SHared automation Operating models for Worldwide adoption

SHOW

Grant Agreement Number: 875530

Insight Article of FEV:
Optimized energy consumption through collaborative driving maneuvers

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under Grant Agreement number 875530

Legal Disclaimer

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Abbreviation List

Abbreviation	Definition
5GAA	5G Automotive Association
ACC	Adaptive Cruise Control
ATC	Aldenhoven Testing Center
BTP	Basic Transport Protocol
CA	Authority Certificate
C-CACC	Centralized Cooperative Adaptive Cruise Control
C-ITS	Cooperative Intelligent Transport Systems
CLM	Cooperative Lane Merge
CMP	Cooperative Maneuver Protocol
CSRF	Cross site request forgery
EEBL	Emergency Electronic Brake Lights
EM	Electric machine
FV	Following Vehicles
GPS	Global Positioning System
HLW	Headlights Warning
HMI	Human-Machine Interface
IP	Internet Protocol
LCMM	Low Carbon Mobility Management (T-Systems app)
MABX	Micro-Autobox
MK5	Cohda wireless V2X CU Module
ML	Maneuver Leader
MPC	Model Predictive Control
MQTT	MQ Telemetry Transport
MV	Merge-in Vehicle
PL	Platoon Lead
SAE	Society of Automotive Engineers
SAP	Service Access Point
SiL	Software in the Loop
TCP	Transmission Control Protocol
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-X (X represents any entity capable of receiving C-ITS communications)

1 SHOW insights: Optimized energy consumption through collaborative driving manoeuvres

Within the SHOW project, FEV is engaged in the development and testing of a predictive and cooperative driving function that incorporates an optimization-based longitudinal vehicle following strategy and merge-in manoeuvre management. Realistic traffic simulations are employed to evaluate the effectiveness of these predictive and cooperative driving functions in terms of energy-saving potential. In specific urban traffic scenarios, it has been determined that the implementation of these functions can result in an energy-saving potential of 21%.

1.1 Centralized Cooperative Adaptive Cruise Control

To enable the holistic coordination of interconnected vehicles, a method is developed to optimize multiple vehicle velocity trajectories within a single control problem. The primary objective of this method is to reduce the overall energy consumption for vehicle propulsion. To achieve this, a centralized cooperative driving function, known as Centralized Cooperative Adaptive Cruise Control (C-CACC), as developed by Klingbeil et al., is initially tested using a scenario involving the platooning of vehicles on the same lane (Figure 1). [1]

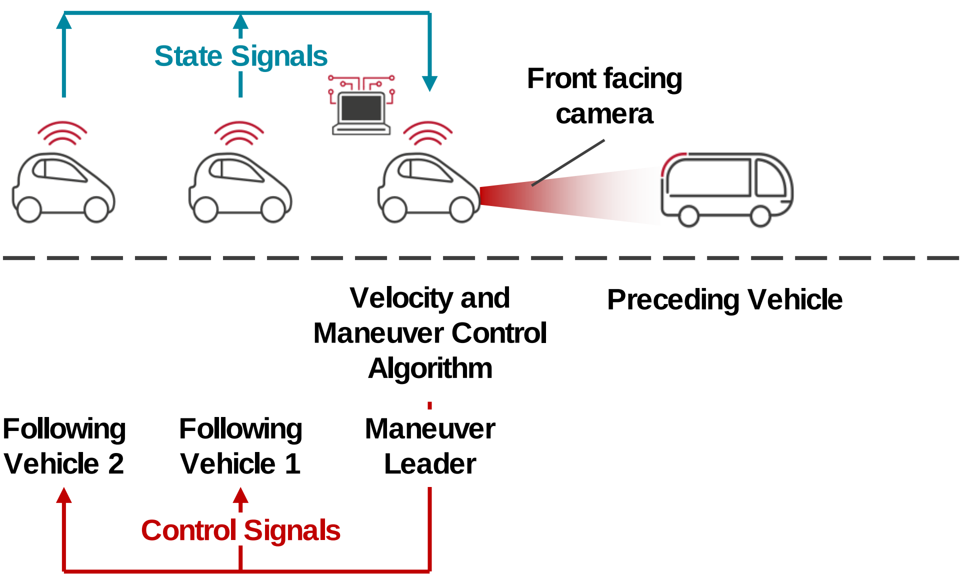

Figure 1: A schematic representation of a centralized platoon control system

Unlike conventional platooning of trucks, which often prioritize aerodynamic advantages through close following, the centralized platooning control in urban areas pursues a different objective. Here, the goal is to optimize the velocity trajectories of all participating platoon vehicles, reducing unnecessary acceleration and deceleration to minimize the overall energy consumption. For this purpose, a linear model predictive control (MPC) algorithm is employed to formulate and solve the optimal control problem.

A comparative analysis was conducted to analyse the potential energy savings between the C-CACC and a state-of-the-art adaptive cruise control (ACC) in an urban setting. The study involved a simulation where a platoon consisting of one manoeuvre leader (ML) and four following vehicles (FV1-4) following a

preceding vehicle (bus) with a predefined velocity profile encompassing urban and suburban areas. The speed limits in these areas were set at 50 km/h and 70 km/h, respectively. To evaluate the energy consumption, a battery electric vehicle plant model was employed. In the reference simulation, all vehicles utilized a state-of-the-art ACC algorithm. The simulation results revealed a significant difference in the velocity profile and electrical motor (EM) power between C-CACC and ACC.

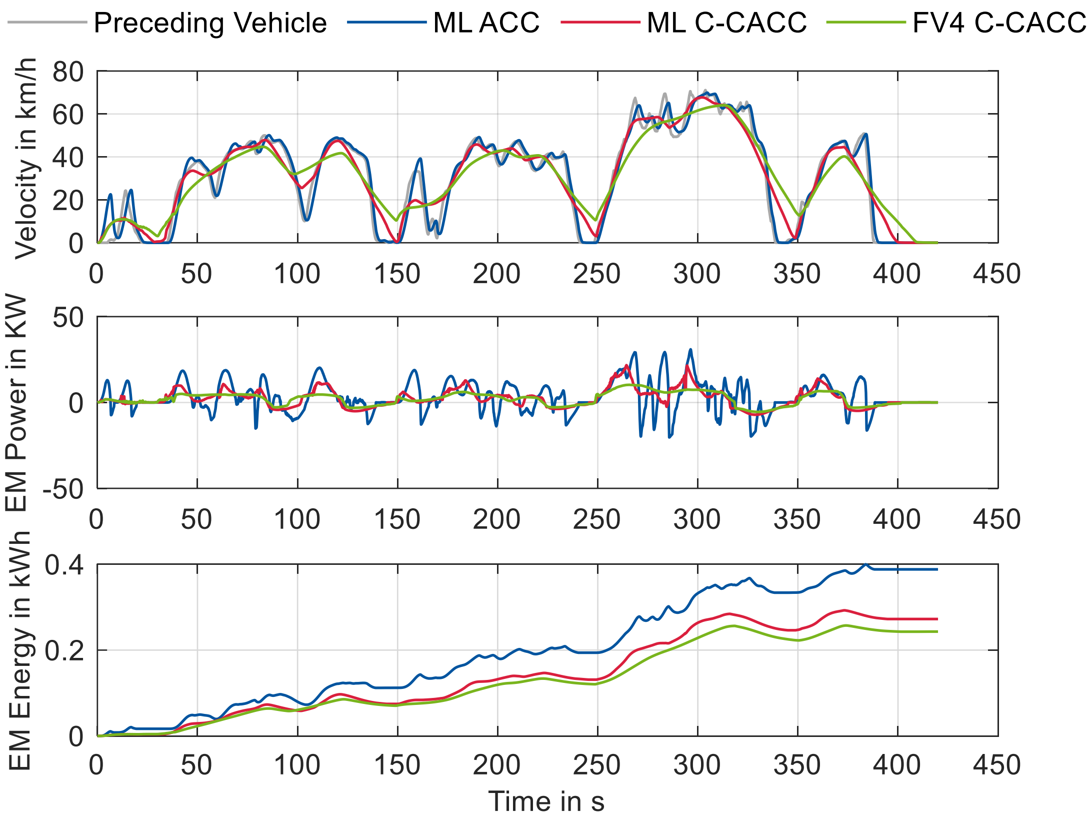

Figure 2: Simulation results of vehicle velocities, EM-power and energy, comparing ML equipped with ACC and C-CACC and FV4 with C-CACC

By comparing the velocity and EM power profiles of the ML using both C-CACC and ACC, it becomes evident that the amplitude of these profiles is lower with C-CACC compared to ACC. This indicates that C-CACC effectively reduces unnecessary acceleration and deceleration, even in scenarios where the preceding vehicle (bus) frequently changes its velocity. As a result, the total energy demand for traction is reduced, leading to an energy-saving potential of 29% (as shown inTable 1).

Another aspect of the energy-saving potential can be observed by comparing the simulation results of the ML and the FV4, both utilizing C-CACC. FV4 exhibits lower deceleration, occurring earlier than that of the ML, which eliminates any standstill phases for FV4 during the simulation with the selected driving profile. The amplitude of the velocity profile for FV4 is even smaller than that of the ML, consequently affecting the overall EM energy consumption. A comparative analysis indicates an energy-saving potential of 11% when comparing FV4 to the ML.

	Test with ACC	Test With C-CACC (ML)	Test With C-CACC (FV4)	Energy Saving Potential (ML C-CACC vs. ACC)	Energy Saving Potential (FV4 vs. ML)
Traction Energy Consumption	13.70 kWh /100 km	9.63 kWh/100 km	8.56 kWh/100 km	29 %	11 %

Table 1: Comparison of traction energy consumption of ML with ACC and C-CACC and FV4 with C-CACC

To validate the simulation results in real-world conditions, FEV implemented the C-CACC algorithm in a demonstrator vehicle equipped with a Micro-Autobox (MABX) as a prototype controller. This integration involved incorporating the C-CACC algorithm solely for the ML into the vehicle's control system. Figure 3 illustrates the schematic representation of the software integration of the C-CACC algorithm within the vehicle.

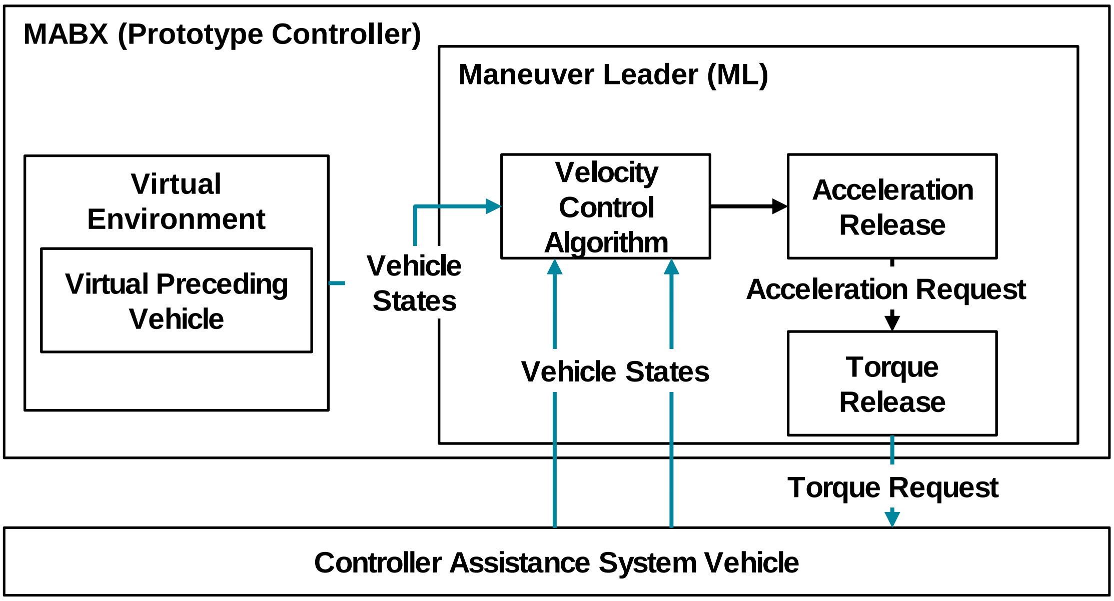

Figure 3: A schematic representation of a software integration of C-CACC algorithm in vehicle

In a virtual environment, the velocity and position of the preceding vehicle (bus) are determined based on the predefined velocity profile, similar to the simulation. These preceding vehicle (bus) states are then transmitted to the velocity control algorithm (C-CACC) implemented in the ML. Additionally, the real-time vehicle states of the ML, such as its current velocity and acceleration, are also fed into the velocity control algorithm through the vehicle controller assistance system.

Using the optimization results obtained from the C-CACC algorithm, the acceleration profile of the ML is calculated. Based on this acceleration profile, the corresponding torque request is generated and transmitted to the vehicle controller assistance system. The vehicle controller assistance system then utilizes this torque request to facilitate the actual vehicle movement and propulsion, enabling the ML to move forward according to the desired velocity and acceleration determined by the C-CACC algorithm.

The real vehicle test was carried out at the Aldenhoven Testing Center (ATC), during which measurements of the actual DC Link voltage and current were taken. Like the simulation setup, the velocity profile, EM power, and energy consumption of the ML using both ACC and CACC were plotted in Figure 4.

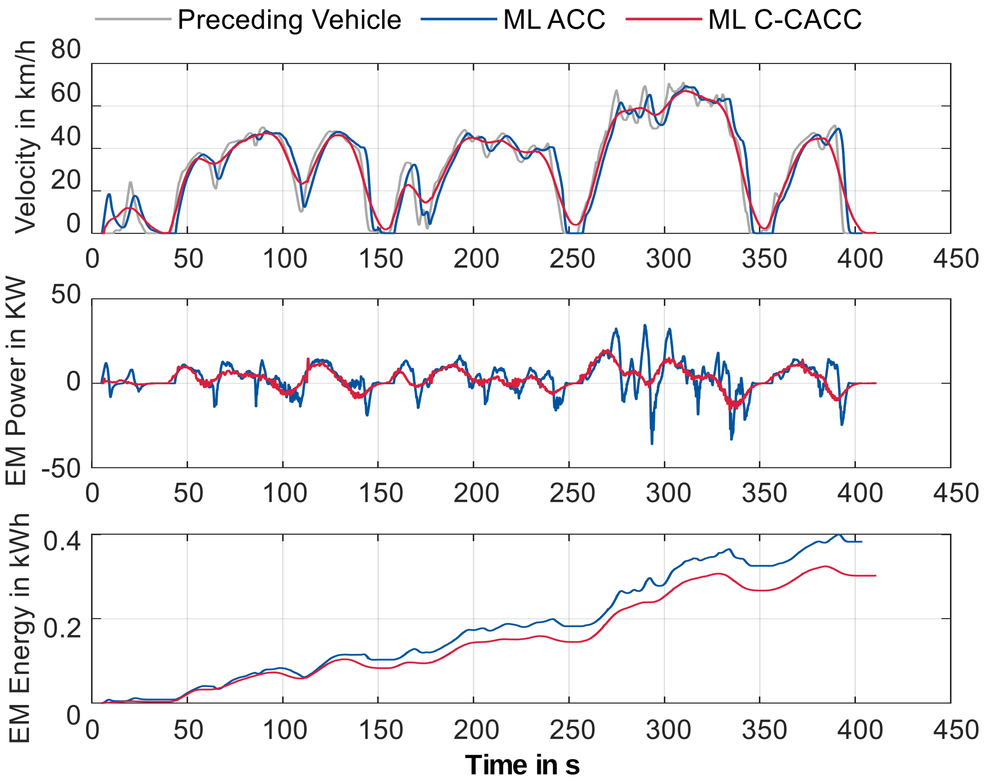

Figure 4: Vehicle test results of vehicle velocities, EM-power and energy, comparing ML equipped with ACC and C-CACC

Similar to the simulation results, the amplitude of the velocity and EM power profiles of the ML using C-CACC is lower when compared to ACC. This reduction in amplitude leads to a decrease in traction energy consumption. Table 2 presents the traction energy consumption of the ML using both ACC and C-CACC. The ML using ACC exhibits a traction energy consumption of 10.7 kWh/100 km, whereas the ML using C-CACC achieved a lower traction energy consumption of 8.4 kWh/100 km. This indicates an energy-saving potential of 21% during the real vehicle test with the predefined velocity profile of the preceding vehicle (bus). During real vehicle tests, drivability and comfort was evaluated by different passengers. With reduced acceleration and deceleration, the driving experience could be improved with C-CACC in comparison to ACC only. The driving experience leads to a much more pleasant and smoother behavior and a higher level of acceptance.

	Test with ACC	Test With C-CACC	Energy Saving Potential (ML C-CACC vs. ACC)
Traction Energy Consumption	10.7 kWh /100 km	8.4 kWh/100 km	21 %

Table 2: Comparison of traction energy consumption of ML with ACC and C-CACC

It can be observed that the energy-saving potential differs between simulation and real vehicle testing. This discrepancy is attributed to the differences in vehicle parameter settings between the vehicle model used in the simulation and the actual vehicle. The vehicle model has also different behaviors compared to a real vehicle, leading to variations in the energy-saving potential.

In urban traffic environments, driving scenarios can become more complex due to factors such as varying driving destinations, different driving behaviors, and interactions between passenger cars and public transportation, such as buses. These situations often involve various types of maneuvers, including joining, merging in, and merging out. In the context of the SHOW project, FEV specifically focused on the merging manoeuvre, as represented by the merge-in vehicle in Figure 5.

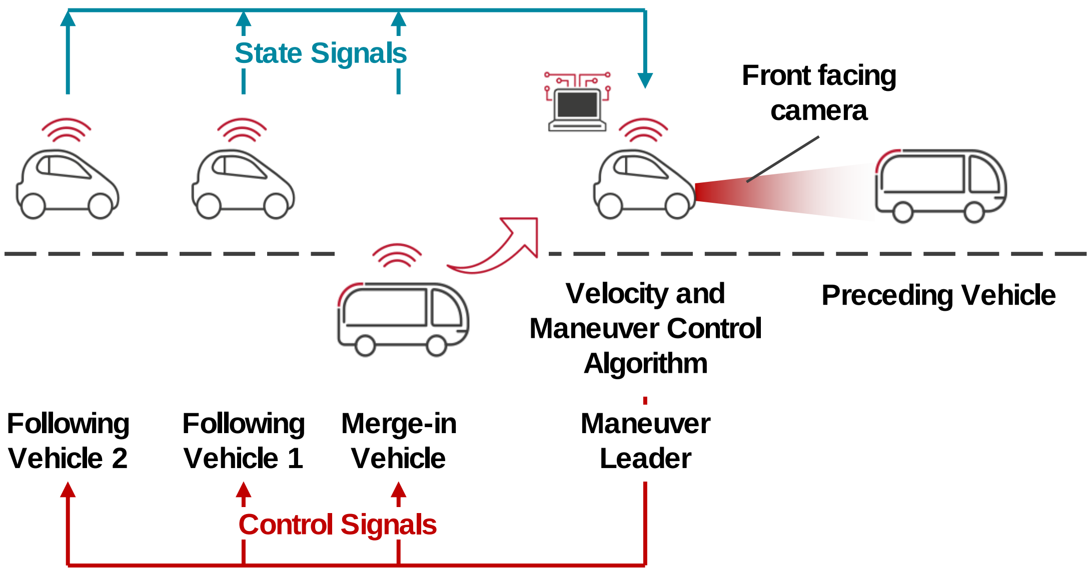

Figure 5: A schematic representation of a centralized platoon control system with merge-in vehicle

If a merge-in vehicle (MV), such as a bus, departs from a bus station and intends to merge into a platoon, it can send a merge request to the ML using V2V communication. Upon receiving this merge request, the manoeuvre controller

algorithm in the ML is activated. The manoeuvre controller then utilizes optimization-based calculations to determine an energy-optimized merging position for the MV. Simultaneously, the ML takes over the velocity control of the MV. Once a sufficient gap between two vehicles is detected, providing enough space for the MV to merge in while maintaining a safe distance, the ML sends a merge enable signal to the MV. Upon receiving this signal, the MV is authorized to perform the lane change and execute the merging manoeuvre.

To facilitate testing in real vehicles, FEV demonstrates a second vehicle equipped with another MABX (Figure 6). In both vehicles, a MK5[1] module is integrated to enable vehicle-to-vehicle (V2V) communication. Furthermore, in the virtual environment, additional following vehicles are simulated.

In the ML, the MK5 module is responsible for transmitting the acceleration request of the following vehicle 1 (FV1). This acceleration request is received in FV1 and then transmitted to the MABX in FV1. Based on the requested acceleration, the corresponding torque is calculated and sent to the vehicle controller assistance system to facilitate the desired vehicle movement.

The vehicle states of FV1 are collected within the MK5 module in FV1. Then, these vehicle states are sent back to the MK5 module in the ML for further processing and coordination. This exchange of information between the MK5 modules in both vehicles enables the cooperative driving and coordination between the manoeuvre leader and the following vehicle.

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[1] MK5: Cohda Wireless' 5th generation On–Board Unit (OBU), MK5 OBU - Cohda Wireless

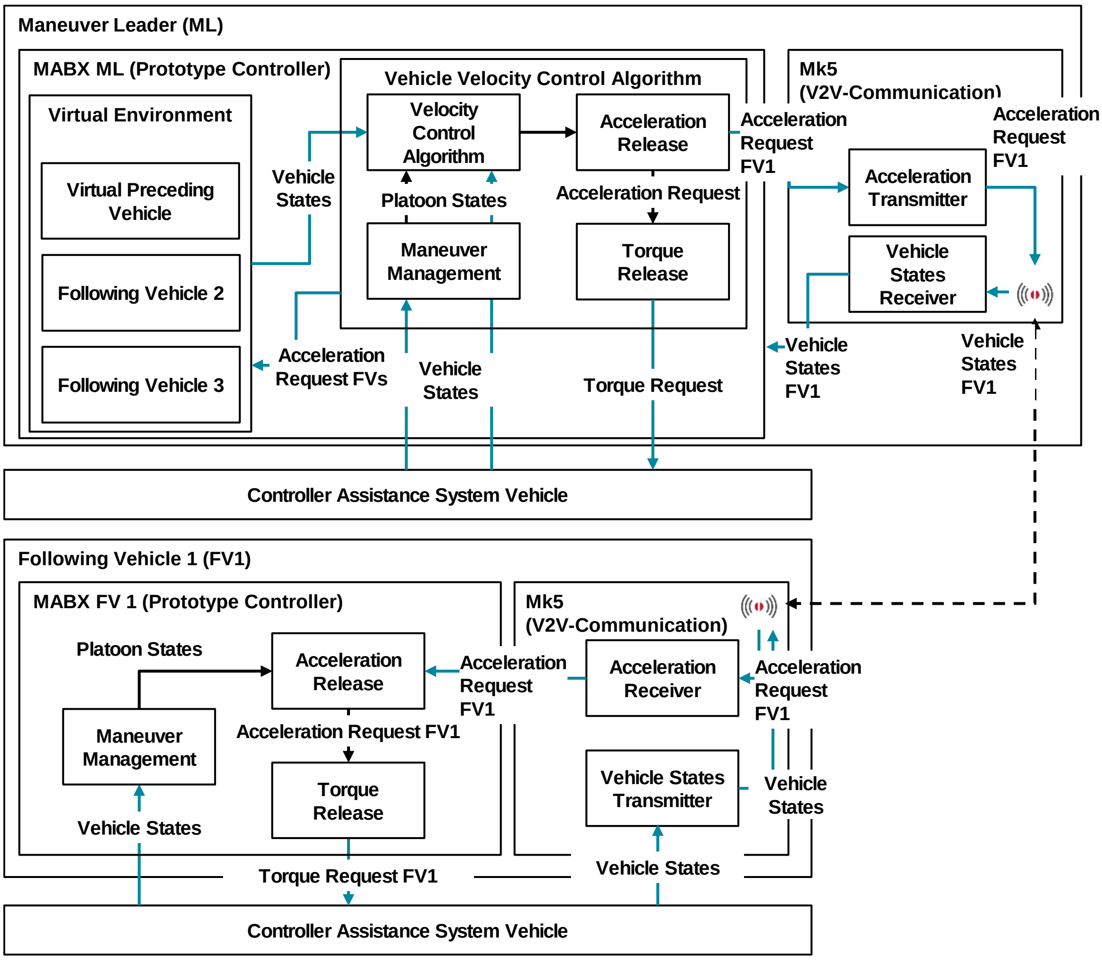

Figure 6: A schematic representation of a software integration of C-CACC algorithm in vehicle ML and FV1

In the following chapter, the V2V communication applied for the merge-in manoeuvre within the SHOW project is presented.

1.2 Vehicle to Vehicle (V2V) Communication

For the manoeuvre as described in Chapter 1.1 the bus driver triggers execution of a co-operative manoeuvre. The entities in the system of vehicles, control module and communication modules interact by means of direct Vehicle-to-Vehicle (V2V) communication. The communication entities take different roles for the manoeuvre cooperation: manoeuvre initiation, manoeuvre coordination and manoeuvre control.

The "Bus" (preceding vehicle) is the initiator of the manoeuvre request, the "Maneuver Lead" (ML) takes the coordination and control, and "Follow Vehicles" are as platoon members centrally controlled by the ML (Figure 7). Note that the ML and the Platoon Lead (PL) are the same vehicle in this setup. The ML coordinates and controls the manoeuvre, it hosts the C-CACC Software Module.

For communication each of the entities implement the service "Cooperative Lane Merge" (CLM), and the underlying "Cooperative Maneuver Protocol" (CMP).

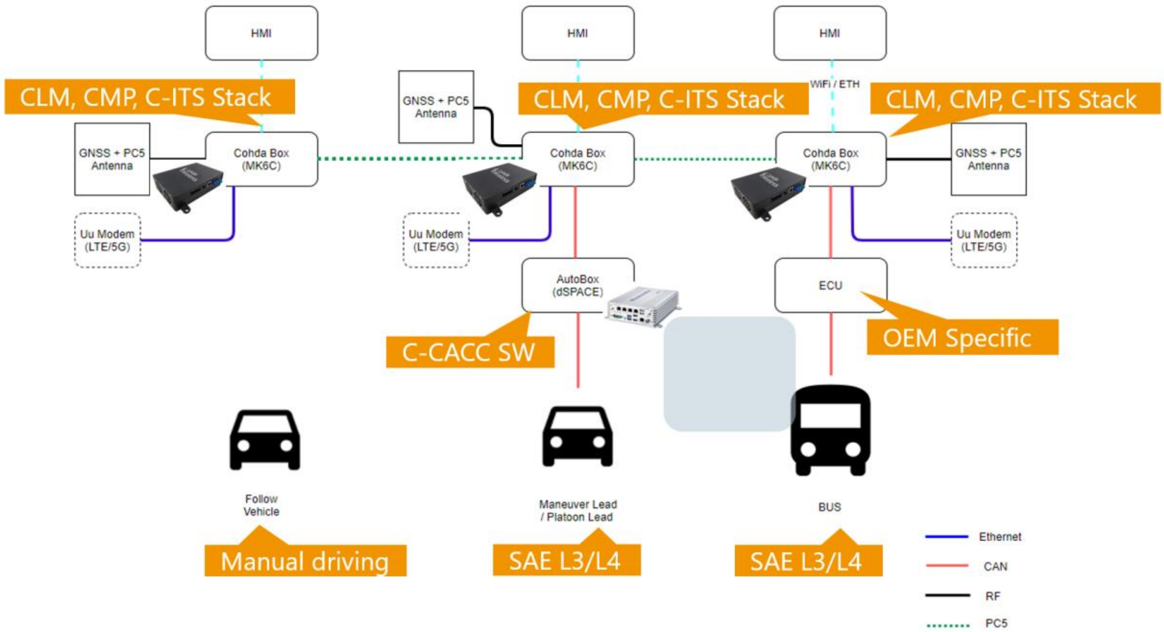

Figure 7: System Architecture – CLM=Cooperative Lane Merge; CMP= Cooperative Maneuver Protocol; SAE L3/4 = Driving Automation Level 3 or 4

Both, the CLM and the CMP where designed and implemented by FEV.io GmbH, based on proposals from the 5GAA [2].

The communication protocol stack is depicted in Figure 8: The lower layers (Access, Geo Networking and Basic Transport Protocol (BTP)) are used as provided by the Codha Wireless V2X Module (MK5 or MK6). Those Layers are standardized by C-ITS standards[3]. The standard services of the Facility Layer

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[2] Ref: 5GAA White-Paper "C-V2X Use Cases Volume II"
[3] Ref: C-ITS-Brochure-2020-FINAL.pdf (itsstandards.eu)

and Application Layer are enhanced by new FEV.io proprietary services “CMP” on the Facility Layer level and the “CLM” on Application Layer level.

Generally, for layered communication architectures services of a lower layer are offered through Service Access Points (SAPs) to higher level services. Concretely for the given implementation the CMP for example uses the (standard) services of the BTP layers (SAP_{BTP}) and offers its own services to the CLM (SAP_{CMP}).

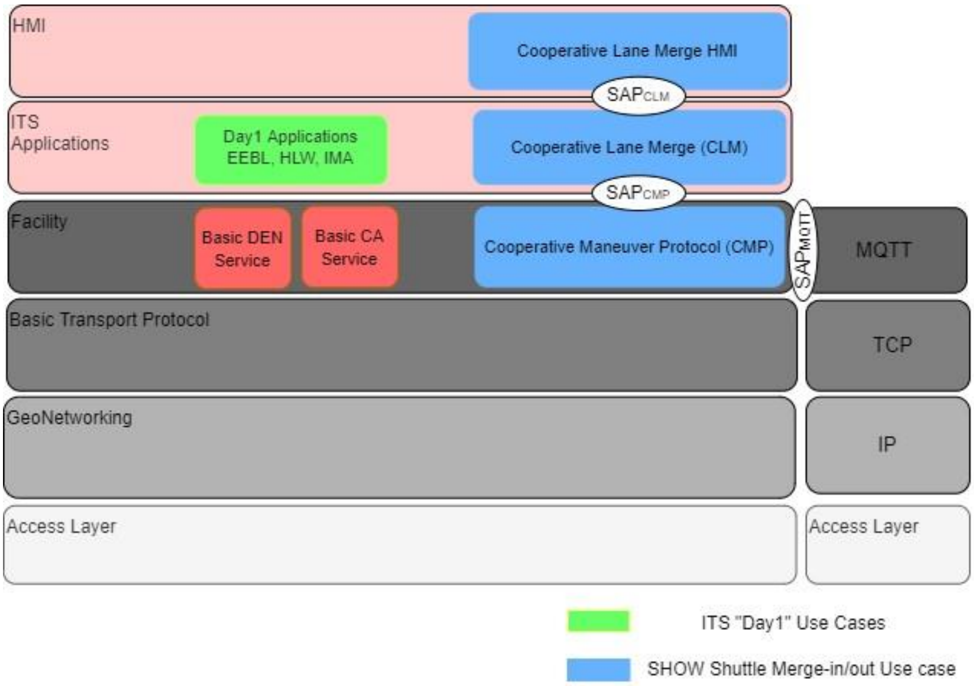

Figure 8: Enhancements of the C-ITS Protocol Stack to realize a Cooperative Maneuver Use Case and communication.

The protocol stack on the right-hand side of Figure 8, i.e. the MQTT Service on top of TCP/IP is used for simulation purposes as a Software in the Loop (SiL) system. In such a system the MQTT message broker service is used instead of the BTP service.

The Protocol Sequence

The communication protocol used for the SHOW project is illustrated in the Sequence Diagram in Figure 9. The first phase, the “Connection Establishment” phase is initiated by the bus driver who would like to enter or leave the ongoing traffic. This event triggers the build and send of the Maneuver Intent Request (MIR) message, which transports the manoeuvre intent, the type of manoeuvre some vehicle information to the target vehicles. The collaborative manoeuvre is acknowledged in a three-way-handshake: Maneuver Intent, Maneuver Feedback and Maneuver Confirmation.

After the decision for the common manoeuvre is made, the ML/PL takes the control over the platoon members and sends the desired vehicle acceleration and/or deceleration values in a regular manner.

After all, the bus driver can stop the manoeuvre any time with either an explicit “Maneuver Stop Request” or by any manual override of a vehicle function.

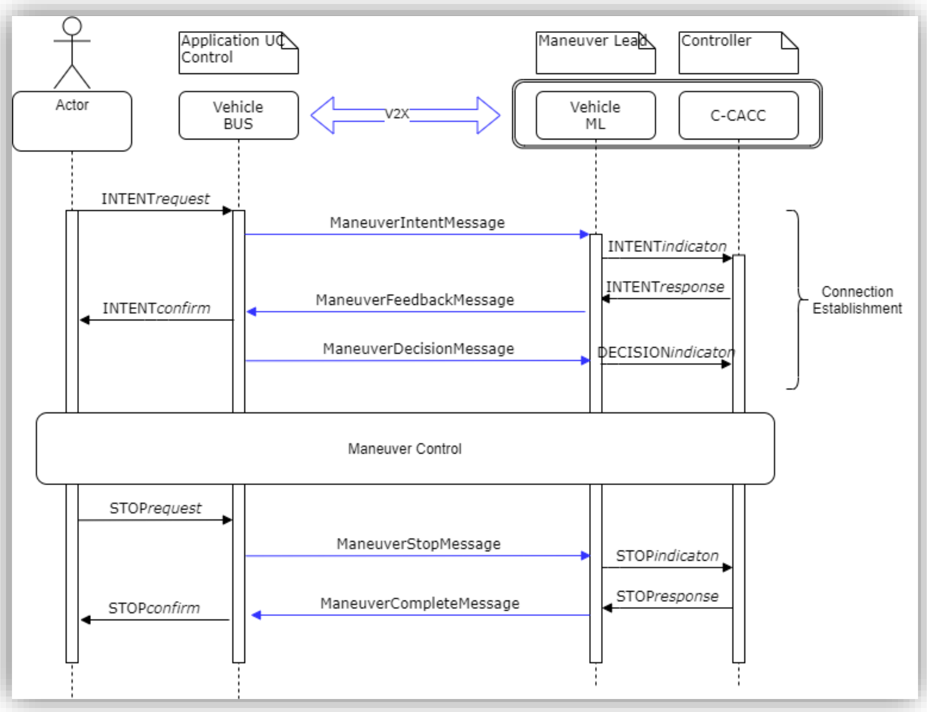

Figure 9: Sequence Diagram for the Cooperative Maneuver Protocol (CMP)

1.3 Limitation and Challenges

During the integration and testing of C-CACC in two demonstrator vehicles with V2V communication, FEV encountered the following limitations and challenges:

1. The accuracy of the positions of all vehicles within a platoon can impact the results of the algorithm.
2. The effectiveness of C-CACC heavily relies on reliable and low-latency V2V communication.
3. Integrating C-CACC into a larger scale transportation system requires significant computational power to handle the coordination and communication between vehicles.

Indeed, beyond the SHOW project, further research activities need to be conducted to achieve safe and stable platooning on ATC and in urban areas.

2 Outlook

2.1 Re-use of SHOW solution for Hi-Drive

FEV.io GmbH is also a project member of the Horizon 2020 Hi-Drive[4] Project, allowing for a continuation of the work developed during SHOW.

The communication technology (i.e. protocol stack code libraries) from SHOW can be re-used and enhanced for the Hi-Drive context. The anticipated principle for the communication protocol stack is outlined in Figure 10:

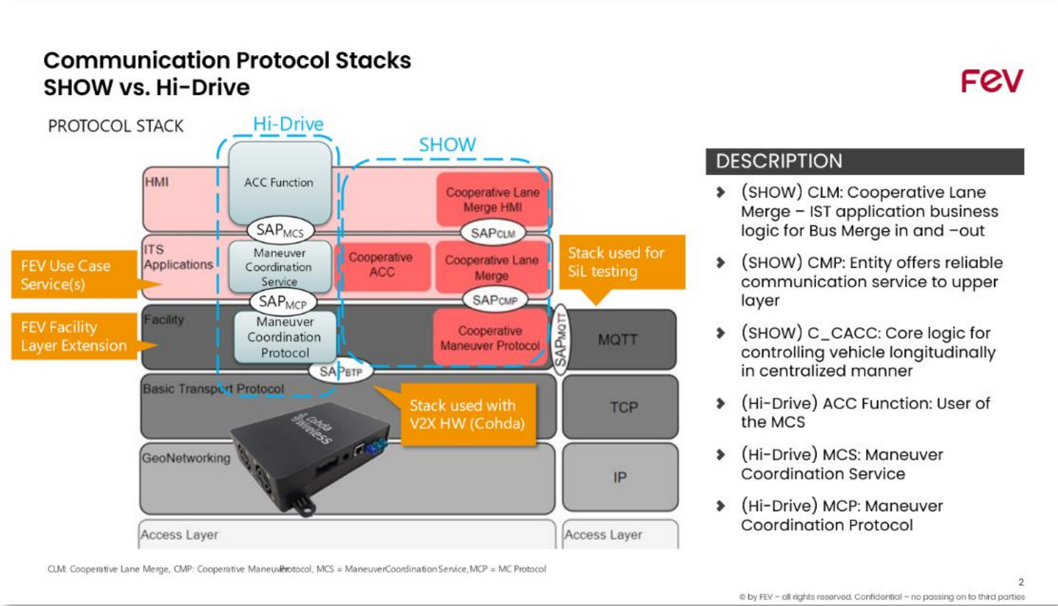

Figure 10: Re-use and enhancement of the SHOW code base for the Hi-Drive project

2.2 Integration speed trace from LCMM-System of Frankfurt shuttle

For further investigation of energy-saving potential, the recorded speed profiles of the Frankfurt shuttle bus can be used as the preceding vehicle's

[4] Hi-Drive Deployment of Higher Automation

driving profiles. A segment of the driving profiles is depicted in the following Figure 11.

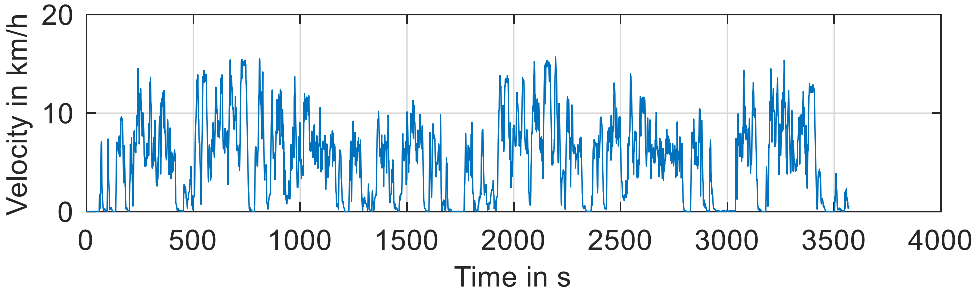

Figure 11: A segment of the Frankfurt shuttle driving profiles

3 References

[1] X. Klingbeil, M. Wegener, H. Zhou, F. Herrmann and J. Andert, "Centralized model-predictive cooperative and adaptive cruise control of automated vehicle platoons in urban traffic environments," IET Intelligent Transport Systems, 2023.

[2] 5GAA White-Paper “C-V2X Use Cases Volume II”, https://5gaa.org/content/uploads/2020/10/5GAA_White-Paper_C-V2X-Use-Cases-Volume-II.pdf

[3] C-ITS-Brochure-2020-FINAL.pdf (itsstandards.eu), https://www.itsstandards.eu/app/uploads/sites/14/2020/10/C-ITS-Brochure-2020-FINAL.pdf

[4] Cohda Wireless’ 5th generation On–Board Unit (OBU), MK5 OBU - Cohda Wireless, https://www.cohdawireless.com/solutions/hardware/mk5-obu/

[5] European Program "Horizon 2020" project Hi-Drive, Hi-Drive Deployment of Higher Automation, https://www.hi-drive.eu/