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State of Art on Infrastructure for Automated Vehicles

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State of Art on Infrastructure for Automated Vehicles

Research report summarizing the scientific knowledge, research projects, test sites, initiatives, and knowledge gaps regarding infrastructure for automated vehicles.

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20th December 2016

Contents

1. Introduction

This state-of-the-art will review the scientific literature, completed and on-going projects, testing facilities, and initiatives on the topic of automated vehicles and infrastructure. The purpose is to present the results of studies directly on this topic and studies and projects that are not directly related to this topic but which provide relevant information on the implications on infrastructure. The search was based on web search, scientific journals, conference proceedings and symposia, as well as contact with key figure persons in this field. This led us to identify the gaps in literature and avenues for future research.

The following databases search engines where examined: Google Scholar, Scopus, Web of Science, and TRID using the following keywords and terms: “road infrastructure AND automated vehicles OR self-driving vehicles”, “road design AND automated vehicles OR self-driving vehicles”, “cooperative systems AND road infrastructure”, “digital infrastructure AND automated vehicles”, “physical infrastructure and automated vehicles”. Only reports in English were included from 1995 on. Furthermore, more detailed information regarding projects, test sites, and initiatives which were missing in the literature and reports were complemented by contacts with related experts and researchers by e-mail.

The overview resulted in the division into: scientific literature on physical and digital infrastructure, projects, test sites, and initiatives. Projects were sub-categorized into four groups (in parenthesis the number of projects): Cooperative systems (8), automated vehicles (2), cooperative and automated vehicles (3), vehicle platooning (4)); test sites into three groups: test sites dedicated for automated and/or connected vehicles (11), living labs (8), and test sites with potential use for automated and connected vehicles (which basically include a wide range of test sites used by vehicle manufacturers).

The remaining of the report is structured as following: section 2 provides and overview of the scientific literature on physical and digital infrastructure, followed by section 3 which presents the overview of projects. Section 4 describes the different test sites for automated and cooperative systems, and section 5 lists the various initiatives to promote the knowledge and deployment of automated vehicles. Finally, section 6 presents the identified research gaps, and section 7 suggests future research directions.

2. Overview of Scientific Literature on Physical and Digital Infrastructure

Following the rapid development in technology and the desire for sustainability, there has been in recent decades considerable advancement and development in the aspects related to the physical and digital infrastructure. For example, Lamb et al. (*1*) presents in his paper the Forever Open Road concept which is within the research programme of the Forum of European Highway Research Laboratories. This program redefines how roads are designed, constructed, operated and maintained in the future. It relates to both the physical as well as the digital infrastructure. According to the authors, the Forever Open Road will be constructed from pre-fabricated elements, built and maintained using sustainable materials. It will have adaptable capacity provision (lanes, hard shoulder & central reserve), and built-in services and communication systems. It will measure its own condition, harvest energy and clean and repair itself. It will communicate with vehicles and will allow for automated driving.

The following paragraphs summarize recent studies in this domain. These studies were categorized into two categories, physical infrastructure and digital infrastructure.

2.1 Physical infrastructure

Scientific literature on the implications of vehicle automation on the physical infrastructure is relatively scarce compared to the digital infrastructure. Among the earliest research attention on this aspect is done within the California PATH research program. Deshpande et al. (*2*) develop in their paper the Automated Highways Systems (AHS) in which the infrastructure design comprises the highway configuration such as the number and width of lanes, and whether specific lanes are dedicated for automated vehicles, and how vehicles switch between manual and automated lanes (transition lane or dedicated access ramp), the connection to urban arterials, number of exits and entrances and the spacing between them, and emergency arrangements. Infrastructure design also includes the digital part, i.e., sensors and beacons and communication between the vehicles and the infrastructure. However, this will be elaborated on in section 2.2 of this report.

Among the studies that were found, Nitsche, Mocanu and Reinthaler (*3*), defined the requirements on the infrastructure regarding the use of highly automated driving based on a literature review which included 30 studies, and a web questionnaire in which 54 international experts participated. 76% of the respondents rated the role of the infrastructure for automated driving as very important. The authors identified from the questionnaire the most important infrastructural factors that influence the performance of three respective automated driving systems groups. The factors that mostly influence the lane assistance systems group are mainly related to the lane markings, their visibility and harmonization, road work markings, and defined and visible road delineation and continuous edges or kerbs. For the collision avoidance systems, the complex urban road environment and poor visibility due to bad weather are most challenging for those systems, and therefore, infrastructure-based warning systems for bad weather and poor visibility, road surface with a sufficient friction coefficient to allow emergency maneuvers, presence of wireless communication beacons at certain locations, and pedestrian and bicyclist protection and shielding at (urban) intersections are important. Finally, for the speed control systems, lane marking, roadside V2I/I2V, infrastructure-based warning systems for bad weather and poor visibility, and traffic signs (clear, consistently placed, and harmonized), are considered to be important factors. To summarize lane marking were found to be important for all the three groups of systems. However, these three groups of systems do not cover the whole range of subsystems in automated transport.

Hayeri, Hendrickson and Biehler (*4*) investigated in a project commissioned by the Pennsylvania Department of Transportation (PennDOT) the implications on transportation infrastructure under the assumption that by 2040 all vehicles will be automated and connected. The authors indicate that in this case since lane keeping system will guarantee that vehicles stay within their lanes, it would be possible to reduce the width standards of lanes, shoulders, clear zones, and medians. As a result an additional lane can be created, which could be for example dedicated for platoons. However, clear zones for emergency or maintenance operation will still be required, but probably with narrower width as automated vehicles have precise location and positioning capabilities. The authors highlight the possibility of using managed lanes (such as: High Occupancy Vehicles (HOV) lanes and High Occupancy Toll (HOT) lanes) as experimentation and first adoption areas for connected and autonomous vehicles.

Washburn and Washburn (*5*) discuss in their report the potential impacts of automated vehicles on geometric roadway design. The authors discuss in the report the impact of two factors that largely impact the road geometric design: vehicle performance and sight distance. With respect to the vehicle performance, the authors indicate that even if future vehicles can achieve larger values of acceleration and deceleration and better braking technologies, the need to consider human tolerance to the resulting forces and comfort criteria will limit the maximum acceleration rates used in autonomous vehicles. Also, this will be limited by energy consumption and emissions which are important criteria as well. With respect to sight distance, the authors also emphasize the automated vehicles will not perform better than humans in situations where the line of sight is limited, such as detecting objects around the bend of a curve in the horizontal alignment, and behind a crest curve in the vertical alignment. These conclusions, the authors indicate, will probably change when automation is combined with connectivity, i.e. V2X. However, still in case of failure in connectivity, the previous conclusions, of no change in the geometric design, would still apply.

McDonald and Rodier (*6*) summarize in their paper the discussion results at the Friday Ancillary workshop: "Envisioning Automated Vehicles within the Built Environment: 2020, 2035, 2050" during the TRB/AUVSI Automated Vehicles Symposium 2014. In the workshop 110 participants joined from various backgrounds and disciplines and formed small teams (6-8 members) to dwell on and to discuss a certain aspect of automated vehicles. One of the main topics included 'Investment and Redesign of the Freeway System'. The experts summarized in the paper the changes in freeway design that are expected as a result of the advancement in technology. Among these changes: (1) Fast lanes or lanes with higher speeds could be provided for automated vehicles, with dedicated off-ramps. These ramps could allow for vehicle speeds of 100 mph (~160 km/h). They could be steeply banked and shorter becoming mini ramps integrated with arterials; (2) Trucks could be separated by type and speed. Truck travel on highways could be restricted to night-time; (3) Medians could be replaced and used to accommodate other modes of travel or even turned into park space; and (4) HOV (High Occupancy Vehicles) lanes are converted to dedicated lanes. These dedicated lanes will assist with initial transition to automated vehicles. The group of experts working on the street design in urban environment, 'complete streets', had two approaches, the first is based on providing a separated lane for automated vehicles. However, this approach would require building tunnels and bridges, especially at crossings. The second approach is based on the concept of 'self-organization', i.e., there would be no lanes, no curbs, no delineation, and no regulation. This could be however the most challenging scenario for automated vehicles. The space use would be changed and redefined, for example, drop-off and pick-up areas for automated vehicles replacing street parking, virtual traffic controls replacing the existing physical controls and fewer physical traffic signals. This available new space can be allocated for other modes of travel like cyclists and pedestrians.

Chen, Balieu and Kringos (*7*) used the finite elements modelling approach to analyse and investigate the potential consequences to the long-term service performance of practical physical road infrastructure, and mainly the pavement rutting performance, after the advent of the implementation of AVs on a large scale. The impact on the pavement rutting performance will be affected by several factors, such as vehicle's wheel wander, lane capacity, and traffic speed. The authors concluded that there are several influencing factors that will counterbalance their effects on the pavement. While the decreased wheel wander and increased lane capacity could bring an accelerated rutting potential, the increase in traffic speed would negate this effect. Therefore, the judgment whether the resulting effect is positive or negative, depends actually on the practical road and traffic conditions.

Somers and Weeratunga (*8*) wrote an internal report on the potential implications for main roads in Western Australia. The authors addressed various aspects in the report besides the impact on transport infrastructure, such as, mobility, ownership, and safety benefits. With respect to the infrastructure, the authors conclude that with fully automated vehicles (level 4), the safety margins adopted in road infrastructure design (such as: wide lanes, shoulders, guardrails, rumble strips) will mostly not be required. Furthermore, the authors indicate that automated vehicles will increase the throughput per lane and enable to decrease lane width. Lumiaho and Malin (*9*) in their research report to the Finnish Transport Agency 'Road Transport Automation - Road Map and Action Plan 2016–2020', also indicate the potential of reducing the width of lanes dedicated to automated vehicles.

Lutin, Kornhauser and MASCE (*10*) provide a relatively short overview of the implications of automated vehicles on the transportation engineering profession. With respect to the road design, the authors indicate that, platooning, for example, might require a special lane. The precise positioning of the vehicles will allow to reduce the width of the lane, while new wear patterns of the pavement would appear which would require changes to pavement design. The authors also indicate that the new reality might lead to redefinition of the speed limit and the way it is determined, for example dynamic speed limit based on the road and traffic condition and mix (automated and traditional vehicles). Carsten and Kulmala (*11*) indicate that automated vehicles could be programmed to drive more evenly across the whole width of the driving lane, thus reducing pavement wear.

2.2 Digital infrastructure

In the literature there are many studies that addressed different aspects of the digital infrastructure. Sanchez, Blanco and Diez (*12*) indicate that in order to achieve full advantage of vehicle automation, connectivity between vehicles, between vehicles and vulnerable road users, and between vehicles and the infrastructure is essential. To develop this connectivity, several challenges and milestones should be accomplished, including: affordable sensing technology, perception strategies, high-precision positioning, communication technologies, new-generation digital maps, HMI concepts, electronic architecture, reliable actuators, road infrastructure and signalling technologies, cloud computing, connectivity services, and development and validation methodologist, tools, and testing.

The scientific papers found in the literature were categorized into the following sub-topics: Sensors, connectivity and cloud, digital maps and road database, and exact positioning of the vehicle. The following paragraphs summarize these studies.

Sensors, Connectivity and Cloud

Birk, Osipov and Eliasson (13) describe in their paper the CRIS (Cooperative Road Infrastructure System) developed in the scope of the iRoad project in Sweden. The authors indicate that the uniqueness of CRIS is that the road surface itself becomes an intelligent entity. This means that the road surface is composed of nodes, called road marking units (RMU), these are intelligent electronic devices integrated in road markings of next generation consisting of two different sensors: a magnetic sensor and a high-performance accelerometer, and have the ability to measure and estimate properties of the road surface, vehicles and estimate traffic situations. The accuracy of the estimation depends on the distribution of the road marking units on the road. This will facilitate linking the driver with the car and the road side infrastructure, and support the driver in providing: (1) queue end warning; (2) warning of driving in the wrong direction on the highway (ghost driving); and (3) warning of the overtaking driver about the critical distance to the car driving in the opposite direction (overtaking assistance). The reliability of CRIS is still under research.

Rebsamen et al. (14) explored in their study the value of using existing infrastructure sensors (such as traffic cameras) to improve safety and efficiency of autonomous vehicles in a simulation experiment and a field test in an urban environment. The case study used was of a pedestrian crossing the road. The authors argue that an infrastructure sensor could provide essential information regarding the surrounding environment of the vehicle which sometimes (such as in a case of occlusion by objects or other vehicles) can be missed by the vehicle on-board sensors.

Authority and Zhang (15) made a review of studies on automated and connected vehicles. Based on this literature review, the authors summarize the infrastructural needs for the different levels of automation, and the infrastructure expansion needs. At level 4 automation, the following is needed:

- Speed limit beacons for controlling speed and regulating traffic flow through construction sites or inclement weather.
- Safety messages from roadway infrastructure for enhanced traffic signal operations.
- Warnings to drivers of unexpected queues.
- Magnetic nails/reflective striping for lane keeping.
- Infrastructure-assisted merging and lane changing, aided by RSUs.
- Investments in full swing for dedicated lanes to enable platooning of vehicles.

Gerla et al. (16) discuss in their paper the evolution from intelligent vehicle grid to autonomous, Internet-connected vehicles and vehicular cloud. The Internet of Vehicles will have communications, storage, intelligence, and learning capabilities to anticipate the customers' intentions. The authors investigated the advantages of vehicular cloud, and at the same time present the challenges it faces.

Eltoweissy, Olariu and Younis (17) in their position paper introduce the term Autonomous Vehicular Clouds (AVCs), which are autonomous clouds of vehicular computing, communication, sensing, power and physical resources. The main aim of the AVC is to provide on-demand solutions to events that cannot be dealt with reasonably in a proactive way or with pre-assigned assets. Unique characteristics of the AVC are the autonomous cooperation among vehicular resources and the ability to offer a seamless integration and decentralized management of cyber-physical resources. The authors illustrate in their paper the applicability of this concept in several cases that can be categorized under two scenarios: traffic management scenarios (such as synchronizing traffic lights after clearing an accident) and asset management scenario (such as management of parking facilities).

Hayeri, Hendrickson and Biehler (*4*) indicate in their paper that current radio advisories and ITS message signs will be obsolete in a fully connected environment where V2I and V2X will directly transfer the information to an on-board units in vehicles. However, in case of no connectivity, i.e. only autonomous cars situation, the autonomous car then can read the information presented on the ITS message signs using its video cameras. The authors indicate that signals at intersections will still be needed, despite connectivity between vehicles, to facilitate safe operation for bicyclists and pedestrians, and in case of connectivity failure. The authors however expect that V2I capabilities will reduce the overall cost of traffic management compared with the traditional ITS capabilities. The authors identify three initial steps that the Department of Transportation (DOT) can take to enhance safety through V2I DRSC enabled technologies, these are: (1) identify locations for roadside units that would generate substantial safety and/or mobility benefits such as high crash intersections, narrow roads, tunnels and sharp curves; (2) identify traffic signal systems and other ITS locations (e.g. toll facilities, ramps) that would need equipment (i.e. controller) upgrades; (3) collaborating/partnering with private companies to enhance data sharing capabilities.

Digital Maps & Road Database

TomTom (18) indicate that digital maps are needed for automated vehicles for purposes of navigation, planning, localization, and comfort. These maps should be highly detailed (3D lane geometry), highly accurate (sub-meter absolute, decimetre-level relative), and richly attributed (lane-level attributes, position landmark, road DNA). Road DNA provides robust and scalable positioning content.

Noh, An and Han (19) present and test a cooperative system by V2I communications for highly automated driving. This system consists of data fusion based situation awareness and distributed reasoning based situation assessment. The data fusion integrates road infrastructure with a high-precision road map to produce the V2I augmented map. This would not only not only extend the range of environmental perception but also improves the performance of situation awareness. The distributed reasoning evaluates the risky level of the current situation in terms of road infrastructures through the use of independent local experts. The authors tested the system in two scenarios, black ice and construction site, on a highway section in KATRI, South Korea. The authors concluded that the performance of the system was sufficiently reliable for highly automated driving.

Lee (20) proposed a design of a road database for self-driving vehicle which includes dynamic data (such as: temporarily closure of roads) as well as static data on roads using the Entity – Relationship model. The authors extracted 6 entities and 10 relationships as requirements of the road database. These entities are: location, node, link, waypoint, traffic light, and crosswalk.

Hu et al. (21) indicate that for automated vehicles, the road database is considered as the most fundamental element.

Bauer and Mayr (22) developed a road database system that takes into account for each location on the road the geometrical characteristics as in road construction planning, such as the curvature of the road. This detailed data of the road is needed in order to develop a Velocity Profile Planning Module, which adapts the speed of the vehicle based on the road design characteristics.

Bonnefoi et al. (23) present in their paper the two sub-projects of Safespot. One of these two is the COSSIB subproject, for Cooperative Safety System Infrastructure Based, where the applications are processed on the road side. This includes five sets of application processed on the road side, which are: hazard and incident warning, speed alert, road departure prevention, cooperative intersection collision prevention, and safety margin for assistance and emergency vehicle. These applications will improve road users' safety in major dangerous situations.

Shields (*24*) indicate in his presentation at the Automated Vehicle Symposium 2016, that some in-vehicle control processes can be helped by reliable knowledge of the road network, including:

- Information about blocked or hard-to-find elements such as some signs and traffic signals;
- Knowledge of the coming lanes that the vehicle should be in;
- Knowledge of coming curves, hills, and speed limit reductions;
- Knowledge of coming pavement surface quality;
- Recognition of signs in all languages and forms;
- Information about difficult weather conditions;

- Reduction in sensor recognition processing by providing guidance about non-moving road items;
- Improving relative positioning by using landmarks that have reliably known positions.

Exact Positioning of the Vehicle

Böhm and Scheider (25) indicate that the main challenges when it comes to cooperative systems between the vehicles and the infrastructure are exact geo-positioning of the vehicle, the matching of the event to the in-car map-database and the proper presentation to the driver. Furthermore, the authors emphasize that for cooperative systems targeting enhancing safety, lane-specific positioning is recommended. This can be done by a fusion of several in-vehicle sensors that lead to an optimum map matching process, and calibration of the On-Board-Equipment at gantries along the road network.

Rademakers et al. (*26*) introduce in their paper a new approach for accurate positioning of automated vehicles. This approach relies on combining multiple positioning methods and is based on Global Navigation Satellite System (GNSS) to obtain absolute position. The authors developed an affordable and sub-meter position accuracy method called: 'Single Frequency Precise Point Positioning (SF-PPP)'. This method uses a low cost receiver with single frequency, single antenna and single GNSS constellation (GPS). The receiver provides raw measurements to the SF-PPP algorithm which corrects them for different kind of errors. This method was ported to a low cost Commercial Off-The-Shelf (COTS) embedded platform in C++. The selected platform is a Raspberry Pi version 2 with a u-Blox NEO 7P GPS receiver. The corrections for the raw measurements are received from a network service via a 4G modem. The PPP method is validated with an RTK system which is cm accurate. The results of testing the method reached an accuracy of 0.5 meter in open area environments, while in more closed environments where obstructions are close to the road, and the effect of reflection decrease the level of accuracy to between 0.5 – 3.0 meters.

2.3 Summary

The search for scientific literature on the topic of infrastructure and automated vehicles revealed that there is a large research effort with respect to the digital infrastructure, including sensors, connectivity and cloud, digital maps and road database, and exact positioning of the vehicle, while for the physical infrastructure the scientific literature is scarce.

With respect to the physical infrastructure it was revealed that the existing scientific literature mostly assume that all vehicles are with automation level 4. There is a lack of studies which considers scenarios where there is a mix of vehicles, automated and traditional. Many of the reviewed studies indicate the possibilities of reducing the width of driving lanes, medians, and shoulders. However, this would require careful investigation on the implications on the pavement maintenance, and traffic safety in case of emergency situations. Also with respect to vehicle performance and sight distance, which are parameters that impact the design of the vertical and horizontal alignment, it is not foreseen to be changed dramatically, as passenger comfort limits the acceleration and deceleration forces that humans can tolerate, and environmental emissions concerns limit these values as well. Furthermore, in case only automation with no connectivity, vehicles will still have limitation of sight distance when there are obstacles, like trees, other vehicles, and by the road design itself (like crest curve or a bend). Projects in the US indicate the possibility of using managed lanes as dedicated lanes for connected and automated vehicles.

With respect to the digital infrastructure, connectivity between the vehicles and the infrastructure, between vehicles, and between vehicles and other road users, such as vulnerable road users is essential to utilize the full advantage of vehicle automation. This connectivity would require advancement in areas such as sensing technologies, precise positioning, and digital maps. Researchers indicated the additional benefit of using information from infrastructure sensors which otherwise can be missed if relying only on vehicles' sensors. Road signs and ITS message signs can still be essential in case of failure in connectivity, and in areas where vulnerable road users are present. For full deployment in real life there is a need for detailed digital maps especially in hectic urban environments, video camera monitoring, car sensors that work in all weather conditions, and G5.

3. Overview of Projects

There are several completed and on-going projects that address automated vehicles, vehicle platooning, cooperative systems, automated and cooperative systems, and infrastructure (see Figure 1). The focus was on projects that could have relation to the infrastructure, or in which the infrastructure component was addressed in the project. Therefore, it is not a comprehensive list of projects. Furthermore, projects related to the urban environment were excluded from this list.

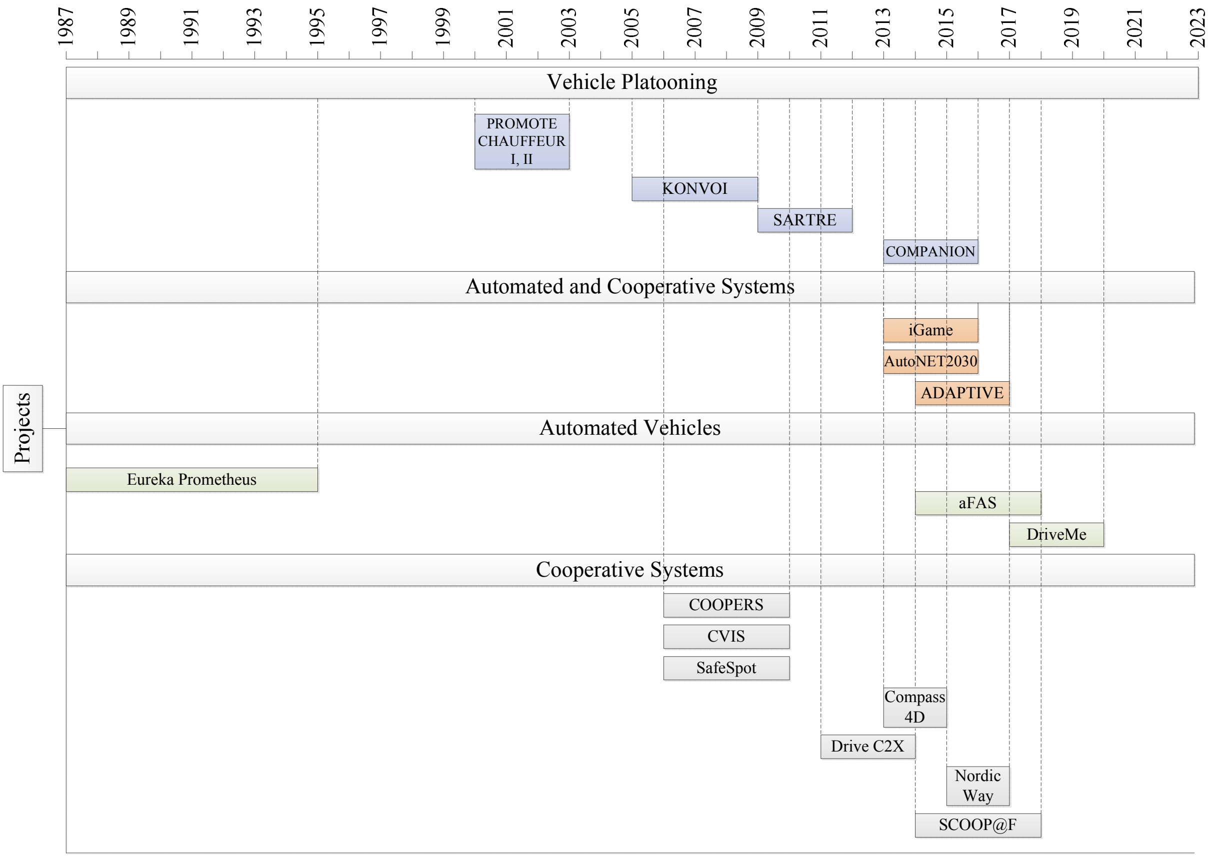

Figure 1: Overview of projects in the field of automated and cooperative systems.

The following sub-sections summarize these projects, their main goal, time plan, contribution, and key results.

3.1. Cooperative Systems (X2I)

Several projects were/are focused on the technology of cooperative systems, where fast and wireless exchange of information is in the core of this technology.

- **CVIS**

Project name: CVIS - Cooperative Vehicle Infrastructure Systems

Funding: European (6th RTD Framework Programme)

Duration: 07/06 - 06/10

Main goal: CVIS by Kompfner (*27*) focused on the core technologies underlying cooperative infrastructure systems. The main goal of CVIS was to create a *wireless* vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) network with an *open platform*, and *increase road efficiency and safety* through vehicle-infrastructure cooperation.

This was done by creating a peer-to-peer (P2P) network containing nodes with similar architecture and no particular hierarchy, making the system robust and scalable. Alongside the technical developments, several deployment enablers for cooperative systems have been found; mainly focusing on accessibility, security, utility, business models and reliability.

Key results: The main achievement has been the creation and validation of hardware and software prototypes of the in-vehicle and roadside elements of an integrated platform for "connected vehicle" applications and services. These elements were integrated at test sites and validated in field trials, including large-scale real life demonstrations at public events. CVIS has developed a technology platform providing wide-ranging functionality for data collection, journey support, traffic and transport operations and driver information.

Relation to Infra: this project focused on the digital infrastructure, and more specifically on the vehicle-to-Infrastructure communication. It also focused on techniques for enhanced vehicle positioning and the creation of local dynamic maps, using satellite positioning, radio triangulation and the latest methods for location referencing.

- **COOPERS**

Project name: COOPERS - Cooperative Systems for Intelligent Road Safety

Funding: European (6th RTD Framework Programme)

Duration: 02/06 - 01/10

Main goal: To define, develop and test new safety related services, equipment and applications using two way communications between road infrastructure and vehicles from a traffic management perspective. Vehicles connected via continuous wireless communication with road infrastructure on motorways exchange data and information relevant for the specific road segment. The road segment data is exchanged to increase overall road safety and enable co-operative traffic management, putting focus on road operators and drivers (*28*). Test results have shown that the system successfully increases safety by harmonising behaviour. However, impact at different penetration levels and traffic conditions has not been tested (*29*).

Key results: COOPERS provided vehicles and drivers with real time local situation based, safety related traffic and infrastructure status information distributed via dedicated Infrastructure to Vehicle Communication link (I2V). I2V will extend massively the responsibility and liability of the infrastructure operator compared with today in terms of reliability and accuracy of information to advice drivers / vehicles. The highest effect of I2V communications will be achieved in areas of dense traffic also known as areas where risk of accidents and traffic jams is extremely high. The real time communication link between infrastructure and vehicle can also be used vice versa for V2I communication utilising vehicles as floating sensors to verify infrastructure sensor data as primary source for traffic control measures.

Relation to Infra: the focus in this project is on the digital infrastructure, and on vehicle-to-Infrastructure communication. The real time communication link between infrastructure and vehicle can also be used vice versa for V2I communication utilising vehicles as floating sensors to verify infrastructure sensor data as primary source for traffic control measures.

- **SAFESPOT**

Project name: SAFESPOT - Cooperative systems for Road Safety

Funding: European (6th RTD Framework Programme)

Duration: 02/06 - 01/10

Main goal: One of the main aims of SAFESPOT was to develop a 'Safety Margin Assistant' which will extend 'in space and time' the safety information available to drivers by:

- using both the infrastructure and vehicles as sources (and destinations) of safety-related information, and definition of an open, flexible and modular communications architecture;
- developing the key enabling technologies: accurate relative localisation, ad-hoc dynamic networking, dynamic local traffic maps;
- developing a new generation of infrastructure-based sensing techniques;
- testing scenario-based applications to evaluate the impacts and end-user acceptability;
- defining the practical implementation of such systems, especially in the interim period when not all vehicles will be equipped;
- evaluating the liability aspects, regulations and standardisation issues which can affect implementation: involvement of public authorities from the early stages will be a key factor for future deployment.

Key results: the implementation and validation of the so-called 'safety margin assistant' that can provide drivers with all essential information about a potential risk sufficiently in advance to avoid the need to undertake emergency and risky manoeuvres, having sufficient time to properly react to collision risks.

Relation to Infra: Mostly to digital infrastructure, similarly to COOPERS and CVIS. This project resulted in Local Dynamic Maps (LDM) concept definition, implementation and demonstration. This key original result entered as a topic in the ETSI ITS TC standardisation activity. Analysis and experimentation of available and new sensors to be used at infrastructure level. New sensing techniques and wireless sensor networks were analysed.

- **A2-M2 CONNECTED CORRIDOR**

Project name: A2-M2 Connected Vehicle Corridor

Funding: Department of Transport as part of the Road Investment Strategy.

Duration: 2014-2017

Main goal: The main goal was derived from the Road Investment Strategy: "Incentivise the advancement of in-vehicle, vehicle-to-vehicle, and vehicle-to-infrastructure technologies, through the provision of roadside Wi-Fi: Target M2, M20, M26, M25". The creation of connected corridors is for initially to test, and then deploy, the technology –as a cornerstone of the UK strategy.

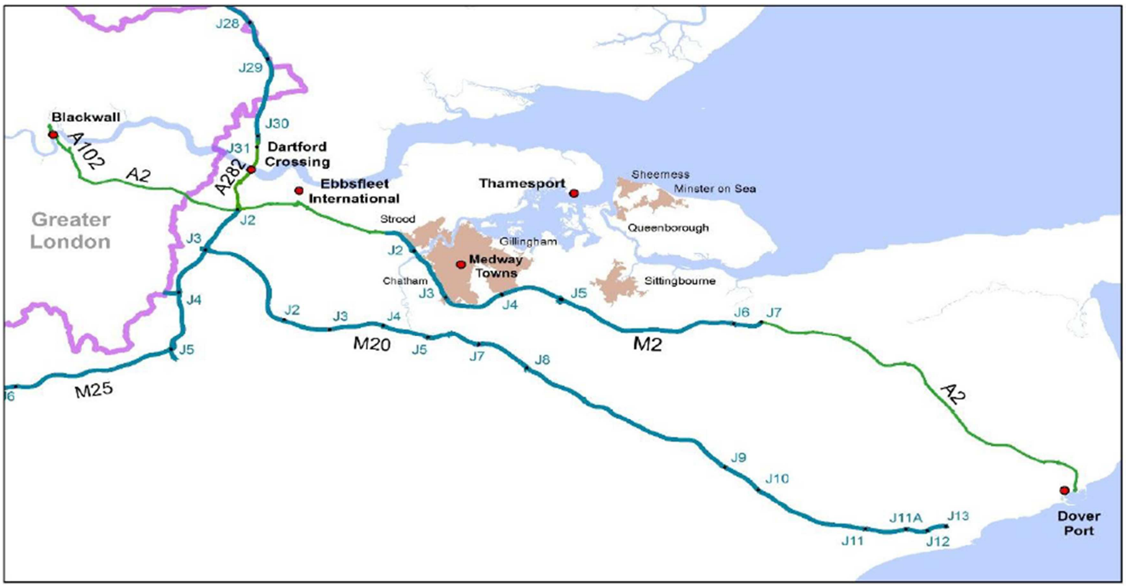

Figure 2: A2-M2 Connected Vehicle Corridor (Ref: Department of Transport).

The first deployment is planned to be in 2017.

Relation to Infra: Develop vehicle-to infrastructure technologies, through the provision of roadside WiFi.

- **Drive C2X**

Project name: Drive C2X

Funding: European Commission

Duration: 2011-2014

Main goal: to deploy a set of cooperative ITS functions at seven test sites in Europe in order to run Field Operational Tests. DRIVE-C2X supports the development of standard compliant (EU mandate M/458) cooperative systems implementations as well as their integration into vehicles (cars and motorbike) and road side infrastructure. A FESTA based test methodology support the assessment of cooperative driving based on Field Operational Test data as well as user feedbacks. The objectives are:

- Create and harmonise a Europe-wide field operational testing environment on cooperative systems.
- Evaluate cooperative systems through impact assessment, technical evaluation and user acceptance.
- Promote cooperative driving.

Key results: DRIVE C2X partners have successfully developed a cooperative ITS reference system, based on open software environment. This reference system was then validated and successfully implemented on vehicles and road side infrastructures at the DRIVE C2X test sites. Field Operational Tests were carried out at all the test sites and log data was collected and post processed to build a centralised cooperative ITS event database. The Cooperative driving evaluation, including the technical evaluation, the impact assessment and the user acceptance, confirmed the technical maturity of cooperative systems with promising safety impacts and positive user perception.

Relation to Infra: DRIVE C2X goes beyond the proof of concept done in previous projects like COOPERS, CIVIS and Safespot, and addresses large-scale field trials under real-world conditions at multiple national test sites across Europe to test the cooperative systems.

- **NordicWay**

Project name: NordicWay

Funding: Co-financed by the European Union

Duration: 2015-2017

Main goal: enable vehicles to communicate safety hazards through cellular networks on a road corridor through Finland, Norway, Sweden and Denmark. The project is a collaboration between public and private partners in the four countries, and is co-financed by the European Union within the Connecting Europe Facility programme 2015-2017. NordicWay demonstrates the concept of Cellular C-ITS service utilising 3G and 4G/LTE communication.

The end goal of the project is to lay the foundation for automated cloud communication via cellular networks with data generated by vehicle on-board sensors and the surrounding infrastructure. Communication will be established between vehicles, smart devices on the road, service providers, road administrators as well as other public administrations. A business model and a detailed scenario for the roll-out of cellular based C-ITS services will also be developed.

Three core Safety Related Traffic Information (SRTI) services will be provided:

- cooperative hazardous location warning;
- cooperative weather and slippery road warning;
- probe data services + additional national services;

The trial area comprises Main Road 1 (E18) Helsinki–Turku, Ring Road I and Ring Road III. The duration of the trial, starting on 11 May 2016, is one year.

Relation to Infra: this is the first large-scale pilot using cellular communication (3G and LTE/4G) for C-ITS. Nordic roads are characterised with long networks, low traffic volumes, 100% 3G coverage and very good 4G coverage, hot spots (tunnels and traffic signals) which facilitates the testing and evaluation.

- **SCOOP@F**

Project name: Système Coopératif Pilote @ France

Funding: Co-financed by the European Union

Duration: 2014-2018

Main goal: SCOOP@F is a Cooperative ITS pilot deployment project that intends to connect approximately 3000 vehicles with 2000 kilometres of roads. It consists of 5 specific sites with different types of roads: Ile-de-France, "East Corridor" between Paris and Strasbourg, Brittany, Bordeaux and Isère. SCOOP@F is composed of SCOOP@F Part 1 from 2014 to 2015 (ongoing) and SCOOP@F Part 2 from 2016 to 2018. Its main objective is to improve the safety of road transport and of road operating staff during road works or maintenance.

SCOOP@F Part 2 includes the validations of C-ITS services in open roads, cross border tests with other EU Member States (Spain, Portugal and Austria) and development of a hybrid communication solution (3G-4G/ITS G5). SCOOP@F Part 2 will cooperate with ongoing European pilot projects and the EU C-ITS platform. The project aims at reaching a critical mass in the number of tested vehicles, roads and services, in order to provide a representative evaluation of C-ITS. It also stimulates collaboration between automotive manufacturers and road operators, the exchange of best practice and innovation in solving common problems.

Relation to Infra: validations of C-ITS services in open roads, cross border tests with other EU Member States (Spain, Portugal and Austria) and development of a hybrid communication solution (3G-4G/ITS G5).

- **Compass4D**

Project name:

Funding: EU co-funded project

Duration: 2013-2015

Main goal: to prove the concrete benefits of cooperative systems for citizens, city administrations and companies. Compass4D has installed equipment and implemented cooperative services on almost 300 roadside units and traffic lights and on more than 600 vehicles, with over 1200 drivers involved in the pilot tests across seven European cities: Bordeaux, Copenhagen, Helmond, Newcastle, Thessaloniki, Verona and Vigo. Compass4D target users are drivers of buses, emergency vehicles, trucks, taxis, electric vehicles and private cars.

As the focus of Compass4D is on actual deployment, these services have been implemented through a combination of established technologies and available pre-commercial equipment. Dedicated short-range communication (ITS-G5) and cellular networks (3G/LTE) have been used, following ETSI TC ITS standards.

The Compass4D services are:

- Red Light Violation Warning (RLW)
- Road Hazard Warning (RHW)
- Energy Efficient Intersection (EEI)

Key results: The results of these pilot operations proved the benefits of such services towards safer and cleaner road transport in urban areas.

Relation to Infra: Dedicated short-range communication (ITS-G5) and cellular networks (3G/LTE) which have been used.

3.2. Automated Vehicles

- **aFAS**

Project name: Driverless automatically driving impact protection vehicle for construction sites on motorways.

Funding: Federal Ministry of Economic Affairs and Energy (BMWi)

Duration: 08/2014 – 07/2018

Main goal: The project will develop and test, in road traffic and under real conditions, an automatically driving vehicle, which will slowly drive fully automatically behind moving construction sites. Therefore, the focus of the "aFAS" project is the development of a rear impact protection vehicle which functions fully-automated and unmanned and increases safety, in particular also the safety of the operating staff.

Key results: On-going project.

Relation to Infra: Maintained lane marking is important for the operation of the automatically driving vehicle.

- **Drive Me**

Project name: Drive Me

Funding: European (7th RTD Framework Programme)

Duration: 2017-2020

Main goal: Large-scale autonomous driving pilot project with 100 self-driving Volvo cars (IntelliSafe Autopilot) with real customers for one year. The goal is to test automated vehicles (level 4) on public roads, ring around Gothenburg. The characteristics of the road are: 30 miles (~48 km) typical commuter roads around Gothenburg, with median dividers, 70 km/h, no intersections, no pedestrians or cyclists. There is plenty of separation between lanes.

The safety systems in the car are redundant (two systems for each functionality).

Key results: On-going project.

Relation to Infra: The project will investigate the infrastructure requirement for automated vehicles when they are mixed with traditional vehicles on existing motorways.

3.3. Cooperative and Automated Vehicles

- **AdaptIVe**

Project name: AdaptIVe – Automated Driving Applications and Technologies for Intelligent Vehicles

Funding: European (7th RTD Framework Programme)

Duration: 2014-2017

Main goal: AdaptIVe develops various automated driving functions for daily traffic by dynamically adapting the level of automation to situation and driver status. Further, the project addresses legal issues that might impact successful market introduction.

AdaptIVe research and development addresses four of six automation levels from the SAE scheme: assisted, partial automation, conditional automation, high automation.

The targets for research and developments are the following:

- Demonstrate automated driving in complex traffic environments. Test integrated applications in all possible scenarios taking into account the full range of automation levels.

- Enhance the perception performance in complex scenarios by using advanced sensors supported by cooperative and communication technologies.
- Provide guidelines for the implementation of cooperative controls involving both drivers and automation.
- Define and validate specific evaluation methodologies.
- Assess the impact of automated driving on European road transport.
- Evaluate the legal framework with regards to existing implementation barriers.

Key results: On-going project.

Relation to Infra: Lessons that can be potentially learned from this project are the adaptation of automation levels to different environments varying in complexity (such as highways versus urban environment). The project will also address the role of the digital infrastructure, V2I and I2V.

- **AutoNet2030**

Project name: Co-operative Systems in Support of Networked Automated Driving by 2030

Funding: European FP7 framework programme.

Duration: 2013-2016

Main goal: to develop and test a co-operative automated driving technology, based on a decentralised decision-making strategy which is enabled by mutual information sharing among nearby vehicles. The project is aiming for a 2020-2030 deployment time horizon, taking into account the expected preceding introduction of co-operative communication systems and sensor based lane-keeping/cruise-control technologies. By taking this approach, a strategy can be worked out for the gradual introduction of fully automated driving systems, which makes the best use of the widespread existence of co-operative systems in the near-term and makes the deployment of fully automated driving systems beneficial for all drivers already from its initial stages.

The inter-vehicle co-operation is meant not only among automated vehicles, but extends also to manually driven vehicles. Drivers shall receive maneuvering instructions on their HMI; the ergonomy and non-distraction of this new user interface shall be validated. This system shall be optimised to make safe, predictable, and efficient maneuvering decisions.

The technology developed in AutoNet2030 shall be validated through drive-testing and simulation tools. The final results shall be showcased in late 2016.

The objectives of the project are:

- Specifications of V2X messages for automated driving, also feeding ETSI ITS standardization.
- Development of maneuvering control algorithms for cooperative vehicle automation.
- Development of cost-effective on-board architecture for integrated sensing and communications.
- Development of a new HMI facilitating the interaction between manually driven and automated vehicles.

Key results:

- Cooperative Automated Driving can further improve safety, comfort and traffic efficiency;
- AutoNet2030 has defined use-cases and communication requirements for Cooperative Automated Driving:
    - Convergence between V2X and stand-alone AD.
    - Communication complements on-board sensors, no replacement.
- Current V2X Standards in EU are insufficient to meet Cooperative Maneuvering and Cooperative Sensing requirements of AutoNet203.
- AutoNet2030 has defined extension to EU standards for V2X communication and contributes to ongoing standardization activities in EU.

Relation to Infra: Mostly relates to digital infrastructure, and to extending the EU standards for V2X communication. Enhancing the perception performance in complex scenarios by using advanced sensors supported by cooperative and communication technologies.

- **Ko-HAF**

Project name: Ko-HAF – Cooperative Highly Automated Driving

Funding: Germany's Federal Ministry for Economic Affairs and Energy (BMWi)

Duration: 06/2015 – 11/2018

Main goal: The objective of Ko-HAF (Kooperatives, hochautomatisiertes Fahren - Cooperative highly automated driving) is the next significant step towards autonomous driving, the highly automated driving at higher speeds. These next-generation systems are characterized that the driver do not need to monitor permanently the system. However, the driver must be able to take over the control of the vehicle within a certain time reserve. For this purpose, forecasts for environment detection and the automation of the longitudinal and lateral control of the vehicle have to be improved. Within Ko-HAF a so-called Safety Server as back-end solution will be developed. The vehicles of different partners communicate via GSM with this Safety Server and apply the environmental performance of their own onboard sensors (e.g. quality of markings) in. In Safety Server, this information is collected, evaluated and compressed, so a digital map can be provided to vehicles which has the foresight range invoice required for highly automated driving.

Furthermore, the system will be tested under virtual conditions and also implemented into some test vehicles. The test area is located around the city of Frankfurt, in the triangle between Offenbacher Kreuz, Frankfurter Kreuz and Bad Homburger Kreuz on the motorways A3, A5 and A661. Figure 3 present the test routes:

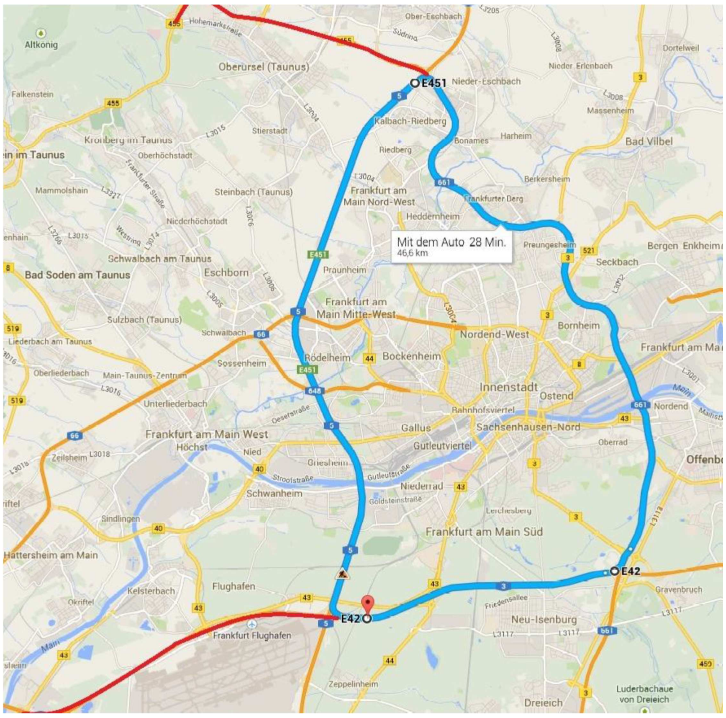

Figure 3: Planned test area around the city of Frankfurt.

Key results: On-going project.

Relation to Infra: Digital maps of the road environment and infrastructure equipped with roadside ITS stations.

- **iGame**

Project name: iGame

Funding: European FP7 framework programme.

Duration: 2013-2016

Main goal: speeding up real-life implementation and interoperability of wireless communication based automated driving. The i-GAME project is an applied research approach that employs a combination of research and demonstration in the interoperable exchange of messages (vehicle-to-vehicle and vehicle-to-infrastructure communication) in a standardized way.

Three scenarios are tested: merging on highway, cooperative intersection, and emergency vehicle warning.

There are four partners in the i-GAME consortium: the Dutch-based TNO and Eindhoven University of Technology (TU/e), the Spanish IDIADA and Viktoria Swedish ICT.

Key results:

The results of the i-GAME research project were made available to the teams so that they could be demonstrated in May 2016 in the second GCDC on the A270 highway between Helmond and Eindhoven according to three scenarios. Apart from the communication technology itself, it was the application in the vehicles that was key to enabling good manoeuvrability through automated acceleration, braking and steering.

This means that automated lane-changing on motorways was possible in three developed scenarios:

- Vehicles that merge or join a line of vehicles, known as platoons.
- Automated crossing and exiting a junction.
- Automated space-making for emergency vehicles in a traffic jam. (This third scenario is a demo scenario that is not part of the competition).

Relation to Infra: Digital infrastructure, V2I and I2V communication.

3.4. Vehicle Platooning

- **KONVOI**

Project name: Development and Examination of the application of electronically coupled truck convoys on highways

Funding: German national funding

Duration: 2005-2009

Main goal: The project focused on the topic platoons of heavy trucks, in which vehicles follow a lead truck fully automatically with small gaps to improve aerodynamics. At the same time the small gaps and a digital transmission of driving parameter via V2V communication enable a reduction of needed road area and an improvement of traffic flow.

Within the KONVOI project five experimental vehicles were provided with the necessary information, vehicle and automation technology to allow the build-up of short as well as long truck convoys on highways under real traffic conditions. Hence, the experimental vehicles within this project were provided among others with actuators for intervention in steering, drive train, brake, environmental sensors for object detection in near and far range as well as equipment for the inter-vehicle-communication (IVC) and a man-machine-interfaces (MMI) for the system's handling.

Key results: A platoon of four heavy trucks of the brands MAN and IVECO, which drove with gaps of 10 m, were developed and successfully tested in real traffic in 2009. Overall the platoon was operated for 3100 km in real traffic. Thereby the KONVOI system was the first platoon system worldwide, which was tested in real traffic. The trucks were equipped with a V2V and V2I communication system, a mono camera as well as lidar and radar sensors. On the basis of the real traffic drives it could be shown, that a safe operation of platoons is possible.

Relation to Infra: No direct relation to infrastructure, however the successful platooning with mixed vehicles on current highways, did not lead to the conclusion of a need to adapt the road design. However, it should be bared in mind the penetration rate of platooning in the test cases.

- **PROMOTE CHAUFFEUR I, II**

Project name: PROMOTE CHAUFFEUR I, II

Funding: European (5th RTD Framework Programme)

Duration: 2000-2003

Main goal: As a continuation of the CHAUFFEUR I project of the Telematics Application Programme, CHAUFFEUR II had two general aims. Firstly, the tow-bar technology demonstrated in CHAUFFEUR I was further developed into a system that can be transformed into a saleable product. At the end of CHAUFFEUR II, a "CHAUFFEUR Assistant", that supports the driver and allows him/her to follow another vehicle was developed, not only CHAUFFEUR equipped trucks, at a safe distance. Secondly, CHAUFFEUR II looked into the future. A fully operable truck platoon was realised. Typical Platoon manoeuvres were presented in a test track environment. CHAUFFEUR II does not only have technical goals. An important part of the project was system evaluation on a theoretical and a practical level. Especially cost/benefit analysis and user trials and workshops.

CHAUFFEUR II was tailored around the following two objectives:

- Realisation of three truck Platoon and demonstration of typical platooning manoeuvres in test track environment (Platooning).
- Extension of the Tow-Bar system developed in CHAUFFEUR I by intoperable system functions that allow following of any other truck and reduce drivers' workload (CHAUFFEUR Assistant). The CHAUFFEUR Assistant functions can be described as a combination of truck-adaptive-cruise-control (enhanced ACC) and lane keeping. Furthermore, advanced vehicle control features such as brake performance estimation to optimise braking capabilities were added.

Key results: In general, the CHAUFFEUR II project has proven the technical and operational feasibility of CHAUFFEUR Assistant and Platooning. Five prototype vehicles have been constructed, that do successfully perform the applications, which were defined in the beginning of the project.

Relation to Infra: No direct relation to infrastructure, however the successful platooning with mixed vehicles on current highways, did not lead to the conclusion of a need to adapt the road design. However, it should be bared in mind the penetration rate of platooning.

- **SARTRE**

Project name: SARTRE (Safe Road Trains for the Environment)

Funding: Financed by EU FP7

Duration: 2009-2012

Main goal: The aim is to encourage a step change in personal transport usage through the development of safe environmental road trains (platoons). Systems will be developed in prototype form that will facilitate the safe adoption of road trains on un-modified public highways with full interaction with non-platoon vehicles. The programme addressed the 3 cornerstones of transportation issues, environment, safety and congestion while at the same time encouraging driver acceptance through the increased “driver comfort”.

Key results: This project highlighted the potential for implementing road trains on conventional highways, with platooned traffic operating in a mixed environment with other road users.

- Control system performance is enhanced using real-time V2V data
- Five vehicle road train of mixed types
- Based on existing technologies with some software enhancements, combined with advanced control software
- Up to 90 km/h and 4 m gaps

    - 90 km/h is truck speed limit
- Interactions with non-platoon traffic
- Tested on test tracks and public roads
- Demonstrator system - not a production implementation
- Fuel consumption results
    - - 16% for following vehicles
    - - 8% for lead vehicle

Relation to Infra: No direct relation to infrastructure, however the successful platooning with mixed vehicles on current highways, did not lead to the conclusion of a need to adapt the road design. However, it should be bared in mind the penetration rate of platooning.

- **COMPANION**

Project name: Cooperative dynamic formation of platoons for safe and energy-optimized goods transportation.

Funding: EU FP7-ICT

Duration: 2013-2016

Main goal: COMPANION is a three-year European research project aiming at identifying means of applying the platooning concept in practice in daily transport operations: research on the actual creation, coordination, and operation of platoons. This will be achieved through the development of a real-time coordination system to dynamically create, maintain and dissolve platoons, according to a decision-making mechanism, taking into account historical and real-time information about the state of the infrastructure (traffic, weather, etc.). The consequence is that platoons will be no more composed just of vehicles with common origins and destinations, but they will be created dynamically on the road, by merging vehicles (or sub-platoons) that share subparts of their routes.

The project also examined how to present information to drivers regarding where they can join and leave platoons, as well as suggest common regulations for the EU that would permit shorter distances between trucks in the platoon.

Key results:

A total of four demonstrations were performed, most of the tests cases in the scope of the demo were successful. Two simulation based demonstrations and two on public roads permitted to verify almost all of the requirements. These open road tests have also been used to evaluate the driver acceptance of the system. The demonstration has been evaluated on highways and interurban roads of three different EU countries.

Relation to Infra: Similar to the previous projects, there is no direct relation to infrastructure, however the successful platooning with mixed vehicles on current highways, did not lead to the conclusion of a need to adapt the road design. However, it should be bared in mind the penetration rate of platooning is limited during these test cases.

3.5. Summary of projects in relation to infrastructure

The reviewed projects were categorized into four groups: cooperative systems, automated vehicles, cooperative and automated vehicles, and vehicle platooning. For each of the projects the relation to the infrastructure, if existed, was identified. Table 1 summarizes for each category the main points that were identified:

Table 1: Relation to Infrastructure for Each Project Group

Project group	Relation to Infrastructure
Cooperative systems	• Digital infrastructure, V2I and I2V; • Techniques for enhanced vehicle positioning; • Local dynamic maps; • New sensing techniques and wireless sensor networks; • Dedicated short-range communication (ITS-G5) and cellular networks (3G/LTE);
Automated vehicles	• Maintenance of lane marking; • Current on-going projects, such as the DriveMe project will investigate the infrastructure requirement for automated vehicles when they are mixed with traditional vehicles on existing motorways;
Cooperative and automated vehicles	• Digital infrastructure, V2I and I2V; • Adaptation of automation levels to different environments varying in complexity; • Extending the EU standards for V2X communication; • Enhancing the perception performance in complex scenarios; • Digital maps of the road environment; • Infrastructure equipped with roadside ITS stations.
Vehicle platooning	• No direct relation to infrastructure, however the successful platooning of trucks on conventional highways with other vehicles in these projects, did not lead to the conclusion of a need to adapt the current road design infrastructure to facilitate platooning. However, it should be bared in mind the limited penetration rate of platooning in these test cases.

4. Overview of Test Sites

There are multiple test sites around the world. These can be divided into three categories: test sites that are dedicated to testing automated and connected vehicles, living labs, and test sites that have the potential to be used for testing automated and connected vehicles in the near future. It can be noticed that in recent years there has been an increasing trend in many countries to develop such test sites especially those that are dedicated for automated and connected vehicles. The following sections summarize the main features of these test sites. The list below is comprehensive, but not complete.

4.1 Test sites dedicated for automated and/or connected vehicles

- **Saxton Transportation Operations Laboratory**

The Saxton Transportation Operations Laboratory (Saxton Laboratory) is a state-of-the-art facility for conducting transportation operations research. The laboratory is located at Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA. The laboratory enables FHWA to validate and refine new transportation services and technologies before committing to larger scale research, development, testing, and deployment phases, and serves as a gateway where Federal staff, contractors, and academia collaborate on cutting-edge research. The Saxton Laboratory also supports professional development and technology transfer of innovative service concepts and technologies through knowledgeable onsite staff, physical prototype systems, and advanced simulation capabilities.

The Saxton Laboratory comprises three testbeds:

- Data Resources Testbed (DRT) – Provides researchers with access to live and archived multisource transportation data to support transportation system performance measurement and transportation system management applications. The testbed assembles and archives data, hosts traffic datasets, analyses operations and performance, provides advanced visualization tools to improve situational awareness, and aids strategic program and tactical operations decision making.
- Concepts and Analysis Testbed (CAT) – Incorporates a repository of macroscopic, mesoscopic, and microscopic transportation models to allow simulation runs and visualizations of representative traffic networks and experimental strategies to improve safety (to some extent), mobility, and environmental performance. The testbed allows FHWA research staff to refine the experimental strategies through direct interaction with the models and to determine the potential value of potential strategies to various stakeholders.
- Cooperative Vehicle-Highway Testbed (CVHT) – Enables FHWA to explore enabling technologies for connected vehicles and to assess the potential of new transportation services based upon cooperative communication. The facilities, equipment, staff support, and other resources of this testbed enable FHWA researchers to develop prototypes, install systems in the roadside infrastructure and on vehicles, and conduct tests directed to investigate and answer key research questions needed to further connected vehicle research efforts.

The three testbeds help FHWA fulfil multiple operations research missions. For example, for a given test requirement, FHWA can validate fundamental technologies, collect data for proof-of-concept testing, and assess benefits through simulation by using the Saxton Laboratory testbeds.

The Saxton Laboratory includes the following facilities, which can support a broad range of research needs, particularly testing connected automation applications.

Connected Vehicle Fleet

- Radar and Ultra Sonic Sensors
- Front and Rear-Facing Cameras
- 5.9 GHz Dedicated Short-Range Communications (DSRC), Wi-Fi, and 4G Cellular/LTE Communications
- Data Collection and Processing Systems
- Localization System
- Electronic Throttle and Brake Control Units

Vehicle Preparation Garage

- Equipment Installation
- Maintenance and Storage

Connected Traffic Signal

- Roadside Communications (Roadside Equipment and Black Box)
- Information Processing

Connected Road

- 5.9 GHz DSRC
- Wireless Pavement Sensors
- High-Speed Cameras
- Weather and Global Positioning System Base Station
- Worldwide Interoperability for Microwave Access (WiMAX), Cellular, and DSRC Communications

- **Mcity Test Facility**

The Mcity Test Facility (closed facility) is located in Michigan, in the United Sates and was opened in July 20, 2015. It covers an area of 32 acres (4 km^2) at the University's North Campus Research Complex. It includes an urban, sub-urban and highway environment. Its goal is to facilitate testing the performance of *automated and connected vehicles* on different road facilities and as well connectivity to the infrastructure (V2V and V2I). It includes approximately five lane-miles of roads with intersections, traffic signs and signals, sidewalks, benches, simulated buildings, street lights, and obstacles such as construction barriers.

Its roadway attributes include: 1000' North/South straight section; various road surfaces (concrete, asphalt, brick, dirt); variety of curve radii; ramps; two, three, and four-lane roads; roundabout and "tunnels"; sculpted dirt and grassy areas.

Its road-side attributes include: variety of signage and traffic control devices; fixed, variable street lighting; cross walks; lane delineators; curb cuts; bike lanes; grade crossings; hydrants; sidewalks; and "Buildings" (fixed and movable).

Website: http://www.mtc.umich.edu/test-facility

Due to safety and confidentiality concerns, access is limited to those involved in testing and research. It is designed to support rigorous, repeatable testing of new technologies before they are tried out on public streets and highways.

Figure 4: Mcity Testing Facility.

About $10 million has been invested in the test facility, with funding coming from U-M and MDOT. MTC is working closely with 15 Leadership Circle member companies, each investing $1 million over three years, and engaging in thought leadership.

- **GoMentum Station**

GoMentum Station testing facility is located in California, the United Sates and was opened in October 2014. It is the result of a joint effort of the Contra Costa Transportation Authority and its partners, bringing together automobile manufacturers, communications companies, technology companies, researchers and public agencies with the aim of accelerating the next generation of transportation technologies. It covers 5,000 acre (about 20 km^2) featuring 20 miles of paved roadway. It facilitates testing, validation, and commercialization of connected vehicle (CV) applications and autonomous vehicles (AV) technologies to define the next generation of transportation network infrastructure. It also contains an urban environment.

Figure 5: GoMentum Station Testing Facility.

Website: http://gomentumstation.net/

- **AstaZero**

The name is a combination of ASTA - Active safety Test Area and Zero, which refers to the Swedish Parliament's vision for road safety with zero dead and seriously injured in traffic.

The AstaZero facility is located close to Gothenburg in the south western part of Sweden, where the climate allows all-year-round testing with warm summers and cold winters. The test site is only half an hour drive from Landvetter International Airport, and accessible by motorway.

The AstaZero was constructed for the development, testing, and certification of active safety systems. The test focus is on:

- Vehicle dynamics
- Driver behaviour
- V2V and V2I
- Functional reliability
- Communications technology

The test site facility consists of four test environments, where scenario based tests can be carried out in a repeatable and structured manner. These four test environments are: city area, multilane road, high speed area, and rural road as illustrated in Figure 6. The test site also has a 400 meter section for testing bicycle safety.

Figure 6: AstaZero test site facility.

<u>General Design</u>

Communication resources and technology:

- Wi-Fi coverage for the area;
- High speed internal connection in all control rooms and garages;
- Mobile phone coverage in the area;
- Video conference;
- V2V and V2I – installation prepared.

Roadside infrastructure:

- Conduit for electric power, fibre and communication/control. Installed along the full length of the acceleration roads, the multilane road and the rural road;
- Access points every 150 meters;
- Underpasses to remote side at each access point;
- V2V and V2I;
- Conduit to appropriate control rooms for future installations.

Differential GPS:

- Base station which covers the whole area;
- Target – Hunter systems with Real Time Kinematic (RTK);
- Video system synchronized to position.

Description of the Rural Road

The Rural road is specially designed for different tests of driver behaviour and is full of sudden obstacles such as wild animals (as dummies), slip roads and highways, at the same time as the monotonous environment makes it easy for the driver to lose concentration. It is approximately 5.7 km long. Half of it is designed for travelling at maximum 70 km/h and to other half for maximum 90 km/h.

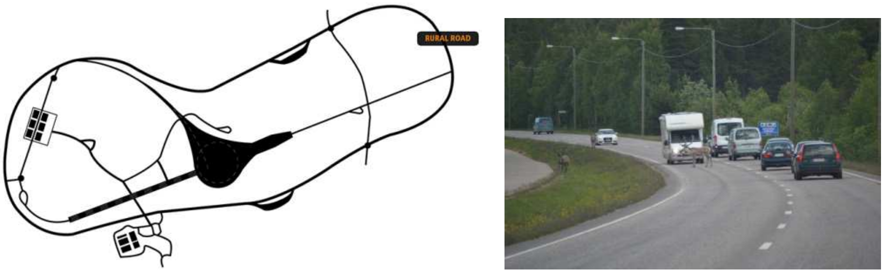

Figure 7: AstaZero Rural Road.

Its features include:

- Normal road standard/ safety.
- NOT for advanced driving.
- Slightly hilly, max 4.5% incline.
- For Bi-directional traffic.
- Normal setup=right hand traffic and one-way traffic.
- Foundation for traffic signs.
- Hidden access to public roads.
- Traffic signs showing: Distance, name of the place, curve radius.
- Electronically controlled signs, 4 pcs.

Prepared places for testing with different targets like pedestrians, cyclists, crossing vehicles, bus stops, etc.

Description of the City Area

A city environment where interactions with dummy pedestrians, cyclists, busses and other road users can be carried out. It includes varying street widths and lanes, bus stops, pavements, street lighting, building backdrops. The road system includes roundabouts, a T-junction, a return loop and a lab area.

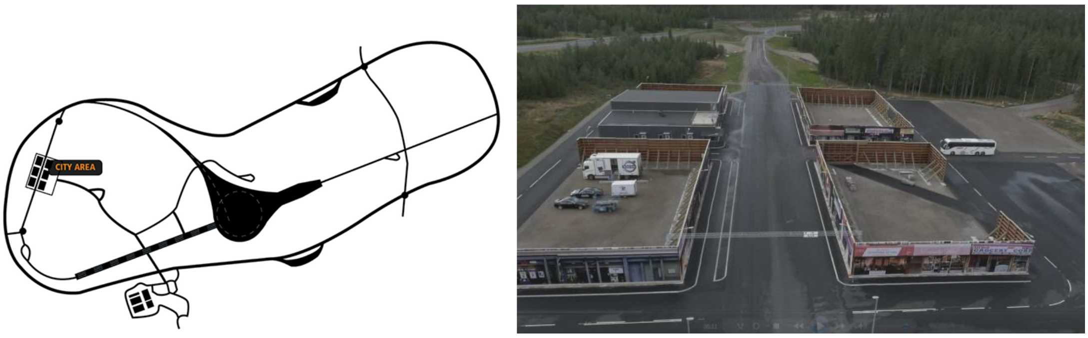

Figure 8: AstaZero City Area.

Its features include:

- Each block 40 by 25 meters, approx.
- Streets have a 2% incline for good drainage into sewage drains.
- Acceleration roads longer than 150 meters before the intersection.
- Main street equipped with "Portals" with traffic signs.
- Pavements, bike lanes and lane markings.
- Crossing street, 7 meters wide plus pavements.
- Pedestrians crossing with signs.
- Prepared foundations for additional traffic signs.
- Outlet to charge electric vehicles and batteries.
- Refuge, traffic signs, curbs and traffic lights.
- Equipment to generate various scenarios.

Description of the Multilane Road

The multilane area is 700 metres long and connected to the High Speed Area. It is possible to change the direction of travel in different lanes, as well as to build a temporary central barrier and different types of traffic barrier railings.

The whole area is lit to the normal standard for road lighting. The lighting is designed in four sections that can be individually switched on and off so that one can easily vary between lit and unlit environments. This will make it possible to run tests with repeatable lighting or with the track completely dark or with partial lighting.

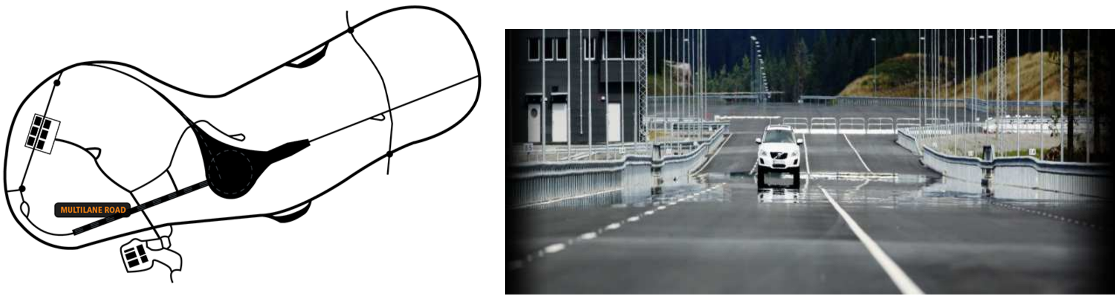

Figure 9: AstaZero Multilane.

Its features include:

- Four lanes with space for barriers.
- Acceleration road approx. 300 meters long, 7 meters wide with turning loop for long vehicles.

- 2% lateral incline for good drainage, split between lane 1 and lane 2.
- Small intersection.
- “Portal” with road signs.
- Separate control tower:
    - Two stories high for good visibility.
    - Platform on the roof for visitors and prepared space for 100 spectators.
- Parking space with outlets to charge electric vehicles and batteries.
- Warehouse for equipment like traffic signs and cones.
- Remote control of targets, balloon cars and driving robots.

Description of the High-Speed Area

The high-speed area is located at the center of the AstaZero facility. It consists of a circular area with drop-shaped entrances. The circle is 240 meters in diameter and has two acceleration roads. In the High Speed Area, a number of different avoidance tests can be carried out, including manoeuvres at very high-speeds (250 km/h). The tests are possible due to AstaZero’s comprehensive knowledge of measurement and positioning technology.

The High Speed Area is connected to the Multilane road and consists of a circle, 240 metres in diameter with “drop add-ons”. It slopes 1 percent laterally and is completely flat in the longitudinal direction, (flatness 1.0 acc. to IRI).

The High Speed Area has two acceleration roads. Acceleration road one is approximately 1 kilometre long. In addition to the two acceleration roads, it is also possible to use the multilane road for acceleration, which means vehicles can enter the High Speed Area from three different directions.

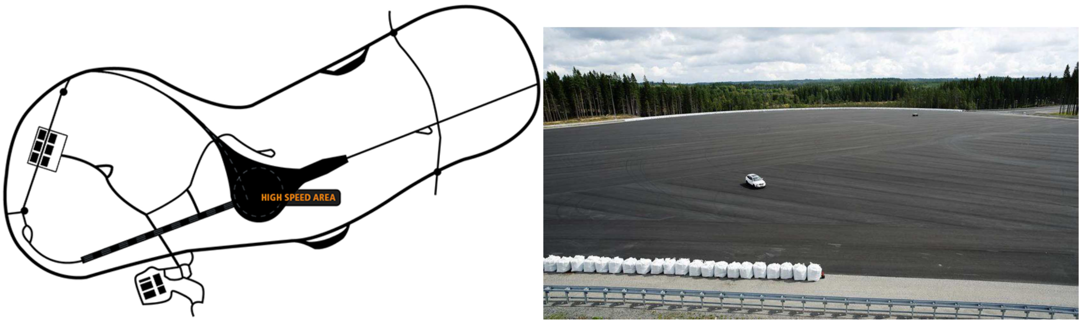

Figure 10: AstaZero High Speed Area.

Its features include:

- Asphalt acc. to SN75-80.
- Basic illumination.
- Rigid fences around the whole area with cushions in front.
- Turning loop for long vehicles (25,25 m) at the end and halfway with a width of 7 metres.
- Separate control tower.
- Two stories high for good visibility.
- Parking space with outlets to charge electric vehicles and batteries.
- Space for 10 cars plus one bus.
- Warehouse for equipment, traffic signs and cones.
- Remote control of targets, balloon cars and driving robots.
- Misc.

- Calibration area at the first turning loop. (for gyros)
- Conduit along the acceleration roads. (for future needs)
- Prepared area for 100 spectators.

Website: http://www.astazero.com/\

- **Virginia Testing Facilities**

Virginia Tech Transportation Institute has several testing facilities, including:

Virginia Smart Road: The Virginia Smart Road is a full-scale, closed test-bed research facility managed by VTTI and owned and maintained by the Virginia Department of Transportation (VDOT). The Smart Road, also sometimes called the Smart Highway, is a 2.2-mile-long (~3.5-km) 2-paved lane highway, controlled-access test track, completed in 2002 near Blacksburg, Virginia, home of Virginia Tech (VPI&SU), and the highway is being used as a transportation research facility for highway and bridge research as well as for vehicular systems research and for Intelligent Transportation Systems (ITS) research. Dispatchers monitor the Smart Road from a computer-equipped control center that is staffed 24/7. Researchers can directly and indirectly observe highway traffic and driver performance using surveillance cameras available in the control room. Engineers can also control the lighting and the weather on the Smart Road. Its features include:

- Three bridges, including the Smart Road Bridge (the tallest state-maintained bridge in Virginia).
- 24/7 access control and oversight with full-time staff that coordinate all road activities.
- Lighting and weather system controls.
- Safety assurance and surveillance.
- 7 roadside equipment units that facilitate connected-vehicle communications.
- 2 mobile roadside equipment sites.
- A connected-vehicle-compatible intersection controller model.
- 14 pavement sections, including an open-grade friction course.
- In-pavement sensors (that detect such factors as moisture, temperature, strain, vibration, and weigh-in-motion).
- A zero-crown pavement section designed for flooded pavement testing.
- AASHTO-designated surface friction testing facility.
- 75 weather-making towers.
- Artificial snow production of up to four inches per hour (based on suitable weather conditions).
- Production of differing intensities of rain with varying droplet sizes.
- Fog production.
- 2 weather stations with official National Oceanic and Atmospheric Administration (NOAA) weather available within one mile
- Variable pole spacing designed to replicate 95% of national highway systems.
- Multiple luminaire heads, including light-emitting diode (LED) modules.
- An optical fiber communication system.
- Ethernet fiber transceivers and Ethernet switches.
- A differential GPS base station for precise vehicle locating.

- A signalized intersection with complete signal phase and timing (SPaT) using remote controls
- Wide shoulders for safe maneuvering during experimental testing.

Figure 11: Virginia Smart Road.

- **Cooperative Intelligent Transport Initiative (CITI)**

Located in the Illawarra region, Sydney, Australia. The Cooperative Intelligent Transport Initiative (CITI) is a CITS testing facility (known as a 'testbed') is a large-scale CITS testbed dedicated to heavy vehicles. The area shown in Figure 12 outlines where the technology will be used, which includes Appin to the north, Port Kembla to the south and Picton to the west and includes Mount Ousley and Picton Road. The technology will only work when driving within this area. When you drive outside this area you won't receive any alerts on your display.

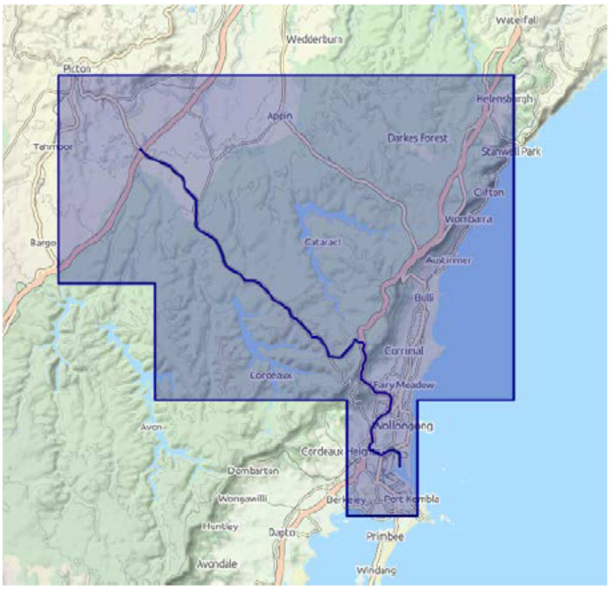

Figure 12: The area included in the CITI project.

Features of the CITI testbed:

- 60 vehicles fitted with CITS.
- A roadside transmission station broadcasts speed limit information to heavy vehicles about the 40km/h truck and bus zone down the Mount Ousley descent.
- Three intersections equipped with CITS to provide red signal information.
- A data collection and storage system.
- A licence from the Australian Communications and Media Authority to broadcast on the 5.9GHz radio spectrum

CITI allows heavy vehicle drivers to receive safety messages about upcoming hazards and potential crashes, such as: intersection collision warning, forward collision warning, heavy braking ahead warning, traffic signal phase information, and speed limit information. The messages come via technology attached to other vehicles, as well as structures such as traffic signals.

CITI is trialling connected vehicles and infrastructure, but not automated vehicles at this stage. The equipped infrastructure (signalised intersections and portable roadside trailers) are equipped with Dedicated Short Range Communication (DSRC) radio units that can send and receive data. The 5.9GHz bandwidth is used to do this. Currently heavy vehicles are equipped. In addition to this, there are two connected light vehicles and a motorcycle belonging to Transport for NSW that are being used for testing. In the coming month, 10 buses will be equipped, and next year the plan is to include light vehicles as well.

- **Gothenburg Test Site**

The Gothenburg test site is a large-scale functional test site located in the south of Sweden. The test site has been operated by SAFER JRU since 2008. It includes both a public site and a closed track. The test site is split into two regions, off limits for normal traffic: **Stora Holm**, a closed test track 15 minutes from the Gothenburg city centre, is used for safety critical and non-traffic regulation compliant performance testing as well as the large closed test track used by Volvo Cars and Volvo Trucks. The **City Race Track** in the middle of Gothenburg exists since October 2009 and has been used for demonstrations of cooperative systems during a high-level EU meeting. It is a closed track located 1 km from Lindholmen Science Park that can be used for development testing and demonstrations.

Altogether, available roads consist of more than 100 km of highway and urban roads, respectively, and more than 50 km rural road. There are more than 100 intersections equipped with traffic lights located along these roads.

The test site has particular climate conditions: tests which require snowy conditions can be performed here during the winter season from December to February. Winter tyres are required from December through March.

- **Texas A&M Testing Facility - RELLIS Campus**

Texas A&M Transportation Institute (TTI) is developing a test bed for testing connected and automated vehicle (CV/AV) applications and human-machine interfaces using vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle communication in a controlled environment. The RELLIS campus is conveniently located just 8 miles/15 minutes from Texas A&M University's main campus.

TTI has expanded in recent years in conducting connected and automated vehicle research at this campus. Last month they successfully tested and demonstrated a new Level-2 truck platooning system at this facility. They have DSRC 5.9 Ghz communication infrastructure on these roadways and TTI vehicles for research applications with this technology. They are developing other applications such a wrong-way driving detection system using connected vehicle technology and a transit/bus/pedestrian CV/AV test bed.

The testing area consists of two 1.2 mile (1.9 km) runways with several additional miles of taxiways and perimeter roads. This allows for both high-speed and low-speed testing. There is also an urban grid area that services the many buildings at the campus. This street network could be reserved and closed off for low-speed urban use testing (this had been done less frequently). Testing is already being conducted by Texas A&M University and TTI researchers. Outside firms could use the facilities.

There are plans to enhance these facilities as the RELLIS campus development continues.

- **SISCOGA - -SIStemas Cooperativos de Galicia**

This test site is located in the Northwest region of Spain, in A Coruña. It was inaugurated in March, 2002. The extensive ITS equipment allows a real time monitoring of the traffic situation in that area of Spain. The test site includes:

- More than 60 Km of roads controlled by the DGT North-West Traffic Management Center
- 21 Cameras
- 19 Variable Message Panels
- 10 high precision meteorological stations
- 30 Road Side Units.

The main goal of this test site is to:

- Prepare and implement a permanent “Intelligent Corridor in Spain to test and validate C2X systems.
- Realize a FOT on C2X systems with around 10 vehicles.
- Conduct impact assessment of cooperative technologies to improve traffic road safety and efficiency.
- Define and implement of evaluation methodologies applied to cooperative systems.
- Interoperability assessment among different C2X technology providers, vehicles and, eventually, different Member States.

- **Shanghai Automobile City**

This designated test area is designed for testing connected and automated vehicles technologies on urban roads. It was opened since around 2013. It is located in Shanghai, China and covers a total area of 7.4 km^2. This test site is led by SIAC (Shanghai Automotive Industry Cooperation). The use of the testing facility is limited to weather conditions with no snow.

- **Proving grounding of Research Institute of Highway, MOT**

This designated test area is designed for testing vehicle reliability, durability & connected and automated vehicles technologies on highways and urban roads. It is led by Research Institute of Highway, MOT. It is located in Beijing, and covers an area of 2.4 km^2. The development of this test site is in stages: since 1980s for vehicle reliability and durability; part is available for testing CAV since 2000+, and part is under construction. Equipment in this facility are being installed to generate snow, and fog in a tunnel.

4.2 Living labs

- **Virginia Connected & Automated Corridors (VAC/ VCC)**

The Virginia Automated Corridors (VAC) is a new initiative that will provide an automation-friendly environment that government agencies, original equipment manufacturers, and suppliers can use to test and certify their systems, providing a system migration path from test-track to real-world operating environments. These test corridors enable the testing of connectivity between the infrastructure and vehicles (I2V) and between vehicles (V2V), as well as automated vehicles. Testing of Level 4 automation. Some situations requires from the driver to take control, such as work zones, un-expected conditions. The proclamation, issued on March 2015 by the governor of Virginia, allows the testing of any automated vehicle on Virginia roads under the guidance of the Virginia Tech Transportation Institute (VTTI). The VAC features are:

- Multiple testing environments, including more than 70 miles of urban interstates and rural arterials in the Northern Virginia area, the Virginia Smart Road and Virginia International Raceway test tracks, and roadways in the Town of Blacksburg.
- Access to dedicated high-occupancy toll (HOT) lanes in conjunction with Transurban, which develops and manages more than 40 miles of express lanes located along the VAC.
- Pavement markings implemented in conjunction with the Virginia Department of Transportation (VDOT), which will maintain standards for both completeness of markings and retro reflectivity properties.
- High-definition mapping, real-time traffic and incidents, intelligent routing, and location cloud technology for automated and connected vehicles supported by HERE, a high-definition mapping business.
- Ubiquitous one-centimeter accurate localization facilitated by a multi-channel, high-precision global navigation satellite system with real-time kinematic corrections, an inertial navigation system providing dead-reckoning, and an update rate up to 100 Hz.
- Sophisticated, unobtrusive data acquisition systems that record time-synchronized data to the nearest millisecond using multiple (i.e., two to six) cameras and sensors.
- Remote monitoring and data streaming.
- Existing connected-vehicle infrastructure and systems installed along the Virginia Connected Corridors (VCC).
- No bond required for automation testing in Virginia; licensing and insurance provided through the Commonwealth, with Institutional Review Board approval and certification for safe human research involvement facilitated via VTTI.

The percentage of road miles in the VAC is consistent with the percentage of national road miles. Specific roadways of the VAC also were selected that had existing naturalistic driving data available to support comparative research.

Table 2: Characteristics of Virginia Automated and Connected Corridors.

VAC Roadway Environment	Use Case(s)	SAE Level(s) of Automation	Connected via DSRC, cellular and HD Mapping
Northern Virginia Highways and Arterials	Freeway Platooning Highway Autopilot Operation in Urban Setting	2-3	Yes
Town of Blacksburg	Urban Chauffeur Automated Taxi	4	No
Virginia's Smart Road	Closed Test Track	1-5	Yes
Virginia International Raceway	Closed Test Track	1-5	No
All Virginia Roads	Many	1-5	No

- **Dutch Integrated Test site for Cooperative Mobility (DITCM)Setting**

The Helmond smart mobility living lab provides a home for companies, education institutes as well as public and private research centres and test facilities in the field of automotive technology and smart mobility. Founded in 2009, and will be fully operational in 2020. The living lab is composed of two roads N270 and A270.

The N270 main road that runs through the Helmond city centre is equipped with a state-of-the-art Cooperative Traffic Controller network that is operational on 25 crossings on a stretch of 2 km.

The A270 motorway is equipped with 56 cameras for real-time vehicle detection and tracking and 20 ITS G5 road side units.

The DITCM test site is located on the A270 and N270 roads in between the cities of Helmond and Eindhoven. It consists of both a motorway and urban environments. The DITCM test site is 8 km long, with 6 km of motorway. Roadside equipment is responsible for vehicle detection and V2X communication. All other equipment is placed indoor and includes sensor fusion facilities, application platforms and a traffic management centre.

- **Cooperative C-ITS Corridor**

Collaboration between Austria, Germany and the Netherlands in implementing cooperative ITS corridor. The corridor runs between Rotterdam, Breda, Tilburg and Eindhoven to Venlo (A16 - A58 - A2 - A67) and will provide two cooperative ITS services:

  - Warning at road works (Roadworks Warning)
  - Sensor Data from vehicles (Vehicle Probe Data)

The corridor will become operational in 2020. The basic technology was successfully tested in practice during several demonstration projects. The year 2016 will be devoted to pre-deployment and to further refine the specifications. The Road Works Warning service will be tested in practice at several road sections, over a longer period. Not only in the Netherlands, but also coordinated across the borders. The time frame is as following:

- 2015 Research stage, exchange of information with suppliers
- 2016 Pre-deployment: refinement of the specifications and extensive testing
- 2017 Start of the tender process
- 2018 Operational services

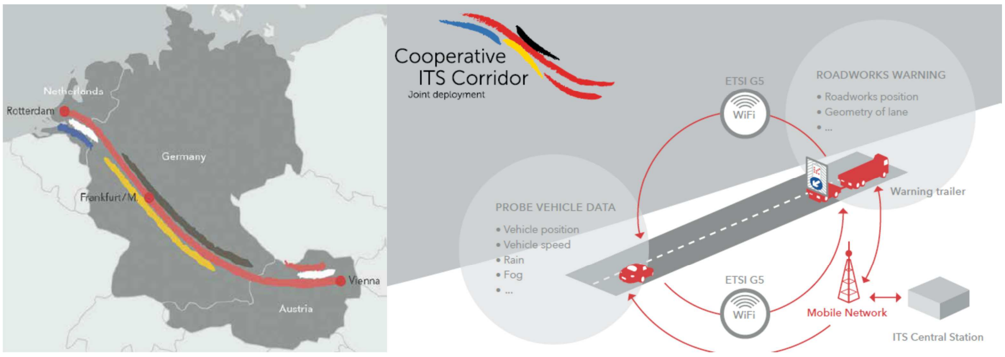

Figure 13: C-ITS Corridor.

The main objectives are to: improve road safety, reduce incidents and traffic jam, more efficient use of the road network, reduce CO2 emissions.

- **A9 Autobahn**

A 529 km long stretch of the A9 motorway in Germany, which runs from Munich to Berlin, will become a Digital Motorway Test Bed. Its objective is to test, assess and develop new technical advances in automated driving.

This test corridor will facilitate trials for new partially and highly automated technologies. Connectivity in the form of car-to-car (C2C) or a car-to-infrastructure (C2I) communication is also one of the priorities in the Digital Motorway Test Bed: connecting cars to each other and to the relevant traffic infrastructure.

The Federal Government has joined forces with companies in the automotive industry and the digital technology sector to operate tests in the A9 corridor, in a "Digital Motorway Test Bed". This will be used by the research community of the automotive and digital technology sector and academia to test their innovations. It promotes trial operations of highly automated to fully automated vehicles. It is focused on connected driving using car-to-car and car-to-infrastructure communications with sophisticated sensor technology, high-precision digital maps and real-time communications with the latest transmission standards.

- **A12 in Tyrol**

This road section in Austria, with a total length of 20 km, From km72 at Ampass extending to km52 at Vomp, is operated and maintained by ASFINAG. It is a 2+1 configuration (2 lanes and the hard shoulder) in both directions. It includes 20 single-direction overhead gantries, 11 gantries in the Innsbruck to Kufstein direction (one free text, all others VMS) and 9 gantries in the opposite direction from Kufstein to Innsbruck (all VMS). It is prepared for testing cooperative systems. As an example, part of this road section was used in the COOPERS project (*29; 30*).

- **Drive Me**

In the Drive Me project Volvo will test its automated vehicles on a public road test route of 80 km (ring road of the city of Gothenburg) in 2017. The route is in a suburban environment, with average speeds of 70km/h, with no pedestrians and plenty of separation between lanes. No specific infrastructure adjustments or equipment were installed. The purpose is to test the performance of the automated vehicles on regular public roads.

Figure 14: Drive Me test route.

The Drive Me fleet will consist of 100 XC90s equipped with the latest self-driving technology. Detailed digital map of the route will support the operation of these vehicles.

The objective is to learn from experience on the: trust of customers in the technology, understand how human drivers react to and interact with self-driving cars, learn about how to change the physical and virtual world (and infrastructure) to support self-driving cars.

- **UK CITE**

A project to create a globally unique test environment for connected and autonomous driving in the UK. UK Connected Intelligent Transport Environment (UK CITE).

This will enable automotive, infrastructure and service companies to trial connected vehicle technology, infrastructure and services in real-life conditions over the next two-and-a-half years on roads in Coventry and Warwickshire in the West Midlands.

Initial off-road tests will take place at HORIBA MIRA in Nuneaton, Warwickshire, before the trials start on the public roads as early as 2017.

The connected environment will be on 40 miles of roads within Coventry and Warwickshire, and will seek to understand how the technology can improve journeys, reduce traffic congestion and provide in-vehicle entertainment and safety services through better connectivity.

The UK Connected and Intelligent Transport Environment (UK CITE) creates a real-world-lab for companies to test how connected and autonomous vehicles (CAV) can interact with communications infrastructure (so called V2X). The project will install the relevant infrastructure along sections of the

M42, M40, A45, A46 and Coventry city centre. This test environment will be available to other vehicle manufacturers or fleet users who wish to test V2X technologies. It will act as a world class research asset to attract R&D to the UK.

CAV test vehicles will examine the impact of V2X on road safety, traffic flow and the ability to provide other services like WiFi. Cyber-security will also be included from the outset.

V2X will improve a vehicles journey through the road network. E.g. in case of an accident instead of an expensive gantry on the motorway a connected car could provide warnings and guidance to the driver, or an autonomous vehicle could respond automatically. The impact on the UK road network will be simulated based on these trials - enabling the UK to get the most benefits from CAV for the least infrastructure cost.

- **SPAIN SPA**

The location of this pilot in Spain is the public roads Burgos -Vigo -Madrid + E90 from Madrid. The test duration was one week. The goal was to perform functional tests of driving automation on open roads (highways, motorways) to evaluate system performances. This concerned driving automation levels 2,3,4. Standard Map and GPS were used.

Experimentations had to take place in ”normal” weather conditions. Sunny, rain, day or night. Extreme conditions such as heavy Fog, heavy rain or heavy snow (or a combination) had to be avoided. In this case the system is deactivated. During the experimentation of November 2015, the weather was compatible with the system.

In terms of infrastructural support, to facilitate deployment of the system(s) used, lane marking and good traffic sign positioning are needed for the system. It is also important that the infrastructure fulfil perfectly the standards or norms : track width, lane marking colours, traffic signs, working zone signalization.

Additional (or different) measures to be taken compared to the pilot phase include the provision of some information of infrastructures: eHorizon, HD Map of driven zones.

- **Tre VTT**

The Automated driving test site in Tampere, Finland is located in the city area and the focus is on urban automation scenarios (see Figure 15).

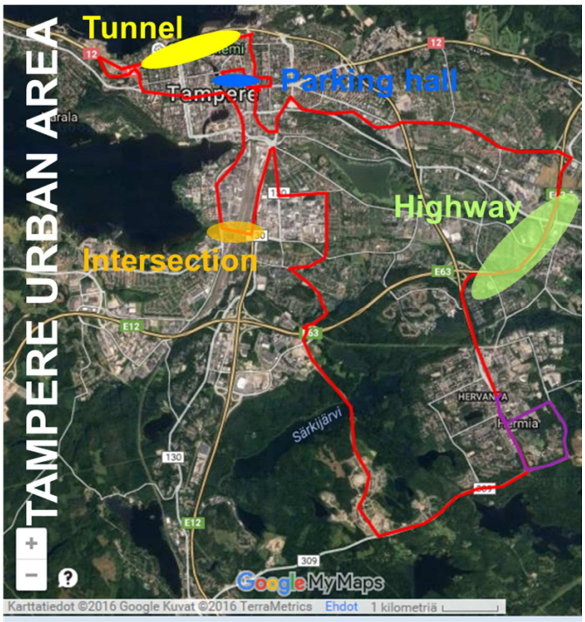

Figure 15: The test site route round the Tampere city.

The test site is generated for serving the Finnish SME companies to test new technologies in the area and enter to the autonomous driving markets. Adverse weather conditions are one of the key topics in the area. The intention is to verify suitable on-board sensors technologies which performance is sufficient even in rainy or snowy conditions.

Scope: 2 vehicles will be equipped with the level 3-4 automation functions. The special 20 km route across the city is planned for testing tunnel, left turning and parking automation functions and feasibility of the ICT infrastructure of the city for automated vehicles.

Involved system(s):

- The transport ICT infrastructure of the city including maps and geographical landmarks.
- Cooperative traffic lights in intersection area
- Route plan in real traffic
- 2 vehicles with having flexible embedded software to add and modify the automated functions

Duration: The test site will be alive at least 2019. However, further development will done continuously and after 3 years it will be very different compared to the existing implementation.

Level of automation is used and whether connectivity is applied: The support system from the infrastructure side is designed currently for L2 automation. However, one aim of the project is to further develop the ICT infrastructure to support L4 automation when the practical requirements are clear.

Other relevant information: The first step is to generate the facilities and vehicles which are adapted to the city environment and tackle the intersection, tunnel and parking problems. This is intended to be ready by middle of 2017. Then (2018-2019) penetration of the automated vehicles will be increased and, ITS G5 stations and monitoring facilities will be added to the Tampere infrastructure.

The infrastructural support that is needed to facilitate this pilot include ITS G5 stations and later on 5G mobile broad band network. The ICT infrastructure of city is used for ensuring the pedestrian zones and lanes of the automated vehicles. ICT infra is the supporting function for on-board autonomous driving systems.

For conducting the pilot the following changes and equipment installation were made:

Changes: The cooperative traffic lights are implemented to the intersection where left turning in real traffic is developed.

Equipment installation: The cooperative ITS G5 fog and road weather monitoring unit has been added to the area. The additional sensors are planned on 2018. WiFi base stations and camera monitoring for the fleet management will be implemented. Fleet management and data centre will be created to Hervanta.

Lesson learned from the pilot: The map data in the city is not reliable enough for autonomous driving support in hectic city environment. The improvements will be continuously conducted when the test drives go further. Lack of camera monitoring in big intersection makes difficult to develop reliable in-vehicle autonomous functions. Therefore, monitoring equipment is planned to improve electronic horizon of the self-driven cars.

- **SOHJOA**

The goal of the SOHJOA is piloting automated electric busses on public roads and streets to increase automated driving awareness among cities, organisations and citizens. This concerns automation level 4, with no connectivity. Two automated and electric busses, EasyMile EZ10, are used in the pilot.

Duration: 1st phase: July 2016–November 2016, to be continued in 2017.

Location: Finland: public urban road in Helsinki, Espoo and Tampere as illustrated in

Helsinkis **Espoo** **Tampere**

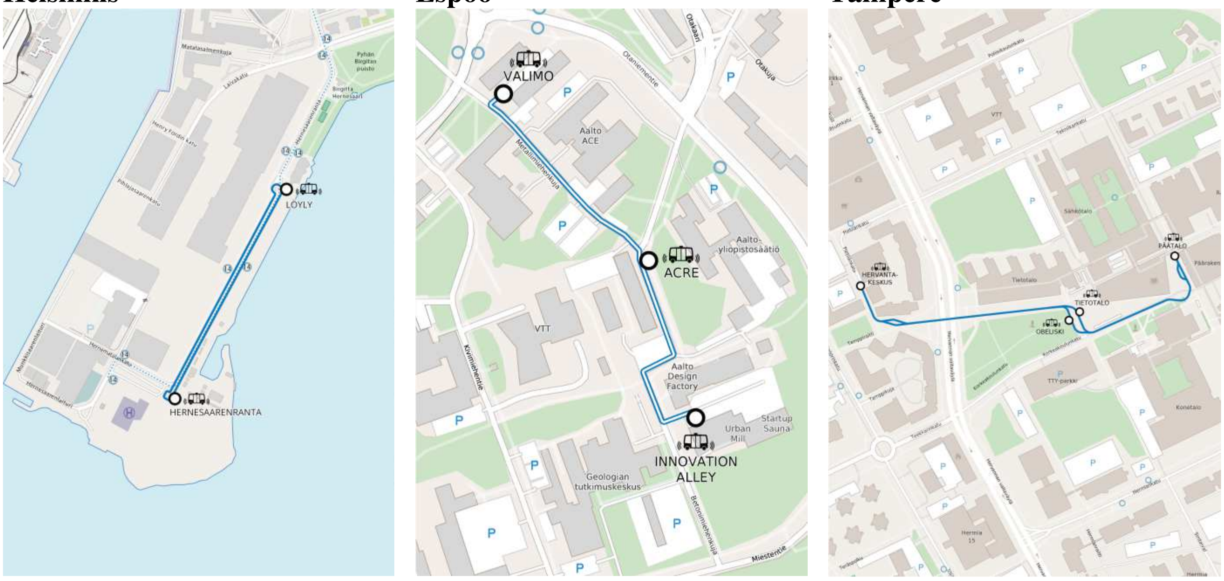

Figure 16: Public urban test sites in Finland.

In terms of the changes that had to be made for the pilot, it included some traffic signs that were added or removed, street marking that were added, and temporary traffic lights that were installed. No additional equipment or signage were needed. The manufacturer specified that the vehicle could not be operated in snowy or icy conditions. For large-scale operation, the AV should function in all conditions.

One observed “requirement” was that the route where the vehicle was operated should have a minimal occurrence of illegal / unspecified parking as these situations proved problematic for fluent operation.

- **Aurora**

The main goal for the test site in Aurora is to validate and assess impacts and performance of automated vehicle (SAE levels 2-4) functions in snowy and icy conditions, and to gather information about what kind of possibilities/ requirements exist for scaling up. The test site will be operational between 09/2017–03/2019. The location of the test site is in Finland: Fell Lapland and other TEN-T road network, see Figure 17.

Figure 17: Aurora test site in Finland.

Changes to road infrastructure are planned (sensors, markings, roadside equipment). Wireless telecommunications network will be available on the test roads (4G/5G).

- **Connected Mobility Arena (CMA) Stockholm**

Connected Mobility Arena (CMA) Stockholm is located in Kista, the "Silicon Valley of Stockholm". CMA Stockholm is a collaborative effort driven KTH, Scania and Ericsson, and it is led by ITRL.

The CMA is creating an open test platform and architecture using 5G cloud services and automated fleets in the suburbs of Kista, Stockholm between 2016-2020. Aiming at public (shared) transport, and working with several aspects: technology, vehicles, system design, service design, business, and users.

4.3 Test sites with potential use for automated and connected vehicles

There are several test sites that belong to the automotive industry which have the potential to be upgraded for testing automated and connected vehicles. The Table below summarizes some examples of these test sites:

Table 3: Examples of Test Sites with Potential for Automated and Connected Vehicles' Testing.

Test site	Country	Characteristics
Transportation Research Center Inc.	Ohio, USA	The 7.5-mile (12.1-km) oval test track contains four asphalt lanes on the front straightaway and curves and five asphalt lanes on the back straightaway. http://www.trcpg.com/
Ford Proving Grounds	Belgium, USA England, Australia	Wide range of road types and events. High speed track, durability/special surface roads, grades, EMC facility, road simulators, fire resistance facility, vehicle dynamics area https://www.fordlpg.com/en/index.htm https://en.wikipedia.org/wiki/Ford_Proving_Grounds
General Motors Proving Grounds	USA, Germany Mexico, Europe Australia, Asia	Wide range of road types and events. https://en.wikipedia.org/wiki/Ford_Proving_Grounds
Volvo Cars' proving ground Hällered	Sweden	Volvo test track, opened in 1973. The outer oval is 6.3 km long. http://www.silhouet.com/motorsport/tracks/hallered.html
Autoliv's Carson City	Sweden	Carson City—located in the real town of Vårgårda, an hour from Volvo headquarters in Gothenburg—is the world's only purpose-built simulated city for testing active safety systems. It's run by Autoliv, a Swedish supplier that researches and manufactures safety components for nearly every car brand in the world. http://www.caranddriver.com/features/how-automotive-safety-tech-is-developed-feature

4.4 Summary of infrastructure characteristics needed for testing and facilitating automated and connected vehicles

Following the overview of the different test sites that exist around the world, this section summarizes the characteristics that are needed for testing, versus characteristics that are needed for facilitating automated and connected vehicles. Table 4 summarizes those characteristics.

Table 4: Infrastructure Characteristics Needed for Testing and Facilitating Fully Automated and Connected Vehicles.

Infrastructure characteristics needed for testing and facilitating fully automated and connected vehicles	**Additional infrastructure characteristics needed for testing fully automated and connected vehicles in dedicated test sites**
• Road side units (to facilitate V2I and I2V)	• Simulation platforms (macro, micro, miso)
• Wi-Fi and 4G/5G cellular communication	• Vehicle preparation garage
• Data collection and processing systems/ control centers	• Various road environments (urban, sub-urban, rural, motorways)
• Global Positioning System (GPS) & high definition digital maps	• Fixed and movable buildings and obstacles
• High precision meteorological stations	• Various traffic facilities (signs, traffic control devices, street lighting, bike lanes
• Video cameras for real-time vehicle detection, tracking, and monitoring	• Variety of curve radii, longitudinal slopes, ramps, roundabouts, intersections, tunnels, central barriers, flat crown slope to test flooding, etc.
• In-pavement sensors (to detect moisture, temperature, strain, etc.)	• Various road surfaces (concrete, asphalt, brick, dirt, slip roads)
• Pavement and lane marking	• Dummy pedestrians, cyclists, busses
• Good traffic sign positioning	• Open high speed area (as in AstaZero, 250 km/h)
• Lane width based on standards	• Control of the environment lighting conditions
• Working zone signalization	• Artificial weather production such as: rain, snow, fog (as in Virginia Smart Road)
	• Wide shoulders for safe maneuvering

5. Overview of Initiatives

Many initiatives were established to promote and advance the development and deployment of automated and connected vehicles, in the Netherlands and worldwide. Table 5 below summarizes those initiatives with respect to their origin country, leader, and years. The goal of each initiative and further information are summarized in the excel sheet.

Table 5: List of Initiatives on Automated and Cooperative Vehicles.

Initiative	Country	Leader/ Initiator	Years
Taskforce Dutch Roads	Netherlands	CROW	
European Truck Platooning Challenge	Netherlands Sweden, Germany Denmark, Belgium	Netherlands	2016
Declaration of Amsterdam	Netherlands	Ministry of Infrastructure and the Environment	2016
InfraQuest workshop 'Infrastructure for automated driving'	Netherlands	InfraQuest, TU Delft	2016
Innovation Expo 2016 'Smart Roads'	Netherlands	Holland ConTech, NLIngenieurs, Bouwend Nederland	2016
GCDC –Grand Cooperative Driving Challenge	Netherlands	Helmond	2016
Smart City Challenge	USA	USDOT	2015-2016
Florida Automated Vehicles (FAV) initiative	USA	Florida Department of Transportation	From 2014
FAST Act: Advanced Transportation and Congestion Management Technologies Deployment Initiative	USA	Federal Highway Administration	2016-2020
Drive Sweden	Sweden	Volvo	2015-2027
TSS- Test Site Sweden	Sweden	Lindholmen Science Park	2006
Singapore Autonomous Vehicle Initiative (SAVI)	Singapore	Land Transport Authority (LTA, and Agency for Science, Technology and Research (A*STAR)	2014-2019
SIP-ADUS - Cross Ministerial Innovation Program (SIP)	Japan	Japanese government	2014
Cooperative Intelligent Transport Initiative (CITS)	Australia	NSW Center for Road Safety	2016
ADVI - Australian Driverless Vehicle Initiative	Australia	The ADVI Centre of Excellence	2015
Horizon 2020 Call on Automated Road Transport –ART 2016-2017	EU	EU	2016-2017
GEAR 2030 roadmap initiative	EU	EU Commission	2016
Oettinger Roundtable	EU	EU Commission	2016
Cooperative Intelligent Transport Systems (C-ITS) platform	EU	EU Commission	2014
iNext	EU	BMW, Intel, Mobileye	2016-2021
STRIA - Strategic Transport R&I Agenda	EU	EU	2016

6. Summary of Vehicle Automation Implications on Infrastructure

This section summarizes, based on insights from the current scientific literature, projects, test sites, and initiatives, the implications of vehicle automation on the infrastructure for each SAE level of automation (in each case assuming 100% penetration level). According to Shladover (*31*) level 5 will not be here until 2075, while level 3 is problematic because of the difficulty to attain drivers' attention after being out of the loop and because some automakers simply will not attempt level 3. However, level 4 automation will probably be realized within the coming decade. In Table 6 a first attempt was made to summarize the requirements from the physical infrastructure to facilitate vehicle automation, followed by Table 7 which summarizes the requirements from the digital infrastructure. These results should be considered with caution, as many of the findings from the scientific literature were not explicitly based on empirical data and results, but on experts' opinions.

Table 6: Physical Infrastructure Requirements to Facilitate Vehicle Automation.
(E-Essential; G2H- Good to have; NE- Not Essential; ? - Unknown)

Physical Requirement	L1	L2	L3	$L4_{toc}$	$L4_{Shuttle}$	L5
Lane markings	?	E	E	E	NE	G2H
Sufficient friction coefficient	E	E	E	E	NE	G2H
Traffic signs	E	E	E	G2H	NE	NE
Lighting	?	?	?	?	?	?
Traffic signals at intersections in urban areas (vulnerable road users)	E	E	E	E	NE	E
Current standards for width (lane, shoulder, median, clear zone)	E	E	E	E	NE (can be reduced)	NE (can be reduced)
Emergency stop zones frequency	?	?	?	?	?	?
Current standards for sight distance	E	E	E	NE With connectivity, (can be reduced)	NE	NE with connectivity, (can be reduced)
Current standards for road curvature	E	E	E	?	?	?
Current speed limits	E	E	E	NE with connectivity, (can be increased/ dynamic)	Not essential	NE with connectivity, (can be increased/ dynamic)
Transition areas	?	?	?	?	?	?

Table 7: Digital Infrastructure Requirements to Facilitate Vehicle Automation.
(E-Essential; G2H- Good to have; NE- Not Essential; ? - Unknown)

Digital Infrastructure Requirement	L1	L2	L3	$L4_{toc}$	$L4_{Shuttle}$	L5
Wireless communication beacons and sensors (roadside V2I/I2V)	G2H	G2H	G2H	E	G2H	E
V2V communication	?	?	?	NE	?	?
Cloud based digital maps	?	?	?	E	E	E
Exact positioning of the vehicle	?	?	?	E	E	E

Table 8 summarizes the impact of vehicle automation on the infrastructure specified for each level of automation (in each case assuming 100% penetration level). For each of the impacts, a proposed measure, if indicated by the literature, is specified in the table.

Table 8: Impact of Vehicle Automation on the Infrastructure.

Phenomenon	Proposed measure/s
Pavement rutting	• Introduce variability • Increase maintenance frequency • Increase durability of asphalt • Increase of traffic speed
Monitoring road friction coefficient	No information
Loads on bridges	Disengage the platoon when entering the bridge (Truck platooning challenge)
Physical separation and segregation: 1) from hazards; 2) between travel directions; 3) between different levels of vehicle automation	No information
Space required/ reduction	No information
Maintenance of road traffic signs (colours) – to be recognized by vehicle sensors	Computer Vision and Machine learning algorithms (example from (*32*))
Maintenance of roadside infrastructure units	No information
Data handling and data storing	No information

As can be noticed from Table 8, there are many knowledge gaps with respect to the impact of vehicle automation on the infrastructure, and the possible measures that can be applied to mitigate or counteract those impacts.

7. Gaps in Knowledge & Future Research Directions

Based on the reviewed scientific literature, projects, test sites, and initiatives, several knowledge gaps with respect to the physical and the digital infrastructure are identified. These are summarized as following:

Physical infrastructure:

- The scientific knowledge with respect to the physical infrastructure is relatively scarce compared to the digital infrastructure;
- There is a lack of research regarding the needed changes in the road geometric design at different penetration levels of vehicle automation and mix of different automation levels. Among the key findings in the Automated Vehicle Symposium 2016, breakout session about ‘"AV-Ready" Cities or "City-Ready AVs"?’, is that the co-existence of automated vehicles and conventional vehicles will be a long (and potentially messy) period;
- From the capacity point of view it is not clear whether the current road network will need to be expanded (adding more lane, road links) to accommodate the traffic demand in the future;
- There are no empirical studies regarding the implications of reducing the lane width, and other cross section elements (such as the shoulder width, median) on the traffic safety performance, and safety perception of drivers/passengers;
- There are few research studies about the implications of automation on pavement rutting under different traffic conditions;
- There is no systematic research regarding the acceleration and deceleration forces that humans can tolerate, or regarding human acceptance of gaps in traffic (such as overtaking gaps, merging, or at intersections);
- No research was found about the implications of automation on load of bridges, and on the structural safety of bridges;
- Most platooning projects were conducted with few platoons, and with no special conditions, as road work or traffic jam, which require research, especially in sensitive locations, like weaving sections, on-ramps, and off-ramps;
- It is not clear whether maintenance of lane-marking (*33*) (retroreflectivity, contrast ratio, width) and lane-marking in general will be needed in the future for camera-based vision systems, and what would be their role if precise positioning is further developed;
- There is no knowledge yet regarding the needed changes in infrastructure for scaling up, and therefore, large scale field operational tests are needed.

Digital infrastructure:

- Further development and improvement of accurate positioning of automated vehicles. In the Automated Vehicle Symposium 2016 (Breakout Group Title: Traffic Flow Of Connected Automated Vehicles), it was indicated that cheap and accurate positioning technology is critical to CACC (Cooperative Adaptive Cruise Control) implementation but is yet a challenge;
- There is a need to develop accurate and dynamic digital maps of the infrastructure and its surrounding, including details regarding the geometric design of the road. In this regard Japan

has an extensive HD base map, and has been working through a cross -ministerial program to develop methods of acquiring and providing dynamic data. However further research is needed;

- There is still no clear picture of the required infrastructure sensors, ITS traffic management, and their role and necessity to facilitate safe traffic operation with automated vehicles, on different types of roads;
- Data amount and data handling; how to collect the appropriate data, how to share the date, and how to store the data. it is still not clear who will handle the large amount of data in the cloud. Among the key findings in the Automated Vehicle Symposium 2016, breakout session about ‘Enabling Technologies’, it was concluded that ‘Data ownership and privacy are essential engineering and policy considerations’;
- Further research is needed on fusion of multi sensing and information for scene understanding and prediction;
- There are several studies and projects about connectivity between vehicles, but only few recent projects (PROSPECT, X_{CYCLE}) about connectivity between vehicles and vulnerable road users. Among the recommended actions suggested in the Automated Vehicle Symposium 2016, breakout session about interactions between automated vehicles and vulnerable road users is to work towards a universal language for AV/VRU communication.

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Appendix A

List of questions of interest to Rijkswaterstaat in relation to the different projects and test sites.

Questions:

1. Can you briefly describe the pilot? (goal, scope, involved system(s), duration, location, etc) and also explicitly mention which level(s) of automation is (are) used and whether connectivity is applied.
2. What infrastructural support is needed to facilitate this pilot? (open question)
   - 2.1. Does the pilot take place on public roads or on a designated area (test track, closed roads, private parking lot, etc.)? Can you provide a map or description of the area?
   - 2.2. Did you make changes (add or remove something) to the area where the pilot takes place? If so, please describe.
   - 2.3. Did you install equipment (e.g. WiFi, sensors, camera's) on the road side to facilitate the pilot? If so, please describe.
   - 2.4. Did you install signage to indicate that a pilot takes place in the area?
   - 2.5. Have you specified under what weather conditions (e.g. snow, hail, sleet, rain, fog, etc.) the pilot cannot take place?
3. What do you think is needed, in terms of infrastructural support, to facilitate deployment of the system(s) used? Does scaling up also effect the infrastructural requirements?
   - 3.1. Are there additional (or different) measures to be taken compared to the pilot phase? If so, please describe
   - 3.2. Are there additional (or different) requirements compared to the pilot phase? If so, please describe (e.g. requirements for security or durability of roadside equipment)
   - 3.3. Where there any changes in the requirements based on the experience of the pilot? If so, please describe?