



THE FUNCTIONAL SAFETY OF ROAD INFRASTRUCTURE IN THE CONTEXT OF AUGMENTED CCAM PHYSICAL, DIGITAL AND COMMUNICATION (PDI) INFRASTRUCTURE SOLUTIONS

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Abstract

The Augmented CCAM project aims to advance the large-scale deployment of Cooperative, Connected and Automated Mobility (CCAM) solutions by developing Physical, Digital and Communication (PDI) infrastructure concepts to support CCAM. To assess the impact of the proposed PDI improvements, an evaluation framework covering eight different impact areas has been created. The objective of the work in the second impact area is to assess the functional safety of the infrastructure in relation to automated vehicles using two key performance indicators: Infrastructure readiness for CCAM and Disengagement rate. The first indicator is based on the five-layer Augmented CCAM PDI support classification scheme, which summarizes all physical, digital and communication elements considered relevant for extending the operational design domain of automated vehicles. The Disengagement rate primarily refers to advanced driver assistance systems that transfer control to the driver in various real-life situations. The paper presents an example of evaluating the functional safety of the infrastructure using these two indicators, demonstrating a (notable) improvement in infrastructure maturity and test vehicle performance when the PDI service was engaged.

Keywords: CCAM, augmented CCAM, physical, digital and communication infrastructure, PDI services, infrastructure functional safety

1 Cooperative, connected and automated mobility

CCAM is the EU's approach to developing connected, cooperative, and automated transport systems. This approach combines digital communication, intelligent infrastructure, and automation with the aim to provide safer, more efficient, and sustainable mobility across Europe. Cooperative, connected and automated mobility (CCAM) refers to the integration of:

- cooperation and coordination between vehicles, infrastructure, and road users
- connectivity, where vehicles communicate with other vehicles and infrastructure
- automation, involving self-driving or highly automated vehicles.

This is enabled through various elements and services, such as:

- traffic control (traffic signs, traffic lights, rules etc.)
- road infrastructure (lane information, geometry, crossings, etc.)
- weather conditions
- illumination conditions
- road pavement conditions
- traffic conditions (safety related events, emerging road works, traffic capacity, volume, etc.)
- surrounding traffic

- digital services (C-ITS Day 1, Day 1.5, Day 2, Day 3+ services, HD maps, digital twins, etc.)
- communication enablers
- digital enablers (ITS stations – RSUs, cellular network base stations, infrastructure perception sensors/surveillance systems, fleet management centers, weather radars, AI-enabled cameras, detection of volatile vehicles, etc.) [1].

The European Commission adopted a strategy for C-ITS in 2016 to support the deployment of connected and cooperative mobility across the EU by preventing a fragmented internal market, establishing a common EU regulatory framework, supporting research and investment, addressing cybersecurity and data protection, and promoting international cooperation on automated mobility [1]. Key related initiatives include:

- C-ITS platform: a collaboration between EU institutions, industry and Member States to develop a shared vision for deploying connected transport systems, provide recommendations for interoperability and deployment strategies, and offer solutions for issues such as data protection, security, and hybrid communication
- C-Roads platform: a network of EU countries and road operators testing real-life deployment of C-ITS services and ensuring cross-border interoperability
- CCAM testing platform: an expert platform established to coordinate open road testing, pre-deployment of automated mobility, and cooperation across research and innovation activities [1].

The European Commission also established the CCAM Partnership under the Horizon Europe program to accelerate the development and deployment of automated mobility technologies in Europe. The CCAM Partnership is a European public–private partnership formed through a Memorandum of Understanding between the European Commission and the private sector represented by the CCAM Association [2]. The partnership coordinates research and innovation activities across Europe to support large-scale deployment of CCAM technologies and the transition towards connected and automated road transport systems. Its main goals include:

- improving road safety and reducing traffic congestion
- reducing the environmental impact of road transport
- ensuring inclusive and accessible mobility for people and goods
- strengthening the competitiveness of the European automotive and mobility industries [2].

The CCAM Association represents industry, research organizations, and other stakeholders participating in the partnership. Contributing to the design of Horizon Europe calls for proposals related to CCAM projects is one of the association’s roles and responsibilities.

2 Augmented CCAM project

2.1 The project’s main contributions to CCAM

The Augmented CCAM – Advancing Infrastructure Readiness for Cooperative, Connected and Automated Mobility project aims to accelerate the infrastructure-led deployment of CCAM in Europe by improving the readiness of road infrastructure, including physical, digital, and communication infrastructure (PDI). The project provides frameworks, tools, and validated evidence to help road operators and policymakers prepare infrastructure for automated and connected vehicles [3]. The key project contributions include:

- Infrastructure classification and framework: The project developed a physical, digital and communication Infrastructure (PDI) support classification scheme, which establishes a

common framework for identifying and evaluating infrastructure elements required for CCAM services. This helps stakeholders understand infrastructure requirements for different automation levels and operational contexts and supports interoperable planning across Europe

- Evaluation and impact assessment frameworks: Augmented CCAM introduced evaluation methodologies and key performance indicators (KPIs) to assess infrastructure-enabled CCAM solutions. These assessments examine impacts on traffic safety, efficiency, environmental performance, infrastructure safety, and some others
- Planning and decision-support tools: The project created several open and interoperable tools to support infrastructure planning and investment decisions, including an Infrastructure Readiness Assessment Tool to evaluate current infrastructure maturity, an Infrastructure Planning Tool to prioritize infrastructure investments, and a collaborative tool to continuously improve the infrastructure classification scheme.

These tools support long-term planning and “no-regret” infrastructure investment strategies [3]. The framework and tools were validated through 13 use cases at seven test sites in France, Spain, and Latvia, as well as a virtual test site. Demonstrations covered scenarios such as vulnerable road user protection, traffic management optimization, emergency vehicle prioritization, and automated driving support. The project also introduced a structured Technology Readiness Level (TRL) evaluation methodology, combining internal assessments with independent expert reviews to objectively measure the maturity of CCAM solutions [3]. With its outputs, the project directly addresses Integrating CCAM into the transport system, the fourth of the seven thematic clusters from the CCAM Partnership Strategic Research and Innovation Agenda. The project also promotes collaboration among stakeholders, including infrastructure operators, vehicle manufacturers, technology providers, policymakers, and research organizations. This collaborative approach supports the development of coordinated strategies for CCAM deployment across Europe.

2.2 Assessment of PDI services

The deployment of CCAM is one of the most transformative developments in the European transport system. Automated and connected vehicles offer improvements in safety, efficiency, sustainability, and accessibility. However, the successful deployment of CCAM technologies depends not only on the vehicles themselves but also on the readiness of the PDI that supports automated mobility services. An important component of the project is the impact assessment framework, which evaluates the effects of PDI-enabled CCAM services across several domains as described earlier. The assessment is based on real-world pilots, traffic simulations, digital modelling and infrastructure readiness assessments conducted across the project’s test sites.

The impact assessment framework developed in Augmented CCAM is designed to evaluate the performance and effects of PDI-enabled CCAM services. The framework provides a systematic methodology for analyzing the outcomes of infrastructure investments and technological innovations. The framework considers multiple dimensions of impact, including:

- traffic safety
- traffic efficiency
- infrastructure functional safety
- environmental sustainability
- service reliability
- trust and cybersecurity
- driving behavior
- socioeconomic costs and benefits.

This comprehensive approach enables stakeholders to evaluate not only technological performance but also broader societal impacts. The framework also defines thirty-five key performance indicators (KPIs) to measure the effectiveness of CCAM infrastructure solutions. These indicators enable consistent comparison across different pilot sites and deployment scenarios. A comprehensive overview of all KPIs, including clear definitions and calculation procedures, is provided in one of the project reports [4]. By combining empirical testing with modelling and simulations, the project provides robust evidence on the effectiveness of infrastructure support services.

2.3 Infrastructure functional safety

The infrastructure functional safety impact area of the Augmented CCAM impact assessment framework uses two key performance indicators: Infrastructure readiness for CCAM and Disengagement rate.

2.3.1 Infrastructure readiness for automated mobility

One of the important impacts assessed in the project concerns the technological advancement of infrastructure systems supporting automated mobility. The project introduces a harmonized PDI support classification scheme, which categorizes infrastructure elements required for five escalating levels of automated driving: from conventional sensing and planning infrastructure to augmented and orchestrated acting infrastructure for mixed fleet operation. This classification helps stakeholders identify infrastructure gaps and prioritize investments. The classification scheme supports interoperability across European transport systems by providing a common reference framework for CCAM infrastructure requirements. It enables infrastructure managers and operators to evaluate the readiness of roads and communication networks for automated mobility services. An online Infrastructure Readiness for CCAM Assessment Tool [5] was developed to assess the CCAM maturity of infrastructure based on the classification scheme. This tool supports road operators by enabling them to:

- map road segments
- define infrastructure characteristics
- answer readiness-related questions
- compare segments with and without specific PDI
- generate readiness scores [6].

After creating road segments, the tool allows users to perform assessments by selecting segment-related elements and answering questions related to these elements (figure 1) and CCAM support services. Finally, the tool provides an overview of the maturity of the mapped road segments, with scores in percentages of the five escalating layers of infrastructure automation (figure 2). Comparing scores for infrastructure in its current support condition for CCAM and after investing in improvements shows the benefit of investing in PDI-related enhancements.

Segmentation Assessment

How to assess the segments in this table?

Segment-ID (click button below to begin assessment)	Parameter RoadType	Available Infrastructure-Elements	Available Connectivity	Copy segment answers from selected segment
26290	<input type="radio"/> All <input checked="" type="radio"/> Highway <input type="radio"/> Rural <input type="radio"/> Urban	<input type="checkbox"/> Bridges, Tunnels <input type="checkbox"/> Pedestrian/cyclists crossings <input type="checkbox"/> Traffic Lights <input type="checkbox"/> Tunnels <input type="checkbox"/> Intersections <input type="checkbox"/> School zones <input type="checkbox"/> Limited access zones <input type="checkbox"/> Merge lanes <input type="checkbox"/> Loading zones	<input checked="" type="checkbox"/> 3G, 4G <input checked="" type="checkbox"/> 5G <input checked="" type="checkbox"/> Short-range communication using RSUs	26290 Apply answers from segment in list to this segment 26290/>
63254	<input type="radio"/> All <input checked="" type="radio"/> Highway <input type="radio"/> Rural <input type="radio"/> Urban	<input type="checkbox"/> Bridges, Tunnels <input type="checkbox"/> Pedestrian/cyclists crossings <input type="checkbox"/> Traffic Lights <input type="checkbox"/> Tunnels <input type="checkbox"/> Intersections <input type="checkbox"/> School zones <input type="checkbox"/> Limited access zones <input type="checkbox"/> Merge lanes <input type="checkbox"/> Loading zones	<input checked="" type="checkbox"/> 3G, 4G <input checked="" type="checkbox"/> 5G <input type="checkbox"/> Short-range communication using RSUs	26290 Apply answers from segment in list to this segment 63254/>

Figure 1 Area of the Infrastructure Readiness for CCAM Assessment Tool dedicated to the assessment of road segments

Segment-ID	Score Layer A	Score Layer B	Score Layer C	Score Layer D	Score Layer E
26290	0%	42%	33%	64%	80%
63254	0%	26%	17%	27%	81%

Figure 2 An example of final assessment scores

2.3.2 Disengagement rate

Disengagement refers to situations in which the advanced driver assistance systems (ADAS) transfer control to the driver in challenging situations, or when the driver feels insecure and decides to take back control of the vehicle. The disengagement rate is calculated by dividing the number of occurrences of disengagement by the total number of repeated tests of the project-developed PDI services. The following figures show examples of the percentages of tests passed and failed: figure 3 for the baseline case, and figure 4 for the experimental case. Comparing the results, a notable improvement can be observed when the PDI service is engaged: the number successfully passed tests increased from 16.7% to 90.2%.

Baseline Scenario (without PDI)

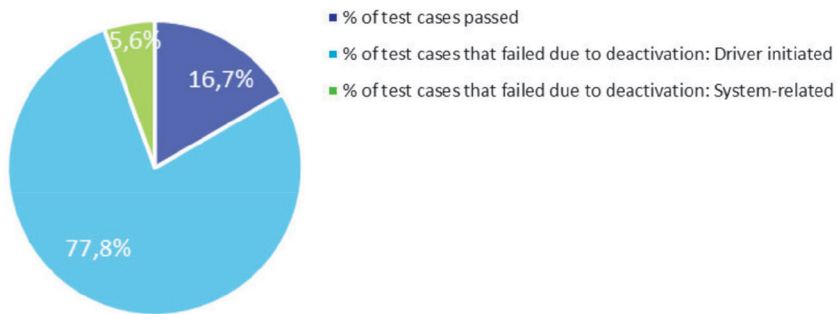


Figure 3 An example of shares of disengagements in a baseline test

Experimental Scenario (with PDI)

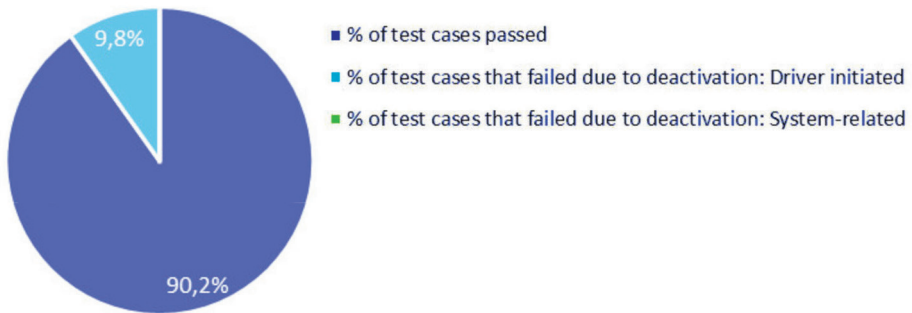


Figure 4 An example of shares of disengagements in an experimental test

3 Conclusion

The Augmented CCAM project marks a significant step towards enabling large-scale deployment of connected and automated mobility in Europe. By developing and testing infrastructure support services, the project demonstrates the essential role of physical, digital, and communication infrastructure in supporting automated driving systems. The impact assessment framework developed within the project offers a comprehensive methodology for evaluating the technological, safety, environmental, and socioeconomic impacts of CCAM infrastructure solutions. Key contributions include a harmonized infrastructure classification framework, innovative infrastructure support services, digital tools for infrastructure planning, validated methodologies for impact assessment, and evidence-based policy recommendations. By combining real-world testing, simulations, and traffic fleet modelling, the project provides valuable insights into the infrastructure requirements for automated mobility. Ultimately, the project supports Europe's transition to safer, more efficient, and sustainable transport systems by enabling informed infrastructure investments and coordinated deployment strategies for CCAM technologies.

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