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Novel approaches for analysing and testing the effect of autonomous vehicles on the traffic flow

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Abstract

Several research projects consider new traffic management approaches for cooperative, connected and automated mobility. However, it is still a challenge to test and analyse the effects of automated vehicles on the traffic flow under real traffic conditions, especially due to the low penetration rate of vehicles with SAE Level 2 and higher. The H2020 project INFRAMIX introduces novel approaches for analysing and testing traffic flow effects by proposing functional systematic tests under human control in real traffic as well as a novel technique of hybrid testing on proving grounds. Hybrid testing uses virtual traffic flow data in real driving tests in order to overcome the limitations of pure simulations and the limited scale of test drives. The results enable a basic understanding of the interaction of autonomous vehicles and the physical and digital infrastructure and will indicate the next steps in mixed traffic management.

Keywords:

Demonstration; Cooperative, Connected and Automated Driving; Mixed Traffic Flow Control

Introduction

The evolving automation of vehicle driving functions, the automation in transport, and the pan-European deployment of Cooperative ITS (C-ITS) [6] motivate the research and development of new traffic control strategies and ITS services. To get ready for the transition phase from conventional towards fully automated traffic flow, the need of testing the new C-ITS services increases. The introduction of higher levels of vehicle automation by the automotive industry and the enhancement of mixed traffic management needs to be synchronized in order to guarantee an efficient and safe traffic flow under mixed traffic conditions, where automated and conventional vehicles share the road.

The latest ERTRAC roadmap [14] depicts the interaction of vehicles' operational design domains (ODDs) with traffic regulations and the infrastructure support classification for automated driving [4], which needs to be analysed and tested before deployment. Various open research questions are addressed. While security issues of new C-ITS services for automated driving are still under investigation, the gap between testing in simulation and real demonstrations need to be examined. Especially when analysing traffic flow and new traffic management strategies that include the fine-grained control of cooperative, connected and automated vehicles (CCAVs), macroscopic effects of conventional drivers and communication-induced controlled vehicles are a matter of particular interest. Furthermore, the development, simulation and testing of new physical and digital infrastructure (PDI) elements [4, 22] is of particular importance for road operators.

Pure simulation cannot handle human factors. On the other hand, pure real tests would require a continuous penetration rate of AVs of at least 10% of the vehicles during 5 minutes (which implies a fleet of more than 100 vehicles) on a short segment of a public motorway to reproduce mixed traffic effects on the network. Since only limited resources of vehicles with higher SAE levels are available,

novel approaches for testing and demonstration need to be introduced. The balanced use of different validation methods is pivotal.

This paper focuses on the demonstration methods used in the H2020 project INFRAMIX and shows first results. One of the aims of INFRAMIX is to investigate mixed traffic of automated and conventionally driven vehicles. Three scenarios of variable complexity were defined: "Dedicated Lane", "Roadwork zone" and "Bottleneck" [19]. They are analysed with the best suited simulation and testing methodologies depending on predefined requirements described in [18]. Studies are conducted in simulation, but also in defined real-world tests. Real world aspects are crucial for validation and a working proof of concept. Taking into account that real testing needs excessive amount of financial and personal resources, new testing methodologies are considered. INFRAMIX develops a new framework of simulation-based testing with real single vehicles in a proving ground and with demonstrating and testing physical and digital infrastructure elements on public roads [17, 18, 19].

Related Work

The further development of ITS systems and new traffic control strategies to test future traffic management, even on a single-vehicle control, are investigated in several research projects. While vehicle validation methodologies and test environments are proposed by various proving grounds and testing areas around the world, automated fleets for demonstrating mixed traffic scenarios with significant shares of automation are not yet available.
Several platforms such as the European ITS Platform (EU EIP) [15] are working on the collection and analysis of all relevant projects on Automated Driving[1]. However, only few projects conduct tests under real conditions but with lower speeds than normally used on motorways. In this line, the UrbanAutoTest [23] in Finland offers 200 km of roads for testing, and the VRA projects [24] contribute greatly in terms of regulations for testing in real traffic conditions. Other relevant projects involved in demonstrations under real conditions are Drive Me [10], a large-scale autonomous driving pilot project in which 100 automated driving cars have used public roads in everyday driving conditions in Gothenburg, Sweden. From the point of view of traffic control strategies, the MAVEN [21] and TransAID [10] projects are also addressing traffic management in mixed traffic in urban scenarios.

Several real test-sites offer the environment to validate new vehicle functionalities, advanced physical and digital infrastructure elements and communication technologies, as outlined in the following.
Applus IDIADA operates test-sites in Spain and China [2]. The Catalonia Living Lab [5], a public-private framework for development and testing of connected and automated vehicle (CAV) technologies, provides test environments required in the development process of connected and automated vehicles. The Spanish INFRAMIX test-site, which is mentioned in this paper, is part of this portfolio. In Austria, there are also different proving grounds for highway and urban use-cases: The Digibus® Austria project [8] pursues to prove a reliable and traffic-safe operation of automated shuttles on open roads in mixed traffic in a regional driving environment. DigiTrans [9] is the Austrian test region for automated and interconnected heavy duty vehicles taking into account the requirements of industry and infrastructure operators and focusing on a user- and impact-driven realization. ALP.Lab, the Austrian Light Vehicle Proving Region for Automated Driving [101] is focusing on light vehicles and hosts the Austrian INFRAMIX test-site. ALP.Lab has a joint cross-border proving ground in cooperation with ZalaZone [25] in Hungary and the AV Living Lab [13] in Slovenia. Other impacts such as adverse weather conditions are addressed in Norway and Finland at the E8 Aurora Borealis snowbox [12].

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[1] E.g.: TransAID, L3PILOT, AUTOPILOT, VI-DAS, MAVEN, AutoMate, KoMoD, DRIVE Me, UKAutodrive, ADAS&ME, COMPANION, AutoNet2030, iGAME, AdaptIVE, Impact Assessment Framework for Automatisation, SOHJOA-6Aika, nuTonomy, CARTRE, interact, SAFETRIP, UrbanAuto Test, AutoNOMOS, Lutz Project, interactive, DRIVE2X, FOTsis, DENSE, CONCORDA, AURORA ARCTIC CHALLENGE (NordicWay2), Autopiloten, C-ROADS, C-ITS Corridor, aFAS, Providentia, ConVex, PRYSTINE, Strategisches Routing, KO-HAF, IMAGiNE , Cloud to SLVA, Mantra, Dirizon, Staple, Rouen Normandie autonomous Lab, Ensemble, TrustVehicle, Coexist, ICT4CART, HEADSTART, MUCCA.

So far, existing tests focus on single vehicles. However, the impact on traffic flow becomes visible at larger penetration rates of automated and connected vehicles. There is a need of investigating of mixed traffic under real world conditions. These tests would be essential for preparing road operators for future automated mobility.

INFRAMIX Demonstration

INFRAMIX, which aims to prepare road infrastructure for mixed vehicle traffic flows, intends to test new C-ITS services for advanced mixed-traffic management and validate the required physical and digital elements virtually and in real worlds on test-sites in Austria, Germany and Spain. The real test-sites presented in this chapter enable the validation of V2X communication with cooperative and connected vehicles and provide new insights in single-vehicle control considering human drivers to act like automated vehicles. Additionally, the trade-off between sub-microscopic simulation and hybrid testing on a proving ground as potential enabler technology for Automated Driving is presented. Hybrid testing [20] addresses the problem of high simulation effort and theoretical approaches by verifying single vehicle behaviour in the closed environment of a proving ground but with a real traffic flow present via simulation. The test-site and methodologies are described in the following.

Spanish test-site

The Autopistas test site is located within the Mediterranean Corridor (TEN-T Network) between Barcelona and the French border. The specific highway segment is a 20 km long four-lane carriageway that includes four intersections and a 180 m tunnel. In 2016, the average daily traffic (ADT) in this section was around 30 000 vehicles per day. The currently available ITS equipment includes different types of variable message signs (VMSs), video cameras, Bluetooth antennas, a weather station, and 104 magnetic sensors for measuring various factors including occupancy, speed, vehicle classification and distance gap per lane. ITS-G5/DSRC short range and long range cellular communication are available at the test-site. Additionally, a proprietary fibre optic ring network with 10 Gbps bandwidth connects the equipment from the test-site to the TMC in real-time [5].

In the context of the INFRAMIX project, the four-lane carriageway offers the possibility of deploying a dedicated lane without compromising the traffic flow. Moreover, the availability of bottlenecks such as on-ramps, and the high occupancy of the segment due to its proximity to an important city and as part of the Mediterranean Corridor provide perfect conditions for testing new traffic control strategies. Thus, the demonstration of the dynamic lane assignment of a dedicated lane, roadworks and bottleneck scenarios in real traffic conditions is planned in Spain.

Figure 1 - AV dedicated lane activated (a) and end of activation (b)

Due to safety restrictions, the dedicated lane (see Figure 2) will be located on the top right lane in a 1km section without exits or entries. Indeed, it will not be possible to evaluate the macroscopic effect in traffic of the activation/de-activation of this dedicated lane due to the low penetration rate of AVs, but the real traffic demonstration will be essential to evaluate user acceptance and, indirectly, the lane-change behaviour of conventional cars. In order to demonstrate this use case, new visual (electronic and fixed) elements are defined and deployed within the test-site in order to guarantee safety for all the users, including VMSs and segregation elements. Figure 1a shows the VMS located at PK 62.3 indicating that the dedicated lane is activated, while Figure 1b shows the end of the activation. Additionally, 5 pictograms painted on the road surface identify the beginning of the dedicated lane; one every 100

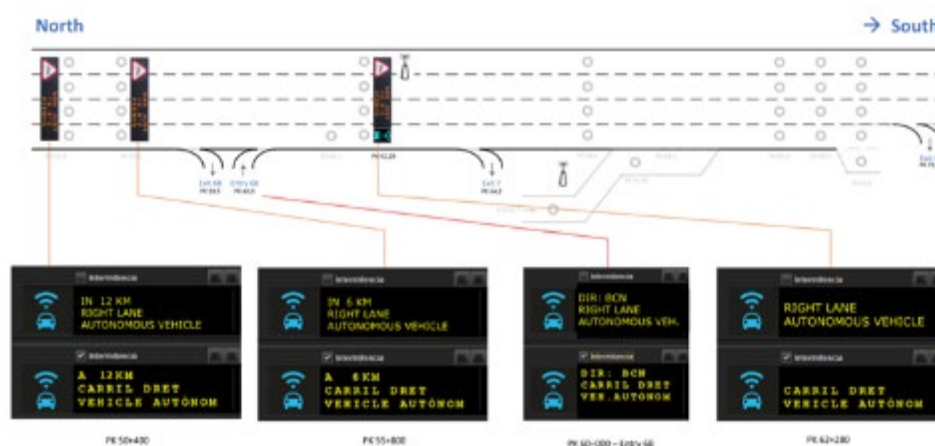meters between PK61.8 and PK62.0 right before the start of the dedicated lane.

Figure 2 - Digital (VMS) and physical signal for dedicated lane scenario

From the digital infrastructure perspective, the validation of the hybrid communication informing users through ITS-G5/DSRC, cellular and VMS simultaneously, will also be conducted. Figure 3 shows in detail the interaction diagram between all the subsystems of traffic management and infrastructure-to-vehicle communication, involved in this demonstration.
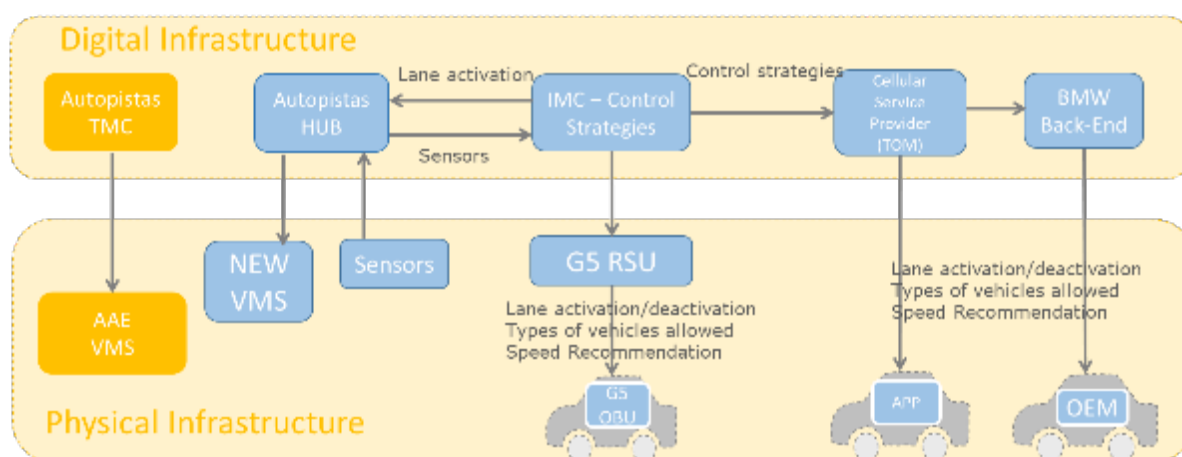

Figure 3 - Systems interaction and planned integrations for the demonstration of the real-time lane assignment under Dynamic Penetration Rate of automated vehicles use case

The second use case will be the road works scenario; an intelligent roadworks trailer including a mobile RSU is planned to be set up. It contains a mobile VMS to signal roadworks warnings visually and will be integrated to the backend via cellular communication and ITS-G5/DSRC for V2X communication. The position of the trailer will be about 1.7km before the actual roadworks.

Regarding bottleneck control, the busiest on-ramp of Girona Sud is taken for demonstration. In analogy to validating the dedicated lane problem in real conditions, the hybrid communication and user perception of enlarging the distance gap between vehicles or of recommending a lane change due to third parties can be investigated. Additionally, the flow control strategy can be supported via VMSs and some effects on the traffic will be observed in real conditions. Nevertheless, due to the low penetration rate of AVs and connected vehicles, the macroscopic effect of new control strategies to facilitate the entrance of automated vehicles to the highway cannot be validated under real conditions.

Austrian test-site

The Austrian motorway operator ASFINAG operates a test track with an approximate length of 20km called ALP.Lab on the motorway A2 close to the city of Graz. The aim of this test track is to provide an extended physical and digital infrastructure for validating Automated Driving functions and test new traffic management strategies for connected automated vehicles. The digital road infrastructure is based

on a fibre-optic network that provides IP-based network connectivity to gantries. HD video-based image processing algorithms, ground based radar sensors and triple-technology traffic detectors are used to provide information about the traffic flow including anonymized velocity, vehicle type and lane usage. By applying an intelligent sensor fusion algorithm to the data gathered over a distance of 1.8km, ASFINAG can generate trajectory vehicle data which can be used to identify the ego-vehicle movement (see Figure 4a) and to record the surrounding traffic of an automated vehicle in complex traffic situations (see Figure 4b).
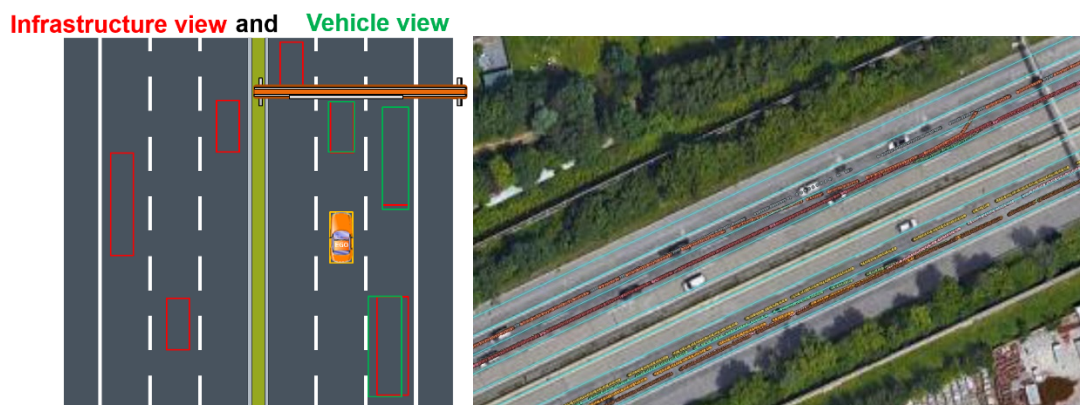

Figure 4 – Combined infrastructure (red) and vehicle (green) view (a) and generated anonymised vehicle trajectories on the real test-site (b)

In addition to the traffic sensor technologies, the test-site is equipped with weather stations, 12 ITS-G5/DSRC road-side units, and intelligent, connected, mobile trailers to provide, e.g., C-ITS Day 1 Services like VMS information, road works warnings and first services for automated vehicles. This data can also be provided via a DATEX II interface to cloud services [7]. This architecture enables the Austrian test-site to validate the hybrid communication (Figure 5a) and user perception of roadwork zone and bottleneck scenarios.
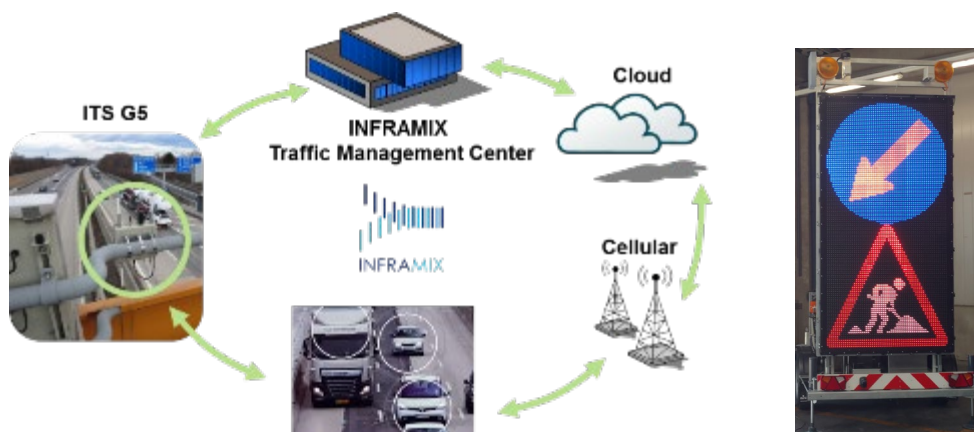

Figure 5 - INFRAMIX hybrid communication model (a) and intelligent roadworks trailer (b)

Especially for the INFRAMIX roadworks scenario, an intelligent roadworks trailer (Figure 5b) is planned to be set up. It contains a mobile VMS to signal roadworks warnings visually and will be integrated to the backend via cellular communication and support ITS-G5/DSRC for V2X communication.

The novel added value of the Austrian test-site is the available ground truth data (see Figure 6a) and 3D playback for analysis (see Figure 6b) which the ALP.Lab test region provides. The ASFINAG road infrastructure, including the sensor fusion trajectories, and the information about the static and dynamic visual signs shape the digital ground truth which can be compared to the recorded vehicle's on-board sensor data and matched with an UHD map. This service can be used by INFRAMIX to gather additional

insights into vehicle movements and end-2-end testing for automated and autonomous driving functions and vehicles in a safe, real and hybrid environment.
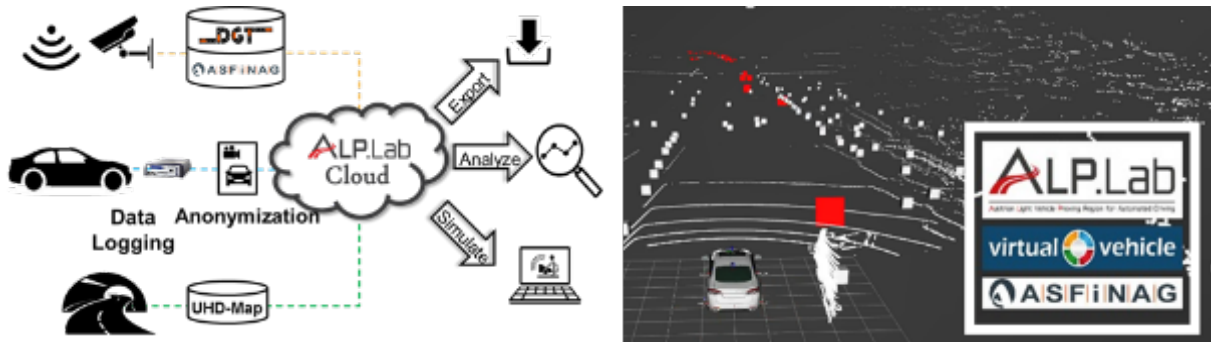

Figure 6 - Collecting Ground Truth (a) and 3D playback technique of infrastructure data (red) and vehicle data (white) (b)

Hybrid Testing and Simulation Studies

When developing *Adaptive Driver Assistance System* (ADAS) functions for autonomous vehicles, one of the main challenges is to test the vehicle behaviour in various driving conditions and traffic scenarios on real roads. In order to guarantee the accurate vehicle response, these scenarios must be performed in repeatable, safe driving conditions. Based on these requirements, a novel testing approach defined as "hybrid testing" is investigated within the INFRAMIX project, where the real VuT (Vehicle under Test) drives on a physical road within a virtual environment. Hybrid testing is a test method where real components and simulated components are combined. A real automated vehicle (AV), in this case a demonstrator vehicle from Virtual Vehicle (VIF), is driven on a proving ground. The Automated Driving function is an SAE Level 3 function enabling automated adaptive cruise control, lane keeping and lane-change functionalities. The sensors of the AV are simulated, and they sense the virtual objects created in the simulated environment and traffic. The virtual objects consist of the vehicles of the surrounding traffic and of the static environment features such as road markings and traffic signs. The use of only virtual sensors naturally implies that the vehicle is not able to sense real objects and road markings in the testing ground. Therefore, hybrid testing will be conducted on an open area, large enough to cover the virtual test track with an additional safety buffer zone, and which utilizes the real vehicle dynamics for the modelled virtual traffic situation on the real test-site. Real infrastructure components are present in form of an RSU (Road-Side Unit) that sends ITS-G5/DSRC messages to an OBU (On-Board Unit), which is integrated in the vehicle. Moreover, using the OBU, the status of the real vehicle can be sent back to the RSU for further processing.

On the proving ground, real road stretches (within the physical limits of the proving ground) and traffic conditions will be modelled. These road stretches reflect highway conditions in Austria respectively in Spain. Besides its typical character of an on-ramp, data from ASFINAG's infrastructure radar sensor is used to obtain data to remodel to real traffic situations (see Figure 4).

The first step of testing is to perform the driving scenarios in a pure simulation environment on the "Independent Co-Simulation Platform" (ICOS) [17]. An advantage of the used co-simulation approach is that it is possible to use much of the pure sub-microscopic simulation environment for the real-time capable hybrid testing. Therefore, simulation modules are classified as "real" (physical) and "virtual" (digital) components to aid the composition of the hybrid-testing simulation framework (see Figure 7).
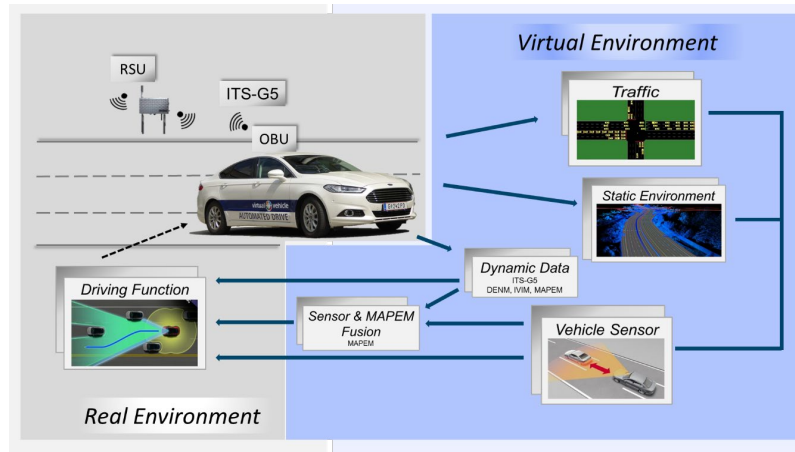
Figure 7 - Physical and virtual systems in hybrid testing

The physical systems in hybrid testing are the Automated Driving demonstrator (the test vehicle), the Automated Driving function, the RSU and the OBU. The Automated Driving demonstrator is a real car and is equipped with an ADAS-Kit that allows to control the car via algorithms running on an on-board electronic control unit (ECU). The Automated Driving demonstrator is linked to a simulation PC, where the models of the virtual systems are running. The Automated Driving function (MWC-*Motorway Chauffeur*) controls the vehicle. It combines the functionality of a longitudinal guidance system with the functionality of a lateral guidance system (the adaptive cruise control, the lane keeping assistant, and the lane change controller, respectively) [16]. A RSU by Siemens mounted on a trailer is used on the proving ground during hybrid testing studies. To be compatible with the RSU equipment, an OBU from Siemens was integrated in the Automated Driving demonstrator to receive and send the ITS-G5/DSRC messages for the different use cases.

The virtual systems in hybrid testing are the traffic simulation, the sensor modules and the static environment. The traffic and environment simulation part of the setup is to be provided by SUMO software. The sensor model and the static environment are the same as in the sub-microscopic simulation. The sensor model takes information about the road markings form the static environment, filters them and passes them to the Automated Driving function. The sensor also takes information about near vehicles from the traffic simulation and provides the environmental perception information to the Automated Driving function. The static environment model provides the map information for the sensor model respectively to be used in the Automated Driving function. It takes information about road markings and traffic signs from the map (in .XODR open drive format) and passes this to the sensor.

In hybrid testing, the sub-microscopic simulation runs on a PC that is located inside the vehicle, and the RSU is located outside the vehicle as part of the test site infrastructure. The PC in the VuT is responsible for running the traffic and environment simulation, sensor models, and object list generation algorithms in a co-simulation environment, while also being connected in real-time to the CAN-bus of the VuT to collect variables relevant for representation of the VuT in the traffic simulation on the PC. For the hybrid tests, the ADAS control functions are based on the vehicle as opposed to having an ADAS function block along with vehicle dynamics simulator in the sub-microscopic co-simulation framework. Additionally, the car is equipped with an OBU for bidirectional communication with the RSU. The AV receives these messages and performs its manoeuvres according to the simulated surrounding traffic and the received ITS-G5/DSRC messages.

INFRAMIX mixed traffic demonstration results

The first results of this novel approach combining test results under real traffic conditions and hybrid testing data are presented in this section.

The demonstrations in Spain will be conducted in September 2019, and thus, first results from the demonstrator will be presented at ITSWC 2019. Autopistas is working on the development of the Autopistas Hub which is essential for running these demonstrations, as it allows the exchange of

information in real time and based on standards. Currently, the Autopistas Hub is already gathering all the necessary data from the test-site and providing it to the simulators. The respective interfaces in order to exchange the control strategies in real time. The tests are performed with three SAE Level 2 vehicles, one conventional vehicle equipped with RSU from AustriaTech and a second conventional vehicle equipped with TomTom API. Additionally, the dedicated lane road surface painting (see Figure 8) will be investigated.

Figure 8 - Dedicated lane road surface painting

The demonstrations in Austria are conducted in different stages. Hybrid testing provides a leap towards a new approach for the verification and validation of simulation. The development is still ongoing, but first promising results are already available. At the stage of the final submission of the paper, test drives on several separate days were conducted on a closed proving ground in Austria. On each of these testing days, several test laps were done. Figure 9 shows the Virtual Vehicle Demonstrator as Vehicle under Test on the proving ground. The application of hybrid testing in a real demonstrator car is by far more challenging compared to the pure simulation in a lab or office environment. In some of the test runs, at low speed, the Proof-of-Concept for hybrid testing could already be shown.

Figure 9 - Vehicle under Test (VuT) driving on a closed proving ground

Figure 10 shows the GPS recordings of the driven trajectory mapped onto a google maps satellite picture. In our experiment the vehicle started on the bottom left corner and drove to the end position on the top right corner. Once the simulation environment was initialized, the break was released manually, but the test driver continued supervising the experiment. During the whole experiment, data between the physical vehicle and the virtual environment was exchanged continuously. Once the break was released, the MWC took over the control and accelerated the vehicle autonomously. After successfully changing lane, the vehicle stopped at the desired final position of the experiment. In addition, the receiving of new C-ITS/DSRC messages was tested successfully. The test drives were used to collect a broad set of Data. The collected data is currently analysed to further improve the novel approach

Figure 10 - Vehicle under Test (VuT) driving on closed test track

Further work is required to raise the understanding of the physical and virtual components in joint operation, used in this demonstration. In future tests, the VuT precepts the surrounding of chosen highway segments in Austria and Spain and will investigate the timing of receiving and sending of new ITS-G5/DSRC messages and vehicle behaviour. In a second stage, communication tests are planned on the Austrian test site. The analysed performance of real-world lane-change scenarios on this proving ground will provide input for public testing.
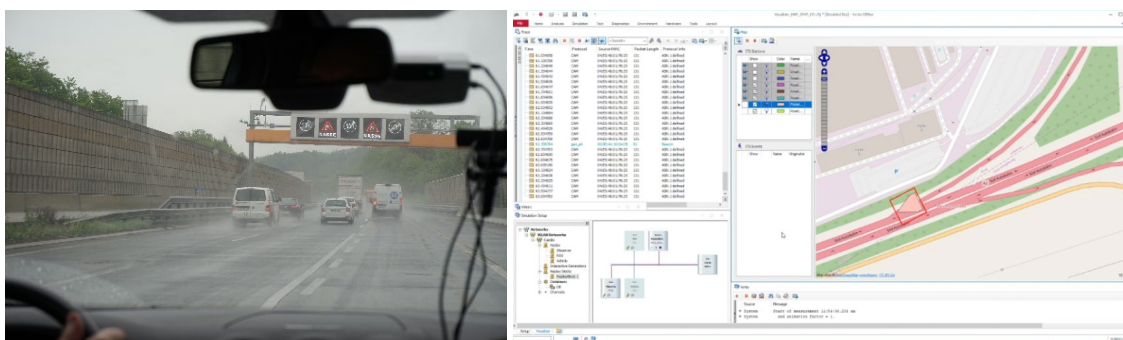

Figure 11 - The VMS (a) and the C-ITS RSUs (b) send the new C-ITS messages for mixed traffic control

The Austrian public test weeks take place in May, October and November 2019 and collect additional input data for modelling V2X communication and traffic control strategies on public roads. Initial tests have already been done (see Figure 11). The final results will be presented at ITSWC 2019.

Conclusion

Testing the effects of automated vehicles on the real traffic flow poses several challenges. Novel techniques combining simulation with real traffic data and real driving tests could overcome the limits of purely virtual tests and test drives with limited number of vehicles. The paper highlights the challenges of mixed-traffic management and the C-ITS supported Automated Driving behaviour that the new conquering mobility trend has to face. Still, the common effort of OEMs, Tier1s, road authorities and universities has to be intensified to further develop and verify the future traffic management approaches.

Acknowledgment

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