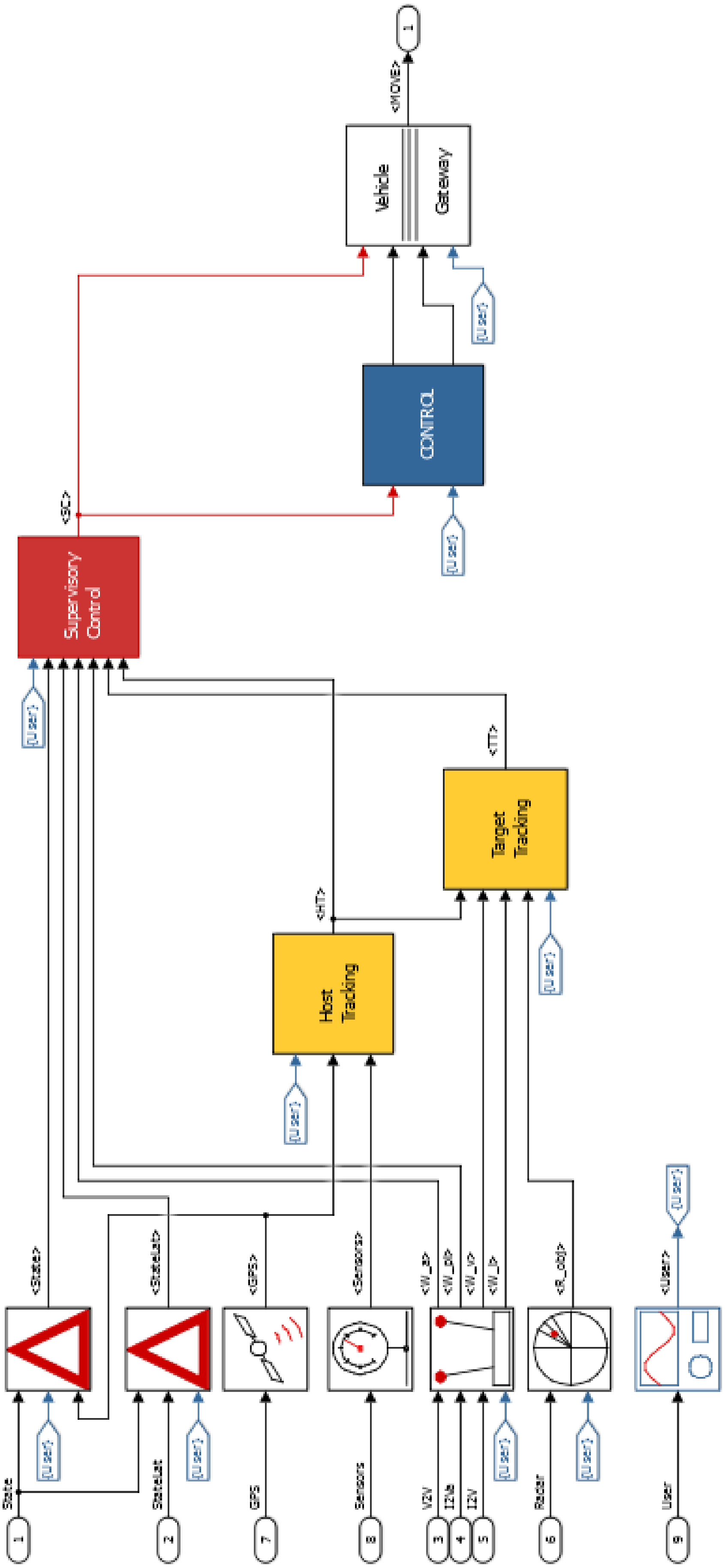


Figure 6: Software architecture for RT Control System

6.2 Physical architecture

The physical components are summarized in Figure 7 and explained in this section. The physical architecture will be the same for two similar trucks. The required hardware components for the RT Control system are:

- High-level control computer: dSPACE Autobox
- Low-level control computer: dSPACE AutoBox (possibly this will be the same dSPACE as used for the high-level control).
- Communication Unit: ITS G5 gateway and antennae, which will be the main focus of work packages 2, 3 and 4.
- HMI platform, to activate and de-activate the controller and monitor the state of the controller and communication.
- On-board sensors:
    - Radar: The follower truck must be able to detect AT1 for the given curvature with sufficient accuracy, which should be in the order of magnitude:
        - Accuracy for longitudinal position measurement: σ=0.2m
        - Accuracy for longitudinal range rate measurement σ=0.1m/s
        - The latency of the radar should be as low as possible.

      This radar may be combined with a camera.
    - GPS: there are two possible GPS receivers which can be used: uBlox (1Hz) or CAEMAX GPSVarioPro, which sends directly on CAN at 10Hz.
    - Vehicle dynamics sensors (wheel speed encoders, accelerometer, gyro, steer angle) These signals will be gated via CAN.
- Laptop, to build the realtime software, to log signals, etc.
- Power supply to supply all the above mentioned systems of power.
- Interface to the driveline via CAN.

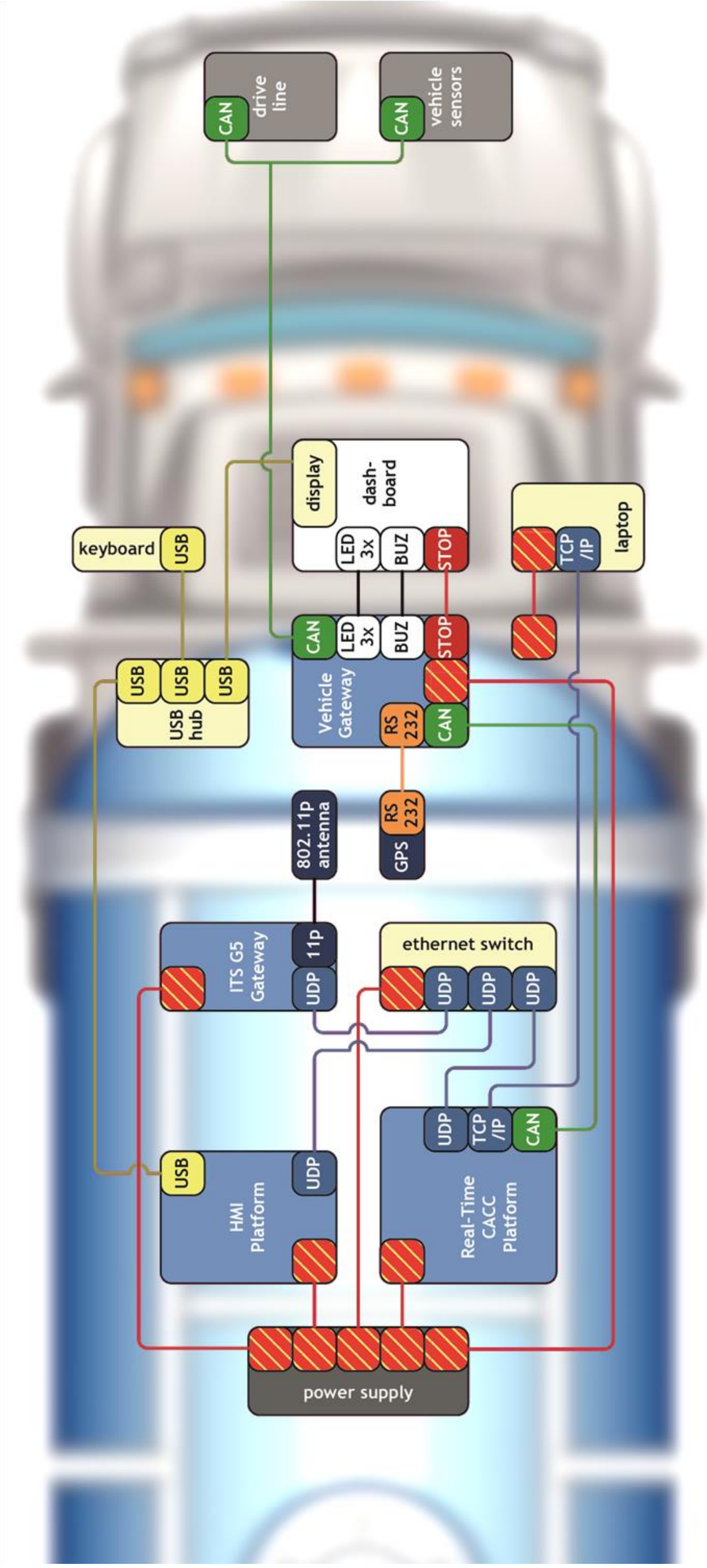


Figure 7: Physical architecture of the truck equipped with the RT Control System.

7 Conclusions

The objective of this deliverable was to describe the CACC requirements and architecture for the nominal functionality and for a set of safety aspects. The safety aspects which will be taken into account focus on communication impairments in combination with braking of the lead truck.

The stakeholder in the field of mobility, and related to the ROADART project are fleet owners, truck OEMs and government. The main stakeholder requirements are fuel efficiency and safety. Fuel efficiency is highest when the inter-vehicle following distance is as small as possible. To reach a short inter-vehicle distance, wireless communication is required to obtain the intended (desired) acceleration of the preceding truck. This nominal CACC behaviour, where wireless communication is available, is presented by means of use cases. When there’s no wireless information available, the minimum distance required to guarantee safety in the case of a braking action initiated by the lead truck is much higher than the nominal operating situation. So, in case a wireless failure occurs, a hazardous situation exists.

Safety aspects with respect to wireless communication impairments are further discussed. The main focus of work package 5 of the ROADART project are threats caused by packet losses. Fail-safety is required to avoid harm to personnel (e.g. by collision avoidance), fault-tolerance is required to maintain system functionality and thereby increase the system availability.

So, three types of controllers could be defined:

1. Controller for operational wireless situation (nominal)
2. Controller for non-operating wireless situation (fault tolerance)
3. Collision avoidance controller (fail-safety)

Possibly, these controllers can be combined into one or two controllers (e.g. with different settings).

To specify the aim of these controllers further and to enable an evaluation, key performance indicators are introduced. These key performance indicators are related to:

1. Safety
2. Stability
3. Availability

To evaluate the key performance indicators, a simulation setup is proposed which includes a vehicle model, a packet loss model and the controller set (RT Control system) including the required functions such as a supervisor, host and target tracking. This RT Control system should be defined such that it can be implemented real-time in a truck.

The software and hardware architecture are agreed upon with the partners in the consortium and are described in section 6.

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