

Chapter 26

Challenges for Automated Cooperative Driving: The AutoNet2030 Approach

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26.1 Introduction

Automated maneuvering capability is expected to hold a key role in future mobility as it can probably provide safer driving conditions, improved comfort, and more efficient traffic management. The so-far relevant research undertaken by both industry and academic institutions mainly amounts to tackling different aspects of pure sensor-based automated driving such as sensing capabilities and V2X communications or vehicle control algorithms. Individual progress made along these threads has contributed to the deployment of integrated ADAS (advanced driver assistance systems) with increased levels of automated functionalities. However, highly automated vehicles are yet to come in mass-market deployment; the latter

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calls for comprehensive investigation of the *complementarity* between onboard sensors, 5.9 GHz wireless communications, and distributed control algorithms.

Triggered by the so-far *limited convergence* between sensor-based automation and cooperative V2X communications, the AutoNet2030 project seeks to research and validate procedures and algorithms for 802.11p-based interaction control among cooperative (automated and manually driven) vehicles focusing on:

- Cooperative decentralized control system to realize fully automated vehicles and drive the advised maneuvering of manually driven vehicles
- V2X-message-based communications to (feed ETSI ITS standardization and) enable automated maneuver planning and traffic flow optimization
- Onboard sensor-based architecture to enable reliable positioning and lane-keeping automation





AutoNet2030 [1] intends to demonstrate how the combination of those three major automotive research threads will make lane-keeping/changing, maneuvering negotiations, and interaction between automated and manually driven vehicles more efficient and reliable. The prototyped cooperative automated driving system will be fully integrated into test vehicles and realistically demonstrated on a test track.

To realize those goals, AutoNet2030 has carefully selected and put together a cross-European consortium of high complementarity and distinct roles. The involved smaller partners such as SMEs (BASELABS, BroadBit Energy), research institutes (ARMINES, ICCS), and universities (EPFL, TUD) bring into the project their specialized high-tech competence in prototyping of automated driving technology, maneuvering control, and sensor data processing. On the other hand, large industrial partners (CRF, Scania, Hitachi Europe) will provide vehicle platforms and largely contribute to the AutoNet2030 system and vehicle integration.





26.2 Use Cases

In order to showcase scenarios with associated customer and societal value, the AutoNet2030 final demo presentations are designed to cover two diverse yet typical driving settings. One demonstration will be performed in highway-like conditions with two heavy-duty trucks and (at least) one manually driven passenger car focusing on (enhanced) variants of the convoy motion; the latter is one of the most promising methods for the introduction of automated driving on highways. The other demonstration is set in a more inner-city-like scenario where fully automated electric prototype vehicles will be used to (mainly) showcase automated functions for safe-fail distributed decision making and intersection coordination.

The set of the *high-speed scenarios* has been deliberately selected to demonstrate the efficiency of cooperative communications and perception capabilities as well as the realization of cooperative maneuvering in an inherently safe manner.

Scenario	Description
1. Joining 	One truck moves in high speed and a second one catches up in the same lane. When the second one approaches the first, they join the same convoy-like motion. After the convoy creation, automated driving functions assist in keeping speed/distance and lane position
2. Merging 	The two cooperative trucks of scenario 1 are approached by a manually driven car which seeks to merge into the same lane with the trucks. Automated driving functions recognize the merging and increase the distance between the trucks. Moreover, HMI in the car advises the driver to adjust speed and steering so that safe merging is possible
3. Leaving 	The three vehicles from scenario 2 are driving in cooperative mode in the same lane. The driver of the manually driven vehicle decides to leave by changing lane and pulling away from the trucks that remain under convoy motion
4. Lane changing 	The two trucks drive in cooperative mode and a manually driven car approaches from behind in the left lane. HMI elements advice the car driver to maintain speed and position. Radar sensors on the trucks and a laser sensor on the car acknowledge that the left lane is free of conflicting objects and thus the trucks safely perform a lane change

The set of the low-speed scenarios has been deliberately selected to demonstrate the efficiency of cooperative communications, perception capabilities, and most notably the realization of cooperative decision making.

Scenario	Description
1. Car following 	Two vehicles drive on the same lane, maintaining a constant distance. First, the speed of the leading vehicle slightly varies, it performs an emergency brake, and then restarts. In both cases, we show how vehicles keep a perpetually safe relation
2. Merging 	Two vehicles that move in cooperative automated mode approach a merging point and are coordinated to merge into the main road. The vehicle having no priority decelerates to provide sufficient space. Using cooperative maneuvering, the merging can be performed in a safe and efficient way
3. Lane changing 	Two vehicles drive in different lanes at the same speed and one decides to change its lane. The vehicle on the targeted lane should decelerate to facilitate a smooth lane change of the other one. Using cooperative maneuvering, the lane change operation can be performed safely and efficiently
4. Intersection 	Two vehicles approach an intersection point with the same speed. A crossing order is decided through V2V messaging and cooperative decision making. Accordingly, the vehicles cross the intersection without collision. Information exchange and cooperative decision making are demonstrated

26.3 Human Machine Interface

Interacting with the vehicle driver is a challenge of major importance when implementing automated driving functions. The AutoNet2030 project has set its focus on the HMI design and development for partially automated vehicles, while it can occasionally (i.e., high-speed use cases) adopt its functionality to inform the users of automated vehicles. The project has relied on the multidisciplinary work of both engineers and cognitive HMI experts aiming to design a user-friendly interface that will facilitate advised maneuvering.

After having analyzed the considered AutoNet2030 use cases, a flow of road/vehicle events and actions (required by the user) has been identified. To cope with the specified requirements (of each use case), an innovative dual-display HMI system has been designed. It consists of a head-up display and a secondary display (i.e., Android device) as illustrated in Fig. 26.1. With this setup, the driver receives the most significant information and related maneuver advices over the HUD; the secondary display projects only informative messages (e.g., the reason why a certain advice is projected) and also provides the interactive capability (i.e., inputs by the driver) when safety conditions allow (e.g., a button to switch between manual and automated mode). In each case, a layout has been defined to cope with the different visual elements, the associated urgency level, and the way information is best presented to the driver. The displayed messages have been determined according to a predefined syntax structure and have been prioritized (for projection) with respect to a designed HMI logic that accounts for their significance.



Fig. 26.1 Indicative screenshots of the dual-screen AutoNet2030 HMI system: HUD (*left*) and Android (*right*)

26.4 Cooperative Control

26.4.1 Distributed Graph-Based Convoy Control

In terms of the distributed convoy case, the problem that we mainly seek to tackle amounts to following instance: We consider an unknown number of intelligent vehicles in a road which are able to communicate with each other locally and can localize themselves. The problem is how these vehicles can establish a dynamic multilane convoy which remains stable while allowing new cars to join and the current cars to leave.

Most of the works in group control of vehicles have been focused on single-lane convoy problems using reactive spacing control methods for consecutive vehicles. Point-follower and vehicle-follower, adaptive cruise control (ACC) [2], cooperative ACC (C-ACC) [3], and local controllers [4] are the main approaches for single-lane convoy control. In these strategies, the desired inter-vehicular spacing is maintained through basic control laws such that every controlled vehicle matches its distance and speed with the vehicle ahead.

AutoNet2030 approach for convoy control is based on the work by Goyal et al. [5], which proposed leaderless graph-based control for multilane convoy. An undirected graph $G = (V, E)$ is defined in which vertexes V correspond to controlled agents (vehicles in this case) and edges E correspond to inter-vehicle communication and relative positioning links. Built upon basic linear algebra, a stable solution to the formation control problem in two dimensions is given by

$$\mathbf{x} = (L \otimes I_2) (\mathbf{x} - \mathbf{b}) + v_G \mathbf{1} \quad (26.1)$$

with $L = I \cdot W \cdot I^T$, where L (called Laplacian matrix) is obtained from the incidence matrix I that defines the edges of G and the weight matrix W which is a diagonal matrix used to tune the weights assigned to the edges. I_2 is simply a 2×2 identity matrix. The (x, y) absolute position vector for all vehicles is given by \mathbf{x} , and the desired offsets of the vehicles to the formation centroid are given by the bias matrix \mathbf{b} . The parameter v_G represents the desired velocity of the vehicles.

To make the graph-based formation control scalable and dynamic, we propose an approach in which graphs containing connections between vehicles are dynamically created, locally maintained, and automatically modified. The main ingredients of the dynamic graphs in our system are *local neighborhood* and *local identifiers*. We define a *local neighborhood* of a vehicle using topological distance, that is, distance measured in number of vehicles. *Local identifiers* allow each vehicle to enumerate the other vehicles in its vicinity using its local coordinate frame, by assigning ordered pairs (2 tuples) containing topological distances in x - and y -axes (in its local right-handed coordinate system). Finally, the Laplacian control (Eq. 26.1) is upgraded to a decentralized approach, assuming a connected (but not necessarily complete) graph, using only relative positioning information. Details are provided in [6].

26.4.2 Cooperative Intersection Management

Currently, traffic lights are equipped in traffic intersections to coordinate conflicting flows and ensure the road safety. However, the efficiency and safety of such system is doubted: 44 % of collisions in the USA are within the intersection area, and delays induced by traffic lights can be high. First proposed in [7], cooperative intersection management (CIM) allows autonomous vehicles to cooperatively cross the intersection without traffic light, fully utilizing the advanced sensing, communication, and maneuver capacities of vehicles. It is shown that CIM brings significant efficiency improvement (in terms of throughput, average delay, etc.) compared with traffic lights.

In AutoNET2030, CIM is one of the major research topics. We adopt a safety-oriented approach to tackle this topic. The goal is to design a mechanism for CIM that is not only efficient but also probably safe. We adopt the priority-based approach to separate the coordination problem into two subproblems: planning of vehicle priorities and brake-safe reactive control of vehicles. Vehicle priorities decide the relative orders of vehicles to cross the intersection. Brake-safe control of vehicles allows a vehicle to avoid collision with other vehicles having higher priorities (prior vehicles) even prior vehicles perform emergency brakes. Under mild assumptions, the overall safety and deadlock-free property of the proposed system can be mathematically proven. More details can be found in [8–10].

26.5 Cooperative Sensing and Perception Layer

26.5.1 Configurable Perception Layer

Building up reliable and accurate knowledge of the environment—often called an environmental model or perception layer—of autonomous vehicles is a crucial requirement in order to perform automated maneuvers in a safe and efficient manner. In general, the environmental model comprises static and dynamic entities which need to be observed and tracked over time. As both stages, decision making and control algorithms, directly depend on the robustness and the accuracy of the environmental model, this is considered a core part in automated driving.

Typically, several perception sensors such as radar, lidar, and camera are used in order to perceive the surrounding of the host vehicle. These asynchronous sensor information are continuously combined with data fusion algorithms in order to build a unified environmental model. The intuition behind this multisensor data fusion approach is usually twofold: First of all, as the field of view of a single sensor system is often limited due to physical constraints, combining multiple sensors that are mounted at different locations increases the surveillance area. Secondly, and this is usually more important, by using heterogeneous sensors, the overall robustness and performance can be increased as the combination of the particular sensor features

(e.g., radar sensors can directly observe a radial velocity component, while camera systems usually give a proper estimate of the object's width) yields an improved environmental model.

Within the AutoNet2030 project, a full-scale 360° environmental model that integrates onboard perception sensors as well as communication information is required in order to safely perform and demonstrate the anticipated use cases for high- and low-speed scenarios as elaborated in Sect. 26.2. The perception layer has to be efficiently implemented to meet the real-time conditions and optimally exploit the computational resources of the embedded computers used inside of the test vehicles. Moreover, as AutoNe2030 deliberately uses several heterogeneous vehicle platforms, the 360° perception layer has to be easily adoptable to different vehicle configurations. For example, this includes the capability of easily replacing a radar sensor from one particular manufacture to another as well as the ad hoc configuration of sensor properties such as mounting position or sensor noise characteristics. In order to cope with the challenge of having a configurable 360° environmental model, a novel tool-based development approach [11] is used inside of AutoNet2030:

- **Prototyping:** In this stage, the environmental model is developed by performing a probabilistic data fusion among several sensors in the high-level programming languages C# and C++ with rich debugging capabilities. The data fusion is realized by using the probabilistic sensor data fusion framework BASELABS Create. This SDK leverages an incremental development process where each sensor can be added one by one until the final 360° configuration is reached. The resulting environmental model is tested and validated, both with recorded and online measurement data for each vehicle platform.
- **Vehicle integration:** In this stage, the already validated and tested environmental model is automatically transformed from high-level C# code to static embedded C-code that is appropriate for pre-series integration at ECU level. The automatic code transformation ensures that the C-code is functionally fully equivalent to the already tested C# version from the prototyping step.

26.5.2 V2X Communications for Automated Driving

Recent research activities [12] and successful field trials of V2X communication [13] are bringing the application of V2X communications to autonomous driving closer to reality. Cooperative autonomous driving is also the object of the European R&D projects i-GAME,¹ AdaptIVe,² and COMPANION.³

¹<http://www.gcdc.net/i-game>

²<http://www.adaptive-ip.eu>

³<http://www.companion-project.eu>

V2X communications for autonomous driving represent a natural evolution of the communication system for cooperative vehicles. Initial V2X communication systems have been designed to provide driver assistance, which corresponds to level 1 in the definition of automation levels in SAE J 3016.⁴ Higher levels of automation introduce new requirements that need the definition of new or enhanced messages, communication protocols, and their standardization for cooperative autonomous driving [14].

In order to practically implement V2X communications among heterogeneous vehicles, standardization is needed to guarantee their interoperability. For this reason, the ETSI Technical Committee in Intelligent Transport Systems (ITS) recently published the GeoNetworking standard, which defines forwarding algorithms for packet transport in VANETs. Furthermore, periodical Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM) allow vehicles to exchange information using a common language.

CAMs allow each road user participating in a V2X network to transmit periodically their station type, time, position, velocity, and many other parameters. This rather comprehensive description of an object state in combination with a communication range of up to 1000 m in perfect conditions makes CAM data appealing candidates for improved multisensor data fusion.

However, V2X communication in general and CAM transmissions in particular have some distinctive characteristics compared to classical onboard perception sensors. For example, this includes a global coordinate system, dynamic update rates according to the CAM trigger rules, as well as high latencies due to the communication channel. In AutoNet2030, the potential of V2X to complement the environmental model is investigated.

Furthermore, the AutoNet2030 project is researching new communication protocols and message types specifically designed to support the cooperative sensing and maneuvering among autonomous vehicles. In particular, new cooperative sensing messages, broadcast by every vehicle at a rate of 1 Hz to all its neighbors, are required to share the detected objects (such as vehicles, pedestrians, cyclists, etc.) among the cooperative vehicles. For the cooperative maneuvering functionality, several new types of messages are needed. For instance, the transmission of convoy messages coordinates the maneuvering of a multilane formation of vehicles, and the cooperative lane change service supports maneuver negotiations among vehicles aiming to perform a lane change, as well as relative space reservation. More details about these dedicated messages for cooperative autonomous driving are found in a recent paper [14].

⁴http://www.sae.org/misc/pdfs/automated_driving.pdf

26.5.3 Road Data Fusion Module

The road data fusion module aims at increasing the accuracy of the observations and detections of the road geometry as provided by individual vehicle perception components as well as the V2X sensor information. Road attributes as captured by lane markings, road boundaries, and map matched/refined GPS position are extracted from the available object tracking/image processing and positioning units and are fused using the map road geometry. The output of the module essentially increases the information availability and robustness of the system (e.g., lane information may be artificially reconstructed in absence of visible lane markings using only map data). It constitutes an accurate representation of the road geometry in the form of a road-segments list, each of one is described by clothoid model equations [15].

26.6 Conclusion and Outlook

We have presented the main parts of the AutoNet2030 body of work and notably the way the consortium has addressed the related automated driving challenges along the threads of the system architecture, the distributed control algorithms, and the cooperative perception capabilities. What is yet to be accomplished amounts to the standardized use of 5.9 GHz V2X communications for automated driving, the finalization of the AutoNet2030 software modules, and their integration in the available vehicle platforms. Test-track validation of the cooperative maneuvering control algorithms and overall system functionality will follow. With the successful completion of the above AutoNet2030 objectives, the project envisages to shape the path for cost-optimized and widely deployable automated driving technology.

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