5G for Connected Autonomous Vehicles in Complex Urban Environments

Public report

Project within **FFI *Effektiva och uppkopplade transportsystem***
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Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

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1. Summary

The research project ***5G for Connected Autonomous Vehicles in Complex Urban Environments*** aimed at harnessing the state-of-the-art cellular communication technologies to solve the following two problems:

1. *establishing requirements on the communication to enable a safe interaction of connected autonomous vehicles (AVs) with the surrounding environment* and
2. *learning, and then predicting, the behavior of human road users in traffic situations*.

By considering all road users (pedestrians, cyclists, connected human-driven and autonomous vehicles) as nodes in a cellular communication network, their motion variables (positions, speed, acceleration, orientation, turning rates), along with annotated points of interest (e.g., schools, shops, bus stops) or traffic rules (e.g., signs, crosswalk) can be used to learn and then predict the behavior of human road users in a specific traffic scene. Such predictions, can then be shared with autonomous vehicles to support their motion planning, based on the current traffic scene and how this is predicted to evolve. Such a connected setting is expected to improve the safety and the overall performance of AVs' motion planning, compared to what can be currently achieved with on-board sensors only. Nevertheless, improved (e.g., smoother and safer) motion planning would require the information exchange about the surrounding traffic must be subject to stringent latency and update frequency requirements.

The projects has developed algorithms that 1) can process road users' motion data gathered by 5G cells and predict road users' behavior and 2) exploit Quality of Service (QoS) functionalities in cellular networks in order to improve the overall safety and performance of connected AVs.

The developed algorithms can potentially provide developers of Intelligent Transportation Systems (ITS) technologies with additional tools that *(i) extend the sensing and perception capabilities of vehicles beyond what can be achieved with on-board sensors only*, *(ii) facilitate and improve the motion planning of autonomous vehicles thanks to a better understanding of the surrounding scene* and *(iii) quantify the gain of safety and performance introduced by communication compared to AVs based on on-board sensors only.*

2. Sammanfattning på svenska

Your text…

"Sammanfattning på svenska" shall be written in Swedish and shall be a compressed version of the report, not just a translation of the summary.

3. Background

Autonomous driving (AD) is expected to dramatically enhance our daily mobility. While in a first phase, such enhancements will involve *individuals'* (passengers and road users) safety and comfort, it is natural to question about the long-term impact of AD on the *whole society*. Especially as the number of autonomous vehicles will increase and become dominant. Arguably, letting autonomous vehicles to exchange information about their current state and future plans can enable cooperative behaviors leading to a better usage of the road infrastructure, lower pollutions and energy consumption, while preserving safety. In fact, as pointed out by the conclusions from the Urban Grand Challenge[1], "a number of incidents could have been avoided if vehicles could anticipate the behavior of other vehicles, and that vehicles should cooperate in order for autonomous driving to reach its full potential", like in the demonstration with *three full scale AVs* negotiating a traffic intersection over a wireless network[2]. Furthermore, single AVs are also expected to take advantage of a communication infrastructure that can extend their perception capabilities beyond what can be achieved with on-board sensors only. However, the complex interplay between the vehicles' decision-making and control and the wireless information exchange can limit such potential. Especially in those applications, like multi-vehicle systems, characterized by fast dynamics, where low latency communications are necessary, and dense scenarios, where the exchanged information might be lost or affected by delays. It is, in fact, well-known that *delays* and *information losses* can degrade the overall system performances and ultimately induce phenomena like *instability*. Hence, the advantages of communication in ITS should also be demonstrated in those traffic scenarios where the necessary communication can be guaranteed.

Figure 1. A screenshot of the experimental validation of the pedestrian motion prediction technique in **Error! Reference source not found.**. The full video is at https://youtu.be/0WLCItOMkYU

Besides enabling the cooperation of AVs, wireless communication technologies are envisioned to *extend AVs' perception and decision capabilities*, which today are supported by onboard sensors (cameras, radars, lidars, GPSs) to the largest extent. This can be achieved by conveying to the AV information about the surrounding road users gathered by, e.g., the traffic infrastructure through mobile devices. Applying such idea to *safety critical scenarios*, as shown in Figure 1, requires the information to the vehicle (the predicted pedestrian's behavior for the scenario in Figure 1) to be such that the latter neither

[1] Mark Campbell, Magnus Egerstedt, Jonathan P How, and Richard M Murray. Autonomous driving in urban environments: approaches, lessons and challenges. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 368(1928):4649–4672, 2010.*

[2] Video footage available at https://youtu.be/nYSXvnaNRK4, 2016.

behaves too *conservatively* (e.g., by excessively decelerating) nor degrades unacceptably the *perceived* (and ultimately the *actual*) *safety*. *It is then important to predict the road users' behavior as accurately as possible to avoid disturbing the AV's passenger, while guaranteeing safety at all times.*

4. Purpose, research questions and method

The **goal of this project** is to exploit cellular communication technologies for autonomous driving applications by focusing, in particular, on (i) the requirements on the communication, which are necessary to enable the safe interaction of AVs with the surrounding connected road users (including other AVs) and (ii) the augmented perception and prediction capabilities that road infrastructures based on cellular communication can provide to AVs operating in presence of vulnerable road users (VRUs[3]) and human-driven vehicles.

The *hypothesis* the project has built upon to achieve *objective (i)* is that a communication, aware of the underlying decision problem, can limit delays and information losses to levels, which keep each AV's performance and safety within the design requirements. In particular, by scheduling the communication while taking into account each vehicle dynamics (i.e., the vehicle response to the braking/accelerating and steering commands), its control authority (i.e., the maximum physical acceleration/deceleration and steering) and the safety and comfort requirements (e.g., minimum distance from surrounding objects and/or maximum allowed accelerations), the resulting AVs can be guaranteed to operate while fulfilling safety and design requirements, which are typically set on the vehicle state variables (e.g., distances from other vehicles, speeds, accelerations).

The formulation of *objective (ii)*, instead, is based on the hypotheses that the complex behavior of VRUs in a traffic environment, can be learnt from *big-data sets* gathering, e.g., their absolute positions and velocities, their positions and velocities w.r.t. the other surrounding road users, *collected via their mobile devices*. The scope of the VRUs behaviors observed through localization of their mobile devices is clearly wider than what can be achieved by on-board sensors in AVs, like cameras. Moreover, such localization can be complemented by personalized information like, e.g., the VRUs' and/or non-cooperative vehicles destinations or other info that may influence their behaviors. In this way, a *learning system* can be envisioned that *off-line* elaborates all the information about VRUs and non-cooperative vehicles gathered through mobile devices, while *on-line* provides the AVs with the necessary information to predict the VRU's behavior in real-time and plan accordingly.

The methodologies used in the project to achieve objective (i) have been developed according to a joint communication and control design paradigm, where the limited communication resources are explicitly considered. The idea underlying such approach is

[3] Pedestrians and cyclists.

to prioritize the communication of those vehicles, whose current state measurements are the most important for the coordination task.

The objective (ii) has been achieved by developing algorithms that consist of an *off-line learning phase* and an *on-line prediction phase*. In the learning phase, recorded data about the VRUs (position, velocities, etc.) is used to train a predictor. In the on-line phase the predictor is fed with the current VRUs' state and returns the predicted behavior. While in the existing learning methods the VRUs' behavior is observed through the *vehicle on-board sensors* (typically cameras), our algorithms consume observations made by the cellular network, through VRUs' mobile devices, and stored in edge servers. Such difference enables a much wider scope in the observation of the VRUs' behavior. We have resorted to networked Markov chains trained on data generated by simulators. The developed Markov-based prediction tools have also been embedded in motion planning algorithms to enable a proactive motion planning.

5. Objective

The project has achieved to a large extent the objectives stated in the application and in Section 4 of this report. The only objective that has not been achieved is the experimental validation of the developed algorithms. This has been due to the lack of available vehicles in the Chalmers ReVeRe lab, within the project time frame.

6. Results and deliverables

The results from this project are listed below, with a reference to the corresponding deliverable as defined in the proposal.

1. Collision warning algorithms based on the current VRUs' state and motion (D3.1, D3.2). Although the developed algorithms are not explicitly designed to issue a warning, they can be modified with minimal effort to just issue a warning rather than controlling the vehicle. For example, when our designed planner does not have a solution over a future time horizon, a warning can be issued. That is, a warning is issued when the current vehicle state could lead to an unavoidable accident in a near future.
2. AVs' path planning based on the predicted VRUs' motion (D3.3).
3. Communication schedule algorithms for connected AVs and VRUs (D3.4).
4. Joint communication and coordination algorithms for AVs at traffic junctions (D3.5)
5. 5G QoS levels mapping tools, which map the current AVs' state with the required QoS level (D3.6).
6. Algorithms for training the RUs model (D4.1-D4.3)

The results 1, 2, 6 have contributed to the achievement of objective (ii) while results 3-5 have contributed to the achievement of objective (i).

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects	X	
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions	X	

7.2 Publications

1. C.-J Heiker, P. Falcone, "Decision Modeling in Markovian Multi-Agent Systems", published in 2022 IEEE 61st Conference on Decision and Control.

2. C.-J Heiker, E. Gaetan, L. Giarré, P. Falcone, “Repulsive Markovian Models for Opinion Dynamics”, published in Systems and Control Letters, 2024.

3. C.-J Heiker, P. Falcone, "Trajectory Planning Among Interactive Markovian Multi-Modal Obstacles using Scenario-MPC”, published in 2025 IEEE American Control Conference.

4. C.-J Heiker, Y. Quan, P. Falcone, “Interaction-Aware Motion Planning for Autonomous Vehicles Using Estimated HMMs of Road User Decision Formation”, submitted to Transactions on Intelligent Vehicles, 2026.

5. M. Bahraini, M. Zanon, A. Colombo and P. Falcone, "Communication Demand Minimization for Perturbed Networked Control Systems with Coupled Constraints," 2023 62nd IEEE Conference on Decision and Control (CDC),

Singapore, Singapore, 2023, pp. 3468-3473, doi: 10.1109/CDC49753.2023.10384127.

6. E. Gaetan, L. Giarré, S. Sacone, P. Falcone and C. -J. Heiker, "Modelling Traffic Scenarios via Markovian Opinion Dynamics," *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, Bilbao, Spain, 2023, pp. 1072-1077, doi: 10.1109/ITSC57777.2023.10422274.

7. Colombo, M. Bahraini, M. Zanon and P. Falcone, "Simultaneously Stabilizing Networked Systems With Minimal Communication," in *IEEE Transactions on Automatic Control*, vol. 69, no. 6, pp. 3589-3601, June 2024, doi: 10.1109/TAC.2023.3309001.

8. M. Bahraini, A. Colombo, M. Zanon and P. Falcone, "Robust Control Invariance for Networked Control Systems with Output Feedback," *2022 IEEE 61st Conference on Decision and Control (CDC)*, Cancun, Mexico, 2022, pp. 7676-7681, doi: 10.1109/CDC51059.2022.9992732.

9. Conclusions and future research

This project has contributed to advance the knowledge and the state of the art of connected and autonomous vehicles. In particular, the project has proposed algorithms that enable the use of data gathered from mobile devices (e.g., smartphones, wearables) of human road users (pedestrian cyclists and human drivers) in AD and ADAS systems. The algorithms developed in the project allow training and calibrating tools which can predict the motion of the HRUs in the traffic scene the vehicle operates within, thus enhancing the predicting capabilities of the onboard AD/ADAS systems. The project has shown that the usage of the developed prediction tools anticipates the vehicle actions such that safety is preserved.

In the project, artificial data from simulators have been used. Future projects could instead validate the developed algorithms with real data gathered from mobile devices, thus exposing the algorithms to the accuracy and latency that affect the signals exchanged with the cellular network.

10. Participating parties and contact persons

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Ericsson Research has also contributed to the project as external founder.