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Transportation Research Procedia 00 (2026) 000–000

Transportation Research Procedia

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Road Safety and Simulation 2026 – RSS2026

Towards a Safe System Design for Physical Infrastructure in the Era of CCAM

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Abstract

The transition from human-driven vehicles to Connected, Cooperative, and Automated Mobility (CCAM) systems requires a shift in the way physical infrastructure is designed, managed and maintained. The safe system design should provide a base for that transition by prioritizing, preventing and reducing crashes using a systemic approach, where physical infrastructure, such as roadways, signage, traffic signals, and maintenance, integrates seamlessly with Autonomous Vehicles (AVs) technology to minimize risks and enhance safety for all road users. While the traditional Safe System Design (SSD) focused on human-centered transportation systems, its adaptation to CCAM should redefine the role of infrastructure to support both human-driven and automated vehicles. This paper presents a framework for the safe system design of physical infrastructure for CCAM deployment. This approach is based on an extensive literature review and synthesis of scientific papers, standards, and technical reports. From this review, five principles can be identified as the foundation of the SSD for CCAM systems: (1) Risk mitigation through enhanced infrastructure, (2) Operational Design Domain (ODD) expansion, (3) Seamless integration of mixed traffic, (4) Long-term scalability and global compatibility and (5) Integration of technology-driven infrastructure. Together, these principles establish a way for integrating the SSD with CCAM infrastructure planning. The proposed framework is conceptual and intended as a basis for future development and validation of infrastructure readiness assessment frameworks that can guide policymakers, infrastructure managers, and system designers in prioritizing investments for safe and scalable CCAM deployment.

Peer-review under responsibility of the scientific committee of the Road Safety and Simulation 2026 – RSS2026

Keywords: Connected, Cooperative and Automated Mobility (CCAM); Autonomous Vehicles; Safe System Design; Road Infrastructure; Operational Design Domain (ODD)

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Peer-review under responsibility of the scientific committee of the Euro Working Group on Transportation Annual Meeting 2025 - EWGT2025

1. Introduction

Road traffic crashes are still a major health concern worldwide. According to the World Health Organization, every year 1.19 million fatalities are reported due to road traffic crashes, and many more are injured (World Health Organization, 2024). In this context, improving road safety has become a global priority. The Safe System approach has been increasingly used as a guidance for road safety policy because it ensures shared responsibility among road users and system designers, such as infrastructure managers and policymakers (Khan and Das, 2024). The basic principles of the Safe System approach are directly related to the Vision Zero philosophy, which states that fatalities and serious injury in road transport are ethically unacceptable (Tingvall & Haworth, 1999). Vision Zero also introduced the concept of shared responsibility, which states that road users are responsible for following traffic rules, but system designers are also responsible for improving the transport system after serious crashes (Tingvall & Haworth, 1999). Under this perspective, infrastructure is not only a physical asset but also a safety-critical component that must help prevent serious accidents when errors occur.

At the same time, the emergence of CCAM systems is changing the way transport systems exist and are operated. Autonomous Vehicles (AVs) use sensors, algorithms, and digital connectivity to sense and interpret their environment. As a result, the quality, consistency, and interpretability of physical infrastructure are now critical in shaping automated driving performance (Mantouka et al., 2026). Infrastructure that was originally designed primarily for human perception may not always meet the requirements of automated systems. Recent studies highlight that infrastructure readiness, including road markings, signage, and digital support systems, is an important factor for the safe deployment of AVs (Tengilimoglu et al., 2023).

AVs are also limited to specific Operational Design Domains (ODDs), which define the environmental and operational conditions under which the automated driving system can function safely (SAE International, 2021). Infrastructure characteristics such as road geometry, lane markings, weather conditions, and traffic control devices directly influence the limits of the ODDs. However, despite the increasing attention given to infrastructure requirements for automated vehicles, current research and policy frameworks often address these issues separately from the broader Safe System philosophy.

This is a gap in the existing literature and research. While Safe System Design (SSD) is widely recognized as the basis of road safety policy, it has not yet been clearly defined as a guiding concept for infrastructure planning in CCAM environments or for shaping and expanding automated vehicle ODDs. Existing studies either focus on infrastructure requirements for AVs or on Safe System principles independently, without providing a structured way of connecting infrastructure design with ODD limitations and automated vehicle performance. As a result, there is currently no integrated framework that links Safe System principles with infrastructure design requirements for automated mobility.

The aim of this paper is to propose a simple and applicable framework for SSD in physical infrastructure in the era of CCAM. This framework is based on structured synthesis of scientific literature, standards, and technical documents. It structures the literature into five principles that can support infrastructure readiness assessments and help policymakers and road authorities with investment priorities for CCAM.

The remainder of the paper presents the review method, introduces the proposed framework, explains the five SSD principles that emerge from the literature, and then discusses implications and limitations of the proposed approach.

2. Methodological Approach

This study employed a qualitative approach based on a literature review and qualitative synthesis of scientific literature, international standards, and technical reports on automated mobility and road safety. The objective of this review was to identify key infrastructure attributes and system design principles that influence the safe operation of automated vehicles and their interaction with existing transport systems.

The literature review focused on three main research domains: (i) the Safe System approach and its principles in road safety policy, (ii) infrastructure requirements for automated and connected vehicles, and (iii) definitions and frameworks related to ODDs. Relevant sources included peer-reviewed journal articles, reports from international organizations and EU-funded research projects, and technical standards addressing automated vehicle testing, infrastructure readiness, and cooperative transport systems.

Through the literature review, key infrastructure-related factors were identified and grouped into main categories, including road geometry, traffic control elements, roadside environment, infrastructure condition, and digital support systems. These categories were then examined from a Safe System perspective, by linking them to core safety principles such as error tolerance, safe speeds, protection of vulnerable road users, and system reliability.

This step helped translate general infrastructure features into safety-relevant concepts for automated mobility. Based on this process, five key principles were identified that describe how infrastructure can support the safe deployment of CCAM systems.

The proposed framework therefore combines knowledge from road safety policy, automated vehicle research, and infrastructure design into a structured approach. The five principles presented in the following section provide a clear way to understand how infrastructure can support the safe integration of automated vehicles in mixed traffic environments and fully autonomous environments.

3. Safe System Design Framework for CCAM Infrastructure

The transition to CCAM systems presents a shift in the way in which transportation systems are designed and operated. Therefore, this transition requires a change in the traditional SSD approach. Traditional SSD focuses mainly on reducing human errors in driving and is based on five main elements such as safe roads, safe speeds, safe vehicles, safe road users, and effective post-crash response (Tingvall and Haworth, 1999). However, in a highly automated mobility environment, SSD needs to consider the interaction between automated driving systems, infrastructure, and all road users. This study focuses on the "safe roads" principle of the traditional SSD, as it directly relates to the design, condition, and performance of physical infrastructure, which is critical for the safe operation of automated vehicles. The principles of Safe Systems, such as error tolerance, safe speeds, protection of vulnerable road users, and system robustness become even more relevant in the context of autonomous transport systems. Accordingly, physical infrastructure must consider not just safety and collision prevention, but also the safe interaction between the system and other vehicles and pedestrians, reliability of operations, and adapting the environment to the requirements of different automation levels. This is what the concept of the SSD for CCAM needs to accommodate.

In CCAM systems, infrastructure no longer serves only as a passive element of the transportation system, but it becomes an active element in facilitating the perception, navigation, and decision-making processes of AVs. This increases the importance of infrastructure quality, consistency, and functionality.

In this context, SSD for CCAM can be defined as: "a systemic approach where physical infrastructure, such as roadways, signage, signals, and maintenance, seamlessly integrate with AV technologies in order to minimize risks and ensure safety for all road users." As a result of the synthesis of the literature, standards, and technical reports, five principles were identified that define the role of the infrastructure from the Safe System perspective. These five key

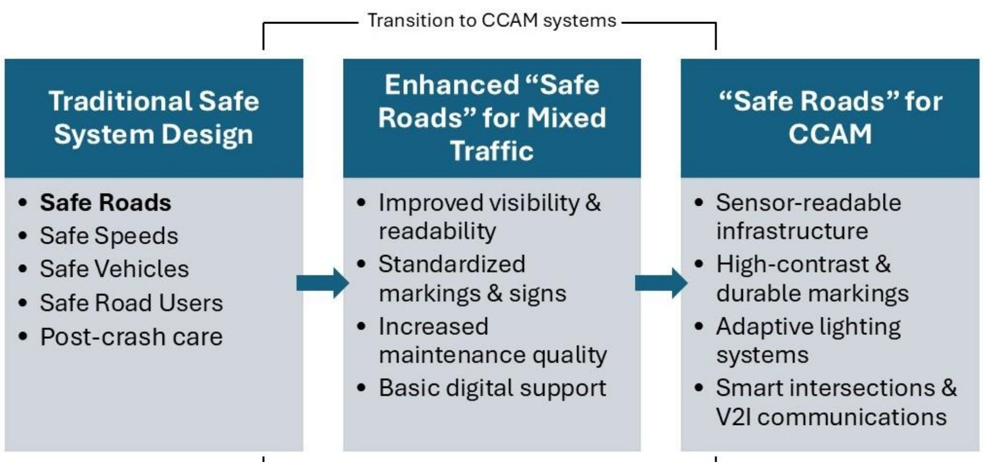

Fig 1. Evolution of the "safe roads" principle from traditional SSD to CCAM-ready infrastructure.

principles are the basis of the SSD framework that is proposed and discussed in the following section. Fig 1 illustrates how the "safe roads" principle evolves from traditional SSD to infrastructure that supports mixed traffic and fully automated mobility.

The five principles presented in this framework were identified through the synthesis of recurring themes across the reviewed literature, standards, and technical reports. Generally the literature agrees that infrastructure readiness, consistency, and digital support systems are important for the safe deployment of automated vehicles, particularly regarding road markings, signage, road condition, and communication systems (Othman, 2021; SAE International, 2021; Tengilimoglu et al., 2023). However, different perspectives exist regarding how infrastructure should evolve to support automated mobility. Some studies emphasize more controlled infrastructure solutions, such as dedicated AV lanes or geofenced operational areas, to support safer deployment under specific conditions (Koopman and Wagner, 2016). Other studies highlight the importance of gradual integration of automated vehicles within mixed traffic environments through adaptive traffic management and vehicle-to-infrastructure communication systems (Qi et al., 2020; Talebpour and Mahmassani, 2016). Rather than treating these approaches as contradictory, the proposed framework combines them into complementary principles that reflect different aspects of Safe System Design for CCAM, from immediate safety needs to long-term infrastructure adaptation.

3.1. Main principles of SSD

Five main principles can be identified as the foundation of SSD for CCAM systems. These principles address the challenges of transitioning from human-driven vehicles to fully automated systems and ensure that infrastructure evolves in alignment with the operational and safety requirements of AVs (Fig 2).

Fig 2. SSD principles for CCAM-ready infrastructure

The first principle is risk mitigation through enhanced infrastructure. This principle builds on the traditional SSD approach but adapts it to the needs of AVs. Enhanced infrastructure focuses on proactive measures to reduce crash risks and ensure rapid incident management when needed. This principle emphasizes the importance of basic but critical infrastructure elements, such as clear and durable lane markings, smooth road surfaces, and well-maintained road geometry to guide vehicles effectively (Othman, 2021). Proper maintenance of infrastructure is essential too, as faded markings, potholes, or uneven surfaces can compromise vehicle navigation and safety (Duvall et al., 2019; Erdelean et al., 2023). Safe speeds should be managed through clear and consistent signage, supported by regulations that harmonize speed limits across roadways to reduce variability and potential conflicts among road users (Tengilimoglu et al., 2023). Additionally, new traffic regulations play a vital role in establishing clear operational boundaries and enforcement mechanisms, ensuring all vehicles comply with safety standards (Claybrook and Kildare, 2018).

The second principle involves the expansion of the ODDs. The ODDs define the specific conditions under which an AV can safely operate, such as weather, lighting, road types and traffic scenarios (SAE International, 2021). Expanding the ODDs requires infrastructure to evolve in ways that accommodate diverse and challenging environments, enabling AVs to navigate safely across a broader range of conditions. One critical aspect of ODD expansion is the development of AV specialized infrastructure. For instance, infrastructure-supported geofencing can be used to define and manage operational zones where AVs can function safely, while allowing a gradual expansion of these zones as conditions improve (Koopman and Wagner, 2016). As AV technology matures, dynamic routing assistance becomes essential for enabling vehicles to respond to real-time changes in traffic or environmental conditions, such as detours, road closures, or sudden weather changes (Khan et al., 2019; Talebpour and Mahmassani, 2016). Additionally, dedicated AV lanes offer a controlled environment that minimizes interactions with human-driven vehicles, thereby reducing the complexity of mixed traffic scenarios (Fakhrmoosavi et al., 2023). Adaptation to extreme conditions is another crucial requirement for ODD expansion. AVs rely heavily on sensors such as LiDAR, cameras, and radar to perceive their environment. These sensors can be compromised by adverse weather conditions, such as heavy rain, snow, or fog. To address this, infrastructure must integrate adaptive lighting systems to improve visibility in low-light or low-visibility scenarios, such as night-time operations or foggy weather (Tengilimoglu et al., 2023). High-contrast road markings, designed to withstand wear and remain visible in harsh conditions, are also vital for ensuring reliable AV navigation (Konstantinopoulou et al., 2020).Flexibility in infrastructure design further supports ODD expansion by enabling AVs to transition seamlessly between different environments, such as urban centers, suburban areas, and rural roads. This includes incorporating features like grade-separated intersections, which minimize traffic conflicts, and dynamic lane management systems, which can adjust lane allocations in real-time to optimize traffic flow (Zhou et al., 2023).

The third principle focuses on the seamless integration of mixed traffic, as AVs and human driven vehicles will share the road for a long time, infrastructure should be designed to promote safety and efficiency for all road users and levels of automation. Clear and consistent road markings, such as high-contrast lane divisions, are essential to guide both AVs and human-driven vehicles, ensuring reliable navigation even in adverse weather or low-visibility conditions (Neumeister and Pape, 2019). Standardized signals and signage also play a significant role in reducing confusion and ensuring that all road users (humans and AVs) interpret traffic information in the same way (Erdelean et al., 2023). Advanced traffic management systems are also important for mixed-traffic integration. These systems use real-time data to dynamically adjust traffic flow, manage congestion, and reduce conflicts between AVs and human-driven vehicles. For instance, adaptive traffic signals can optimize intersection flow by communicating directly with AVs while simultaneously catering to human-driven vehicles (Qi et al., 2020). Smart intersections equipped with pedestrian-detection systems and vehicle-to-infrastructure (V2I) communication further enhance safety by addressing interactions with vulnerable road users, such as cyclists and pedestrians (Abdi et al., 2024). Intersection design is particularly significant in a mixed-traffic scenario. Intersections should incorporate features like designated AV lanes, priority signaling for AVs, and pedestrian-friendly designs to minimize conflicts and ensure efficient navigation (Sharon and Stone, 2017). These measures not only improve safety but also enhance operational efficiency, promoting public trust in the evolving transportation technologies. Seamless integration also involves educating road users about AV capabilities and limitations. Public awareness campaigns and driver training initiatives can help mitigate uncertainty and reduce risky behavior when interacting with AVs (Othman, 2021).

The fourth principle is long-term scalability and global compatibility. Scalability ensures that infrastructure can evolve gradually as technology advances and the adoption of AVs increases (Litman, 2017). Dedicated AV lanes, adaptive traffic systems, and modular road designs can serve as initial steps, expanding as market penetration and public acceptance of AVs grow (Friedrich, 2016). Until full Level 5 automation is achieved, infrastructure should accommodate a transitional phase that supports varying levels of automation, from human-driven vehicles to fully autonomous systems (SAE International, 2021; Shladover, 2018). This requires flexible and adaptable solutions, as permanent infrastructure tailored to Level 5 AVs, such as fully autonomous zones or intelligent traffic networks, may not yet be viable or necessary during earlier stages. Transitional infrastructure, therefore, should balance offering features like high-contrast lane markings, standardized signals, and real-time V2I communication systems for mixed traffic environments while remaining scalable to avoid becoming outdated as automation progresses. Global compatibility ensures that AVs can operate across different regions and countries (ISO, 2023). That requires a standardization of physical and digital infrastructure. These include uniform road markings, signage, and communication protocols to enable consistent performance regardless of geographic location.

The fifth principle is the integration of technology-driven infrastructure with the traditional physical infrastructure. Technology-driven infrastructure refers to V2I communication systems that enable AVs to exchange real-time information with roadways, traffic signals, and other elements. For instance, digital traffic signs can provide AVs with updates on road conditions, congestion, or weather, allowing for more informed navigation (Khan et al., 2019). Similarly, sensors can monitor traffic flow, detect non-recurrent events, and provide this data to AVs, so as to improve situational awareness and safety (Ramkumar et al., 2024). Moreover, High-Definition (HD) mapping and precise geofencing capabilities can improve AV positioning and route planning (Yang et al., 2024). However, this principle also emphasizes the importance of safe digital systems, the same way traditional infrastructure incorporates safeguards like crash barriers and medians, technology-driven infrastructure must include cybersecurity measures and fail-safe mechanisms to protect against digital threats and ensure system reliability (Algarni and Thayananthan, 2022).

To summarize the findings of the proposed framework, Table 1 presents the five SSD principles along with the main infrastructure measures associated with each principle and their expected impact on CCAM systems. Although the principles are presented separately, they are closely related and may involve trade-offs during implementation. For example, measures introduced to improve safety and reduce risks may temporarily limit the seamless integration of mixed traffic, while ODD expansion may require additional technology-driven infrastructure that should remain scalable over time. This summary provides an overview of how physical infrastructure can support the safe and efficient deployment of automated mobility. Additionally, it emphasizes the need for developing relevant indicators for evaluating infrastructure performance. The development of relevant indicators is critical in evaluating road safety and ensuring its compatibility with SSD principles in the context of CCAM systems.

Table 1. SSD principles, related infrastructure measures, their impact on CCAM systems, and example measurable indicators for assessing infrastructure performance.

SSD principle	**Infrastructure Measures**	**Expected Impact on CCAM**	**Example Measurable Indicators**
Risk mitigation through enhanced infrastructure	High quality horizontal markings, consistent vertical signage, smooth pavement surfaces, regular maintenance, traffic regulations	Improved perception, reduced crash risks	Lane marking retroreflectivity (cd/m²/lux), pavement condition index, signage visibility distance (m), maintenance frequency
ODD expansion	AV lanes, geofencing capabilities, adaptive lighting, dynamic routing support	Operation in more diverse conditions	% of network covered by AV-compatible infrastructure, geofenced area coverage (%), illumination levels (lux), availability of real-time routing data
Seamless integration of mixed traffic	Standardized horizontal and vertical signage, V2I communications, adaptive traffic signals / smart intersections	Reduced conflicts, safer interaction	V2I communication latency (ms), intersection delay (s), conflict rate (near-misses), signal compliance rate (%)
Long-term scalability	Standardized physical and digital infrastructure, modular design	Cross-region operation, future readiness	% infrastructure compliant with standards, interoperability index, upgrade frequency
Technology-driven infrastructure	Sensors, HD maps, digital signage, cybersecurity & fail-safe systems	Better situational awareness	Sensor coverage (% of network), HD map accuracy (cm), data update frequency, system uptime (%), cybersecurity incident rate

4. Conclusions

The transition to CCAM systems is changing the way transport systems operate and how road infrastructure supports safety. While the Safe System approach is widely used in modern road safety policy, its application to automated mobility is still limited. AVs depend on the quality, consistency, and readability of infrastructure to perceive and interpret the road environment. As a result, infrastructure design, maintenance, and digital support systems play an increasingly important role in ensuring safe automated driving.

This paper addressed this issue by proposing a conceptual Safe System Design framework for physical infrastructure in the era of CCAM. The framework was developed through a synthesis of scientific literature, standards, and technical reports related to road safety and automated mobility. From this review, five key principles were identified: (1) risk mitigation through enhanced infrastructure, (2) expansion of Operational Design Domains, (3) seamless integration of mixed traffic, (4) long-term scalability and global compatibility, and (5) integration of technology-driven infrastructure with traditional road infrastructure.

These principles provide a structured way to understand how infrastructure can support both human-driven and automated vehicles while maintaining the main goal of the Safe System approach: preventing fatalities and serious injuries. The proposed framework can support infrastructure planning and help policymakers and road authorities prioritize investments for the safe deployment of CCAM systems.

This study is conceptual and does not include empirical validation. Therefore, future work should focus on translating these principles into measurable indicators and assessment tools that can evaluate infrastructure readiness for automated mobility in real-world road networks.

Acknowledgements

This work is part of the FRODDO project which is co-funded by the EU Horizon Europe Research and Innovation Programme under Grant Agreement No. 101147819.

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