Austroads

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Design Principles for Adapting Roads and Infrastructure for Emerging Mobility Technologies

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Abstract

The purpose of this report is to establish design topics and principles to guide Australasian road agencies in preparing physical and digital infrastructure for emerging mobility technologies. These technologies include automated vehicles (AVs), connected and automated vehicles (CAVs), electric vehicles (EVs), advanced driver assistance systems (ADAS) and cooperative intelligent transport systems (C-ITS).

This report supports safe integration of new vehicle technologies and contributes to ongoing research aimed at building a consistent foundation for future-ready transport networks across Australia and New Zealand.

The methodology involved a comprehensive review of literature, analysis of existing guidance, and engagement with stakeholders. Consultation and research identified priority issues across 2 domains – physical and digital infrastructure – leading to the identification of 24 topic areas. Included in the analysis of each topic area are the challenges, infrastructure considerations, recommended design principles and scope for future research. The report concludes with recommended pathways for applying the principles and an outline of emerging priority areas.

Recognising differing levels of technology maturity and agency readiness, this research also highlights opportunities for guidance development to ensure digital and physical infrastructure remains aligned with technological and operational change across road networks in Australia and New Zealand.

Keywords

Automated vehicles (AVs), connected and automated vehicles (CAVs), electric vehicles (EVs), advanced driver assistance systems (ADAS), cooperative intelligent transport systems (C-ITS).

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About Austroads

Austroads is the association of Australasian transport agencies.

Austroads' purpose is to support our member organisations to deliver an improved Australasian road transport network. To succeed in this task, we undertake leading-edge road and transport research which underpins our input to policy development and published guidance on the design, construction and management of the road network and its associated infrastructure.

Austroads provides a collective approach that delivers value for money, encourages shared knowledge and drives consistency for road users.

Austroads is governed by a Board consisting of senior executive representatives from each of its 11 member organisations:

- Transport for NSW
- Department of Transport and Planning (Transport Victoria)
- Queensland Department of Transport and Main Roads
- Main Roads Western Australia
- Department for Infrastructure and Transport South Australia
- Department of State Growth Tasmania
- Department of Logistics and Infrastructure Northern Territory
- City and Environment Directorate, Australian Capital Territory
- Department of Infrastructure, Transport, Regional Development, Communications, Sport and the Arts
- Australian Local Government Association
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This report has been prepared for Austroads as part of its work to promote improved Australian and New Zealand transport outcomes by providing expert technical input on road and road transport issues.

Individual road agencies will determine their response to this report following consideration of their legislative or administrative arrangements, available funding, as well as local circumstances and priorities.

Summary

This report establishes a set of high-level design principles to assist road agencies in adapting road infrastructure for emerging mobility technologies. The guidance supports integration of automated vehicles (AVs), connected and automated vehicles (CAVs), electric vehicles (EVs), advanced driver assistance systems (ADAS), and cooperative intelligent transport systems (C-ITS). These technologies place new demands on both physical and digital infrastructure, many of which exceed the scope of current standards.

In undertaking this research, the project team used a structured methodology that integrated literature reviews and expert input from targeted stakeholder engagement with Austroads member agencies. This process led to the identification of 24 design topics across 2 domains – physical infrastructure and digital infrastructure. A comprehensive analysis of these topic areas was undertaken to support road agencies to address capability and readiness gaps in creating innovative, effective and efficient future mobility solutions.

Physical infrastructure design topics:

1. Managing transitions of control (automated to manual) (PT1)
2. Ensuring readability of lane markings and road signage by vehicles (PT2)
3. Ensuring compatible road and traffic design for AV navigation and operations (PT3)
4. Maintaining roadway and pavement integrity for AVs and EVs (PT4)
5. Managing mixed traffic interactions with AVs (PT5)
6. Supporting CAV readability of digital roadside signage (PT6)
7. Managing AV interactions with E-scooters, cyclists and personal mobility devices (PT7)
8. Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs (PT8)
9. Minimising urban congestion from AV fleet staging, parking and idle circulation (PT9)
10. Ensuring EV-compatible crash barriers (PT10)
11. Maintenance and asset management for CAV and EV infrastructure (PT11).

Digital infrastructure design topics:

1. Ensuring CAV awareness of temporary and dynamic traffic conditions (DT1)
2. Ensuring data accuracy and validation for AV navigation (DT2)
3. Ensuring reliable CAV communications for continuous data exchange (DT3)
4. Protecting CAV and transport data from cybersecurity threats (DT4)
5. Ensuring CAV compliance with dynamic road regulations (DT5)
6. Supporting multimodal and CAV integration (DT6)
7. Ensuring digital resilience and failover mechanisms for CAV operations (DT7)
8. Improving CAV interaction with emergency vehicles and vulnerable road users (DT8)
9. Optimising CAV and EV fleet management and staging (DT9)
10. Integration of CAV and EV operations into smart city and traffic management platforms (DT10)
11. Ensuring real-time EV and electric CAV charging availability and status updates (DT11)
12. Standardising digital road regulations for EV and electric CAV charging zones (DT12)
13. Supporting CAV interpretation and compliance with traffic signal infrastructure (DT13).

The results of this research are organised by topic area, with challenges, infrastructure considerations, recommended design principles and scope for future research addressed for each topic. In total, these topics cover 135 design principles across both domains, providing non-prescriptive, flexible guidance to support informed decision-making in infrastructure planning, investment, and operational design. In addressing infrastructure challenges such as AV sensor interpretation of markings and signage, kerbside management, mixed traffic interaction, cybersecurity, and integration into intelligent transport systems, these principles offer essential insights into best-practice for adapting road infrastructure for emerging mobility technologies.

A number of cross-cutting design considerations emerged (section 7) which offer important insights for road agencies when applying these design principles for future mobility solutions:

- supporting mixed fleet operation for the foreseeable future
- ensuring clarity and interpretability for both human drivers and machine systems
- enabling safe degraded-mode behaviour when digital systems fail
- aligning implementation with technology readiness and operational need
- maintaining integration between physical and digital infrastructure
- promoting cross-jurisdictional consistency to support network-wide reliability.

The report concludes by outlining some strategies for agencies to effectively apply the design principles in various road agency functions, also highlighting areas of guidance that require development. Through this consideration of the past and current context in which road agencies operate, this research is aimed at ensuring the principles are not only implemented effectively, but that they also remain relevant and actionable as vehicle technologies and agency operations and technologies continue to evolve.

An online tool was created that allows the design topics to be explored by road environment and technology.

While these design topics provide a forward-looking framework, the recommendations in this report are not intended to prescribe a uniform or immediate standard for all agencies. Rather, the design topics offer insight into a range of factors associated with creating future mobility solutions with the broader aim of ensuring a coherent and collaborative approach to future-ready transport networks. As such, all levels of government are encouraged to interpret and apply the guidance in ways that are practical and achievable within their specific circumstances.

This research report represents a significant contribution to shared knowledge on adapting road infrastructure for emerging mobility technologies, and reflects ongoing collaborative efforts aimed at optimising safety, efficiency and responsiveness across all road networks in Australia and New Zealand.

Contents

Tables

Figures

1. Introduction

This section provides an introduction and overview of this report, including its purpose, scope and methodology.

The rapid advancement of transport technologies including automated vehicles (AVs), connected and automated vehicles (CAVs), electric vehicles (EVs), cooperative intelligent transport systems (C-ITS), and advanced driver assistance systems (ADAS), is driving a transformative shift in road and infrastructure design requirements. These technologies hold the potential to significantly enhance safety, efficiency, and sustainability across transport networks. However, their successful implementation depends not only on infrastructure readiness, but also on factors such as policy and regulatory frameworks, technology maturity, economic viability, community sentiment, and clear use-case alignment.

This report addresses these challenges by establishing design principles that ensure the safe and effective operation of emerging road-based transport technologies. It focuses on the identification of gaps in current design standards, analysis of existing guidelines, and the identification of principles to support infrastructure adaptation for future mobility solutions.

This report aims to:

- evaluate the adequacy of current road design standards for CAVs and other emerging technologies
- build on the findings of a literature review conducted by Transport for NSW (TfNSW)
- identify limitations and challenges in existing road infrastructure in supporting future transport technologies
- explore opportunities for planning and design improvements to facilitate the integration and operation of advanced mobility solutions
- lay the groundwork for the creation of detailed, actionable design requirements for future transport infrastructure.

1.1 Purpose

The purpose of this report is to provide coordinated design principles for roads and infrastructure to accommodate the safe and effective operation of emerging transport technologies including AVs, CAVs, EVs, C-ITS, and ADAS.

The project reviews and analyses current road design standards, identifying challenges and limitations, and develops design principles for road infrastructure that support these technologies.

1.2 Scope

This project involved:

- Review and analysis of current road design standards and their suitability for CAVs and future transport technologies such as EVs, ADAS and C-ITS.
- Identification of challenges and limitations in the design of existing roads and infrastructure concerning CAVs and future transport technologies, considering latest international standards and initiatives.
- Identification of planning and design opportunities to support future transport technologies and beneficial outcomes.
- Development of specific and detailed design principles for road infrastructure that support CAVs and future transport technologies.
- Utilisation of the TfNSW literature review focusing on design guides, case studies and frameworks required to support CAVs and future transport integration.
- Creation of a roads and infrastructure design report to support CAVs and future transport network operation and integration.
- Stakeholder engagement with road design teams and consultancies in regard to their key questions and concerns for report chapters and focus areas.
- Development of recommended guidelines to support operation and uptake of future transport including AVs, CAVs, EVs, ADAS, C-ITS, and other future road technologies.
- Development of recommended target review cycles for design guidelines relating to future technologies, ensuring guides remain up to date with current innovations.

This report does not prescribe a fixed hierarchy of infrastructure requirements across emerging technologies. Instead, the design principles are intended to be applied flexibly based on project type, local context, and technology maturity. Prioritisation is addressed through implementation guidance in section 8, which distinguishes between near-term opportunities and longer-term actions. This approach allows agencies to apply only the principles most relevant to their role, context, and strategic objectives, rather than following a blanket order of infrastructure actions.

The design principles are high-level and adaptable. They guide infrastructure planning and decision-making but do not set detailed technical requirements. CAV and related vehicle technologies are still evolving, so it is too early to define fixed specifications that may soon require revision. The principles describe what infrastructure should achieve and allow flexibility as technologies change. This report focuses on responsibilities within Austroads member agencies and does not cover areas controlled by vehicle manufacturers or CAV developers.

This report does not assume that CAVs, EVs or related technologies are fully mature or ready for universal deployment. The principles support staged readiness and should align with policy, regulatory and operational development. Section 8 outlines near-term and longer-term actions so agencies can apply the principles based on local context, role and technology maturity.

About the Design Principles

The design principles presented in this report are intentionally future-focused. They are intended to support infrastructure planning, in the absence of mature design guidance or specifications. They reflect anticipated infrastructure needs over a 20- to 40-year horizon as vehicle technologies continue to evolve.

1.3 Methodology

The project team applied a structured, evidence-based methodology to develop the design principles presented in this report. The approach combined technical research, ongoing stakeholder engagement, and targeted analysis to ensure the guidance is practical, adaptable, and aligned with the future needs of road agencies. The methodology included the following components:

- Literature Review: The team reviewed existing design guidelines, academic research, international standards, and industry reports to assess current practices and identify emerging requirements. This included consideration of a literature review conducted by TfNSW, which provided a focused analysis of infrastructure needs to support CAV deployment and integration.
- Gap and Needs Analysis: The team assessed the adequacy of current road and infrastructure guidance, identifying key gaps across physical and digital domains. This included a review of Austroads and jurisdictional documents to understand the level of road and infrastructure design support for AVs, CAVs, EVs, ADAS, and C-ITS.
- Ongoing Stakeholder Engagement: Stakeholder engagement occurred throughout the project, involving representatives from Austroads member agencies and relevant expert networks. Consultations informed all stages of the project, from initial problem definition and literature sourcing to the identification of priority topics and validation of findings. A national workshop, supported by targeted follow-ups, provided structured input into agency needs and infrastructure design challenges.
- Theme Development and Topic Prioritisation: Drawing on stakeholder insights and research findings, the project team identified 24 priority topic areas, with 11 relating to physical infrastructure and 13 relating to digital infrastructure. These topics reflect the key areas where road agencies require design principles to support deployment of connected and automated mobility technologies.
- Structured Topic Investigation and Design Principle Development: Each topic was researched in relation to context and relevance, identification of key challenges, infrastructure design considerations, related topics, and future research needs. The team developed design principles for each topic that will help guide agency decision-making while remaining adaptable to evolving technologies.
- Report Drafting, Review, and Finalisation: The team prepared the report through an iterative drafting process, incorporating internal review and feedback from Austroads and agency stakeholders. The structure and content were designed to ensure that the principles are clear, actionable, and suitable for application by road agencies. The final version reflects stakeholder input and aligns with Austroads' strategic priorities to support future mobility technologies.

1.4 Terminology

Table 1.1: Terms used in this report

Acronym	Term
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving System
AV	Automated Vehicle
C-ITS	Cooperative Intelligent Transport Systems
C-V2X	Cellular Vehicle to Everything
CAV	Connected and Automated Vehicle
CCAM	Connected, Cooperative and Automated Mobility
CV	Connected Vehicle
DSD	Decision Sight Distance
DSRC	Dedicated Short-Range Communications
EIP	European ITS Platform
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
EVA	Emergency Vehicle Approaching
EVP	Emergency Vehicle Priority
FSD	Full Self-Driving
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAP	Harmonised Access Point
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICVP	Ipswich Connected Vehicle Pilot
ISA	Intelligent Speed Adaptation
ISAD	Infrastructure Support Levels for Automated Driving
ISO	International Organization for Standardization
ISP	Information Service Provider
ITF	International Transport Forum
ITS	Intelligent Transport Systems
LiDAR	Light Detection and Ranging
MRC	Minimal Risk Condition
MRM	Minimum Risk Manoeuvre
NAP	National Access Point
NIST	National Institute of Standards and Technology
OCPI	Open Charge Point Interface
OCPP	Open Charge Point Protocol
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PKI	Public Key Infrastructure

Acronym	Term
PRT	Perception-Reaction Time
RSI	Road Safety Inspection
RSU	Roadside Unit
RTTI	Real-Time Traffic Information
SAV	Shared Autonomous Vehicle
SCMS	Security Credential Management System
SIL	Safety Integrity Level
SPaT	Signal Phase and Timing
SSD	Stopping Sight Distance
TM2.0	Traffic Management 2.0
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VGD	Vehicle-generated Data
VRU	Vulnerable Road User

2. Context of Future Mobility Technology and Infrastructure Requirements

This section provides context for potential agency road and infrastructure design support of future mobility technology against a backdrop of emerging vehicle technology needs, and the development of Intelligent Transport Systems (ITS).

The evolution of vehicle technologies and identification of potential agency infrastructure support requires understanding of their generational progression, interdependency, and potential impacts on road infrastructure design. The European Union (EU EIP 2021a) describes 3 generations of road transport related technologies, as follows:

- First-generation Intelligent Transport Systems (ITS): Includes familiar infrastructure such as traffic signals and variable message signs. These are static and infrastructure-led.
- Second-generation Cooperative Intelligent Transport Systems (C-ITS): Adds connectivity, allowing vehicles to communicate with each other and with infrastructure (e.g. roadwork alerts, traffic signal timing).
- Third-generation Connected, Cooperative and Automated Mobility (CCAM): Combines connectivity, cooperation, and automation. These systems rely more heavily on digital data and enable advanced automation.

These 3 generations are not separate; they build upon each other. Agencies should consider how each layer interacts and how infrastructure can adapt accordingly. Although traditional ITS remains essential, the focus now is on challenges posed by C-ITS and CCAM technologies.

Although electric vehicles (EVs) are not explicitly part of the EU’s CCAM classification, they form a key part of the broader future mobility landscape. EVs introduce their own requirements, including for charging infrastructure, kerbside design adaptations and to manage access and turnover. This also requires planning and design support, even if EVs are not relying on cooperative or automated driving.

The following examples illustrate third-generation CCAM systems currently deployed in Barcelona (WeRide/Renault in Figure 2.1 below) and San Francisco (Waymo in Figure 2.2 below), and highlight the types of road related physical and digital infrastructure support that agencies may need to consider for broader implementation.

Figure 2.1: WeRide/Renault automated shuttle operating in Barcelona, Spain

Source: Transport Management Consulting (2025) ©.

The WeRide vehicle trial operates in a 2.2 km public road loop with fixed stops in Barcelona city. The ‘robobus’ operates in a vehicle fleet that consists of small vehicles, delivery vehicles, motorcycles and bicycles. The network includes traffic signal-controlled intersections and fixed pedestrian crossings, and passes through highly populated areas with uncontrolled pedestrian activity. It uses a combination of 10 cameras and 8 LiDAR units supported by high-definition maps and digital infrastructure (WeRide 2025; Muñoz and Wilson 2025).

Figure 2.2: Waymo robotaxi operating in San Francisco, United States

Source: Transport Management Consulting (2024) ©.

Waymo robotaxis demonstrate Level 4 autonomy (the ability to perform most driving tasks independently) in complex urban conditions, such as in San Francisco. Its operating environment includes public streets with varied horizontal and vertical geometry, signalised and unsignalised intersections, mixed vehicular traffic (including trams) and high pedestrian activity. Vehicles pick up and drop off passengers at the kerbside, and this include use of loading zones and bus stops, which may contravene kerbside regulations (as seen in Figure 2.2 above).

Bonos (2025) notes that Waymo's robotaxis received 589 parking tickets in 2024 for various parking infringements. This behaviour is explained by Waymo as vehicles taking the safest option available when picking up and dropping off passengers (Bonos 2025). The vehicle operates without a safety driver in designated geofenced areas, relying on a suite of sensors including high-resolution LiDAR, cameras, and radar to provide 360-degree perception. These inputs feed into advanced onboard neural networks and reasoning systems that allow the vehicle to safely navigate complex urban environments (Waymo 2024a). In May 2025, Waymo’s Co-CEO demonstrated how Google’s Gemini large language model (LLM) is integrated into the 6th-generation Waymo Driver to interpret ambiguous parking instructions, enhancing kerbside performance (Google for Developers 2025).

In addition to automation and connectivity, both WeRide and Waymo rely on fully electric vehicle platforms. This adds further complexity for agencies (and vehicle operators) to consider not only digital infrastructure but also access to reliable, scalable EV charging infrastructure either at fleet depots or within the road network.

2.1 TfNSW literature review

Transport for NSW (TfNSW) provided an unpublished literature review, which served as an input to this report. The material was used as background input only. The review focused on future mobility systems, with particular emphasis on Connected and Automated Vehicles (CAVs). It synthesised academic research, government publications, industry whitepapers, and trial-based evidence to assess infrastructure readiness across physical, digital, and electric vehicle (EV) domains in the Australian context.

The review concluded that implementing a strategic and balanced infrastructure approach is essential. It recommended leveraging advanced vehicle technologies to minimise the need for widespread infrastructure upgrades, while prioritising targeted enhancements where they are critical for safety, system reliability, and public confidence. TfNSW advised against blanket upgrades, favouring evidence-based, staged interventions.

Key findings of the review are summarised below.

Integration approaches

The review identified two principal pathways for supporting CAV deployment:

- Infrastructure-based solutions, which involve investment in features such as machine-readable road markings, Vehicle-to-Everything (V2X) communication systems, embedded sensors, and enhanced signage.
- Infrastructure-less (vehicle-led) solutions, which depend on advanced on-board technologies (e.g. LiDAR, radar, GPS, cameras) and minimal reliance on external infrastructure.

The review highlighted the likely coexistence of both approaches and stressed the importance of planning for mixed-technology environments. These environments involve road networks shared by vehicles with varying levels of automation and connectivity, ranging from conventional vehicles to fully autonomous, connected systems.

Differing stakeholder views

The report drew on a 2022 global survey of 168 mobility experts, including Tengilimoglu et al. (2023). This revealed differing perspectives on infrastructure priorities:

- Academic stakeholders identified physical infrastructure as the second most important priority after policy and legislation.
- Agency representatives assigned lower importance to physical changes, placing greater emphasis on regulatory and governance frameworks.
- European respondents supported earlier infrastructure upgrades compared to other regions, highlighting a divergence in deployment strategies.

These findings underscore the lack of international consensus on the timing, scale, and responsibility for infrastructure adaptation.

Physical infrastructure requirements

The review outlined several infrastructure enhancements that could support safe and reliable CAV operation:

- Line markings: Requirements include high-contrast, weather-resistant, and durable materials, as well as consistent application of edge and centre lines to ensure machine readability.
- Signage: Recommendations include standardised placement, consistent mounting height and angle, enhanced visibility, and long-term durability.
- Road and asset design: Proposed changes include updates to lane geometry, kerb configurations, intersections, ramps, and bridge reinforcement to handle increased vehicle loads. Pavement upgrades and design adjustments were also noted to support reliable sensor performance.
- Dedicated infrastructure: The review noted the value of designated CAV and EV lanes or parking areas and emphasised the need for enhanced maintenance regimes.

Evidence presented in the TfNSW report include information from trials by AIMES, Transurban, and CAVI. This demonstrated that minor inconsistencies in road markings or signage could disrupt automated operations, reinforcing the need for uniform infrastructure standards and regular condition monitoring.

Digital infrastructure and cybersecurity requirements

The review identified several areas of digital infrastructure preparedness that could assist CAVs:

- Lack of standardised V2X communication protocols and mapping formats, which hinders interoperability between vehicle systems and infrastructure.
- Cybersecurity vulnerabilities, requiring robust encryption methods, secure communication standards, and access control mechanisms.
- Dependence on high-definition mapping, real-time data exchange, and redundant systems to ensure the continuity of automated functions.
- The necessity of deploying advanced communication networks, including 5G, DSRC, and roadside units (RSUs), to support responsive vehicle-to-infrastructure interaction.

While the literature concentrated on V2X-enabling technologies such as 5G and DSRC, it did not address broader telecommunications infrastructure. The review also acknowledged the need for mixed-fleet resilience, ensuring that systems can accommodate a range of vehicle types and fail safely in the event of disruption.

Electric vehicle infrastructure requirements

Although not the primary focus, the review highlighted several infrastructure needs for EVs, including:

- Expansion of EV charging facilities, with emphasis on strategic placement, wireless charging, and battery swap technologies.
- Structural upgrades to bridges and pavements to support the increased weight of EVs, particularly for freight.
- Integration of energy planning considerations, including power availability, lighting, access, and safety around EV charging points.

Practical examples from trials

The review cited several real-world projects that informed infrastructure implications:

- AIMES (Melbourne): Highlighted challenges with road marking consistency and variability in V2X system performance.
- Transurban trials: Reported instances of lane-keeping failure caused by faded markings and ambiguous signage.
- CAVI (Ipswich): Demonstrated the integration of vehicle-to-infrastructure communication in a live road environment.
- CITI (Sydney): Referenced as a key urban testbed for broader intelligent transport system (ITS) deployment.

These examples reinforced the theoretical findings and illustrated how infrastructure gaps can affect system reliability in practice.

Summary

The TfNSW review concludes that the transition to CAV and EV systems does not require a complete reconstruction of existing road networks. However, it does necessitate targeted infrastructure upgrades, particularly in road markings, signage, digital connectivity, and cybersecurity. The review emphasises the importance of evidence-led planning, cross-sector collaboration, and adaptable design frameworks to manage evolving risks, operational demands, and long-term system resilience.

2.2 Existing Austroads and agency guidance

A broad range of design guidance relevant to AVs, CAVs, ADAS, C-ITS, and EVs has emerged across Australia and New Zealand. However, this guidance is fragmented, varies in depth, and is not yet consolidated into a single source or framework that road designers can confidently apply.

Across Commonwealth, state, and local government, agencies are beginning to address CAV-relevant infrastructure needs, but guidance remains in development and often lacks specificity on design standards. Austroads has led much of this work, supported by individual agency pilots and strategic documents.

Austroads design publications such as the *Guide to Road Design* (AGRD) and *Guide to Traffic Management* (AGTM) contain only limited direct references to vehicle technology, with few clear design principles aimed at supporting CAVs. While some parts, such as *AGTM Part 9: Transport Control Systems – Strategies and Operations* (Austroads 2020) and *AGRD Part 1: Objectives of Road Design* (Austroads 2025a), acknowledge emerging technologies, they do not provide deployment-ready guidance for CAV-supportive infrastructure.

Meanwhile, a growing body of Austroads research reports and pilot/trial findings are beginning to inform more targeted recommendations. These include guidance on digital infrastructure, EV charging signage, physical road modifications, and the provision of agency data to support AV navigation and compliance. A summary of relevant Austroads publications is provided in Appendix A.

2.2.1 Limitations and gaps

Despite progress with road agency guidance, several key limitations and gaps remain, including:

- No consolidated road and infrastructure design guidance: Practitioners face difficulty determining which Austroads or agency documents apply to new vehicle technologies. There is no single integrated source addressing the infrastructure needs of AVs, EVs, and connected vehicle systems.
- Uneven focus on physical and digital design: Many guides prioritise physical infrastructure but do not provide coordinated digital infrastructure principles for CAV readiness.
- Limited real-world scalability: Lessons from trials and pilots have identified issues such as degraded lane markings, sign occlusion, or emergency vehicle detection failures. However, responses remain preliminary. Greater operational experience and validated practice are needed before design principles can be applied at network scale. Some issues identified through trials may also be resolved as vehicle technologies mature, rather than requiring immediate changes to physical infrastructure**.**
- Emerging but inconsistent local guidance: Some jurisdictions (e.g. NSW, QLD, WA, VIC) and local governments have developed CAV or EV readiness strategies, but these are often high-level and lack detail on road design, digital coordination, or access regulation (e.g. EV charging zone rules).

2.2.2 Agency needs

The review of existing materials indicates that while useful foundations exist, current guidance is insufficient to fully support future-ready road infrastructure design. Road planners and designers lack a clear, authoritative source of principles that combine physical, digital, operational, and regulatory infrastructure for CAV integration. To assist coordination, there is a need to:

- develop a consolidated and updateable set of road and infrastructure design principles across both physical and digital infrastructure
- address the interface between CAV capabilities and infrastructure design needs
- promote alignment between national and local strategies to reduce inconsistency.

A table of other relevant government publications reviewed for this work is provided in Appendix A.

2.3 Potential agency approaches to supporting mobility technologies with road and infrastructure design changes

Road and transport agencies must navigate complex technical, regulatory, and operational landscapes as they prepare for the integration of future mobility technologies. Their responsibilities span planning and design, cross-sector collaboration, and ensuring resilience in both physical and digital infrastructure systems. Agencies play a critical role in enabling connected and automated vehicle (CAV) systems, while managing evolving expectations around safety, equity, and sustainability.

The ways in which agencies support mobility technologies will vary significantly depending on context. Some jurisdictions may focus on foundational upgrades that support vehicle perception; others may invest more heavily in communications infrastructure or dedicated CAV corridors. Importantly, there is no single model – agencies will make strategic decisions based on local priorities, resourcing, risk appetite, and timing.

To reflect this variability, a spectrum of potential support strategies is proposed. This spectrum describes a continuum from minimal intervention (e.g. expecting CAVs to adapt to existing infrastructure) to more advanced infrastructure support (e.g. road simplification and vehicle-infrastructure cooperation). This framing helps position the design principles in this report as adaptable tools rather than fixed requirements.

2.3.1 Spectrum of infrastructure support strategies

A useful reference point is the Connected Roadway Classification System (CRCS) developed under NCHRP Project 20-24(112) (NASEM 2019). It outlines 4 potential approaches to enhancing roadway readiness for CAVs:

- **Leave as is – roads built for human drivers**

  Maintain current infrastructure. Vehicle manufacturers are expected to adapt to existing conditions without public sector intervention.

- **Add roadway communications – talking with the road**

  Deploy communications infrastructure (e.g. C-ITS roadside units) to support cooperation between vehicles and infrastructure.

- **Enhance roadway for vehicle sensors – seeing the road**

  Improve physical attributes such as road markings, signage contrast, and surface consistency to aid machine vision and sensor performance.

- **Adjust geometrics, usage, and control – simplifying the road**

  Modify road layouts, signal timing, or traffic flows to optimise environments for automation and vulnerable road user safety.

These 4 strategies form a spectrum of infrastructure support. Agencies may adopt different positions on this spectrum depending on their objectives. This approach may shift over time as technology matures or expectations evolve. For example, one agency may initially focus on enhanced markings for ADAS and enabling vehicle-communications on particular roads, then gradually introduce road design changes to support higher levels of automation in other corridors.

It is worth noting that not all infrastructure can or should be modified. Agencies will need to balance the pace of vehicle technology development with infrastructure budgets, legacy constraints, and public acceptability. A PCG member from Queensland TMR observed that these decisions resemble previous shifts in infrastructure standards, such as accommodating heavier vehicles via upgraded pavements and bridges. However, in this case, there is greater uncertainty around vehicle needs and future scenarios.

Some stakeholders, including NACTO (2024), have raised concerns that adjusting infrastructure for CAVs may inadvertently reduce pressure on industry to ensure vehicles are safe and self-sufficient. However, from a practical perspective, many agencies are already adapting infrastructure to respond to other transport changes, including increased freight demand, micromobility use, and electrification. Infrastructure support for CAVs can be seen as part of that ongoing evolution.

2.3.2 Implications for design principles

Given the range of possible road and infrastructure support strategies, the design principles developed in this report (in sections 5 and 6) are intended to be flexible, scalable, and context-sensitive. They support agencies in preparing for connected, automated and electric vehicles at different levels of readiness, depending on their available resources, local constraints, and strategic goals.

To ensure ongoing relevance and utility, the design principles align with the following foundational needs:

- Alignment with broader goals: Principles support wider infrastructure objectives such as transport efficiency, safety, sustainability, and resilience.
- Support for incremental and long-term changes: Principles are usable both for near-term gaps and future-facing infrastructure programs.
- Enable local adaptation: Principles allow regional flexibility while maintaining consistency with national and international frameworks.

Later sections of the report (notably section 8) outline how these principles can be applied selectively, allowing agencies to focus on the aspects of infrastructure most relevant to their position on the support spectrum, and to support a particular situation (e.g. trials, corridor upgrades, long term investment).

These principles are not intended for blanket implementation. Rather, they function as a flexible reference menu that agencies can draw from based on their objectives, constraints, and readiness. Whether preparing for trials, enabling staged deployment, informing corridor upgrades, or identifying infrastructure gaps during planning or design, the principles provide a structured way to navigate what matters most in a given context. They support informed, scalable decision-making at any point along the infrastructure support spectrum — ensuring actions remain aligned with local needs, technology maturity, and evolving system goals.

It is also important to recognise that many current challenges with CAV and EV deployment reflect the evolving maturity of vehicle technologies themselves, not just infrastructure limitations. The design principles in this report are therefore not intended to compensate for immaturity in vehicle technology, but to support scalable readiness for a range of vehicles as capabilities evolve. Infrastructure adjustments should be matched to realistic deployment timeframes and informed by the pace of vehicle technological development.

2.4 Safe System alignment

The Safe System approach underpins national road safety strategies across Australia and New Zealand. It recognises that people and systems make mistakes, and that infrastructure should be designed to reduce the risk of death or serious injury when such failures occur.

Although this report does not focus on traditional road safety infrastructure, Safe System principles provided an important foundation to drive the investigations. These principles have been considered when developing the infrastructure design responses presented in later sections, particularly in relation to degraded operation, human-machine interaction, protection of vulnerable road users, and fail-safe infrastructure.

This approach ensures that the transition to future mobility technologies continues to support a road system that is both technologically advanced and safe by design.

3. Stakeholder Consultation

This section details the results of stakeholder consultation conducted to identify specific road and infrastructure design areas of interest that would inform and guide the literature review and subsequent development of road and design principles to support vehicle technologies.

Guided by author knowledge and an initial literature scan, a workshop was conducted with PCG members and a wide range of agency representatives. This workshop was attended by more than 25 agency representatives across a range of business areas. The workshop sought input on key road and infrastructure design topics to support vehicle technologies that were most in need of design principles.

The workshop aimed to identify:

- which areas of road agencies were represented by the attendees (see section 3.1)
- examples of road and infrastructure design challenges stakeholders had encountered in recent projects involving CAVs, EVs, or other future technologies (see section 3.2)
- which physical and digital infrastructure areas posed the greatest uncertainties for transitioning to future mobility, and where participants wanted to see design principles developed (see section 3.2.3)
- additional guidance used by agencies (see section 3.3)
- gaps and issues to resolve in guidance (see section 3.3).

Stakeholder input was obtained from the workshop and follow-up consultations with attendees. Results of the exercises are summarised in the subsections below.

3.1 Road agency areas represented

The tally of attendees and their area of road agency representation are shown below in Table 3.1 below. Note that most attendees represented multiple business areas.

Table 3.1: Workshop attendee areas represented

Representation	Areas
Highest representation (5-7 votes)	Operational technology/ITS (7 votes)
	Active transport/micromobility (6 votes)
	Road safety (6 votes)
	Traffic engineering (6 votes)
	Road design (5 votes)
Moderate representation (3 votes)	Infrastructure delivery
	Testing of vehicle technologies
Lower representation (1-2 votes)	Road design standards
	Asset management
	Vehicle technology

3.2 Stakeholder road and infrastructure design challenges

Consultation workshop participants were asked to share examples of road and infrastructure design challenges they had encountered in recent projects involving AV, CAVs, EVs and other future vehicle technologies. A range of answers was provided across several physical and digital infrastructure topics.

The results reflect stakeholder perspectives. They do not imply that infrastructure change is always required or that a single set of requirements applies across all vehicles. In some cases, the challenges raised may reflect the current immaturity of vehicle technologies (e.g. sensor limitations, variability in system design) and may be resolved through future improvements in vehicle capability. The purpose of this exercise was to identify infrastructure implications that may warrant further investigation.

3.2.1 Physical infrastructure design challenges

In the workshop, participants were invited to identify infrastructure challenges observed or anticipated in relation to emerging vehicle technologies. These were assessed for relevance to road and infrastructure design. These relevant physical infrastructure challenges have been categorised according to their relative road infrastructure design category, as follows:

- Vehicle design and road standard implications:
  - Design vehicle changes (e.g. weight, skid resistance, curve radii impacts)
  - Larger, heavier vehicles (including EVs) breaching road safety barriers
  - Impact of heavier electric vehicles on safety and road structures
  - Impact of width of electric vehicles on road design aspects.
- Road safety and visibility challenges:
  - Vehicle blind spots and lack of direct vision
  - Identifying bikes and micromobility devices (e.g. scooters)
  - School and other zones with more than just speed limit being recognised
  - Guidance on pedestrian crossings and pedestrian refuge
  - Where on-road cycleways and kerb ramps are located/start or end
  - Cost of implementing infrastructure to control vehicle speeds at conflict points with people walking and cycling.
- Pavement markings, road signs, and traffic control devices:
  - Ghost lines when road marking is wiped out
  - Vienna convention on road signs for ADAS systems (e.g. no text under speed signs)
  - Line marking requirements for ADAS in a new motorway
  - Line marking width and retroreflectivity standards
  - Traffic signal lantern backing board standard
  - Poor line marking removal causing multiple visible lines in wet/sunny conditions
  - Refresh rate on VMS meant the signs cannot be read by cameras on vehicles
  - Currently looking into the impact of wide centre-line markings on vision systems.
- Resilience and reliability of roadside infrastructure:
  - Impacts of vandalism. Ensure robust and fail-proof infrastructure
  - Long maintenance time to reinstate ITS infrastructure.

- Digital and connected infrastructure considerations:
  - Network and communication coverage across the network
  - C-ITS technology to support CAVs.
- Interactions with level crossings:
  - Level crossings (non-separated or unprotected).
- Active transport hub interactions:
  - Transport interchanges with higher active transport use and buses.
- Policy and governance considerations:
  - Lack of standards for determining safety of AVs
  - Guidance required on how to ensure accuracy of information provided by infrastructure.

Author interpretation of each challenge and commentary indicating its relevance to road and infrastructure design, are provided in Appendix B.

3.2.2 Digital infrastructure design challenges

The workshop also digital infrastructure challenges. Relevant digital infrastructure challenges have been categorised according to their relative road infrastructure design category, as follows:

- Data collection, sharing, and standardisation:
  - Roadworks: Collecting and sharing detailed, quality, real-time data
  - Road disruptions: Collecting and sharing detailed, quality, real-time data
  - Standardisation of data and quality validation for sharing with industry
  - Digital representation of physical disruptions (e.g. flooding).
- Connectivity and system resilience:
  - Connectivity in remote areas
  - Telecommunications network outages
  - Ensuring strong enough mobile coverage to enable CAVs
  - A strong digital connectivity backbone to support CAVs and EVs.
- Policy, governance, and privacy concerns:
  - Protocols for open information sharing between agencies and CAVs
  - Privacy concerns surrounding the sharing of CAV location data
  - Vehicle manufacturers' willingness to share vehicle-generated data (VGD) with government (and consumer concerns)
  - Cybersecurity of remote data sharing and access
  - Policy required on how to manage traffic (e.g. vehicle priority system).

- Digital Applications for Transport Safety and Management:
  - Understanding what digital applications are actually useful for industry advancements in safety technologies
  - Using mobile phones as a V2X device. Security, latency, and accuracy concerns
  - VMS and vehicle onboard CCTV recognition
  - Impacts of digital infrastructure system failure. Mitigations for failure
  - Interruptions to signal sequence (Heavy Rail/Emergency Vehicle Priority (EVP)) needed for accurate signal timing
  - EV charging locations – may be on map but current use and status not live.

Author interpretation of each challenge and commentary indicating its relevance to road and infrastructure design, are provided in Appendix B

3.2.3 Road and infrastructure design priority topics areas

The workshop also focused on identifying higher priority which physical and digital infrastructure topic areas that lacked guidance for transitioning to future mobility, and where participants wanted to see design principles developed. While the purpose of this exercise was to identify priority topic areas for researching, the consultation process found that priorities were dependent on agency business areas represented by attendees. Thus, rather than provide a prioritised list of topics, the results were used to confirm the list of topics to be addressed by the principles in section 5.

Results of the prioritisation exercise are provided in Appendix B.

3.3 Design guidance sources

The identification of design challenges and priorities in section 3.2 above prompted discussion on the current sources of guidance used by agencies and the limitations of existing documentation. Participants were asked to list design references currently in use and then list known gaps in road and infrastructure guidance relevant to emerging mobility technologies.

In this exercise, participants were first shown the range of existing Austroads and known agency design-related documents published from 2017 to 2024. Participants were then asked to list any other additional sources they use to inform road and infrastructure design guidance. Publications from the following sources were identified:

- iMove - Australian Cooperative Research Centre focused on transport and mobility innovation projects
- EU CCAM Platform - European Union platform coordinating connected, cooperative and automated mobility (CCAM) research and policy
- NAPCORE - European project supporting harmonisation of National Access Points for transport and mobility data sharing
- C-Roads Platform - European initiative for cross-border testing and deployment of C-ITS
- ETSI Standards - Technical standards developed by the European Telecommunications Standards Institute for C-ITS and V2X communication.

Participants then identified gaps or issues related to existing road and infrastructure design guidance to support mobility technology, which was used to guide the research and development of principles. The gap/issue topics raised were a combination of technical concerns and overall contextual considerations, and are listed as follows:

- Line and Pavement Marking – Issues with inconsistent markings, non-standard treatments, maintenance intervention levels; and AV perception of ghost lines/markings, coloured lines, and pavement markings.
- Traffic Signals – Challenges were noted regarding traffic management policies and the difficulty of modifying long-established standards.
- Signage – Concerns about sign placement, consistency, electronic sign refresh rates, non-standard signage, and maintenance intervention levels.
- Road Safety – Crash reduction factors related to CAVs was questioned, particularly how safety benefits from future mobility solutions can be reliably forecast.
- Document Form and Presentation – Participants recommended that new guidelines should be integrated into existing Austroads documentation, rather than creating separate, stand-alone documents, to ensure alignment with current standards.
- Road User Consideration – Design principles should cater for all road users.
- Future Forecasts and Planning – Speculative nature of future mobility uptake and development, urban sprawl risks, and economic justifications may impact decision making for long-term infrastructure planning.
- ITS Systems and Operational Technology – Managing the risk of ‘data overload’ and ensuring targeted/valuable information is used in systems.
- Industry Needs and Business Case Considerations – Infrastructure changes should align with actual industry and vehicle requirements, as business case considerations will drive CAV deployment and influence infrastructure needs.

4. Research Findings – Road and Infrastructure Design Topics

This section presents an overview of the key physical and digital road and infrastructure design topic areas relevant to the integration of CAVs and EVs.

Based on the stakeholder consultation workshop (see section 3), several physical and digital infrastructure design topics were identified. Research was conducted to confirm the workshop findings and identify additional relevant topics.

The topics covered in this section are a synthesis of the stakeholder consultation, research, and author knowledge. They reflect key considerations for supporting AVs, CAVs, ADS, C-ITS and EVs. While not all issues fall fully within the remit of road agencies or are addressable through infrastructure design alone, they serve as a framing structure for the development of practical guidance and further investigation.

Common across all topic areas is the need to uphold Safe System principles, including tolerance for error, protection of vulnerable users, and elimination of death and serious injury. This is regardless of whether a human or automated system controls a vehicle.

Each topic is examined using a structured approach, considering existing challenges, emerging practices, and potential road and infrastructure design responses. The findings inform principles for road and infrastructure design adaptation and highlight gaps requiring further research. A list of the physical and digital topic areas is provided below. Topic-specific findings are presented in section 5 (physical topics) and section 6 (digital topics).

4.1 Physical road and infrastructure design topics

The following 11 physical topics were identified:

- **PT1 – Managing transitions of control (from automated to manual)**

  Focuses on physical infrastructure that enables safe and predictable transitions from automated to manual driving, including designated stopping zones, consistent signage, and layouts that support minimal risk manoeuvres/minimal risk condition (MRM/MRC).

- **PT2 – Ensuring readability of lane markings and road signage by vehicles**

  Ensures that line markings and signage are consistently visible and interpretable by AV sensors. Includes standards for contrast, material durability, temporary markings, and placement consistency across jurisdictions and work zones.

- **PT3 – Ensuring compatible road and traffic design for AV navigation and operations**

  Addresses road geometry, speed transitions, and lane configurations that support safe and reliable AV navigation. Emphasises intersection layout, curve design, and physical continuity to reduce misinterpretation by AV systems.

- **PT4 – Maintaining roadway and pavement integrity for AVs and EVs**

  Focuses on pavement structure and resilience under heavier EV axle loads and AV lane-discipline patterns. Includes adaptive maintenance techniques and wear monitoring for AV-priority corridors.

- **PT5 – Managing mixed traffic interactions with Avs**

  Physical solutions that support safe coexistence of AVs and human-driven vehicles, such as lane separation, turn control, and infrastructure that mitigates ambiguity in shared zones.

- **PT6 – Supporting CAV readability of digital roadside signage**

  Focuses on visual and digital signage formats (e.g. VMS, CMS, VSL) that ensure AVs can detect and interpret roadside messages under various conditions.

- **PT7 – Managing AV interactions with e-scooters, cyclists and personal mobility devices**

  Supports safe interaction between AVs and micromobility users by guiding kerb design, midblock crossing treatments, protected lanes, and detection-optimised infrastructure for VRUs.

- **PT8 – Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs**

  Kerbside environments for AV access, including geofenced stopping zones, manoeuvring space, and integration with dynamic access and enforcement regimes.

- **PT9 – Minimising urban congestion from AV fleet staging, parking and idle circulation**

  Manages staging and idle fleet behaviour by providing off-street holding zones and in-network staging areas to prevent kerbside congestion and disruption to general traffic.

- **PT10 – Ensuring EV-compatible crash barriers**

  Roadside barrier design to reflect EV mass and crash characteristics, ensuring that safety systems remain effective for a changing fleet mix.

- **PT11 – Maintenance and asset management for CAV and EV infrastructure**

  Maintenance responsibilities and strategies for AV- and EV-related assets, such as roadside units, digital-ready signs, and machine-readable infrastructure. Emphasises predictive and condition-based maintenance.

4.2 Digital road and infrastructure design topics

The following 13 digital topics were identified:

- **DT1 – Ensuring CAV awareness of temporary and dynamic traffic conditions**

  Focuses on the timely digital delivery of roadworks, lane closures, detours, and emergency conditions to support safe AV navigation when physical layouts change unexpectedly.

- **DT2 – Ensuring data accuracy and validation for AV navigation**

  Ensures that digital representations of geometry, restrictions, and routing logic are accurate and verifiable to support reliable localisation and rule compliance.

- **DT3 – Ensuring reliable CAV communications for continuous data exchange**

  Uninterrupted communication between CAVs, infrastructure, and agencies (V2X), supporting navigation, infrastructure status, and traffic coordination.

- **DT4 – Protecting CAV and transport data from cybersecurity threats**

  Applies authentication, encryption, and threat detection to safeguard CAV communication and digital infrastructure from malicious interference or spoofing.

- **DT5 – Ensuring CAV compliance with dynamic road regulations**

  Delivery of traffic rules in machine-readable formats to support CAV compliance with time-based, location-based, and dynamic restrictions such as speed zones and detours.

- **DT6 – Supporting multimodal and CAV integration**

  Coordination of digital access and dispatch among CAVs, transit vehicles, and micromobility services at the kerbside and in shared transport corridors.

- **DT7 – Ensuring digital resilience and failover mechanisms for CAV operations**

  Safe degraded-mode operation when communications or digital infrastructure fail, using fallback logic and minimum risk manoeuvres.

- **DT8 – Improving CAV interaction with emergency vehicles and vulnerable road users**

  Addresses digital alerts and overrides that help AVs recognise, yield to, and safely interact with emergency vehicles and human responders.

- **DT9 – Optimising CAV and EV fleet management and staging**

  Digital coordination of staging, parking, and routing for AV and EV fleets to reduce congestion and improve kerbside efficiency.

- **DT10 – Integration of CAV and EV operations into smart city and traffic management platforms**

  Use of real-time CAV/EV data in integrated platforms for traffic control, incident response, and infrastructure planning.

- **DT11 – Ensuring real-time EV and electric CAV charging availability and status updates**

  Live updates on charger availability, power status, and expected wait times to support dynamic EV and electric CAV routing decisions.

- **DT12 – Standardising digital road regulations for EV and electric CAV charging zones**

  Machine-readable access rules for kerbside and charging zones to ensure consistency between digital permissions and physical signage.

- **DT13 – Supporting CAV interpretation and compliance with traffic signal infrastructure**

  Delivery of traffic signal state and logic to AVs through digital feeds and spatial referencing (e.g. SPaT/MAP), complementing visual interpretation.

A summary of investigation findings for each topic is presented in section 5 (physical topics) and section 6 (digital topics).

5. Physical Road and Infrastructure Design Topics

This section presents research findings related to the 11 physical road and infrastructure design topics identified.

Physical road and infrastructure topics relevant to this project were identified in section 4.1 and are discussed in the subsections below.

Most topics in this section focus on how infrastructure design, condition or visibility influences the safe and effective operation of EVs and CAVs. However, some topics also consider how the characteristics and behaviours of these vehicles create challenges for infrastructure managers and road agencies. Two topics reverse this framing, examining how AV and EV usage impacts pavement durability (PT4) and contributes to urban congestion (PT9), with a focus on how agencies can mitigate these effects. PT8 (kerbside management), presents a mixed framing, where impacts are described for both vehicle operations and agency or infrastructure performance. In these cases, the challenge and impact tables reflect this dual perspective, considering both how infrastructure supports CAVs and EVs, and how agencies can respond to operational impacts.

5.1 Managing transitions of control (automated to manual) (PT1)

This topic addresses the role of physical road infrastructure in supporting safe transitions of control from automated to manual driving. It focuses on enabling planned and unplanned handovers through appropriate stopping locations, signage, and roadside environments. The topic supports minimum risk manoeuvres (MRMs) and transition areas for human takeover, especially where vehicles must exit their operational design domain (ODD) or respond to changing conditions.

An AV is a vehicle that includes an ADS, but which may also be controllable by other means, such as being driven by a human. Some modes of operation may also be mixed, in which both the ADS and a human driver have active roles.

Note that this topic excludes consideration of Active Safety Systems (ASS) as they do not undertake the driving task on a sustained basis (SAE 2021). While ASS may impact the driving task, the transitions in and out of ASS inputs are not full transitions of control to or from the human driver, as the human driver must remain engaged throughout.

A transition of control occurs when some parts of the driving task are transitioned from the ADS to the human driver, or vice versa. The focus of this subsection is on transitions from the ADS to the human driver, where the human driver needs to take on sustained lateral and longitudinal vehicle motion control (SAE 2021), i.e. steering, acceleration and braking. This transition may occur at different levels of existing human engagement in the driving task, from involved in either lateral control (steering) or longitudinal control (acceleration/braking) as applies at Level 1 automation, through to not required to have any involvement, as applies for Level 4 automation (SAE 2021).

A transition of control can occur for various reasons, including:

- planned (or foreseen) need but transition of control is avoided, such as by routing around challenging situations so that no transition of control is ultimately required
- planned (or foreseen) need implemented by a controlled transition while the vehicle is travelling
- planned (or foreseen) need implemented by a controlled transition but while the trip has been paused and the vehicle is stopped
- unplanned (or unforeseen) need, where a human takes control but with a less than desired transition period; maybe initiated by ADS (system aware and requests) or human (system did not request)
- unplanned (or unforeseen) need, where the ADS does not transition to human driver but instead implements a Minimum Risk Manoeuvre (MRM) to reach a Minimal Risk Condition (MRC).

A distinction between planned and unplanned transitions is whether the ADS knew far enough in advance that a transition of control would be required. That advance awareness may be before the vehicle starts its trip (e.g. days, hours or minutes), right through to the minimum lead-time for a suitable transition. A recurring question in research has been establishing what the minimum time might be for a successful transition of control to a human. A meta-analysis of 129 studies (Zhang et al. 2019) identified reported takeover response times varying from 1.5 to 30 seconds, and that superior human driver responses (better situational awareness, improved driving responses) were achieved when longer handover times were provided (Vlakveld et al. 2018). Assuming that the transition is initiated by the ADS, such a transition period can only commence once the ADS has determined that a transition is required – which for some transitions might not occur (i.e. human decides to intervene).

A recent Australian study (IMOVE 2023) investigated real-world takeover response under controlled AV trial conditions. Participants received takeover requests (TORs) via visual and auditory prompts only and were not engaged in distracting non-driving tasks. The study found that takeover times (TOTs) ranged from under 3 seconds to as long as 6–7 seconds, with an average of approximately 5 seconds. Based on these findings, the study recommended that a minimum of 5–6 seconds be allotted for safe driver takeover in similar contexts. However, it also noted that TOTs are likely to be longer if drivers are engaged in secondary tasks or if TORs are issued without haptic feedback. These results support the continued need to research scenario-specific TOR lead times.

An important assumption underpinning this topic is that road infrastructure owners and operators will benefit from safety practices embedded into AV operations. This creates a dependence on regulators and Automated Driving System Entities (ADSEs) to ensure such practices are in place. The assumption does not suggest that ADSs are flawless, but rather that their risk exposures are managed in a way that supports safe integration with existing infrastructure. Two examples from the 2025 Aurora Automated Truck safety case Aurora (2025) demonstrate how ADSEs can reduce road agency risk by embedding such practices:

- Reducing the likelihood that a transition needs to occur: “We know that icy conditions can occur and the Aurora Driver is not currently designed to operate in them. As a result, we operationally control our exposure to them by not deploying the Aurora Driver when roads are icy.”

  This limits unexpected AV behaviour on unsafe roads, thereby reducing the burden on infrastructure owners to accommodate or mitigate for such edge cases.

- Reducing the impact of transitions that do occur: “To minimize the likelihood of stopping on the shoulder of a busy freeway, the Aurora Driver [Automated Truck] will, if possible, drive to and stop at a designated ‘preferred pullover’ location. These locations are just off the highway on frontage roads, where our trucks can pull over in such a way that minimizes collision risk, minimizes nuisance to other road traffic, and facilitates recovery if needed.”

  This supports infrastructure managers by ensuring that unplanned stops occur in pre-assessed, lower-risk locations, reducing collision and recovery complexity.

As AV operations expand, opportunities may also emerge for road agencies to access selected in-service AV data, such as fallback events or repeated hesitation during transitions. This will help to identify where infrastructure features (e.g. signage issues, unclear layouts, or stopping zone design) contribute to degraded AV performance. This concept aligns with international safety assurance frameworks (e.g. UNECE WP.29 2024) and supports the case for a safety data feedback loop, where real-world vehicle behaviour informs future infrastructure improvements.

5.1.1 Key challenges

The core challenge lies in enabling ADSs to hand control to human drivers safely and efficiently when required. Road agencies must ensure that infrastructure supports both planned and unplanned transitions, including appropriate stopping zones, clear signage, and layouts that align with ADS operational expectations. Without these features, transitions can introduce delays, unsafe manoeuvres, or failures to respond appropriately to environmental or operational changes. Managing transitions of control (automated to manual) may present several challenges. Table 5.1 presents these key challenges, example scenarios and their impact on AV operations.

Table 5.1: Key challenges that impact managing transitions of control (automated to manual)

Key challenges	Example scenario	Impact on AV Operations
Transition to manual control required but no manual control option is available	ADS in a robotaxi is aware pre-trip of temporary works conditions outside of its ODD preventing access to a pick-up point, and either offers an alternative pick-up point or declines the trip.	Reduces ability to serve requested destinations, resulting in limited trip availability and constrained fleet coverage in areas with dynamic or unmodelled conditions.
Planned transition to manual control executed with some minor undesired impacts	ADS sensors identify an unanticipated condition outside of the ODD (e.g. protest march on route), identifies a safe parking area to await support from remote support centre.	Interrupts trip continuity and introduces delay; requires reliable decision-making to avoid unsafe or disruptive responses during routing changes.
	ADS in a large truck needs a suitable location for a human driver to join at the boundary between line-haul (within this truck's ODD) and local last-mile (outside this truck's ODD).	Requires suitable, pre-identified physical infrastructure (e.g. truck rest area) to ensure safe and legal handover without obstructing traffic or delaying logistics.
Unplanned transition to manual control executed with many undesired impacts	ADS identifies a sensor failure and seeks to initiate an MRM to achieve an MRC; however, its appraisal of available options results in stopping in a live traffic lane.	Creates safety risks for surrounding traffic and road users; highlights critical need for accessible safe stopping zones and robust fallback strategies.
Failure to identify need for transition to manual control executed with undesired impacts	ADS fails to identify a situational awareness failure (e.g. failed to detect an excavation in road, and also failed to identify that this failure had occurred), requiring a partly alert human driver to initiate a late takeover of control.	Results in delayed or unsafe intervention, increasing collision risk; exposes system gaps in hazard detection, redundancy, and fail-safes.

5.1.2 Road and infrastructure design considerations

Several road and infrastructure design considerations have been formulated below in Table 5.2. These are centred around a risk management approach seeking to mitigate risk exposures from transitions of control.

Table 5.2: Road and infrastructure design considerations related to PT1

Design element considerations	Description	Supporting references
Minimising frequency and severity of unplanned transitions	Physical infrastructure designed to align with ADS operational expectations reduces the need for unexpected control handovers.	• Tengilimoglu et al. (2023) • Aurora (2025)
Infrastructure support for situational awareness	Use of digital infrastructure and clear temporary traffic layouts helps ADS detect and anticipate conditions requiring transition.	• Tengilimoglu et al. (2023)
Provision of safe stopping areas	Emergency lanes, shoulders, or predictable pullover locations support MRMs during unplanned transitions.	• Tengilimoglu et al. (2023) • Aurora (2025)
Designated areas for planned transitions	Suitable locations provided for scheduled human takeover, such as AV truck changeover zones or AV-accessible ride-hail points.	• Aurora (2025)
General AV-compatible road design	Incorporation of good practice infrastructure that supports AV operation across typical conditions, benefiting both AVs and human drivers.	• Tengilimoglu et al. (2023) • Austroads (2023)
Machine-readable temporary and incident layouts	Temporary traffic management and incident zones designed to be identifiable by AV sensors within lead time windows.	• Tengilimoglu et al. (2023)
Enable infrastructure feedback via AV transition data	Agencies should explore mechanisms to collect data on where transitions occur, why they were triggered, and whether infrastructure contributed to fallback events, to inform future road upgrades.	• UNECE (2024) WP.29/2024/39

5.1.3 Related topics

Topics related to PT1 include those listed below in Table 5.3.

Table 5.3: Topics related to PT1

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Transitions may be influenced by signage clarity and AV interpretation reliability.
DT1	Ensuring CAV awareness of temporary and dynamic traffic conditions	Transitions during dynamic traffic changes need timely digital updates.
DT13	Supporting CAV interpretation and compliance with traffic signal infrastructure	Signal-based handover logic connects with digital traffic signal compliance mechanisms.

5.1.4 Principles

Principles derived from the above evidence that relate to PT1 are shown in Table 5.4 below.

Table 5.4: Principles related to PT1

Principle	Description
Account for ADS capabilities and limitations	Understand ADS as a road user with defined limitations, similar to how infrastructure considers human driver capabilities.
Design infrastructure to support general ADS operation	Provide infrastructure that is more amenable to ADS operation, especially where this also benefits human drivers and is practicable and affordable.
Recognise that infrastructure can enhance ADS performance	While ADS should operate under current conditions, targeted infrastructure improvements can raise performance from acceptable to better than acceptable.
Ensure temporary conditions are machine-readable	Temporary works and incident response layouts should include cues that enable ADS to determine an appropriate course of action with sufficient lead time.
Coordinate physical and digital infrastructure	Complement physical infrastructure with digital systems to support ADS situational awareness, particularly for dynamic or temporary conditions.
Consider availability of safe stopping areas	Plan for suitable stopping locations that support both planned and unplanned transitions, avoiding reliance on stopping in live lanes.
Adapt layouts for temporary and emergency conditions	Evolve temporary works and incident response layouts to include safe stopping opportunities and communicate them effectively to ADS.
Use operational feedback to refine transition infrastructure	Disengagements and MRM events can highlight inadequacies in road layout, signage, or stopping zones. Agencies should use this data to improve transition design.

5.1.5 Future research areas

Whilst there is some coverage of the PT1 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified below in Table 5.5.

Table 5.5: Potential research topic areas related to PT1

Research topic area	Description
Analyse real-world transitions of control	Study transition types (e.g. MRM to MRC, remote support) to better target infrastructure and operational responses.
Evaluate temporary and incident layout improvements	Identify updates to layouts that would improve ADS handling of real-world transition scenarios.
Determine minimum safe transition time for human takeover	Investigate how much lead time is needed for effective and safe handover from ADS to human drivers across different scenarios.
Evaluate value of stopping lanes versus smart motorway layouts	Examine whether the safety benefits of continuous stopping lanes justify changes to modern managed motorway designs.
Assess current temporary traffic management suitability for ADS	Review whether existing guidance and practices for temporary works provide sufficient cues and safety margins for ADS systems.
Investigate specific heavy vehicle transition requirements	Heavy vehicles may require dedicated infrastructure (e.g. wider bays, longer pull-in distances) for safe and legal transitions.

References for PT1

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5.2 Ensuring readability of lane markings and road signage by vehicles (PT2)

This topic addresses the physical design, visibility, and maintenance of roadway elements, including line markings, signage, and signal features. These elements must be reliably detected and interpreted by both human drivers and vehicles. It includes both permanent and temporary infrastructure, such as markings used during roadworks, detours, and incident response.

Key considerations include width, contrast, retroreflectivity, durability, and standardisation of placement to support robust performance across varied environments and operational conditions. Emphasis is placed on ensuring readability and interpretability by machine vision systems used by an automated driving system (ADS), advanced driver assistance system (ADAS), and ASS (active safety system), while maintaining compatibility with human driver needs.

This topic also includes guidance on the physical visibility, placement, and occlusion risks related to traffic signals. However, traffic signals are addressed more fully in DT13, which focuses on the interpretation of signal logic, SPaT/MAP feeds, and fallback behaviours.

Note on structure: This subsection differs in format to other topic subsections in this report, reflecting its basis in Austroads (2023) AP-R696-23, which undertook a comprehensive review of more than 100 sources in identifying minimum requirements for signs, signals and line markings to support automated vehicle operation across static and temporary conditions. Accordingly, the structure follows a more technical and evidence-based format aligned with that source, rather than scenario-based challenge-framing presented in the other topic subsections.

The successful detection and interpretation of line marking and road signs by ADS has been a major focus of prior Austroads research, as identified in Austroads (2023) and adapted for presentation below (see Table 5.6).

Table 5.6: Past Austroads reports addressing physical infrastructure for AVs

Reference	Title	Value
Austroads 2017	*Assessment of Key Road Operator Actions to Support Automated Vehicles,* AP-R543-17	Austroads' first identification of the range of issues that may affect preparations for AVs including physical infrastructure. Helped set scope for later projects.
Austroads 2018a	*Harmonisation of Pavement Markings and National Pavement Marking Specification,* AP-R578-18	General update to pavement marking practice that included some references to possible AV needs and informed updates to Australian Standards (AS 1742).
Austroads 2018b	*Implications of Traffic Sign Recognition (TSR) Systems for Road Operators,* AP-R580-18	Investigated potential changes to traffic signs to support the operation of TSR systems. Issues list remains relevant and informed scope and detail of later projects.
Austroads 2019a	*Infrastructure Changes to Support Automated Vehicles on Rural and Metropolitan Highways and Freeways: Audit Specification (Module 1),* AP-T347-19	Reviewed available information to establish auditable quality standards for AV readiness, including for traffic signs and line marking.
Austroads 2019b	*Infrastructure Changes to Support Automated Vehicles on Rural and Metropolitan Highways and Freeways: Project Findings and Recommendations (Module 5),* AP-R606-19	Provided summarised findings from Module 1 to 4, but importantly also set out implications of these findings along with recommendations for future work. Approach to reporting recognised and catered for the variability in capability between systems.
Austroads 2019c	*Infrastructure Changes to Support Automated Vehicles on Rural and Metropolitan Highways and Freeways: Asset Standards (Module 3),* AP-R604-19	Examined gaps between the audit standards and national and jurisdictional standards for physical infrastructure, including new and in-service quality requirements for signs and line marking.

Reference	Title	Value
Austroads 2019d	*Infrastructure Changes to Support Automated Vehicles on Rural and Metropolitan Highways and Freeways: Road Audit (Module 2),* AP-T348-19	Undertook an extensive field audit across Australia and New Zealand using a practical implementation of the audit standards established in Module 1 and three complementary methods.
Austroads 2020a	*Implications for Pavement Markings for Machine Vision,* AP-R633-20	Examined performance of automated steering systems with various line qualities and included some recommendations of specifications and standards.
Austroads 2020b	*Guidance and Readability Criteria for Traffic Sign Recognition Systems Reading Electronic Signs,* AP-R627-20	Investigated electronic sign readability for use in the design and testing of electronic signs.
Austroads 2022	*Minimum Physical Infrastructure Standard for the Operation of Automated Driving,* AP-R665-22	Established what types and timings of investment may be warranted to support AVs, including recommendations that traffic signs, line marking, and traffic signals are priority areas for investment. Also identified the key benefits to human drivers from some investments in physical infrastructure (e.g. improved line marking, signs).
Austroads 2023	*Minimum Requirements for Traffic Signs, Traffic Signals and Line Markings,* AP-R696-23	Provides decision making support to agencies on future physical infrastructure practice changes required to support CAVs in the areas of line marking, road signs (static and electronic) and traffic signals.

Source: Adapted from Austroads (2023).

Austroads (2023) research on minimum requirements for traffic signs, traffic signals and line markings identified specific changes to guidelines and standards are required at this point, and what further action might be warranted to help determine other specific changes.

In reviewing the detailed changes, Austroads (2023) initially considered design principles and user needs for ADS. For certain topics, such as road signs, developing design principles was generally the most that could be achieved.

In establishing design principles, Austroads (2023) established key context, which have been considered in this report as follows:

- Human road users remain critical when considering any changes.
- Driving automation systems are a heterogenous user group that include different capabilities and stages of development across ASS, ADAS and ADS.
  - There is significant variation in perception capabilities between these different categories of systems and between different systems within each category.
  - There has been significant growth in capability over time, and further capability growth is reasonable to anticipate.
- Stakeholders generally agree more on the high-level principles, but differ significantly on the specific standards and specifications.
- Digital infrastructure is expected to play an important complementary role to physical infrastructure.

Detection and interpretation of longitudinal line marking

Austroads (2023) identified longitudinal markings (e.g. edge lines, lane lines) as the most widely discussed infrastructure elements for supporting ASS, ADAS, and ADS. Important features include line width, reflectivity, and contrast, as well as design aspects like dashed line patterns, lane start/end layouts, and contrast treatments. Temporary markings and effective removal of outdated lines are also critical to ensure reliable system performance.

Austroads (2023) identified that vehicles with ASS, ADAS and ADS detect longitudinal lines that delineate traffic lanes so that they can:

- know if another vehicle is about to cross out of a lane to decide whether to intervene
- plan and control the steering path ahead within a lane
- understand traffic restrictions, such as whether a particular lane line can be crossed (e.g. broken line)
- help determine their detailed position in space (localisation) to complement positioning from GPS and other sources.

Meeting these perception needs requires perception systems to successfully:

- detect and assess the position of longitudinal lines in the short distance ahead of the vehicle
- assess the likely position of longitudinal lines in the longer distance ahead of the vehicle
- assess the form of the line (e.g. edge line, single broken lane line, double two-way barrier lines).

Line width

Austroads (2023) found that wider lines may offer improved performance, but it was less clear that they were an essential minimum requirement:

- Adoption of wider lines, with a focus on 150 mm wide lines, may result in improved performance for all longitudinal line types (edge, lane, dividing) compared to narrower lines (e.g. 100 mm).
- There was no clear consensus as to whether wider lines (i.e. 150 mm) were critical or only useful for achieving acceptable performance, but there was general acceptance that they were at least useful.
- Wider lines are not the only quality attribute of relevance, and some road managers have considered prioritising investment on other attributes (e.g. wet retroreflectivity in wet conditions) or requiring wider lines only for some line types and/or some road types.

Retroreflectivity in dry conditions

Austroads (2023) found general agreement that levels of dry retroreflectivity are important to the performance of ASS, ADAS and ADS in dry night-time conditions. There was however no consensus as to what might represent an essential minimum requirement:

- There is high confidence that lines maintained to 150 mcd/lux/m^2 dry retroreflectivity or above should assist good performance.
- There is less agreement that 150 mcd/lux/m^2 dry retroreflectivity represents a minimum acceptable value. Some testing showed consistent acceptability for low values (e.g. > 50 mcd/lux/m^2) and there is no agreement on a specific minimum cut-off value for acceptable performance.
- Achieving suitable minimum levels of retroreflectivity in wet conditions may provide an effective alternative minimum (as the wet value tends to be lower than the dry value and becomes the determining factor in performance achieved). It is easier to measure dry than wet retroreflectivity and the dry method is more commonly used. Any acceptance of dry retroreflectivity levels below 100 mcd/lux/m^2 should therefore take care to avoid unacceptably low wet retroreflectivity.

Retroreflectivity in wet conditions

Austroads (2023) found general agreement that levels of retroreflectivity in wet conditions is important for the performance of ASS, ADAS and ADS in wet night-time conditions.

- There is high confidence that lines maintained to 75 mcd/lux/m^2 wet retroreflectivity or above should assist good performance.
- There is less agreement that 75 mcd/lux/m^2 wet retroreflectivity represents a minimum acceptable value. Some testing showed consistent acceptability for low values (e.g. > 10 mcd/lux/m^2).
- There is no agreement on a specific minimum cut-off value for acceptable wet retroreflectivity performance.

Contrast to surrounding pavement

Austroads (2023) found general agreement that the level of contrast to the surrounding pavement is relevant for the performance of ASS, ADAS and ADS in daytime conditions:

- There is however no agreement on specific contrast requirements. The most common recommendation for a luminance contrast ratio is 3:1; however, results of local and international field testing appear to suggest that this may be excessive; and that reliable performance is often achieved at lower contrast ratios.
- While lines with lower contrast ratios may perform well in some test conditions, they may be less clear during more challenging conditions (e.g. wet and/or sun glare).

Use of treatments to improve contrast between lines and surrounding pavement

Contrast treatments such as those shown in Figure 5.1 below provide one method of achieving suitable contrast between lines and light-coloured pavement. Austroads (2023) identified wide support from automotive stakeholders for their use, but also two alternative designs (e.g. 'Oreo' pattern or lead-lag) with different supporters.

Figure 5.1: Examples of contrast patterns

"Oreo" Pattern

"Lead-Lag" Pattern

Source: ASC (2021).

Crumbling of worn lines

Austroads (2023) found that crumbling or wearing lines have been identified as an issue in some literature due to potential loss of shape, retroreflectivity and/or colour. Other than a general desire to avoid crumbling or worn lines, no more detailed guidance was discernible.

Design of broken line patterns

Austroads (2023) identified some discussion as to whether a change in the broken line pattern, such as used for lane lines, to include more stripe relative to gap, will increase the amount of stripe for detection.

Australia uses a 3 m stripe/9 m gap pattern and New Zealand uses a 3 m stripe/7 m gap pattern. The United States, where much of the discussion identified by Austroads (2023) emanates from, generally uses a 3.2 m stripe/9.6 m gap pattern, but some recent advocacy favours change to a 4.8 m stripe/8.1 m gap pattern.

Other than noting that this balance between stripe and gap was a feature to monitor in international literature and potentially subject to local field testing, no specific guidance was discernible.

Design of layouts where lanes start or end

Locations where lanes start or end include merges, diverges, lane additions and lane drops. Austroads (2023) found that these locations are frequently discussed as presenting a challenge for systems interpreting line marking, particularly if there are any gaps in the markings (i.e. where a continuity line is not provided).

- Most discussions in literature, including observations from testing, focus on diverges and lane additions rather than merges or lane drops. However, this may reflect the use of line following capabilities rather than explicit lane change capabilities (where the ability to navigate merges and lane drops becomes more relevant).
- Clear delineation of exit diverges (e.g. continuity lines provided, gore marked with chevrons, step-out marking included) was a high priority for auto industry stakeholders.
- Further requirements for merges and lane drops may emerge as vehicle functionalities that seek to handle these road features become more common.

Austroads (2023) identified some specific recommendations for New Zealand (chevron marking for all motorway exit gores rather than only some, monitor for reported problems from the lateral gap of 1.8m between motorway merge edge lines at their point of termination). A further watching brief was recommended for Australia and New Zealand as to any problems emerging for wide lanes (>4m) based on prior Austroads findings (Austroads 2020).

Provision of edge lines

Austroads (2023) found that the availability of an edge line of suitable quality was noted in industry feedback to improve performance of ASS, ADAS and ADS, even for those systems that had some capability to detect unmarked edges.

Prior Austroads work (Austroads 2019a) found an existing high prevalence of edge lines on rural roads in the surveyed Australian and New Zealand networks.

It was not possible to confidently assess whether additional edge line provision was merely desirable and useful or essential, due to limited local, and no identified international, testing of performance for unmarked edges (Austroads 2023). The desirability was however clear:

> *Provision of lines on both sides of the lane of travel remains likely to be the easiest situation to achieve good performance for ASS, ADAS and ADS, even if reasonable performance is possible with lesser marking (e.g. a line only on one side of a lane). Improved performance for ASS, ADAS and ADS could therefore be considered a supporting reason for any additional marking of edge lines that may occur as part of safety investment programs to support human drivers.*

Offset of edge line from edge of pavement

Austroads (2023) identified that some previous stakeholder discussions noted that it was preferable to maximise contrast and clarity of an edge line by having a minimum distance of pavement outside the edge line. However, very little documented discussion can be found on this and the approach in Australian Standards, and particularly the 2022 update thereto, appears to already provide for any likely requirements in this regard.

Use of less common types of longitudinal line marking

Austroads (2023) found a strong expressed general desire in literature and across stakeholders for avoidance of 'non-standard' treatments.

An example of the challenge that these treatments can pose to machine vision systems was identified in a prior Austroads project (Austroads 2019d) where an asset inventory machine vision system incorrectly identified as a wide centreline treatment as if it provided a narrow third central lane (as shown below in Figure 5.2).

Figure 5.2: Wide centreline incorrectly interpreted as a narrow lane by machine vision

Source: Austroads (2019b).

The tension between standardisation and innovation was explored in Austroads (2023), which identified New Zealand's TCD Manual Part 5 (NZTA 2020) as noting that 'at sample sites, wide centrelines have reduced all injury crashes by 20%, fatal and serious injury crash rates by 30% and the rate of death and serious injuries by 50% because they are effective in reducing head-on crashes which typically kill or injure more people per crash'. This safety benefit means there would be a reasonable preference to address any issues for ASS, ADAS and ADS that would assist their continued use rather than to abandon the treatment type. To that end, Austroads (2023) recommended efforts to achieve greater consistency within designs for wide centrelines (which currently differ between jurisdictions) rather than reversion only to standard centrelines.

Design of treatments to delineate special use lanes

Austroads (2023) identified that special use lanes such as for bicycles, buses or trams/light rail vehicles are an important and increasing part of the traffic management toolkit in Australia and New Zealand. There was however a comprehensive lack of discussion in the literature of ASS, ADAS and ADS performance around special use lanes, either locally or internationally.

Considerations for temporary line marking

Austroads (2023) found broad agreement that temporary line markings cause challenges when there are poorly removed redundant lines (e.g. blackened but still reflective) and/or multiple sets of lines (e.g. yellow temporary lines alongside permanent white lines). Temporary lane lines may be particularly critical for effective ADAS and ADS operation as the temporary conditions may differ from a vehicle's underlying map expectation. The consistently agreed approach to address temporary line marking challenges was to ensure only the currently applicable set of lines is visible and that redundant lines are effectively removed or covered.

Detection and interpretation of traverse, chevron and symbolic markings

Transverse lines (e.g. stop lines), chevron and diagonal markings and symbolic markings (e.g. directional arrows at traffic signals) are used by ADAS and ADS as both primary and supporting information sources.

Austroads (2023) found that these marking types had been subject to much less investigation than longitudinal markings. There was some discussion on the importance of these markings and the value of consistent provision but there was no particular indication that current marking quality (such as width or retroreflectivity) was inadequate.

Detection and interpretation of road signs

Austroads (2023) identified the following factors as likely to be important to the successful detection and interpretation of road signs. There are few variances between the identified good practice for machine vision and good practice for human drivers. The most notable difference is in the capability to interpret text – for human drivers there is some variability in capability, but for most drivers at least some ability to read and interpret text, however for machine vision systems this was generally not the case.

Factors identified as important were:

- The sign is in an expected position that is within the camera's field of view:
    - mount within expected lateral offsets and mounting heights for side-mounted signs
    - consider mounting height for overhead signs (some camera systems had limited ability to view signs higher than 5.4 m)
    - the system's capability to ascertain the application of signs to specific lanes or carriageways.
- The sign is of an expected design that closely matches the system's training set:
    - use of larger signs can improve detection rates as it provides a greater number of pixels to detect and recognise
    - standardise all signs throughout the country.
- School speed zone signs were a noted example of where this was not currently the case:
    - prefer the use of pictograms and limit use of text.

- Most systems were not identifying as having the capability to read text on signs, but rather merely to match them to a sign within their library:
  - where total information loads are high, limit the amount of information and the number of signs needing to be detected, recognised and actioned at any one location by spreading longitudinally along the road.
- The sign is clearly visible and legible to the camera system:
  - achieving this requires management of degraded and damaged signs as well as ensuring sight lines are not blocked by vegetation or other obstructions.

Special considerations for electronic road signs

Electronic road signs are used to provide variable management and/or increased conspicuity of traffic restrictions and to provide traveller information. Austroads (2023) review focused on signs that convey road rules and traffic regulations (e.g. variable speed limit signs (VSLS) or illuminated No Right Turn) rather than information signs such as variable message signs (VMS).

Austroads (2023) found that the general good practices for general road signs apply also to electronic signs. One area of special additional requirement was for the visibility of LED signs to machine vision systems, caused by refresh or flicker rate of LEDs. There is broad industry support for the adoption of a minimum refresh rate of 200 Hz, at least for regulatory signs (e.g. speed limit, turn restriction). In parallel to any improvements to LED flicker, developments in camera systems were identified as trying to reduce susceptibility to this problem.

Detection and interpretation of traffic signals

Austroads (2023) notes that current signal hardware and placement practices were developed for human drivers, and do not consistently support machine vision systems. Key issues include misalignment, occlusion, ambient glare, and inconsistent use of target boards or colour contrast. To improve detection, Austroads recommends measures such as black backing boards, LED refresh rates of at least 200 Hz, and consistent mounting practices.

For safe and lawful signal compliance, ADS and ADAS-equipped vehicles must be able to:

- detect the presence of traffic signal lanterns, with or without assistance from mapped 3D signal locations (noting that temporary signals may not be pre-mapped)
- determine which signal heads apply to the intended vehicle movement
- correctly identify the signal aspect (e.g. red, amber, green) associated with that movement.

Austroads (2023) also highlights substantial variation in traffic signal design and practice across jurisdictions, both internationally and within Australia and New Zealand. For example:

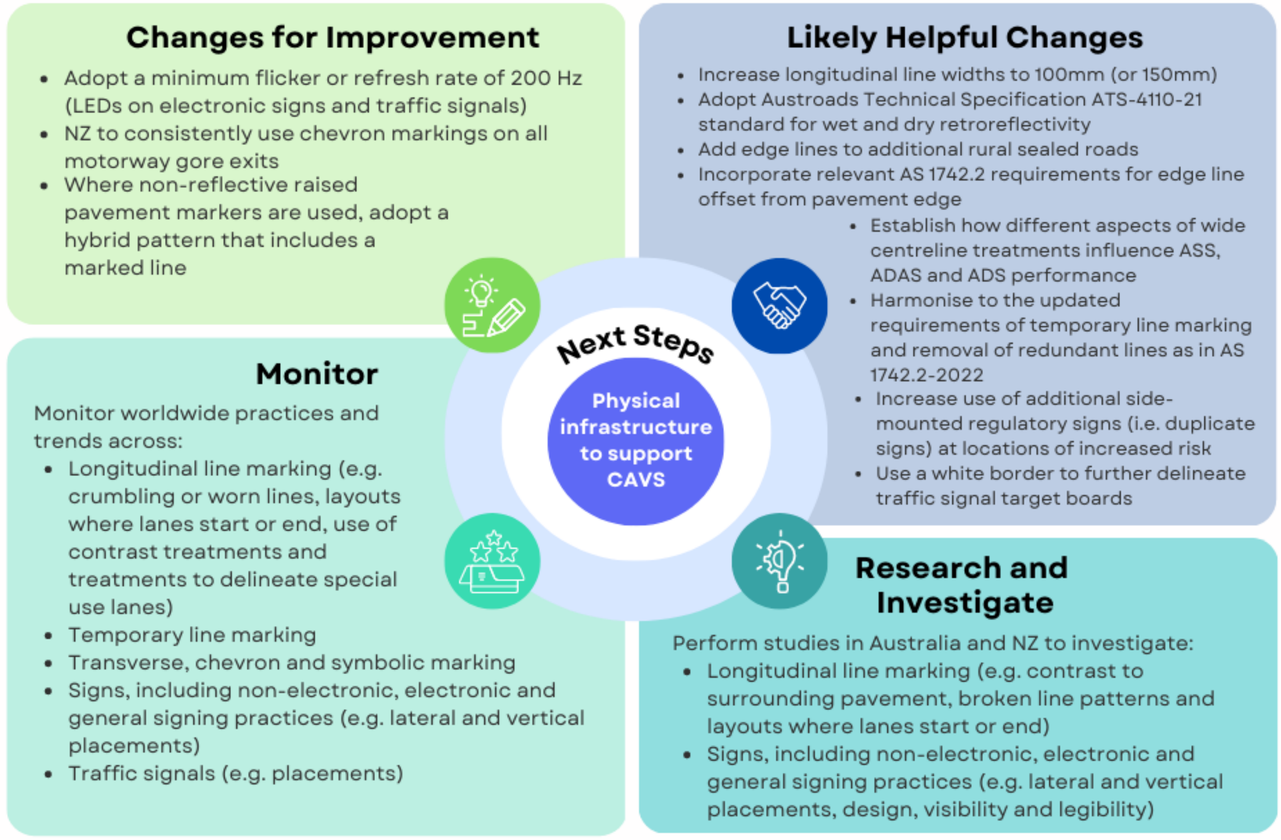
- signal heads may be oriented vertically or horizontally
- lantern quantity, placement, and redundancy levels vary significantly between intersections and states.

This variation increases the likelihood that machine vision systems will require localised training or calibration to reliably interpret Australian and New Zealand traffic signals, particularly when relying solely on visual perception (Austroads 2023).

Recommendations

Austroads (2023) identified several areas for potential future research, in addition to a small set of areas where changes could be made now. These are shown below in Figure 5.3.

Figure 5.3: Recommendations summary



Changes for Improvement

- Adopt a minimum flicker or refresh rate of 200 Hz (LEDs on electronic signs and traffic signals)
- NZ to consistently use chevron markings on all motorway gore exits
- Where non-reflective raised pavement markers are used, adopt a hybrid pattern that includes a marked line

Likely Helpful Changes

- Increase longitudinal line widths to 100mm (or 150mm)
- Adopt Austroads Technical Specification ATS-4110-21 standard for wet and dry retroreflectivity
- Add edge lines to additional rural sealed roads
- Incorporate relevant AS 1742.2 requirements for edge line offset from pavement edge
- Establish how different aspects of wide centreline treatments influence ASS, ADAS and ADS performance
- Harmonise to the updated requirements of temporary line marking and removal of redundant lines as in AS 1742.2-2022
- Increase use of additional side-mounted regulatory signs (i.e. duplicate signs) at locations of increased risk
- Use a white border to further delineate traffic signal target boards

Next Steps

Physical infrastructure to support CAVS

Monitor

Monitor worldwide practices and trends across:

- Longitudinal line marking (e.g. crumbling or worn lines, layouts where lanes start or end, use of contrast treatments and treatments to delineate special use lanes)
- Temporary line marking
- Transverse, chevron and symbolic marking
- Signs, including non-electronic, electronic and general signing practices (e.g. lateral and vertical placements)
- Traffic signals (e.g. placements)

Research and Investigate

Perform studies in Australia and NZ to investigate:

- Longitudinal line marking (e.g. contrast to surrounding pavement, broken line patterns and layouts where lanes start or end)
- Signs, including non-electronic, electronic and general signing practices (e.g. lateral and vertical placements, design, visibility and legibility)

Source: Austroads (2023).

5.2.1 Related topics

Topics related to PT2 include those listed below in Table 5.7.

Table 5.7: Topics related to PT2

Related topic (code)	Related topic title	Reason for cross-reference
PT3	Ensuring compatible road and traffic design for AV navigation and operations	Road geometry affects line placement and signage visibility.
DT3	Ensuring reliable CAV communications for continuous data exchange	Agencies should provide use reliable communication means and transfer methods to support data exchange.
PT6	Supporting CAV readability of digital roadside signage	Addresses readability of dynamic signage (VMS, CMS, VSL).
DT2	Ensuring data accuracy and validation for AV navigation	Digital representation of signage should align with physical placement for AV interpretation.
DT5	Ensuring CAV compliance with dynamic road regulations	Dynamic regulations should be reflected both physically (signs) and digitally.
DT13	Supporting CAV interpretation and compliance with traffic signal infrastructure	Traffic signal visibility and placement should complement digital SPaT/MAP messaging logic.

5.2.2 Principles

The principles listed below in Table 5.8 are derived from Austroads (2023) and related insights, and defines underpinning guidance for infrastructure adaptation to support AV line and sign detection.

Table 5.8: Principles relating to PT2

Principle	Description
Design for human and machine vision	Road infrastructure should meet visibility and recognisability requirements for both human drivers and automated systems, ensuring shared usability.
Favour consistency over innovation	Use standardised markings and signage where possible. Avoid novel treatments (e.g. non-standard centrelines or symbolic formats) unless machine compatible.
Prioritise critical use locations	Focus enhancements (e.g. wider lines, continuity lines, edge lines) in high-risk or high-use areas like merges, diverges, exits, or signalised intersections.
Support with digital redundancy	Physical elements (e.g. signs, signals, speed limits) should be matched by accurate digital representations, especially where AVs rely on fallback logic.
Maintain visibility under all conditions	Ensure signs and markings remain clear in adverse weather, night conditions, and glare—using wet retroreflectivity, contrast treatments, and durable materials.
Phase implementation based on use and risk	Implement upgrades in stages, prioritising routes with AV trials or early adoption. Not all roads require immediate compliance with emerging AV standards.

5.2.3 Future research areas

Based on the findings of Austroads (2023), Table 5.9 below summarises the lane marking and road signage features that have confirmed minimum requirements, those that considered beneficial but not yet essential, and those where further research is required. It supports agencies in prioritising updates to physical infrastructure and identifying areas needing further evidence or standardisation.

Table 5.9: Summary of signs and lines element readiness and future research requirements

Infrastructure element	Purpose for ADS/AV systems	Adequacy of current practice	Minimum requirement confirmed?	Further research needed?
Line width (e.g. 150 mm)	Improves detection and tracking of lane boundaries	Often adequate; wider lines preferred by stakeholders	No 150 mm is useful, but not confirmed as essential	Yes Cost-benefit and condition-specific needs
Dry retroreflectivity	Night-time visibility under dry conditions	Variable across networks	No ≥ 150 mcd/lux/m² helps; no agreed minimum	Yes Especially for acceptable lower bounds
Wet retroreflectivity	Night-time visibility under wet conditions	Often inadequate	No ≥ 75 mcd/lux/m² helpful; low value acceptability unclear	Yes Minimum threshold performance uncertain
Contrast to pavement	Daytime visibility and lane clarity	Inconsistent, especially on light pavements	No 3:1 ratio common, but may be higher than needed	Yes For adverse conditions (glare, wet)
Edge line provision	Enhances localisation and lane keeping	Generally good in rural areas; patchy elsewhere	No Desirable, but not proven essential	Yes For unmarked edges and urban areas

Infrastructure element	Purpose for ADS/AV systems	Adequacy of current practice	Minimum requirement confirmed?	Further research needed?
Broken line pattern	Supports detection and distinction of lane types	Practice varies globally	No No standard proven better; US patterns under review	Yes Comparative testing needed
Start/end lane markings (e.g. diverges)	Helps ADS recognise lane additions and exits	Variable clarity, especially at diverges	No Industry prioritises continuity lines and chevrons	Yes For merges, drops, and wide lanes
Temporary markings	Guides AVs during changed traffic conditions	Often problematic (e.g. conflicting lines)	Yes Only current lines should be visible and redundant lines removed	Yes Implementation quality and methods
Worn/crumbling lines	Affects line shape, visibility, and recognition	Performance degrades with wear	No Avoidance preferred; no standard for degradation	Yes Thresholds and impact require study
Wide centrelines	Safety benefit for humans; challenge for machine vision	Misinterpretation reported (e.g. as a separate lane)	No Keep for safety, but standardisation needed	Yes Define consistent designs across jurisdictions
Special use lanes (e.g. bus, cycle)	Affects AV compliance with restricted lanes	Little to no machine vision performance data	No Clear evidence gap	Yes Major under-researched area
Static road signs	Recognition and compliance with traffic rules	Adequate where standardised; some national variation	Partially Positioning and design standards aid detection	Yes Especially for non-standard signs and text handling
Electronic signs	Recognition under dynamic or low-contrast conditions	Flicker rate may impair visibility	No 200 Hz refresh rate recommended, not universal	Yes Technology alignment (sign and camera)
Traffic signals	Recognition and response to signal phases	Highly variable design, placement, and arrangements	No Localised training and redundancy often needed	Yes Signal face consistency and layout impact
ADAS/AV perception performance data as feedback input	Identifies infrastructure locations where ADAS/AV systems struggle with marking/sign readability in real-world conditions	Not integrated into current review processes	No Not part of formal practice	Yes explore how ADAS/AV-reported; disengagements and interpretation errors can inform future infrastructure upgrades

References for PT2

Austroads (2019a) *Infrastructure Changes to Support Automated Vehicles on Rural and Metropolitan Highways and Freeways: Project Findings and Recommendations (Module 5)*, AP-R606-19, Austroads, Sydney, NSW.

Austroads (2019b) *Infrastructure Changes to Support Automated Vehicles on Rural and Metropolitan Highways and Freeways: Road Audit (Module 2)*, AP-T348-19, Austroads, Sydney, NSW.

Austroads (2020) *Implications for Pavement Markings for Machine Vision*, AP-R633-20, Austroads, Sydney, NSW.

Austroads (2023) *Minimum Requirements for Traffic Signs, Traffic Signals and Line Markings*, AP-R696-23, Austroads, Sydney, NSW.

ASC (Automotive Safety Council) (2021) *Submission to the Notice of Proposed Amendments to the Manual on Uniform Traffic Control Devices for Streets and Highways*, Docket No. FHWA-2020-0001,

NZTA (2020) *Traffic control devices manual part 5: traffic control devices for general use – between intersections*, Waka Kotahi NZ Transport Agency, Wellington, NZ.

TRB (Transportation Research Board) (2021) *Changing the Manual to Support Deployment of Automated Vehicles* [webinar], National Academies of Sciences, Washington, DC.

5.3 Ensuring compatible road and traffic design for AV navigation and operations (PT3)

This topic addresses the role of physical road geometry in supporting safe and reliable navigation by AVs. It focuses on geometric elements such as curves, intersections, sightlines, and cross-sections that influence AV path planning and decision-making. It also covers transitional and temporary conditions that may affect AV performance. The focus is on physical infrastructure interventions within the remit of road and transport agencies, particularly those supporting consistent interpretation in mixed-fleet environments.

As AV deployments expand into public road networks, physical road design becomes a limiting factor for safe and efficient AV navigation. AVs rely on structured, predictable environments to interpret lane position, rules, and intended paths – tasks that are heavily influenced by geometric layout, signal placement, and the continuity between digital and physical infrastructure.

We are currently in a transition period where AVs and human drivers must coexist. This mixed-fleet condition is expected to persist for decades. As a result, infrastructure design cannot yet be optimised solely for AV capabilities. Instead, it must ensure that road geometry remains interpretable, navigable, and safe for both user types, while avoiding changes that may disadvantage either. This transitional context underpins the principles outlined in this section.

While AV capabilities are still evolving and many minimum infrastructure requirements remain unclear, early planning decisions should begin to anticipate future vehicle needs. Given the long lead times to design, fund, and deliver infrastructure, proactive consideration (even at a conceptual level) can reduce the cost and complexity of future retrofits. This does not mean overdesigning for unknown vehicle technologies, but rather avoiding decisions that could lock in legacy designs unsuitable for more automated vehicles. Planning should begin identifying sections of the road network likely to experience early AV deployment and ensure that future-readiness is factored into design choices, where possible.

Past Austroads work, including Austroads (2017, 2023), outlined both general and specific guidance on infrastructure suitable for AVs. Austroads (2017) highlights that AV operation depends in part on the consistency and machine-readability of physical infrastructure, particularly signage, line markings, and traffic control features. It identifies that AV-capable facilities may require future adjustments to lane widths, stopping sight distances, and intersection layouts, particularly as AV capabilities evolve. It also warns that different treatments between jurisdictions is a challenge to AVs, especially where digital maps do not reflect real-world geometry or temporary changes. Additionally, while Austroads (2023) noted the challenges in identifying true minimum requirements for infrastructure, it also identified that better than minimum infrastructure was likely to still have benefits.

Insights from Canada reinforce the importance of physical roadside features such as kerbs, gutters, and medians. These elements support AV sensor performance but must be maintained (e.g. free of debris or snow) to remain detectable. Painted edge lines on kerbed streets have also been shown to significantly improve machine-vision detection of lane boundaries, especially where kerbs alone are insufficient (CSA Group 2020).

A common research question is whether AVs' advanced sensing capabilities can justify changes to traditional road design standards. Tengilimoglu et al. (2023) examined whether better AV sensing could reduce Stopping Sight Distance (SSD) or Decision Sight Distance (DSD) requirements. They found this may be possible on roads used only by AVs. However, it is unclear how such changes would affect the overall safety benefits attributed to AVs, potentially reducing their safety margins.

Simulation-based modelling by Granà et al. (2024) indicates that auxiliary lanes and extended ramp configurations at freeway interchanges can reduce rear-end and lane-change conflicts between AVs and human-driven vehicles. While focused on interchange geometry, the findings support the broader principle that designs allowing smoother speed adaptation and fewer abrupt interactions can reduce operational risk in mixed traffic. These conclusions are based on microsimulation and may not fully reflect future higher-level AV capabilities.

Other research also points to opportunities for geometric simplification, but not wholesale redesign. CROW (2023) argues that existing geometric standards remain a strong foundation, and that widespread changes are unnecessary in the near term. However, it supports selectively simplifying layouts, including using roundabouts in place of complex intersections, and improving consistency in design to suit AV-dense fleets. These changes should reduce complexity and increase machine readability. CROW (2023) also notes that road elements designed purely for human interpretation (e.g. optical narrowing or certain signage types) may eventually become redundant on AV-only corridors, but should not be removed in mixed-traffic environments.

Woo et al. (2024) assessed the safety impact of road geometry using currently available vehicles equipped with highly capable ADAS (Tesla Model 3 with Full Self-Driving (FSD) and a Hyundai Grandeur with ADAS features) over 6,700 km of Korean roads. They found that vehicle failures requiring human intervention were more strongly correlated with geometric factors (e.g. curve radius, lane width, and streetlight spacing) than human controlled vehicles that were more influenced by traffic volumes. These findings highlight the limitations of current ADAS systems in interpreting road geometry. The authors note that while the findings provide valuable insights into the safety performance of current SAE Level 2 AV systems, they are specific to Korean road conditions, driving habits, and commercially available vehicle technologies. They state that since key functions such as lane-keeping and speed control are also expected in SAE Level 3 vehicles, these insights may help guide infrastructure and policy planning during the transition to higher levels of automation. However, more advanced AVs may yield different outcomes and should be considered separately.

Recent European research from the Saving Lives Assessing and Improvement TEN-T Road Network Safety (SLAIN 2020) project identifies specific aspects of road geometry that influence AV operational safety. These include horizontal curvature continuity, vertical grade transitions, and the placement or reflectivity of roadside objects. Studies suggest that smoother curvature profiles (e.g. continuous curves rather than abrupt line-arc-line patterns) and gradual grade changes improve trajectory stability and AV tracking accuracy. In parallel, reflective roadside objects, such as concrete barriers placed close to the carriageway, can cause misclassification by AV perception systems. These findings support the need for further investigation into the geometric tolerances of AV systems and provide direction for pilot infrastructure treatments in high-automation corridors.

Complementing this, the CoEXist project (2020) explored how AV and human-driven vehicles interact across a range of road environments, including shared spaces, interurban transition zones, and roundabouts. The project developed prototype Road Safety Inspection (RSI) tools intended to help identify geometry-related safety issues that may emerge under different AV driving behaviours. These tools suggest that misalignments between infrastructure design assumptions and AV operational characteristics could influence safety or efficiency. For example, in transition zones (e.g. from high-speed motorways to arterials), AV speed compliance impacted traffic flow where surrounding traffic behaved more variably. Similarly, in shared spaces and roundabouts, conservative AV behaviour was associated with increased delay and conflicts, particularly under low-penetration conditions. These findings support the potential value of developing targeted infrastructure adaptations. It also noted that further scenario modelling is required to identify conditions where AV performance is more impacted by local geometric conditions than for human drivers.

Beyond road geometry and road features, AVs must also respond to the dynamic and temporal nature of road operations, such as changing traffic controls or temporary conditions. For example, a temporal dimension of road operations can be appreciated by stepping through the tasks required for an AV to successfully navigate a road location controlled by traffic signals, as follows:

1. Correctly identify that traffic signal control applies to a location to be traversed by the AV.
2. Correctly identify which sets of traffic signal lanterns apply to the movement to be taken by the AV, and similarly to identify which are not applicable (e.g. do not falsely follow an inapplicable green).
3. Correctly identify the state of the applicable traffic signal lanterns (e.g. red/amber/green).

The first temporal dimension here is the traffic signal state, i.e. whether an applicable traffic signal is red, amber or green is a variable state across time. This same situation applies to other variable traffic controls such as variable speed limits.

Digital mapping can assist AVs by embedding knowledge of the road layout and expected control logic (Wu et al. 2024). The map information used by the AV can substantially assist with tasks one and two in the traffic signal scenario above. This simplifies the problem into determining whether signal lanterns in known positions are red, amber or green. Providing digital traffic signal state information can assist with all three tasks, adding current traffic signal state information.

A challenge can emerge when changes from baseline conditions mean that the mapped expectations of the AV either fail to assist or even confound. For example, this may occur when temporary traffic signals are installed for roadworks, either:

- at a location not normally controlled by traffic signals, or
- at different positions at an intersection that is normally signal controlled (e.g. temporary signals at a location undergoing modification).

A similar challenge may occur for other types of traffic control (e.g. lane temporarily closed for works, speed limit temporarily adjusted for works, lane paths shifted laterally for works, turns temporarily restricted for works).

In the absence of updated map data or digital augmentation, the AV must interpret and respond to changed restrictions based solely on sensor input, which increases risk. While base map management lies with original equipment manufacturers (OEMs), agencies can reduce mismatches by ensuring physical geometry is well-marked, predictable, and aligned with digital broadcasts (e.g. via SPaT/MAP, roadwork data feeds).

Correct digital map information (possibly supporting digital infrastructure) would assist the AV in all these cases. In the absence of updated map data or digital augmentation, the AV must interpret and respond to changed restrictions based solely on sensor input, which is potentially contrary to its baseline expectations.

Anecdotal reports suggest that current AVs may avoid certain road types or features, such as freeways or complex intersections; however, operators provide limited detail about avoidance logic. Social media users and AV testers have posted route comparisons showing that some robotaxis (e.g. Waymo) take longer paths that bypass freeways or difficult urban junctions — possibly due to internal constraints or risk parameters.

Earlier media coverage by Popular Science identified unprotected left turns in the USA (equivalent to unprotected right turns in Australia and New Zealand) as a challenge for AVs (Verger 2019).

Waymo’s filings with the California Public Utilities Commission confirm that the company retains the ability to ‘dynamically adjust operational parameters’, including road type, time of day, and real-time conditions (Waymo 2023, 2024b). While freeway operation is no longer explicitly excluded, the filings provide no technical detail about which specific road features or intersections are avoided.

5.3.1 Key challenges

The core challenge involves aligning road geometry and layout with the capabilities and limitations of AVs. While human drivers can adapt to inconsistent alignments and complex intersections, AVs rely on precise geometry, predictable layouts, and clear guidance to plan and execute movements. Infrastructure that deviates from these expectations can lead to hesitations, misclassifications, or disengagement. Table 5.10 presents these key challenges, example scenarios and their impacts on vehicle operations.

Table 5.10: Key challenges that impact ensuring compatible road and traffic design for AV navigation and operations

Key challenges	Example scenario	Impact on AV operations	Reference
Challenging geometry	An AV encounters a tight curve or skewed intersection with limited sightlines or sharp alignment changes. Sensor views are obstructed, and fallback behaviour is triggered.	Route avoidance, delayed operation, or fallback to human control. May result in increased risk or inability to complete service reliably. Effects are more likely in low-traffic or low-speed environments.	Woo et al. (2024)
Temporary alignment change	Road geometry is temporarily modified due to construction or maintenance, but the AV's map reflects the previous configuration (e.g. lane shift, removed median).	AV detects inconsistency between map and physical environment, potentially triggering emergency stop or rerouting. Impact is greater in high-speed or complex environments where safe decisions require rapid reassessment.	-
Mismatch between physical and digital geometry	A permanent layout change, such as a new roundabout or reconfigured intersection, is not yet reflected in the AV's high-definition map.	AV perceives an unexpected configuration, which may lead to hesitation, misclassification of paths, or operational failure. Risk increases if fallback logic is underdeveloped or if the AV relies heavily on digital mapping over real-time sensing.	-

5.3.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency to ensure compatible road and traffic design for AV navigation and operations are provided below in Table 5.11.

Table 5.11: Road and infrastructure design considerations related to PT3

Design element considerations	Description	Supporting references
Road alignment	Use simplified and predictable horizontal alignment. Avoid complex or excessive curvature. Support AV performance through consistent cross-sections, enhanced pavement markings, lighting, and digital alerts where geometry is unsuitable.	• Austroads (2017) • CROW (2023) • Woo et al. (2024) • SLAIN (2021)
Stopping sight distance (SSD) and vertical curves	In AV-exclusive environments, SSD/DSD may be reduced due to faster sensing and perception-reaction time (PRT) reduction. Must be applied cautiously to avoid reducing safety margins. Smoother vertical transitions may support greater AV stability.	• Austroads (2017) • Intini et al. (2019) • Tengilimoglu et al. (2023) • SLAIN (2021)
Cross-section and lane width	AVs may allow reduced lane and shoulder widths in exclusive environments. In mixed traffic, retain widths for human drivers.	• Austroads (2017) • Intini et al. (2019) • SLAIN (2021)
Intersection design	Use template-based forms; avoid novel designs. More compact layouts may be possible with AV coordination.	• Austroads (2017) • CROW (2023)
Visibility at decision points	Maintain clear sightlines appropriate for AV sensor height and angle. Avoid occlusion from vegetation or furniture particularly at intersections and decision points.	• Austroads (2017) • CROW (2023)
Temporary alignments	When roadworks alter geometry, replicate known layouts. Avoid patterns that may confuse AV perception.	• Austroads (2017) • CROW (2023)

Note: Listed considerations based on Austroads (2017) are exploratory in nature and are non-exhaustive. They are framed as long-term considerations and not intended for current implementation in mixed-traffic environments.

5.3.3 Related topics

Topics related to PT3 include those listed below in Table 5.12.

Table 5.12: Topics related to PT3

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Road geometry influences the visibility and effectiveness of lane markings and signage.
PT8	Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs	Kerb geometry ties into AV pathfinding and parking decisions.
DT1	Ensuring CAV awareness of temporary and dynamic traffic conditions	PT3 discusses temporary alignments due to roadworks; DT1 provides digital delivery of these conditions to AVs.
DT2	Ensuring data accuracy and validation for AV navigation	Accurate digital representation of road geometry supports AV localisation and compliance.
DT7	Ensuring digital resilience and failover mechanisms for CAV operations	Highlights the need for AV-safe road geometry in cases where digital infrastructure fails.
DT13	Supporting CAV interpretation and compliance with traffic signal infrastructure	Road geometry should support AV compliance with signal placement and readability.

5.3.4 Principles

Principles derived from the above evidence that relate to PT3 are shown in Table 5.13 below.

Table 5.13: Principles related to PT3

Principle	Description
Consistent designs	Design geometry, layouts, and markings uniformly across environments to ensure predictable and interpretable road conditions. This reduces variation in AV training and operational risk.
Simple designs	Avoid unnecessary complexity in road layouts. Limit excessive variations in curvature, lane transitions, and unconventional intersections.
Legible designs	Improve the quality and visibility of road features such as markings, kerbs, and barriers to assist both sensor interpretation and human recognition.
Physical designs complemented by digital infrastructure	Support physical design with real-time digital data such as map updates, signal states, and construction alerts to aid decision-making in dynamic conditions.
Mixed-fleet compatible design	Maintain infrastructure usability for both automated and conventional vehicles to ensure safe operations during the long transition period.
Plan for long-term adaptability	Given the long lifecycle of infrastructure, road geometry and layout decisions made today should consider emerging AV capabilities and potential future requirements, even where exact needs are still evolving. Designs should avoid locking in configurations that may limit safe automation uptake.

5.3.5 Future research areas

Whilst there is some coverage of the PT3 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.14 below.

Table 5.14: Potential research topic areas related to PT3

Research topic area	Description
Mixed-fleet performance thresholds	Identify how AVs behave under complex geometry in real-world mixed traffic. Determine safe design margins shared by AVs and human drivers. Research into geometry design that accommodates variable driver behaviour.
Relationship between AV performance and design standards	Investigate how current geometric design standards influence AV system performance. Use real-world data to assess whether AV failures correlate with specific geometric elements (e.g. curvature, cross-section, sight distance, roadside barrier placement and offset).
AV-only design triggers	Explore when infrastructure could safely begin shifting toward AV-optimised geometry (e.g. tighter curves, reduced SSD), based on fleet penetration or corridor classification.
Digital–physical alignment standards	Develop best practices and standards for keeping digital maps and physical layouts in sync, especially during roadworks or reconfigurations.
Geometry-focused audit tools for AV suitability	Develop assessment frameworks or checklists to help road agencies evaluate geometric elements (e.g. curve radii, sightlines, lane alignment, transition zones, inconsistent widths) that may cause hesitation, misclassification, or disengagement in AVs. Focus should remain on physical geometry, not just digital or signage-based readiness.

References for PT3

Austroads (2017) *Assessment of Key Road Operator Actions to Support Automated Vehicles*, AP-R543-17, Austroads, Sydney, NSW.

Austroads (2023) *Minimum Requirements for Traffic Signs, Traffic Signals and Line Markings*, AP-R696-23, Sydney, NSW, Sydney, NSW.

CoExist (2020) *D3.4 General impacts and design recommendations*, H2020 CoEXist Project website, accessed 10 April 2025.

CSA Group (2020) *Connected and Automated Vehicle Technologies – Insights for Codes and Standards in Canada*, CSA Public Policy, Toronto, Canada.

Intini P, Colonna P, Berloco N and Ranieri V (2019) 'Rethinking the main road design concepts for future Automated Vehicles Native Roads', *Trasporti Europei – European Transport*, no. 73, paper no. 3.

SLAIN (Saving Lives Assessing and Improvement TEN-T Road Network Safety) (2020) *D7.2: Other initiatives to meet the needs of automated cars*, SLAIN Consortium.

Tengilimoglu O, Carsten O and Wadud Z (2023) 'Implications of automated vehicles for physical road environment: A comprehensive review', *Transportation Research Part E: Logistics and Transportation Review*, 169(January 2023):102989 DOI:10.1016/j.tre.2022.102989.

Verger R (28 February 2019) 'Left turns are hard for self-driving cars and people alike', *Popular Science*, accessed 7 April 2025.

Waymo (2023) *Operational Design Domain – AV Deployment Zone (Original Filing)*, California Public Utilities Commission.

Waymo (2024b) *Operational Design Domain – AV Deployment Expansion Zone*, California Public Utilities Commission, accessed 9 April 2025.

Woo S, Woo B, Chang Y and Tak S (2024) *Road design on human driver accidents versus automated vehicle failures: Comparison with real-world field data*, IEEE Transactions on Intelligent Transportation Systems website, accessed 9 April 2025.

Wu JD, Miller M, Stoeltje G, Le M, Hwang W, Huang T, Hu N, Zalila-Wenkstern R, Torabi B and Li X (2024) *Digitizing Traffic Control Infrastructure for Autonomous Vehicles (AV):* Technical Report No. FHWA/TX-23/0-7128-R1, Texas AandM Transportation Institute, Bryan, Texas.

5.4 Maintaining roadway and pavement integrity for AVs and EVs (PT4)

This topic addresses pavement wear and maintenance considerations arising from heavier EVs and consistent AV lane use. It focuses on the physical effects of mass, braking behaviour, and tracking, particularly for sprayed seal pavements. The topic includes considerations for road agencies, such as adaptive maintenance, surface treatment, and support for vehicle-side measures like wander modes. Although some implications for structures such as bridges and culverts are mentioned, these are not explored in detail.

AVs may influence road wear patterns through more consistent tracking and changed spacing between vehicles, while EVs, particularly heavier trucks and buses, may increase pavement and surface loading.

Austroads (2017) identified the potential for AVs to:

- track more consistently in a repeated wheel path compared to human driven vehicles, potentially changing the pattern of wear for pavements and road surfaces
- drive closer together in certain situations, such as through truck platooning, possibly changing distributions of loads and levels of loading on bridges.

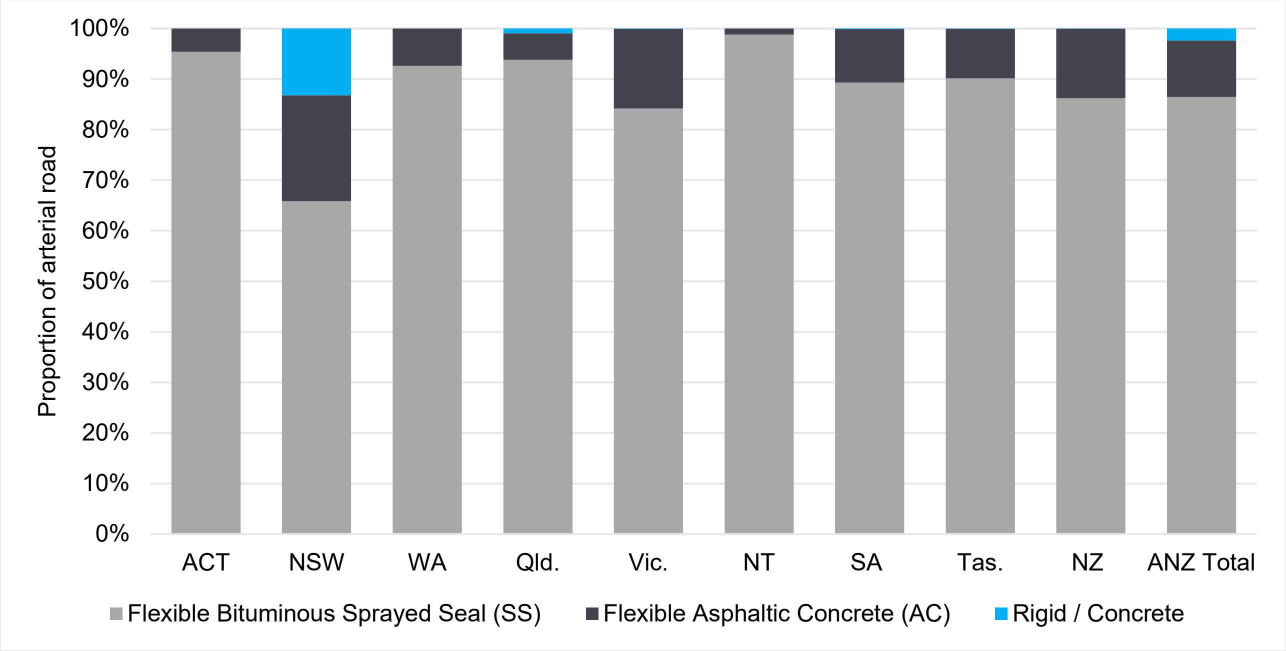
A current Austroads project (NEF6392) is investigating the impacts of increased mass of EV trucks and buses on road infrastructure.

In addition to structural wear, minor surface defects and inconsistencies (e.g. potholes, cracks, rutting, joints, seals) can interfere with AV sensor perception and stability. Scenario-based safety frameworks such as UL 4600 (Standard for Evaluation of Autonomous Products) and ISO 34502 (Road vehicles - Test scenarios for automated driving systems - Scenario based safety evaluation framework) recognise that uneven pavement surfaces may cause vehicle misclassification of navigable space or loss of confidence in trajectory tracking. These conditions may trigger degraded mode behaviour, route avoidance, or emergency fallback, particularly in environments where AVs cannot rely on map updates or digital augmentation.

The impacts of these variables have been identified in hazard classification studies such as Ko et al. (2022), where scenarios involving potholes or puddles were assigned high operational risk scores due to their potential to trigger unplanned stops or erratic manoeuvres. The implication is that even shallow or localised defects may carry disproportionate significance for AV performance, reinforcing the importance of proactive surface condition monitoring, higher intervention thresholds, and integration of AV feedback into maintenance programs, especially in corridors with high automation potential.

Analysis in Austroads (2025b) identified that the primary pavement type for Australian and New Zealand roads is flexible pavement overlain with sprayed seal (see Figure 5.4). This is part reflected by a strong history of road construction at relatively lower cost including use of locally available materials. There is some use of asphalt pavement and concrete pavement in urban areas and on some sections of intercity routes. Pavement types vary around the world, and Austroads (2025b) identified more use of rigid pavements in other countries. This means that impacts of AVs and EVs on Australian and New Zealand pavements may differ from experiences elsewhere.

Figure 5.4: **Australian state managed arterial sealed pavement by pavement type and state and territories, and New Zealand national sealed pavement network**



Source: Austroads (2025).

5.4.1 Key challenges

The roadway and pavement face increased wear and structural stresses due to heavier EVs and the consistent tracking behaviour of AVs. Unlike human drivers, AVs may apply repeated loading to the same wheel paths, while EVs introduce greater vertical and horizontal forces due to their weight and torque characteristics. These changes may accelerate degradation, requiring road agencies to adapt pavement design and maintenance practices.

These impacts may not fully align with international experiences, given Australia and New Zealand's dominant use of flexible pavements with sprayed seals. While research is ongoing, several plausible mechanisms for increased wear or structural stress have emerged. Table 5.15 presents these key challenges, example scenarios and their impacts on vehicle operations.

Note on framing

Unlike most other topics in this report, which focus on infrastructure conditions affecting CAV and EV operation, this section addresses how emerging vehicle characteristics (e.g. mass, torque, lane discipline) influence infrastructure performance and pavement durability. Table 5.5, therefore, presents impacts on pavement performance, not vehicle operation, and reverses the cause-effect structure used for other topics.

Table 5.15: Key challenges that impact maintaining roadway and pavement integrity for AVs and EVs

Key challenges	Example scenario	Impact on pavement integrity	Reference
Pavement impact due to increased mass of electric trucks and buses	Uptake of battery-electric freight vehicles or buses	20–40% additional road wear compared to internal combustion engine vehicles	• Low et al. (2022) • Austroads NEF6392 (not yet published)
Pavement impact due to increased mass of electric cars	Growth in large electric SUVs and passenger vehicles	Considered negligible; light vehicles contribute very little to structural deterioration	• Austroads (2025a) • Low et al. (2022)
Impact due to EV torque and regenerative braking	Use of regenerative braking and high torque under acceleration	May increase horizontal forces, particularly affecting sprayed seals, intersections, and fresh surfaces	• Austroads NEF6392 (subject matter expert feedback)
Pavement impact due to repeated tracking by AV trucks	AV trucks operating without programmed wander modes	Concentrated fatigue and localised pavement damage in repeated wheel paths	• Yeganeh et al. (2024)
Pavement impact due to use of AV truck wander modes	AV trucks programmed to vary lateral position within the lane	Significantly reduces pavement damage; benefit accrues to road managers, not vehicle operators	• Yeganeh et al. (2024)
Pavement impact due to narrower AV lanes	Deployment of AV-dedicated lanes with 3.0–3.25 m width	Higher stress concentration due to narrower lane width, but requires less pavement construction overall	• Tengilimoglu et al. (2023)
AV skid resistance awareness	AVs adjusting braking behaviour based on road surface friction data	Conceptual potential to reduce braking-related surface stress; not yet implemented in practice	• Tengilimoglu et al. (2023)

5.4.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency to maintain roadway and pavement integrity for AVs and EVs are provided below in Table 5.16.

Table 5.16: Road and infrastructure design considerations related to PT4

Design element considerations	Description	Supporting References
Structural pavement strengthening	Reinforce pavement layers on freight corridors subject to heavier EV trucks and buses	• Low et al. (2022) • Austroads NEF6392 (not yet published)
Lane design accommodating AV wander	Support AV systems that enable lateral wander to reduce concentrated wheel path loading	• Yeganeh et al. (2024)
Pavement surface enhancements	Apply higher-resistance surfaces or binders at intersections and steep gradients where torque or braking loads are concentrated	• Austroads NEF6392 (not yet published)
Design calibration for narrower lanes	Assess load distribution and structural needs for AV-dedicated lanes with reduced width (e.g. 3.0–3.25 m)	• Tengilimoglu et al. (2023)
Surface condition monitoring integration	Monitor sprayed seals and other surface treatments for wear caused by torque and braking forces	• Austroads NEF6392 (not yet published)

5.4.3 Related topics

Topics related to PT4 include those listed below in Table 5.17.

Table 5.17: Topics related to PT4

Related topic (code)	Related topic title	Reason for cross-reference
PT10	Ensuring EV-compatible crash barriers	Pavement structure should accommodate EV barrier loads and align with surface durability.
PT11	Maintenance and asset management for CAV and EV infrastructure	Pavement design affects and is affected by maintenance and asset lifecycle planning. There may some opportunities for digital infrastructure to play a role in managing impacts such as through sharing information about skid resistance (to inform braking estimates) and considerations to address pavement damage (e.g. coordinate approach to AV truck wander patterns). There is also some relevance for digital infrastructure awareness of bridge load limits.
DT10	Integration of CAV and EV operations into smart city and traffic management platforms	Data from CAVs can inform pavement wear prediction models and asset prioritisation.

5.4.4 Principles

Insights from current research (including Austroads project NEF6392 (in progress)) suggest that while no major redesign of roads is needed, some targeted adaptations to pavement design, surfacing treatment, and asset management may be required to accommodate the operational characteristics of EVs and AVs.

Pavement structural design and surfacing treatment fall within specialised engineering domains. Any design adaptations should be developed and implemented through updates to existing pavement engineering guidelines and standards.

Where AV or EV-specific impacts arise (e.g. concentrated tracking, increased horizontal loads), mitigation measures such as truck wander modes or surfacing specifications may be incorporated through targeted updates to infrastructure standards or asset management practices.

5.4.5 Future research areas

Whilst there is some coverage of the PT4 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.18 below.

Table 5.18: Potential research topic areas related to PT4

Research topic area	Description
Implementation of AV truck wander modes	Explore regulatory, operational, or incentive frameworks to support consistent use of AV truck wander modes that reduce concentrated pavement wear.
Impacts of electric heavy vehicles	Complete and apply findings from Austroads NEF6392 to understand how increased mass and torque affect pavement performance and surfacing.
Surface effects of EV torque and braking	Investigate the impacts of regenerative braking and high initial torque on sprayed seals, especially during turning or on freshly laid surfaces.

References for PT4

Austroads (2017) *Assessment of Key Road Operator Actions to Support Automated Vehiclesv*, AP-R543-17, Austroads, Sydney, NSW.

Austroads (2025a) *Guide to Pavement Technology, Part 2: Pavement Structural Design*, AGPT02-25, Austroads, Sydney, NSW.

Austroads (2025b) *Zero emission heavy vehicles and road pavements: comparing Australia and New Zealand to Europe and North America*, AP-R725-25, Austroads, Sydney, NSW.

Ko W, Park S, Park S, Jeong H and Yun I (2022) 'Development of freeway-based test scenarios for applying new car assessment program to automated vehicles', *PLoS ONE,* 17(7): e0271532.

ISO (2022) *ISO 34502 Road vehicles — Test scenarios for automated driving systems - Scenario based safety evaluation framework*, International Standards Organization.

Low J M, Haszeldine R S and Harrison G P (2023) 'The hidden cost of road maintenance due to the increased weight of battery and hydrogen trucks and buses – a perspective', *Clean Technologies and Environmental Policy*, 25(3), 757-770.

Tengilimoglu O, Carsten O and Wadud Z (2023) 'Implications of automated vehicles for physical road environment: A comprehensive review',*Transportation research part E: logistics and transportation review*, 169, 102989.

UL (UL Standards and Engagement) (2022) *ANSI/UL4600 Standard for Safety for the Evaluation of Autonomous Products*, UL Standards and Engagement.

Yeganeh A, Vandoren B and Pirdavani A (2024) 'Automated trucks' impact on pavement fatigue damage', *Applied sciences*, 14(13), 5552.

5.5 Managing mixed traffic interactions with AVs (PT5)

The introduction of highly-capable AVs into live, mixed-traffic environments presents critical challenges for road agencies overseeing infrastructure planning and design. Unlike human drivers, AVs respond to traffic situations using rule-based logic and sensor-driven perception. In complex or ambiguous traffic scenarios, this can result in overly cautious, hesitant, or inconsistent behaviours that disrupt traffic flow and create safety risks (ITF 2023, CSA Group 2022).

This topic addresses physical infrastructure measures that help mitigate safety and performance risks arising from mixed traffic environments involving both highly-capable AVs and human-driven vehicles. It focuses on lane design, merge geometry, intersection layout, and treatments that promote predictable interaction and reduce AV–human behavioural mismatches.

Behavioural mismatches emerge from both AV programming and as a result of how human drivers interpret and respond to AVs. For example, Reddy et al. (2022) showed that human drivers adjust their behaviour depending on an AV’s recognisability and driving style. In their experiments, drivers were more likely to accept smaller gaps at intersections when seeing clearly identifiable cautious AVs, and were more hesitant when AVs appeared aggressive or unidentifiable (Reddy et al. 2022). This suggests that road design elements such as consistent lane guidance, predictable movement paths, and clear signals will help reduce uncertainties related to AV–human interaction.

Research has also found that human drivers may intentionally exploit AV caution in competitive driving situations. Trende et al. (2019) found that some drivers may actually try and exploit AV caution during merges. Their simulator studies have shown that human drivers are more likely to cut in front of AVs than other vehicles, anticipating that the AV will yield.

The use of dedicated AV lanes may help reduce conflict in high-volume corridors. Early guidance from NASEM (2018) suggests that these lanes could offer safety and operational benefits, particularly in high-demand scenarios where lane designation can be managed dynamically. However, more recent modelling (Zhang et al. 2023) indicates that these benefits typically emerge when AVs comprise at least 25–30% of traffic, suggesting that fully exclusive lanes may be unsuitable during early deployment phases. The authors found that integrated strategies that include use of roadside units (RSUs) to support vehicle awareness is a more flexible way to support highly-capable AVs in transitional periods than dedicated lanes alone.

Clarity and consistency of road features such as merge geometry, intersection layout, lane continuity, and lane markings affect how vehicles interact in mixed-traffic conditions (CSA Group 2022, ITF 2023, NASEM 2024). NASEM (2024) notes that ADS developers state that one of the most difficult situations for AVs is the unpredictability of human drivers reacting to ambiguous infrastructure (e.g. unclear geometry, inconsistent signage, or non-standard layouts), which can cause confusion for both AV and human drivers. CROW (2023) reinforces that simplified, standardised infrastructure, while not directly focused on human-AV behavioural dynamics, helps reduce ambiguity and supports more consistent decision-making across all vehicle types. These treatments are especially relevant during early phases of AV deployment, where full fleet separation is not feasible and human driver unpredictability remains a key operational risk.

As AVs will operate in complex mixed-traffic environments, their behaviour, including frequent fallback events or hesitation in ambiguous merge zones, may provide insights into infrastructure design issues. Access to selected AV operational data could enable agencies to identify problematic interaction points and iteratively improve lane geometry, signage, or transition clarity. This aligns with the broader international move toward data-informed safety assurance, such as UNECE WP.29 (2024), and supports the rationale for a national safety data feedback loop.

5.5.1 Key challenges

The core challenge is that AVs and human-driven vehicles often interpret traffic conditions differently. Human drivers rely on experience, intuition, and informal cues, while AVs use rule-based algorithms and conservative thresholds. This behavioural mismatch can result in hesitation, overreaction, or inefficient operation, particularly in complex traffic environments.

Mixed traffic interaction challenges often arise from a combination of infrastructure geometry and driver or vehicle behaviour. For example, short merges are geometric features, but they cause issues when AVs and human drivers interpret them differently. These cases are kept within this topic because the primary concern is how such features influence interactions between AVs and human-driven vehicles, rather than the geometric design itself.

Table 5.19 presents these key challenges, example scenarios and their impacts on vehicle operations.

Table 5.19: Key challenges that impact managing mixed traffic interactions with AVs

Key challenges	Example scenario	Impact on AV operations	References
Lack of dedicated merge treatments	AV encounters human driver merging aggressively at end of short on-ramp.	AV yields or brakes suddenly, disrupting traffic flow.	• ITF (2023) • NASEM (2018)
Ambiguous lane drops or transitions	Shared through and turn lane lacks markings to guide AV.	AV hesitates or misinterprets intention, causing delay.	• CSA Group (2022) • CROW (2023)
Mixed vehicle behaviour norms	AV yields at intersection due to uncertain human vehicle speed.	Traffic congestion or AV disengages.	• ITF (2023)
Absence of AV-priority lanes in high-volume corridors	AVs operate in general lanes with unpredictable human drivers.	Frequent braking, inefficient platooning or routing.	• NASEM (2018) • CROW (2023)
Inconsistent merging area geometry	Narrow shoulders or short tapers limit safe merging.	AV struggles to complete merge within conservative gap thresholds.	• CSA Group (2022)
Poor lane discipline by surrounding drivers	Human drivers straddle lanes.	AV fails to maintain safe distance or slows excessively.	-
Conservative AV behaviour in uncertain environments	AV approaches a busy roundabout with no clear priority and multiple human vehicles behaving assertively.	AV waits excessively or disengages.	-

5.5.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency to manage mixed traffic interactions with AVs are provided below in Table 5.20.

Table 5.20: Road and infrastructure design considerations related to PT5

Design element considerations	Description	Supporting references
Extended merge zones	Lengthen on-ramp tapers and include clear lane guidance to reduce last-minute merges and support AV gap identification.	• NASEM (2018)
Lane designation (e.g. turn and through lane clarity)	Provide separate lanes for turning and through vehicles where possible to reduce ambiguous AV decision-making.	• CSA Group (2022)
AV-compatible lane continuity	Maintain consistent lane guidance and markings through intersections and merge zones to aid AV path prediction and reduce hesitation.	• ITF (2023)
Dedicated or managed AV priority lanes	Introduce AV-preferential or managed lanes during peak periods or in AV-dominant corridors where justified by demand or volume thresholds.	• NCHRP 891 • Zhang et al. (2023)
Enhanced merge visibility	Improve signage, surface markings, and sight lines at merge zones to support earlier AV detection and decision-making.	• CSA Group (2022)
Merge zone anti-exploitation treatments	Incorporate longer merge tapers, clearer right-of-way signage, or early merge enforcement to reduce aggressive cut-ins by human drivers.	• Trende et al. (2019)
Simplified intersection priority markings	Clarify right-of-way through enhanced signage and lane channelisation to reduce AV hesitancy in ambiguous intersection environments.	• CROW (2023) • Reddy et al. (2022)
Speed transition smoothing	Use consistent speed zones and reinforce speed changes with physical cues to minimise overreaction to unpredictable conditions.	• CSA Group (2022) • ITF (2023)
Use AV fallback or disengagement data to identify high-risk interaction zones	Investigate where AVs frequently hesitate, disengage, or require fallback due to human behaviour or ambiguous infrastructure, to prioritise design improvements.	• UNECE (2024) WP.29/2024/39

5.5.3 Related topics

Topics related to PT5 include those listed below in Table 5.21.

Table 5.21: Topics related to PT5

Related topic (code)	Related topic title	Reason for cross-reference
PT7	Managing AV interactions with e-scooters, cyclists and personal mobility devices	VRUs are a subset of mixed traffic interactions.
DT8	Improving CAV interaction with emergency vehicles and vulnerable road users	Digital alerts and emergency vehicle coordination enhance mixed traffic safety.
DT10	Integration of CAV and EV operations into smart city and traffic management platforms	Data from CAVs can inform traffic control algorithms for mixed traffic situations.

5.5.4 Principles

Principles derived from the above evidence that relate to PT5 are shown in Table 5.22 below.

Table 5.22: Principles related to PT5

Principle	Description
Design for predictability	Road geometry, lane configurations, and markings should minimise uncertainty in vehicle movements to support AV algorithmic decision-making and human driver anticipation.
Reduce manoeuvre conflict	Where feasible, provide spatial separation or clearly delineated paths for vehicles with differing behaviour models to reduce last-minute negotiation and hesitation.
Support rule-based operation	Infrastructure should provide clear, standardised cues, such as consistent lane markings and intersection control to support AV compliance with traffic rules and behavioural expectations.
Design for human and AV compatibility	Treatments should accommodate both human-driven and automated vehicles without requiring AV-specific configurations that disadvantage other road users or require frequent redesign.
Inform design using observed AV-human interactions	Agencies should monitor AV behavioural logs (e.g. hesitation, override events) to identify points of conflict in mixed-traffic environments and refine physical design approaches.

5.5.5 Future research areas

Whilst there is some coverage of the PT5 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.23 below.

Table 5.23: Potential research topic areas related to PT5

Research topic area	Description
Mixed fleet conflict modelling	Simulation of high AV–human driver interaction zones to identify geometric and operational features that mitigate AV–human driver conflicts.
Merge and ramp treatment effectiveness	Field testing of extended tapers and lane guidance improvements to reduce AV hesitation and flow disruption.
AV lane prioritisation thresholds	Modelling thresholds and demand conditions under which dedicated or preferential AV lanes improve safety and efficiency in mixed traffic.
Human behaviour impact on AV fallback	Testing of infrastructure-related triggers that contribute to AV disengagements, including human unpredictability at intersections and merges.

References for PT5

CSA Group (2022) *Physical and Digital Infrastructure for Connected and Automated Vehicles (CAV)*, CSA Group, Toronto, Canada.

CROW (2023) *Future-Proof Road Infrastructure – Towards a Future-Proof Road Design in the Netherlands*. CROW-KpVV, Ede.

ITF (International Transport Forum) (2023) *Preparing Infrastructure for Automated Vehicles: Transport Outlook 2023 Background Paper*, OECD Publishing, Paris.

NASEM (National Academies of Sciences, Engineering, and Medicine) (2018) *Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles*, Report 891, NCHRP (National Cooperative Highway Research Program).

NASEM (2024) *Infrastructure Modifications to Improve the Operational Conditions of Automated Vehicles 2024, Executive Summary of Phase 1 Findings*, Project 20-102(24), NCHRP (National Cooperative Highway Research Program).

Reddy N, Hoogendoorn S P and Farah H (2022) 'How do the recognizability and driving styles of automated vehicles affect human drivers' gap acceptance at T-intersections?', *Transportation Research Part F: Traffic Psychology and Behaviour*, 90, 451–465. https://doi.org/10.1016/j.trf.2022.09.018

Trende A, Unni A, Weber L et al. (2019) 'An investigation into human–autonomous vs. human–human vehicle interaction in time-critical situations', *Proceedings of the 11th ACM International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 163–167). https://doi.org/10.1145/3316782.3321544

Zhang F, Lu J, Hu X and Meng Q (2023) 'Integrated deployment of dedicated lane and roadside unit considering uncertain road capacity under the mixed-autonomy traffic environment', *Transportation Research Part B: Methodological*, 175, 102784. https://doi.org/10.1016/j.trb.2023.102784

5.6 Supporting CAV readability of digital roadside signage (PT6)

As CAVs become more integrated into transport systems, their ability to reliably detect and interpret dynamic roadside signage is essential for legal compliance, safety, and operational confidence. Unlike human drivers, who rely on contextual judgment and redundancy in visual cues, CAVs interpret traffic signs through machine vision systems, primarily cameras, augmented by HD maps and V2X data. Ensuring that critical regulatory or advisory information is presented in sensor-compatible formats is now a key infrastructure requirement.

This topic addresses how infrastructure design and maintenance practices can support CAVs in visually detecting and interpreting dynamic digital roadside signage. It includes VMS, non-VMS digital signs (e.g. electromechanical CMS), and lane-use control signals. It focuses on factors that influence machine vision reliability, including sensor-compatible contrast, placement, refresh rate standards, and harmonisation of sign formats. While aspects of VSLS readability are addressed in PT2, this topic focuses specifically on the broader class of dynamic signs with variable content or signalling behaviour.

Digital signs can cause machine-readability challenges for CAVs, including those identified by Austroads (2023) that were relevant to VSLSs:

- LED flicker artefacts caused by low refresh rates that disrupt rolling-shutter AV cameras
- low luminance or contrast, particularly under glare, shadow, or fog
- rapid or unstable message cycling, limiting time for full interpretation
- improper mounting or occlusion, placing signs outside common AV camera fields of view
- jurisdictional inconsistencies in icon design or sign structure.

While road condition information can also be delivered digitally (as addressed in DT1), such data is not always available or timely. Physical digital signage remains an essential, and often primary, source of real-time information. Failure to interpret these signs can lead to degraded fallback behaviour, missed warnings, or unlawful vehicle actions.

Austroads (2023) confirms that Australian standards currently require only a 100 Hz LED refresh rate, which meets human perceptual needs but is inadequate for CAV systems. Austroads (2023) review of submissions to the US Manual on Uniform Traffic Control Devices (MUTCD) process found consistent recommendations from AV developers (e.g. GM Cruise, Volkswagen) advocating for a minimum 200 Hz to ensure reliable detection. Signs can have flicker, phantom characters, or partial message dropout. Austroads also engaged Australian sign vendors, who reported no technical barriers to adopting 200 Hz, though field trials are still needed to confirm AV detection performance.

The Austroads (2021) RADCAV Module 3 report provides detailed guidance on the systems architecture and structural data provision of LCS and VSLS information to CAVs. It outlines requirements for structured digital message delivery, including setting values, inventory metadata, location and lane relevance, and integration with agency application programming interfaces (APIs) or roadside units. The report confirms that digital support should complement, not replace, visible infrastructure. These digital support functions are further discussed in DT1.

International studies also reinforce these findings. The EU TransAID (2020) project confirmed that conventional VMS formats often fail to meet machine-vision quality thresholds. Trials showed that low-resolution boards, inconsistent symbol sets, and fast message scrolling significantly reduced recognition accuracy. The study recommended design improvements including standardised icons, slower refresh cycles, and higher visual contrast to improve CAV performance under typical operating conditions.

While VMS readability has been studied, there is little or no publicly available research on how CAVs detect and interpret non-VMS dynamic signage, such as lane control signals, dynamic merge arrows, or symbol-based CMS displays. Although modern vehicles include traffic sign recognition (TSR) systems capable of reading speed limits, research on CAV detection of other signs remains limited.

As roadside signage transitions from human-only infrastructure to dual-mode communication for both drivers and machines, road agencies should ensure that all dynamic electronic signs are sensor-compatible, refresh-stable, and designed for reliable CAV interpretation. This includes harmonising luminance standards, icon formats, message timing, and placement strategies to build future-ready road environments that support both human drivers and automated systems.

5.6.1 Key challenges

The core challenge involves ensuring that digital roadside signage such as VMS and LCS are reliably detected and interpreted by AVs. While human drivers can interpret imperfect or obscured signs, CAVs require high luminance, stable refresh rates and consistent visual formats to avoid misreading or missing critical information. Inconsistent or poorly configured signage increases the risk of non-compliance or degraded operation. Table 5.24 presents these key challenges, example scenarios and their impacts on vehicle operations.

Table 5.24: Key challenges that impact supporting CAV readability of digital roadside signage

Key challenges	Example scenario	Impact on CAV operations	Reference
Occlusion by vehicles or infrastructure	A delivery truck blocks a lane indicator displaying a lane-change arrow.	CAV misses the closure instruction and enters a restricted lane.	-
Low luminance or poor contrast	A VMS displays orange-on-black under high glare.	Sign is not recognised; CAV continues at inappropriate speed.	Austroads (2023)
LED flicker from low refresh rates	A VMS with LEDs operates at 100 Hz.	Camera sees phantom or missing symbols due to rolling shutter conflict.	Austroads (2023)
Message duration too short or unstable	A VMS scrolls multi-line messages every 2 seconds.	AV fails to capture full message in one visual pass.	TransAID (2020)
Misplaced or high-mounted signage	Lane control signs installed above camera field of view.	CAV does not register the sign in time to respond.	Austroads (2023)
Inconsistent icon formats across jurisdictions	One region uses a red X for lane closure, another uses a merge arrow.	CAV fails to map the visual to an expected rule, causing hesitation or misbehaviour.	TransAID (2020)

5.6.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency to support CAV readability of digital roadside signage are provided below in Table 5.25.

Table 5.25: Road and infrastructure design considerations related to PT6

Design element considerations	Description	Supporting references
Sensor-compatible contrast and luminance	Ensure signs use high-contrast colour schemes and luminance levels optimised for camera detection, especially under glare or low-light conditions.	Austroads (2023)
LED refresh rate standardisation	Set a minimum refresh rate of ≥ 200 Hz to prevent flicker artefacts caused by rolling-shutter AV cameras.	Austroads (2023)
Consistent message formats and icons	Use harmonised layouts, symbol libraries, and message formats across jurisdictions to improve machine vision recognition.	Austroads (2023), TransAID (2020)
Message stability and duration	Avoid fast scrolling, rapid switching, or low-dwell message cycles. Maintain persistent display of critical content for full-frame capture.	TransAID (2020)
Placement within camera field of view	Ensure sign positioning (e.g. height ≤ 5.4 m for overhead signs) is compatible with AV sensor visibility zones.	Austroads (2023)
Occlusion mitigation	Reduce visual obstructions by managing vegetation and lateral placement. Prioritise clear lines of sight for AV perception.	Austroads (2023)
Redundant digital message delivery	Supplement critical visual signage (e.g. safety message, lane closures) with structured and standardised digital feeds.	Austroads (2023)

5.6.3 Related topics

Topics related to PT6 include those listed below in Table 5.26.

Table 5.26: Topics related to PT6

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Digital signage complements static signs; should be machine-readable.
DT1	Ensuring CAV awareness of temporary and dynamic traffic conditions	Covers structured digital delivery of dynamic regulatory messages (e.g. VSL, LCS) that complement physical signage.
DT5	Ensuring CAV compliance with dynamic road regulations	CAV interpretation of signage should align with dynamic rules.

5.6.4 Principles

Principles derived from the above evidence that relate to PT6 are shown in Table 5.27 below.

Table 5.27: Principles related to PT6

Principle	Description
Sensor-aligned visibility standards	Design digital signage using luminance, refresh rate, contrast, and placement thresholds validated for AV camera systems, not just human readability. Includes LED refresh rate ≥ 200 Hz and visibility zones within typical camera field of view.
Failover-safe message sequencing	VMS/CMS content should be structured for machine readability; static message phases preferred over scrolling or rapid cycling.
Cross-modality redundancy	Support both physical signage and standardised digital data delivery for critical road messages (e.g. incident and roadwork data feeds), enabling fallback if visual detection fails.
Standardisation across jurisdictions	Align sign fonts, colours, icons, and message formats to support machine-learning consistency and AV transferability between regions.
Digital–physical synchronisation	Ensure the content of VMS/CMS is aligned with digital map and regulation feeds to prevent conflicting instructions to AVs.

5.6.5 Future research areas

Whilst there is some coverage of the PT6 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.28 below.

Table 5.28: Potential research topics related to PT6

Research topic area	Description
Minimum LED refresh rate thresholds	Field-validate the 200 Hz guidance under different ambient lighting and speed conditions.
Message format and symbol recognition	Test AV recognition accuracy across various sign formats, colours, and VMS board types.
Digital–physical consistency monitoring	Develop agency tools to audit alignment between VMS displays and backend digital messages (e.g. for WZDx compliance).
Feedback loops from AV perception data	Use AV logs to detect failed sign readings and identify signage misconfiguration or placement problems.
Machine vision interpretation of non-VMS dynamic signs	Investigate how CAV perception systems detect and interpret non-text-based dynamic signage, such as lane-use control signals, dynamic merge arrows, and symbol-based CMS boards. These sign types are common in freeway and event scenarios but are underrepresented in current trials. Most available studies focus on VMS readability.

References for PT6

Austroads (2021) *Road Authority Data for Connected and Automated Vehicles Module 3: Guidance for Variable Speed Limit Sign and Lane Control Signal Data Provision to Connected and Automated Vehicles*, AP-R662C-21, Austroads, Sydney, NSW.

Austroads (2023) *Minimum Requirements for Traffic Signs, Traffic Signals and Line Markings*, AP-R696-23, Sydney, Australia: Austroads.

FHWA (Federal Highway Administration) (2021) *Manual on Uniform Traffic Control Devices for Streets and Highways (11th Edition Draft),* Department of Transportation, Washington, DC.

TransAID Consortium (2020) *Deliverable D5.4: Signalling for Informing Conventional and Automated Vehicles*, European Union Horizon 2020 Project, DLR, Cologne, Germany.

5.7 Managing AV interactions with E-scooters, cyclists and personal mobility devices (PT7)

Like all other vehicles, AVs, CVs and EVs must safely interact with all other road users, including those classed as Vulnerable Road Users (VRUs) such as pedestrians, cyclists, micromobility users and users of assistive mobility devices.

AVs operating in public environments must be able to detect, classify, and respond to VRUs under current infrastructure conditions, even where unpredictable or non-standard behaviours occur.

This topic covers physical infrastructure design elements that reduce risks and improve safety in interactions between AVs and VRUs. It focuses on geometric treatments, visibility enhancements, and physical separation strategies that road agencies can implement to support safe, predictable behaviour by AVs in mixed-use environments. It excludes vehicle-based countermeasures (e.g. noise emitters, V2X integration) and accessibility of AV services to VRU passengers.

Morris et al. (2021) analysed BITRE data to identify that in Australia during 2019, 18,521 VRUs were admitted to hospital following road accidents (making up 47% of all road collision hospitalisations) and a total of 410 VRUs were fatally injured in accidents (34% of all fatally injured road users). Using data from Queensland, they further identified that about three-quarters of casualties from cyclist–motor vehicle crashes occurred at intersections, compared to about half of the pedestrian–motor vehicle and motorcycle–motor vehicle casualties.

AVs must not only detect VRUs accurately but also anticipate their movements in real time. Unlike motor vehicles, VRUs operate with greater freedom of movement and exhibit more variable behaviours. Hulse (2023) highlighted that pedestrian behaviour is shaped by both conscious and subconscious decision-making. In a London trial, many participants crossed in front of AVs without waiting or respecting safe gaps, despite perceiving AVs as more dangerous than human-driven vehicles.

Classification also presents a challenge. Gilroy et al. (2022) demonstrated that e-scooter riders are frequently misclassified in urban environments, particularly where visual occlusion is common. This misclassification can lead to incorrect predictions that fail to reflect the high travel speed or erratic movement patterns of these users.

In addition to physical movement, communication plays a central role. VRUs often rely on eye contact or gestures to confirm it is safe to cross, but AVs do not replicate these cues. Rezwana and Lownes (2024) observed that the absence of such informal signalling may affect how pedestrians behave and how confident they feel when sharing space with AVs.

5.7.1 Key challenges

The core challenge involves enabling automated vehicles to detect, classify and respond safely to vulnerable road users such as pedestrians, cyclists, e-scooter riders and mobility device users. AVs must operate under conditions where these users may appear suddenly, move unpredictably, or be partially obscured by parked vehicles or roadside infrastructure. Unlike human drivers, AVs cannot rely on informal communication cues such as eye contact or gestures, which can lead to hesitation or misjudged responses. Misclassification is a particular risk for micromobility users, and can also result in inappropriate behaviour, such as incorrect yielding or overcautious movement. Table 5.29 presents these key challenges, example scenarios and their impacts on vehicle operations.

Table 5.29: Key challenges that impact managing AV interactions with e-scooters, cyclists and personal mobility devices

Key challenges	Example scenario	Impact on AV operations	Reference
Available lines of sight to VRUs	Pedestrian (or other VRU) obscured by parked cars, vegetation or buildings.	Difficult to detect, classify and predict. Also difficult for VRU to judge AV (and other vehicles).	Morris et al. (2021)
Prediction of VRU movement	Bicycle travelling in close proximity to planned AV path has an uncertain trajectory.	Difficult to predict – either results in driving response (e.g. slow down) or heightened risk.	Hulse (2023)
Lack of visual cues present with human drivers	Assisted mobility device user uncertain whether AV has observed them and hesitates to cross.	Uncertain assisted mobility device user may hesitate in crossing in situation where they have right of way, requiring AV to have prolonged wait or act as if user is not crossing.	Rezwana and Lownes (2024)

5.7.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency to manage AV interactions with e-scooters, cyclists and personal mobility devices are provided below in Table 5.30.

Table 5.30: Road and infrastructure design considerations related to PT7

Design element considerations	Description	Supporting references
Provision of clear sight lines	Providing good visibility from vehicles to areas of expected VRU activity is likely useful for both AVs and human drivers.	• Morris et al. (2021) • Austroads *Guide to Road Design Part 4* (Austroads 2023)
Kerb extensions (outstands)	Kerb extensions (outstands) may improve sight lines to pedestrians at crossing locations where they might otherwise be obscured by parked vehicles.	• Austroads *Guide to Road Design Part 4* (Austroads 2023) • Austroads *Guide to Traffic Management Part 11* (Austroads 2020)
Separation of road user types	Measures to separate out VRUs from the area where AVs operate are likely to ease the task for AVs. This includes protected bike lanes (e.g. separated by kerb). Provision of separate pedestrian paths is also likely to be useful.	• Morris et al. (2021)
Physical cues	Use of tactile indicators, reflective bollards or visual contrast surfaces to reinforce VRU operating space and AV perception zones.	-
Appropriate use of shared zones	Shared zones are best targeted to places with a matching traffic restriction and genuine low speed operation (e.g. 10 km/h) rather than through a lack of pedestrian facilities.	-
VRU-transmitted data (e.g. C-ITS)	Uptake of C-ITS or similar technologies by VRUs that broadcast their position, trajectory, and characteristics may supplement AV perception especially in high-risk areas such as school zones.	• Morris et al. (2021)

5.7.3 Related topics

Topics related to PT7 include those listed below in Table 5.31.

Table 5.31: Topics related to PT7

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	For AV-detectable signage and line marking aspects.
PT3	Ensuring compatible road and traffic design for AV navigation and operations	Physical road design shapes AV–VRU interactions, especially at crossings and shared zones.
DT8	Improving CAV interaction with emergency vehicles and vulnerable road users	Provides digital infrastructure support for VRU interaction alerts.

5.7.4 Principles

Principles derived from the above evidence that relate to PT7 are shown in Table 5.32 below.

Table 5.32: Principles related to PT7

Principle	Description
Design for predictable interaction	Physical infrastructure should reduce ambiguity in how AVs and VRUs interact (particularly at crossings, midblocks, and shared paths) by improving sight lines and clarifying user priority.
Ensure visibility and line of sight	Layouts should enable clear detection of VRUs by AV sensors. This includes managing occlusion risks near crossings, bike paths, or shared zones.
Support safe separation	Where feasible, infrastructure should provide physical separation (such as kerbed bike lanes or protected paths) between AVs and micromobility users to reduce misclassification risk and operational conflict. Shared AV and VRU zones should be limited to strictly low-speed, controlled environments where AV behaviour is predictable and VRUs can reliably perceive, interpret, and respond to approaching vehicles.
Minimise reliance on human cues	Where informal communication is absent, road design should promote confidence through visible priority and user separation.
Target high-conflict zones first	Midblock crossings, intersections, and constrained shared paths should be prioritised for design upgrades to manage the greatest risk of misinterpretation or delay.

5.7.5 Future research areas

Whilst there is some coverage of the PT7 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.33 below.

Table 5.33: Potential research topics related to PT7

Research topic area	Description
Monitoring international approaches	Maintain a watching brief on how other jurisdictions address AV–VRU interactions through physical or digital infrastructure.
Design guidance for complex urban settings	Identify best practice street designs that balance visibility, separation, and shared space to support AV–VRU safety.
Effectiveness of VRU-transmitted data	Assess the practicality and uptake of VRU-generated position and intent signals (e.g. via C-ITS), especially among cyclists and micromobility users.
Communicating AV intent to VRUs	Explore infrastructure or digital methods that help AVs signal intent to pedestrians and mobility device users in the absence of human cues.

References for PT7

Austroads (2020) *Guide to Traffic Management Part 11: Parking Management Techniques*, AGTM11-20. Austroads, Sydney.

Austroads (2023) *Guide to Road Design Part 4: Intersections and Crossings – General*, AGRD04-23, Austroads, Sydney.

Deshmukh A, Wang Z, Gunn A, Guo H, Sherony R, Feng F, Lin B, Bao S and Zhou F (2023) *A systematic review of safety-critical scenarios between automated vehicles and vulnerable road users*, arXiv preprint arXiv:2305.11291.

Gilroy S, Mullins D, Jones E, Parsi A and Glavin M (2022) 'E-scooter rider detection and classification in dense urban environments', *Results in engineering*, 16, 100677.

Hulse L M (2023) 'Pedestrians' perceived vulnerability and observed behaviours relating to crossing and passing interactions with autonomous vehicles', *Transportation research part F: traffic psychology and behaviour*, 93, 34-54.

Morris A P, Haworth N, Filtness A, Nguatem D P A, Brown L, Rakotonirainy A and Glaser S (2021) 'Autonomous Vehicles and Vulnerable Road-Users—Important Considerations and Requirements Based on Crash Data from Two Countries.' *Journal of Behavioural. Science*, 11, 101. https://doi.org/10.3390/bs11070101.

Rezwana S and Lownes N (2024) 'Interactions and Behaviors of Pedestrians with Autonomous Vehicles: A Synthesis', *Future Transportation*, 4(3), 722-745.

5.8 Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs (PT8)

The limited available kerb space in cities is valuable real estate for movement uses (e.g. moving traffic), access uses (e.g. parking, loading zones) and place uses (e.g. outdoor café seating). International Transport Forum (2018) noted that 'As long as there have been cities, there have been conflicts regarding the allocation of public space amongst different uses and different users -- nowhere has this been more acute than regarding the allocation of street space.' Local tensions beyond these competing uses are also evident, for example protests and court challenges in Melbourne over extended Clearway operating hours (ABC News, 2008).

This topic investigates physical infrastructure design principles for AV- and EV-compatible kerbside environments, focusing on layout, visibility, and dynamic usage. It examines how infrastructure can support safe and predictable interactions between CAVs and kerbside activities, excluding the management of footpath areas except where necessary for kerb access. The focus is limited to the needs arising from AV use (including opportunities where connectivity can assist) and EV charging, without aiming to provide a comprehensive overview of kerb management. For EVs, the focus is on home base charging scenarios (e.g. near a private residence or business) rather than destination charging facilities.

Auckland Transport (2023) defines a kerb zone as including 'the footpath and parking spaces on the side of the road' and notes the following range of competing purposes:

- movement of people and goods by vehicle, on foot, bike, or other wheeled devices
- access to residential properties, local services, employment, and public transport
- places for the collection of rubbish and recycling
- pick-up and delivery of goods and access for service providers
- space for people to meet each other, eat and relax
- trees and other vegetation to green the city, provide shade, absorb greenhouse gases, and clean the air and water
- infrastructure, utilities, and services such as drainage, signs, telecommunications, and gas (Auckland Transport 2023).

In recent years, renewed interest in kerb management in the United States reflects pressures from new sources of demand: the proliferation of shared mobility options like bike share, for-hire vehicle companies, micromobility modes, and e-commerce package deliveries (Mitman et al. 2018). Forthcoming expectation of increased demand from AVs (e.g. Mitman et al. 2021) reflects forecasts that future usage of robotaxis may far exceed current usage of human driven taxis and ride-hail, and likewise automated goods delivery vehicles exceed current operations of couriers and 'gig' delivery workers.

Some AVs, such as Waymo (Google for Developers 2025), use sensor fusion and localisation to visually interpret kerbside signage. However, there are also limits to relying on physical signage, particularly where signs are unclear, obstructed, or vary by jurisdiction. Digital designation of pick-up/drop-off zones would clarify kerbside regulation uncertainty.

Looking within Australia and New Zealand, it is important to note that demands from ride-hail, robotaxi and delivery services are only part of the evolving demands for the kerb. Auckland Transport's (2023) framework notes this as only one of eight challenges and needs, alongside urban densification, changing travel behaviour, safety, universal accessibility, changes to shopping and dining, impacts on community health and the need for green infrastructure (e.g. trees and unpaved spaces). For road agencies, this increasing diversity of kerb demand presents a planning and operational challenge: balancing public, private, and emerging mobility needs within limited physical space.

A particular challenge has been noted for EV owners who lack off-street parking at their home but still rely on home charging as a major charging method. This has resulted in a range of ad-hoc solutions to use home charging with on-street parking, but with problems getting the cable from the house to the car (Cardinal 2024). NSW electricity distributor Ausgrid estimates demand for 11,000 kerbside chargers that could be mounted across the 440,000 power poles in their network (Ausgrid 2024).

5.8.1 Key challenges

The core challenge involves managing the increasing intensity and complexity of kerbside activity driven by automated vehicles. AV passenger services such as robotaxis are expected to generate higher demand for pick-up and drop-off locations than current ride-hail operations, requiring well-defined and accessible kerb spaces. Simultaneously, automated delivery vehicles (both staffed and unstaffed), will change how goods are exchanged, with some requiring dwell time while awaiting goods recipients.

These dynamics highlight the need for safe, legal and sufficiently available stopping locations. Where suitable kerb access is lacking, AVs may need to decline trips, reroute users or obstruct traffic, thus compromising efficiency and safety. Table 5.34 presents these key challenges, example scenarios and their impacts on AV and EV operations.

Table 5.34: Key challenges that impact kerbside management for AVs and EVs

Key challenges	Example scenario	Impact on AV and EV operations
Commencing and completing robotaxi trip requires pick-up and drop-off	Passenger vehicle limited to using suitable pick-up or drop-off locations, however none exists near passenger origin or destination.	• Robotaxi service needs to know in advance and/or dynamically assess suitable locations. • Robotaxi service needs to recommend alternative location or decline service. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) needs to consider provision of suitable locations. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) needs to consider information provision for suitable locations.
	Passenger vehicle limited to using suitable pick-up or drop-off locations, but available location is occupied.	• Robotaxi service needs to know in advance and/or dynamically assess availability (occupied or not) of suitable locations. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) needs to consider level of supply of suitable locations. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) needs to consider dynamic availability information provision for suitable locations. • Robotaxi service and location managers may seek to cooperate on reservation service for suitable locations.
	Passenger vehicle uses unsuitable pick-up or drop-off location, obstructing traffic lanes.	• Road manager and regulators need to consider deterrence and enforcement approaches to manage inappropriate robotaxi stopping to suitable levels. • See also needs for access to suitable locations, information on availability, reservation opportunities, etc. to provide suitable alternative to this behaviour.
	Passenger vehicle uses unsuitable pick-up or drop-off location, requiring exposure of passenger to moving traffic to access vehicle.	• Road manager and regulators need to consider deterrence and enforcement approaches to manage inappropriate robotaxi stopping to suitable levels. • See also needs for access to suitable locations, information on availability, reservation opportunities, etc. to provide suitable alternative to this behaviour.

Key challenges	Example scenario	Impact on AV and EV operations
Completing unstaffed goods delivery	Goods vehicle limited to using suitable delivery parking locations, however none exists near delivery point.	• Delivery service needs to know in advance and/or dynamically assess suitable locations. • Delivery service needs to identify alternative location or decline service. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) need to consider provision of suitable locations. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) need to consider information provision for suitable locations.
	Goods vehicle limited to using suitable delivery parking locations, however available location near delivery point is occupied.	• Delivery service needs to know in advance and/or dynamically assess availability (occupied or not) of suitable locations. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) need to consider level of supply of suitable locations. • Road manager and facility managers (e.g. of shopping centre, entertainment facility) need to consider dynamic availability information provision for suitable locations. • Delivery service and location managers may seek to cooperate on reservation service for suitable locations.
	Goods vehicle uses unsuitable delivery location, obstructing traffic lanes.	• Road manager and regulators need to consider deterrence and enforcement approaches to manage inappropriate delivery vehicle stopping to suitable levels. • See also needs for access to suitable locations, information on availability, reservation opportunities, etc. to provide suitable alternative to this behaviour.
	Goods vehicle uses unsuitable delivery location, requiring exposure of human (operator or recipient) to moving traffic to access vehicle.	• Road manager and regulators need to consider deterrence and enforcement approaches to manage inappropriate delivery vehicle stopping to suitable levels. • See also needs for access to suitable locations, information on availability, reservation opportunities, etc. to provide suitable alternative to this behaviour.
	Goods vehicle waiting for extended period for recipient to attend unstaffed vehicle.	• This is a variant of the general need for access to a suitable delivery location, although it may influence some specific design needs.
Kerbside EV charging (for home base)	Provision of safe kerbside home base charging facilities (e.g. without cables lying across footpaths).	• EV operator needs to know in advance and/or dynamically assess availability (occupied or not) of suitable locations.
	Assured access to home base charging facility when needed.	• Road manager (e.g. local government) needs to consider level of supply of home base charging opportunities. • EV charging services and road managers may seek to cooperate on reservation service for home base kerbside charging.
Scarcity of urban kerb space	Constraining kerbside availability to manage expected levels of demand in urban settings.	• Refer to needs for access to space available facilities, supporting dynamic information and potential for reservation services.

5.8.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency related to kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs are provided below in Table 5.35.

Table 5.35: Road and infrastructure design considerations related to PT8

Design element considerations	Description	Supporting references
Kerb space allocation	Include AV pick-up/drop-off, delivery operations, and kerbside EV charging in kerb use assessments, alongside existing demands.	• Auckland Transport (2023)
Kerb access visibility and demarcation	Assess physical signage, markings, and street design that may obscure or miscommunicate legal kerbside access points. Upgrade physical cues (e.g. paint, bollards, signage) to improve recognition by AVs and road users, and reduce illegal or missed kerb use.	• Adapted from Auckland Transport (2023) • Mitman et al. (2021)
Pick-up and drop-off infrastructure	Apply existing human-driven vehicle guidance as a basis for AV facilities, unless specific AV needs emerge.	• Queensland Department of Transport and Main Roads (2020)
Loading zone design	Retain standard guidance for delivery vehicles. Current pressures relate to demand intensity, not unique AV design needs.	• Austroads *Guide to Traffic Management*, Part 7 (Austroads 2020) and Part 11 (Austroads 2023)
Kerbside EV charging design	Integrate relevant road design and safety principles in kerbside charging layout, including safe cable management.	• NSW Office of Energy and Climate Change (2023)
Pricing and demand matching	Consider kerb pricing models (e.g. time-based access fees) to align demand and supply in busy locations.	• Auckland Transport (2023)

5.8.3 Related topics

Topics related to PT8 include those listed below in Table 5.36.

Table 5.36: Topics related to PT8

Related topic (code)	Related topic title	Reason for cross-reference
PT9	Minimising urban congestion from AV fleet staging, parking and idle circulation	Consider the congestion impacts from CAV kerbside management.
DT6	Supporting multimodal and CAV integration	Supports multimodal digital coordination where kerb use intersects with public transport and micromobility.
DT9	Optimising CAV and EV fleet management and staging	Digital fleet and charging management relies on kerbside space regulation and monitoring.
DT12	Standardising digital road regulations for CAV and EV charging zones	Kerbside digital rules should align with physical design of EV/CAV charging areas.

5.8.4 Principles

Principles derived from the above evidence that relate to PT8 are shown in Table 5.37 below.

Table 5.37: Principles related to PT8

Principle	Description
Use existing human-driven vehicle design guidance as a foundation	Current standards for pick-up/drop-off areas and loading zones (e.g. Austroads Guide to Traffic Management) provide a valid starting point for AV kerbside operations. There is no evidence that AVs require fundamentally different physical infrastructure.
Prioritise solutions that address growing demand	The most critical issue is the increase in kerbside demand. Without intervention, this pressure may exceed the current supply of safe, legal access points.
Apply time-based management approaches	Time-based kerb allocation allows different users (e.g. deliveries, AV passengers) to access the same space at different times, improving efficiency without physical expansion.
Leverage digital infrastructure to complement physical access	Digital tools such as real-time availability, booking systems, and pricing mechanisms will play a central role in managing kerbside usage as demands scale.
Ensure physical access points are available, visible, and sufficient	Scenarios highlight the importance of location, visibility, and availability. CAVs and EVs should reliably identify suitable access zones or risk non-compliance or user frustration.
Design for safe passenger and goods exchange	Several risks emerge when kerb access requires passengers or operators to interact with moving traffic. Infrastructure should support safe handover spaces.
Plan for unstaffed vehicle operations	Unstaffed AVs or delivery vehicles may require unique operating space, longer dwell times, or unattended interaction zones. Infrastructure should reflect these needs.
Support integration of kerbside EV charging into local street environments	Kerbside charging presents distinct design needs, particularly in residential areas without off-street parking. Safety, accessibility, and integration into shared public space should be considered.

5.8.5 Future research areas

Whilst there is some coverage of the PT8 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.38 below.

Table 5.38: Potential research topic areas related to PT8

Research topic area	Description
Best practice examples and lessons learned	Identify successful kerbside management strategies and extract lessons from local and international trials.
Toolkit development	Develop a structured toolkit to support consistent infrastructure planning for AV and EV kerbside access.
Safe kerbside EV charging integration	Investigate safe, practical solutions for kerbside charging where off-street parking is unavailable, focused on pedestrian safety and urban constraints.
Effectiveness of pricing and reservation models	Assess the viability of digital reservation and pricing systems to manage kerb demand across different contexts.
Impacts of constrained urban kerb environments	Evaluate the trade-offs between competing uses in high-demand areas to inform better space allocation and prioritisation.
Accessibility in shared kerb environments	Investigate how kerbside EV and AV infrastructure can support equitable access for mobility-impaired users, especially in dense urban areas.

References for PT8

ABC News (22 May 2008) *Herschel Landes, retailer, talks to Ali Moore about the clearway protest at South Yarra*, [interview audio file], accessed 24 March 2025.

Abel S, Ballard M, Davis S, Mitman M, Sangl K and Wasserman D (2021) *Curbside Inventory Report*, United States Federal Highway Administration report FHWA-HEP-21-028, Federal Highway Administration, Washington, DC.

Auckland Transport (2023) *Kerb Zone Management Framework, A component of the Auckland Parking Strategy*, Auckland Transport, Auckland, NZ.

Ausgrid (2024) *Kerbside charging*, Ausgrid website, accessed 24 March 2024.

Austroads (2020) *Guide to Traffic Management Part 7: Activity Centre Transport Management*, AGTM07-20, Austroads, Sydney.

Cardinal E (12 November 2024) '"Desperate and dangerous": The wildest at-home EV charging set-ups in Australia', *Drive website*, accessed 24 March 2025

International Transport Forum (2018) *The Shared-Use City: Managing the Curb*, Corporate Partnership Report, International Transport Forum.

Mitman M, Davis S, Armet I and Knopf E (2018) *Curbside Management Practitioners Guide*, Institute of Transportation Engineers.

Mitman M, Rixey A, Gibler T, Howell A, Swift T, Weinberger R, Primus J and Abel S (2022) *Dynamic Curbside Management: Keeping Pace with New and Emerging Mobility and Technology in the Public Right-of-Way*, United States National Cooperative Highway Research Program Web-Only Document 340.

NSW Office of Energy and Climate Change (2023) *EV Kerbside Charging for Local Government*, NSW Office of Energy and Climate Change website, accessed 25 March 2025.

Queensland Department of Transport and Main Roads (2020) *Public Transport Infrastructure Manual 2015*, Queensland Department of Transport and Main Roads website, accessed 25 March 2025.

Short A (14 November 2019) 'Garçon! D.C. Requires Curb Reservations for Deliveries', *Streetsblog USA*, accessed 24 March 2025.

5.9 Minimising urban congestion from AV fleet staging, parking and idle circulation (PT9)

This topic focuses on physical infrastructure needs, including staging zones, kerb use and urban design, to support AV fleet operations; along with considerations related to the increasing electrification of AV fleets.

The evolution of AVs, particularly in fleet-based operations such as ride-hailing, autonomous taxis, and automated deliveries, poses unique challenges to transport infrastructure and congestion management. While AVs offer significant potential to enhance urban mobility by potentially reducing accidents, optimising traffic flows, and enabling efficient use of space, they also introduce risks that could exacerbate urban congestion if not managed effectively. Specifically, AV fleet management practices such as idle cruising, inefficient vehicle rebalancing, and clustering in high-demand zones can result in increased congestion and kerbside conflicts (Millard-Ball 2019, OECD/ITF 2023, NASEM 2022).

Unmanaged AV fleets operating without coordinated parking, staging, or dispatch strategies may lead to vehicles frequently circulating empty, commonly known as 'zero-occupancy cruising' or 'zombie miles'. Studies indicate that this behaviour could potentially double urban vehicle kilometres travelled (VKT), severely impacting road network performance and increasing greenhouse gas emissions (Millard-Ball 2019, NASEM 2022). NACTO (2024) similarly identifies that AVs operating without proper regulation have already demonstrated disruptive behaviours, such as blocking traffic lanes, interfering with transit, and creating kerbside conflicts in dense urban environments. Furthermore, fleets clustering at popular passenger pick-up points, major transport hubs and CBDs create acute kerbside competition, interfering with other road users, including freight operators, public transport, and active mobility modes (OECD/ITF 2023).

As AV fleet electrification accelerates, pressure on urban kerbside and staging areas is expected to increase. Austroads (2022a) highlights that many urban locations currently lack suitable charging infrastructure. This is particularly the case at the kerb or near high-demand trip generators, which can force EVs into inefficient circulation while searching for available chargers. This can contribute to localised congestion, kerbside competition, and reduced fleet responsiveness.

In high-turnover areas such as CBDs, retail centres, and public transport hubs, Austroads (2022a) warns that poorly designed charging infrastructure (such as narrow accessways, insufficient bays, and suboptimal parking orientations) can lead to queuing, blocked lanes, and pedestrian conflicts. These risks mirror international concerns about unmanaged AV and EV fleet behaviours, including idle cruising and kerbside clustering, particularly in areas lacking integrated planning between physical infrastructure and fleet operations. Without dedicated, well-located charging and waiting areas, the combination of automated and electric fleets may amplify the very congestion issues they are intended to mitigate.

This challenge is exacerbated by the lack of nationally consistent signage and markings for EV charging and low-emission vehicle zones, compounding access inefficiencies for electrified AV fleets. As identified by Austroads (2022b), inconsistent symbols and markings across states and territories can create confusion for both private users and fleet operators, and may reduce operational efficiency. This is particularly a concern in high-demand urban locations where kerbside space is contested. Without clear, standardised visual indicators, EV users and fleet operators may struggle to identify or appropriately access designated spaces. This will further contribute to access inefficiencies, enforcement challenges, and road safety risks.

Integrating physical infrastructure interventions with digital coordination tools is emerging as a critical strategy to mitigate AV-induced congestion. Digital kerbside management, geofencing, predictive fleet dispatching, and dynamic staging area allocation can reduce unnecessary vehicle circulation, alleviate kerbside conflicts, and optimise overall fleet operations.

5.9.1 Key challenges

A key issue involves managing congestion risks from AV fleets that operate without adequate parking or staging infrastructure. In the absence of designated zones, AVs may cruise empty between trips, cluster in high-demand areas, or stop illegally, adding to traffic volumes and kerbside pressure. These behaviours can interfere with public transport, freight and micromobility users. Most cities also lack policy and planning frameworks to allocate space for AV-specific infrastructure, limiting agencies' ability to respond effectively. Table 5.39 presents these key challenges, example scenarios and their impacts on AV operations.

Note on framing:
Unlike most other topics in this report, which focus on infrastructure conditions affecting CAV and EV operation, this section addresses how AV fleet behaviours influence road network performance. It focuses on how unmanaged staging, cruising and kerbside activity contribute to congestion, rather than how infrastructure affects AV operation. The table below therefore presents impacts on the road network, not vehicle performance, and reverses the typical cause–effect structure used elsewhere in this report.

Table 5.39: Key challenges to minimising urban congestion from AV fleet parking and staging

Key challenges	Example scenario	Impact on road networks	References
Insufficient physical staging infrastructure	Large numbers of AVs attempt to stage in limited kerbside or off-street locations near major events or transport hubs.	Physical congestion at kerbsides, blocked traffic lanes, pedestrian and cyclist disruptions, and compromised public transport access.	• OECD/ITF (2023)
Lack of clearly marked AV loading/unloading zones	AVs randomly stop at crowded locations for passenger pick-up/drop-off, without defined physical kerb spaces.	Traffic lane blockages, unsafe passenger boarding/alighting conditions, kerbside competition, and reduced overall kerb efficiency.	• NACTO (2021) • OECD/ITF (2023)
Physical proximity of staging areas to high-demand zones	Dedicated staging zones for AVs are physically distant from high-demand pick-up points, causing unnecessary travel and rebalancing.	Increased AV circulation, extra empty kilometres driven ('zombie miles'), and additional congestion.	• OECD/ITF (2023)
Competing kerbside uses (public transport, freight, active transport)	AV fleets seeking kerbside spaces conflict physically with existing high-priority uses, such as bus lanes, cycleways, and freight loading zones.	Reduced transport efficiency, increased user conflicts, safety hazards for vulnerable road users, and degraded overall mobility outcomes.	• NASEM (2022) • OECD/ITF (2023) • NACTO (2024)
Legacy infrastructure design incompatible with AV use	Existing parking structures and kerbside designs do not physically support AV-specific requirements (e.g. boarding, alighting, vehicle staging).	Inefficient kerb usage, prolonged passenger loading/unloading, increased pedestrian-vehicle interaction risks, and lower throughput of kerbside facilities.	• NACTO (2021) • OECD/ITF (2023)
Insufficient physical charging infrastructure (electrified AV-specific)	Electrified fleet AVs seek limited kerbside or off-street charging facilities during peak operational periods, resulting in queues or blockages.	Physical congestion at charging points, vehicle spill-over onto surrounding streets, compromised availability of charging bays for other users, and impeded traffic flow.	• NASEM (2022) • OECD/ITF (2023) • CROW (2023)

Key challenges	Example scenario	Impact on road networks	References
Physical design constraints of existing charging facilities (electrified AV-specific)	Charging infrastructure designed primarily for private vehicles (e.g. single-bay chargers, poor physical access) is inadequate for larger electrified AV fleets, causing operational bottlenecks.	Inefficient use of charging infrastructure, extended dwell times at chargers, congestion around charging facilities, and fleet operational disruptions.	• NASEM (2022) • CROW (2023)
Lack of EV-compatible staging or holding areas (electrified AV-specific)	Absence of designated physical staging or holding zones that include charging facilities near high-demand pick-up locations forces EV fleets into inefficient idle circulation or distant charging.	Increased zero-occupancy EV circulation, additional road congestion, prolonged fleet response times, and degraded operational reliability.	• OECD/ITF (2023) • CROW (2023)

5.9.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency to minimise urban congestion from AV fleet parking and staging challenges are provided below in Table 5.40.

Table 5.40: Road and infrastructure design considerations related to PT9

Design Element	Description	Supporting references
Dedicated AV staging zones	Physically defined off-road or kerbside staging facilities explicitly designed for AV holding, charging, or waiting near major urban trip generators (e.g. CBDs, public transport hubs, airports).	• OECD/ITF (2023) • NACTO (2021, 2024)
Optimised AV boarding/alighting areas	Clearly marked kerbside infrastructure designed explicitly for AV passenger pick-up/drop-off, physically separating these activities from general kerbside uses, thus reducing lane blockages and user conflicts.	• NACTO (2021) • OECD/ITF (2023)
Flexible kerbside infrastructure design	Adaptable physical kerbside spaces designed to accommodate AV staging, short-term waiting, and passenger transfers. Examples include modular kerb extensions, flexible lane configurations, and time-variable loading zones supported by physical signs and pavement markings.	• NACTO (2021) • OECD/ITF (2023)
Physical integration of mobility hubs	Redevelopment of traditional parking facilities into multimodal hubs that physically support AV staging, passenger transfer, and fleet servicing. Such hubs reduce the physical footprint of idle vehicles within busy urban precincts.	• OECD/ITF (2023)
Physical buffer zones near high-demand areas	Provision of designated physical buffer zones (areas adjacent to high-demand passenger pick-up locations), where AV fleets can temporarily idle without disrupting main traffic flows or active travel paths	• OECD/ITF (2023)
Signage and road markings for AV zones	Enhanced physical signage and road markings clearly designating AV-only staging, waiting, and kerbside access areas, improving compliance and reducing accidental misuse by other road users.	• OECD/ITF (2023) • NACTO (2021)

5.9.3 Related topics

Topics related to PT9 include those listed below in Table 5.41.

Table 5.41: Topics related to PT9

Related topic (code)	Related topic title	Reason for cross-reference
PT5	Managing mixed traffic interactions with AVs	Unmanaged AV staging and kerbside conflict directly affect human driver interactions.
PT8	Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs	Overlaps with physical kerb use, layout visibility, and shared allocation principles.
DT9	Optimising CAV and EV fleet management and staging	Fleet staging and dispatch logic requires digital kerb access enforcement.
DT10	Integration of CAV and EV operations into smart city and traffic management platforms	Traffic platforms can optimise staging zones using AV data feeds.
DT11	Ensuring real-time EV charging availability and status updates	Staging and idle strategies rely on real-time charger location and occupancy status data.

5.9.4 Principles

Principles derived from the above evidence that relate to PT9 are shown in Table 5.42 below.

Table 5.42: Principles related to PT9

Principle	Description
Efficient use of kerb and road space	Clearly defined physical staging areas prioritising AV and EV fleet operations, separated from general traffic and other users to minimise congestion and conflicts.
Support physical–digital infrastructure integration	Physical infrastructure (staging zones, EV charging facilities) designed specifically to integrate seamlessly with digital fleet management systems and dynamic kerbside allocation.
Adaptability and scalability	Physical designs (kerbside layouts, charging facilities, staging hubs) should be modular and scalable to accommodate changing AV and EV fleet sizes, technology evolution, and operational demands.
Design for physical safety and user coexistence	Design of staging, loading, and charging infrastructure prioritises physical safety, accessibility, and compatibility with other urban transport modes, protecting vulnerable users.
Design to reduce emissions and idle travel	Infrastructure designed explicitly to encourage efficient vehicle movements, minimise unnecessary AV and EV idle circulation, and support energy-efficient operations, reducing congestion and emissions.
Equitable access to AV infrastructure	Physical AV and EV staging and charging facilities equitably distributed to ensure accessibility and balancing demands across locations.
Collaborative stakeholder engagement	Active collaboration with stakeholders (local authorities, fleet operators, infrastructure providers, and community representatives) to ensure infrastructure meets diverse operational needs and supports broader urban mobility objectives.

5.9.5 Future research

Whilst there is some coverage of the PT9 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.43 below.

Table 5.43: Potential research topic areas related to PT9

Research topic area	Description
Physical infrastructure impact assessment	Evaluate the direct impacts of AV and EV physical infrastructure (e.g. staging and charging zones) on congestion and overall traffic network performance.
AV/EV infrastructure design standards	Establish comprehensive physical design guidelines for AV and EV staging areas, kerbside access points, and integrated charging facilities.
Behavioural analysis of AV/EV interactions	Investigate behavioural impacts of AV and EV fleets interacting with other road users (public transport, pedestrians, cyclists) and how physical design influences these interactions.
Equity and accessibility analysis	Examine equitable distribution and accessibility of AV/EV staging and charging infrastructure across different communities.
Infrastructure adaptability studies	Research the long-term adaptability and scalability of physical infrastructure designed for evolving AV and EV fleet requirements.

References for PT9

Austroads (2022a) *Guidelines for Low and Zero Emission Vehicle Charging Infrastructure Installation*, AP-G98-22, Austroads, Sydney, NSW.

Austroads (2022b) *Standardised Signage and Pavement Symbols for Low and Zero Emission Vehicles*, AP-R667-22, Austroads, Sydney, NSW.

Millard-Ball A (2019) 'The autonomous vehicle parking problem', *Transport Policy*, vol. 75, pp. 99–108, https://doi.org/10.1016/j.tranpol.2019.01.003.

NASEM (National Academies of Sciences, Engineering, and Medicine) (2022) *Dynamic Curbside Management: Keeping Pace with New and Emerging Mobility and Technology in the Public Right-of-Way, Part 1: Dynamic Curbside Management Guide and Part 2: Conduct of Research Report* (NCHRP Project 20-102(26), The National Academies Press, Washington, DC, USA, https://doi.org/10.17226/26718.

NACTO (National Association of City Transportation Officials) (2021) *Blueprint for Autonomous Urbanism: Second Edition*, NACTO, New York.

NACTO (National Association of City Transportation Officials) (2024) *Principles for Autonomous Vehicles on City Streets*, NACTO, New York.

OECD/ITF (2023) *Preparing Infrastructure for Automated Vehicles*, International Transport Forum, Paris.

5.10 Ensuring EV-compatible crash barriers (PT10)

This topic covers crash barrier design in response to increased EV mass and crash energy. It focuses on containment upgrades, impact geometry, and safety risks in mixed fleet environments. However, it does not address AV crash avoidance logic or digital-only mitigations.

EVs and in particular, battery-electric SUVs and commercial trucks, are significantly heavier than comparable internal combustion engine (ICE) models due to the mass of their battery packs. A battery powered vehicle often has 20–30% more mass than ICE equivalents (Bird 2025). This extra mass increases the kinetic energy in crashes, raising challenges for roadside safety infrastructure that was originally engineered for lighter vehicles. Roadside crash barriers (e.g. guardrails, bridge rails, wire rope, concrete New Jersey kerbs etc.) are critical in absorbing impact energy and redirect vehicles that leave the roadway.

It is noted that many existing barrier systems were tested and rated using vehicles around 1,500–2,000 kg, reflecting typical sedans or pickups of past decades, not the 2,500–4,000 kg EVs increasingly common today (Browne 2023, Bird 2025). This can be seen in recent University of Nebraska-Lincoln tests illustrating the catastrophic damage of a concrete barrier (destruction of concrete and more than 50% higher typical lateral displacement) when impacted by a 3,000 kg pickup truck at 100 km/h at a 25-degree angle (Reed 2024). This raises concerns that current road barriers may not be suitable to contain modern EVs.

This issue is of increasing importance due to increasing EV adoption and the advent of CAVs. EV sales are rising and policy settings in many countries target 50% or more of new vehicle sales to be electric by 2030–2035 (Reed 2024, Browne 2023). Notably, recent research (Reed 2024) indicates EVs are involved in run-off-road crashes at roughly the same rate and speeds as ICE powered vehicles. However, an EV’s greater momentum can result in more severe barrier impacts.

Infrastructure bodies are beginning to respond. Although not focused on EVs directly, Austroads has undertaken world-first crash tests involving a 36-tonne truck, SUV, and sedan to validate the performance of bridge barriers under heavier loads. These trials are informing updates to AS 5100 and highlight the need to re-examine barrier capacity for modern vehicle masses, including EVs (Austroads 2023).

Accordingly, there is a need to ensure that roadway barriers can continue to support new vehicles. Adapting EV compatible crash barriers is crucial to maintain safe roads in an era of vehicle electrification and autonomy (Winfree 2025).

5.10.1 Key challenges

The core challenge involves adapting roadside barriers to safely contain the greater mass and altered crash dynamics of electric vehicles. Many existing systems were designed for lighter internal combustion vehicles and may not withstand the higher impact forces or different crash behaviours of EVs. Features such as low centres of gravity and battery placement introduce new failure modes, including underride and excessive deflection. Retrofitting barriers may be difficult in constrained environments, and current standards are not fully aligned with emerging EV characteristics. Table 5.44 presents these key challenges, example scenarios and their impacts on vehicle barrier performance.

Table 5.44: Key challenges that impact design and performance of crash barriers due to EVs

Key challenges	Example scenario	Impact on barriers	References
Increased vehicle mass and impact energy	A 4 t electric truck veers off a curve.	Impact forces exceed containment design; risk of barrier rupture or vehicle vaulting.	• Winfree (2025), Bird (2025) • Reed (2024)
Low centre of gravity and battery rigidity	Low-slung EV sedan hits W-beam barrier.	Barrier may ride over vehicle; failure to redirect properly.	• Reed (2024)
Inadequate barrier geometry	Standard W-beam barrier on urban arterial with high EV traffic.	Barrier height insufficient for EV profile; increased underride or override risk.	• Browne (2023) • Reed (2024)
Legacy standards and outdated barriers	Guardrail installed under old design tested with 1.5 t sedans.	Barrier underperforms when struck by heavier EVs due to outdated design assumptions.	• Browne (2023) • Bird (2025)
Mixed vehicle fleet	EV SUV and ICE ute involved in multi-vehicle collision on bridge.	Combined mass exceeds barrier's engineered load tolerance.	• Austroads (2023)
Prior unaddressed barrier damage	Previously struck barrier not replaced or repaired.	Reduced structural capacity causes barrier to fail under next EV impact.	• Austroads (2023)

5.10.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for EV-Compatible Barriers are provided below in Table 5.45.

Table 5.45: Road and infrastructure design considerations related to PT10

Design element considerations	Description	Supporting references
Design for increased mass and impact energy	Use higher-containment level barrier systems (e.g. MASH TL-4, EN 1317 H2-class) in corridors with heavy EV or truck traffic. These barriers are crash-tested against heavier vehicles and reduce risk of penetration or excessive deflection. Apply risk-based prioritisation to focus upgrades on high-risk roads, bridges and freight routes.	• Winfree (2025) • Bird (2025)
EV-informed barrier testing	Incorporate EV-equivalent vehicle weights and crash profiles into testing protocols. Standards such as MASH and EN 1317 should evolve to include vehicles >2 t in 'normal' test categories.	• Browne (2023) • Reed (2024)
Revised barrier geometry and rail profiles	Adjust barrier height and shape (e.g. taller W-beams, thrie-beam profiles) to reduce risk of underride or override by low-profile EVs. Profiles should be modelled against current and emerging vehicle types.	• Reed (2024) • Browne (2023)
Prioritised upgrades based on risk	Focus upgrades on high-speed, high-risk locations such as bridges, curved alignments, and constrained urban areas with frequent EV or heavy vehicle flows. Use CAV data to flag high-impact zones.	-

5.10.3 Related topics

Topics related to PT10 include those listed below in Table 5.46.

Table 5.46: Topics related to PT10

Related topic (code)	Related topic title	Reason for cross-reference
PT3	Ensuring compatible road and traffic design for AV navigation and operations	Crashes may be more likely on poor curves or gradients; barrier upgrades may be triggered by road geometry risks.
PT4	Maintaining roadway and pavement integrity for AVs and EVs	Barriers should align with pavement conditions, especially for heavy EVs.

5.10.4 Principles

Principles derived from the above evidence that relate to PT10 are shown in Table 5.47 below.

Table 5.47: Principles related to PT10

Principle	Description
Design for evolving vehicle mass	Infrastructure should accommodate the increasing mass and energy profiles of EVs, including SUVs, vans and commercial vehicles. This includes selecting containment levels (e.g. MASH TL-4, EN 1317 H2) aligned with real-world vehicle characteristics.
Align standards with EV characteristics	Testing protocols and design specifications should evolve to reflect the physical properties and crash dynamics of EVs. Standards such as MASH and EN 1317 should incorporate > 2 t vehicle categories as standard.
Anticipate and mitigate emerging failure modes	Infrastructure design should account for EV-specific failure modes (e.g. underride, over-penetration) and adjust barrier geometry, height, and anchoring accordingly.
Target upgrades using risk and safety data	Barrier upgrades should be prioritised based on crash risk, corridor type, and traffic composition. CAV and AV data can support dynamic identification of high-risk locations based on crash data (e.g. near-misses, loss of control) and the prevalence of heavier vehicles on key corridors.

5.10.5 Future research areas

Whilst there is some coverage of the PT10 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.48 below.

Table 5.48: Potential research topic areas related to PT10

Research topic area	Description
EV-specific crash testing protocols	Further development of barrier crash tests using modern EVs (e.g. 2.5–4 t SUVs and trucks) to ensure accurate performance assessment under real-world conditions.
Failure modes under EV impact	Research into how barrier geometry, anchoring, and material performance contribute to underride, override, or barrier breach when impacted by EVs.
Digital asset mapping and AV integration	Development of HD maps containing barrier attributes (type, containment level, condition), with real-time updates from digital maintenance systems to support AV navigation and incident prediction.
Smart barrier systems	Exploration of embedded sensors and communications capabilities that can detect barrier impacts and notify AVs road agencies/infrastructure maintainers in real time.

References for PT10

Austroads (2023) *Updating the Bridge Barrier Design Guidelines*, Austroads Transport Infrastructure Program update, Austroads website, accessed Oct 2023.

Bird S (15 March 2025) 'Electric cars 'so heavy they can smash through motorway barriers'', *The Telegraph*, accessed 24 March 2025.

Browne D (9 February 2023) 'Exclusive: National Highways commissions research over EV crash barrier concerns.' *Highways Magazine* (UK)

Reed L (29 July 2024) 'Nebraska tests suggest U.S. highways are not ready for widespread EV use.' *Nebraska Today*, University of Nebraska-Lincoln.

Van Cleave K and Novak A (18 September 2024) 'Electric vehicles raise concerns about whether safety infrastructure can handle their weight in a crash', *CBS News*.

Winfree G (6 February 2025) 'We need new barrier safety standards for EVs', *Traffic Technology International*, opinion column.

5.11 Maintenance and asset management for CAV and EV infrastructure (PT11)

This topic covers the maintenance and lifecycle management of infrastructure that supports automated and electric vehicles, including roadside units (RSUs), machine-readable signage, and AV-relevant pavement features. It focuses on governance, ownership clarity, and predictive maintenance integration.

The emergence of CAVs and EVs is transforming infrastructure needs and maintenance expectations for road agencies. Unlike previous vehicle innovations, CAVs rely heavily on the condition and readability of existing infrastructure, such as lane markings, road signs, and traffic signals, while also depending on new digital infrastructure, like C-ITS RSUs and vehicle-to-infrastructure (V2I) communication networks (NASEM 2024a, 2024b).

This shift necessitates changes in how agencies plan, fund, and manage their assets. NASEM (2024b) highlights that many transportation departments lack clear frameworks for maintaining newly deployed digital roadside equipment. Similarly, existing maintenance standards for pavement markings and signage may be insufficient to support AV perception systems, with degraded or inconsistent assets leading to safety and operational concerns (NASEM 2024a).

AVs also present challenges for traditional pavement design and maintenance strategies. AVs exhibit reduced lateral wander, creating concentrated wear paths that may lead to faster rutting and fatigue, especially under freight applications and platooning conditions. These patterns are unlikely to be accommodated by existing surface design lives or material selection assumptions, requiring reassessment of lifecycle cost and maintenance planning frameworks (FHWA 2021).

Recognising these emerging pressures, international transport agencies are responding through reforms in asset governance, digital integration, and predictive maintenance. For example, MetroPlan Orlando (2020) recommends region-wide coordination and training for managing RSUs and smart signal hardware. CROW (2023) promotes infrastructure adaptability and monitor-and-adapt strategies over fixed-interval maintenance models. The CSA Group (2022) calls for digital and physical infrastructure to be planned, operated, and retired under a consistent lifecycle asset management framework, supported by machine-readable standards and cross-agency data sharing.

In the context of CAVs and ADAS-equipped vehicles, asset performance is not only assessed through traditional inspections but can also be informed by feedback data from vehicle systems themselves. These include perception errors (e.g. failure to detect signage or markings), repeated disengagements, or fallback events triggered by deteriorated or ambiguous infrastructure. Accordingly, road agencies may benefit from developing structured safety data feedback loops, where operational data from vehicles is used to identify requirements for maintenance or upgrade. This emerging practice aligns with digital maintenance strategies in other domains and supports a more responsive, risk-based approach to infrastructure upkeep.

For EV charging equipment, road agencies remain responsible for the integration, surface upkeep, and coordination of infrastructure within the public road corridor. Austroads (2022) guidance confirms that agencies may oversee aspects such as pavement integrity, signage, lighting, and security around EV charging sites, particularly where located on public land. In addition, agencies may contribute to site maintenance planning, including inspections, cleaning, fault reporting, and asset lifecycle coordination. This is particularly the case where charging infrastructure is co-located with rest areas or roadside facilities.

5.11.1 Key challenges

The core challenge involves maintaining emerging infrastructure that supports CAV and EV operations, including sensors, communications assets and charging systems. These assets often require more frequent and specialised maintenance, more frequent technology upgrades, and new asset management protocols. Road agencies should integrate these elements into legacy systems while adapting funding models to manage shorter lifecycles, evolving service models, and the growing interdependence of physical and digital infrastructure. Table 5.50 presents these key challenges, example scenarios and their impacts on asset performance and road agency maintenance operations.

Table 5.49: Key challenges that impact maintenance and asset management for CAV and EV infrastructure

Key challenges	Example scenario	Impact on vehicle operations	Supporting references
Lack of ownership clarity	RSU installed by project team is not adopted into asset register.	RSU fails and remains offline for months due to no assigned maintenance body.	• MetroPlan Orlando (2020) • NASEM (2024b)
Legacy inspection cycles	Markings inspected every 12 months, but fade within 6 months.	ADAS and AV lane departure system disengages in faded zones, causing fallback to manual mode.	• NASEM (2024a) • FHWA (2021)
Inadequate digital asset tracking	RSU or signal controller failure is not recorded in the asset management system (AMS).	Fault remains undetected, undermining CAV routing or signal priority.	• CSA Group (2022)
No predictive maintenance model	AV cameras detect increasing surface degradation, but agency responds only after user complaints.	AVs avoid rough sections or disengage; operators receive no early warning.	• CROW (2023)
Lack of ADAS and AV-aware design standards	Signs and markings installed per legacy standards without consideration of machine readability.	ADAS and AV sensor misreads signage due to occlusion or low contrast.	• NASEM (2024a) • CSA Group (2022)
Staff skills and training gaps	Field crew unsure how to test or reset RSU after storm damage.	Delays in infrastructure recovery affect CAV functionality and system redundancy.	• MetroPlan Orlando (2020)
Inconsistent agency practices	State controls C-ITS deployment, local government owns signage and road markings.	Inconsistent maintenance leads to fragmented readiness across network.	-

5.11.2 Road and infrastructure design considerations

Potential road and infrastructure design considerations for an agency related to maintenance and asset management for CAV and EV Infrastructure are provided below in Table 5.50.

Table 5.50: Road and infrastructure design considerations related to PT11

Design element considerations	Description	Supporting references
Machine-readable pavement markings and signage	Ensure road markings and signs are installed to machine-readable standards (e.g. contrast, reflectivity, durability).	• FHWA (2021) • NASEM (2024a)
Lifecycle-aligned digital infrastructure	Design RSUs, cabinets, and sensor hardware with modular components and known service life to support predictable maintenance and upgrade cycles.	• NASEM (2024b) • CSA Group (2022)
Asset registry integration	Mandate that new AV-supportive infrastructure is registered into the AMS with digital IDs, location, condition triggers, and maintenance responsibilities.	• CSA Group (2022) • MetroPlan Orlando (2020)
Condition monitoring compatibility	Specify digital infrastructure to support fault reporting, self-diagnosis, or passive condition tracking where feasible (e.g. RSU heartbeats, alert logs).	• CSA Group (2022)
Cross-jurisdictional maintenance handover	Require infrastructure design packages to include clearly assigned maintenance roles for RSUs, signage, and CAV-related components across agency boundaries.	• MetroPlan Orlando (2020)
Design for field serviceability	Select components and placement (e.g. pole height, cabinet layout) to enable safe, rapid roadside servicing by agency crews or contractors.	• NASEM (2024b)
Feedback-driven maintenance triggers	Consider AV feedback data (e.g. loss of lane tracking, reports) as a supplemental trigger for line marking refreshment and maintenance priorities.	• CROW (2023)
Maintenance documentation handover	Ensure that as-built infrastructure data includes not only technical specs but also maintenance schedules, supplier information, and diagnostic procedures.	• NASEM (2024b)
Incorporate CAV feedback data into infrastructure safety audits	Include disengagement, fallback, or poor localisation events from CAVs as input into route assessments, especially where traditional crash or complaint data are lacking.	-

5.11.3 Related topics

Topics related to PT11 include those listed below in Table 5.51.

Table 5.51: Topics related to PT11

Related topic (code)	Related topic title	Reason for cross-reference
DT7	Ensuring digital resilience and failover mechanisms for CAV operations.	Resilient failover infrastructure requires maintenance for uptime.
DT1	Integration of CAV and EV operations into smart city and traffic management platforms.	CAV data integration supports predictive maintenance and asset lifecycle modelling.

5.11.4 Principles

Principles derived from the above evidence that relate to PT11 are shown in Table 5.52 below.

Table 5.52: Principles related to PT11

Principle	Description
Design for lifecycle	Digital and hybrid roadside assets should be specified, recorded, and maintained with defined lifecycle expectations and service intervals.
Enable predictive maintenance	Integrate sensor data, vehicle feedback, or automated diagnostics into condition monitoring to trigger maintenance before degradation affects AV operations.
Assign clear ownership	Explicitly define maintenance responsibility for new digital assets (e.g. RSUs) across public and private actors, and across jurisdictional boundaries.
Integrate with asset systems	CAV-supportive infrastructure should be integrated into existing asset management systems (AMS) with metadata, condition triggers, and lifecycle planning.
Design for maintainability	Roadside infrastructure should be designed for easy, safe servicing, with swappable modules, accessible placement, and clear service protocols.
Use CV/CAV feedback to prioritise maintenance	Sensor data from CV/CAV fleets (e.g. degraded line detectability) can be used to trigger earlier refresh cycles for markings, signs, and surfaces.
Upskill the workforce	Maintenance teams should be trained and equipped to support digital roadside infrastructure, including diagnostics and remote resets.

5.11.5 Future research areas

Whilst there is some coverage of the PT11 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 5.53Table 6.5 below.

Table 5.53: Potential research topic areas related to PT11

Research topic area	Research Opportunity
Durability of AV-critical markings and signs	Long-term field testing to determine how environmental conditions and materials affect machine readability over time.
Predictive maintenance models using CAV data	Development of algorithms that ingest AV sensor feedback (e.g. lateral stability, marking detectability) to inform maintenance prioritisation.
Lifecycle costing frameworks for digital roadside assets	Economic models that incorporate installation, serviceability, upgrades, and failure rates for RSUs, sensors, and V2I infrastructure.
Standardised asset data structures for digital assets	Templates and metadata frameworks to support inclusion of CAV-supportive infrastructure into existing asset management systems.
Skills and workforce transition pathways	Analysis of training needs, procurement roles, and certification requirements to manage emerging roadside technologies.
Multi-jurisdictional maintenance governance	Case studies or governance frameworks to define ownership and funding roles between state and local agencies for shared digital assets.
Impact of automation on routine maintenance scheduling	Modelling how consistent AV pathing patterns affect pavement deterioration timelines.

References for PT11

Austroads (2022) *Low and Zero Emission Vehicle Charging Infrastructure Installation*, AP-R676-22, Austroads, Sydney.

CSA Group (2022) *Physical and Digital Infrastructure for Connected and Automated Vehicles (CAV),* CSA Group website, accessed April 2025,.

CROW (2023) *Future-Proof Road Infrastructure – Towards a Future-Proof Road Design in the Netherland,* CROW, Ede.

FHWA (2021) *Impacts of Automated Vehicles on Highway Infrastructure*, Report No. FHWA-HRT-21-015, Federal Highway Administration, Washington, DC.

MetroPlan Orlando (2020) *Connected and Automated Vehicle (CAV) Readiness Study: Final Report*, MetroPlan Orlando, Florida.

NASEM (2024a) *Connected and Autonomous Vehicle Technology: Infrastructure Modifications to Improve the Operational Conditions of Automated Vehicles – Phase I Executive Summary*, National Academies of Sciences, Engineering, and Medicine, Washington, DC.

NASEM (2024b) *Connected and Autonomous Vehicle Technology: Determining the Impact on State DOT Maintenance Programs*, National Academies of Sciences, Engineering, and Medicine, Washington, DC, https://doi.org/10.17226/27625.

6. Digital Road and Infrastructure Design Topics

This section presents research findings related to the 13 digital road and infrastructure design topics identified.

Digital Road and Infrastructure topics relevant to this project were identified in section 4.2 and are discussed in the subsections below.

Most topics in this section focus on how digital systems, data quality and communication infrastructure influence the safe and effective operation of EVs and CAVs. However, some topics also consider how the data demands and behaviours of these vehicles introduce challenges for agency platforms and system management. Two topics, DT9 (CAV and EV fleet management and staging) and DT10 (CAV and EV integration into traffic and smart city platforms), present a mixed framing, where impacts are described for both vehicle operations and the performance of agency digital systems. In these cases, the challenge and impact tables reflect this dual perspective. They consider both how digital systems support CAVs and EVs, and how agencies can respond to increased operational and integration demands.

6.1 Ensuring CAV awareness of temporary and dynamic traffic conditions (DT1)

This topic covers how CAVs receive real-time information about temporary or changing traffic conditions, such as roadworks, lane closures, detours, and speed changes. It focuses on the digital delivery of this data from road agencies to vehicles.

CAVs rely on real-time updates to navigate safely and efficiently. However, temporary road conditions such as construction zones, emergency closures, traffic diversions, or event-based lane shifts require dynamic adaptation to ensure smooth traffic flow and road safety. A lack of real-time or consistent traffic data can result in confusion, unsafe manoeuvres, or failure to comply with traffic regulations.

A combination of C-ITS, AI-driven prediction models, and robust V2I communication plays a crucial role in providing timely and accurate updates for automated vehicles, particularly in addressing infrastructure inconsistency and enabling system-level traffic coordination (Alam and Georgakis 2022). Ensuring that CAVs receive and correctly interpret critical road data is key to enabling safe and predictable vehicle behaviour.

Queensland TMR (2020a, 2020b) specifications PSTS015 and PSTS016, along with findings from iMOVE (2023), demonstrate that CAVs rely on the completeness and timeliness of digital messages for safe navigation in dynamic environments like roadworks. Limitations in message content, timing, or context (e.g. absence of driveable path) can constrain AV performance, especially when onboard perception is insufficient.

Development of standards such as the IEEE 2846 standard (IEEE 2022), enable AVs to make conservative and safe decisions using mathematically reasonable assumptions about other road users' behaviours. IEEE 2846 defines a minimum set of assumptions for automated driving systems (ADS) to use in their motion planning logic. However, these assumptions apply to structured, predictable environments (e.g. road users follow rules, geometry is fixed, pedestrians cross at crossings). Currently, IEEE 2846 does not account for temporary or irregular road changes, such as short-term lane closures, temporary traffic control, or incidents. In these cases, external data updates or digital feeds will help support appropriate and safe CAV behaviour.

Austroads’ (2021) RADCAV report emphasises the need for standardised, high-quality digital traffic updates from road/transport agencies, as CAVs depend on real-time information from multiple sources, including road agencies and third-party navigation providers. The Austroads RADCAV outputs include a series of reports providing targeted business and technology reference architectures for provision of six data sets including roadworks, incidents, static speed limits, variable speed limit signs (VSLS) and lane control signals (LCS), traffic signals, and vehicle height and load restrictions. Data can be delivered using a range of V2I-based direct communication, and cloud-based updates will be required to support CAV operations across jurisdictions.

This approach is supported by NCHRP (2024) that identifies how infrastructure inconsistencies (e.g. ghost markings, non-standard work zone signage) challenge CAV perception. Real-time updates are crucial for maintaining operational safety within the ODD of automated systems.

In Europe, EU Delegated Regulation 2022/670 mandates that real-time road condition updates (e.g. hazards, roadworks, weather events) be made machine-readable and available via National Access Points (NAPs). All Member State NAPs provide data in agreed formats and to defined quality levels. This directly supports CAV interpretation of temporary traffic changes across regions. The Infrastructure Support Levels for Automated Driving (ISAD) framework (INFRAMIX 2019) further reinforces the need for digital event-based updates, with Level C and above road readiness requiring dynamic infrastructure feeds (e.g. temporary closures, speed changes).

One potential approach to harmonisation in the provision of road and traffic data by Australian and New Zealand government transport agencies is being investigated by Austroads (2025) via the Harmonised Access Point (HAP) concept. This approach is modelled on the EU NAP approach and encourages multiple transport agencies to provide high-value road and safety related traffic information to information service providers (ISPs) for OEMs in agreed formats and quality levels. This data focuses on the Australasian New Car Assessment Program (ANCAP) 2025 Speed Limit Information Function data, and includes curve speed warnings and road hazards. This approach is being piloted in the Queensland Harmonised Access Point Initiative (HAPI).

6.1.1 Key challenges

The core challenge involves ensuring that CAVs can detect or receive timely information about temporary and dynamic traffic conditions such as roadworks, incidents or special events. Unlike human drivers who can interpret signage, signals or informal cues, CAVs rely on digital inputs or standardised visual markers to adapt their behaviour. Gaps in data coverage, inconsistent signage or delays in updates may result in inappropriate or unsafe responses. Table 6.1 presents these key challenges, example scenarios and their impacts on vehicle operations.

Table 6.1: Key challenges that impact ensuring CAV awareness of temporary and dynamic traffic conditions

Key challenges	Example scenario	Impact on CAV operations	References
Lack of real-time updates for roadworks, lane closures, or special events	A CAV does not receive a temporary detour update and approaches a closed motorway exit.	The vehicle continues toward a blocked road, causing confusion, unsafe stops, or manual intervention.	• Austroads (2021)
Inconsistent static and dynamic data (e.g. location accuracy, latency, errors)	A vehicle crosses state borders and misinterprets speed limits or traffic signals.	The CAV misreads traffic rules, risking compliance failures.	• Austroads (2021) • Tengilimoglu et al. (2023)
Unexpected traffic conditions not captured digitally	A traffic signal is turned off and operated manually, but the CAV still expects standard phasing.	The AV assumes signal priority and proceeds unsafely through the intersection.	• Alam and Georgakis (2022)

Key challenges	Example scenario	Impact on CAV operations	References
Lack of harmonisation in data sharing between agencies and ISPs	A peak-hour bus lane is not recognised by the CAV due to data format mismatch.	The AV enters a restricted lane, breaching road rules.	• Austroads (2021)
Poor visibility of temporary or event-driven lane changes	AV misreads inactive pavement lights as lane indicators during an event.	The AV performs unnecessary lane shifts or hesitates dangerously.	• Austroads (2021)
Missing real-time integration of environmental factors into AV navigation systems	Speed limits change due to rain, but the update is not delivered to AV systems.	The AV continues at normal speed, increasing crash risk.	• Austroads (2021)
Lack of use of common digital standards (e.g. DATEX II, WZDx)	A roadwork zone with temporary signage is not machine-readable.	AV fails to reroute or reduce speed, risking unsafe operation.	• Tengilimoglu et al. (2023) • Austroads (2021)

6.1.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to ensure CAV awareness of temporary and dynamic traffic conditions are provided below in Table 6.2.

Table 6.2: Road and infrastructure design considerations related to DT1

Design element considerations	Description	Supporting references
Standardised real-time event delivery	Real-time road condition updates delivered via V2X channels including cellular, DSRC, and cloud feeds.	• Austroads (2021)
Capability and readiness	Agencies should use Austroads' phased model and reference architecture (Day 0.5 to Day 4) to benchmark readiness, identify gaps and guide improvements in data provision to CAVs.	• Austroads (2021)
Use of international standards (WZDx, DATEX II)	Common data formats (e.g. WZDx, DATEX II) used to support interoperability and consistency.	• Austroads (2021) • Tengilimoglu et al. (2023)
Publication via National Access Points (NAPs) or Harmonised Access Points (HAPs)	Digital event information published via structured nationally common or consistent platforms.	• Austroads (2025)
Agency data quality management	Data management frameworks incorporating metrics, validation, update frequency, and governance processes.	• Austroads (2021)
Low-latency communication infrastructure	Long-range and short-range communications infrastructure used to support timely delivery of safety-critical updates.	• Khan et al. (2019)
IoT-enabled smart signage	Digitally connected signage capable of dynamic updates based on traffic or environmental conditions.	• Alam and Georgakis (2022)
Predictive and interactive traffic management	Bidirectional frameworks enabling AV-generated data to inform event planning and predictive modelling.	• Austroads (2021) • ERTICO (2020)
Use of AV data for validation	AV operating data used to assess accuracy and performance of digital road messages.	• Austroads (2021)
Multi-source integration and data translation	Translation protocols and data exchange agreements used to support integration with third-party navigation services.	• Austroads (2021)
Metadata and digital sign synchronisation	Metadata precision and alignment with physical signs managed to ensure AV interpretability.	• Austroads (2021)

Related topics

Topics related to DT1 include those listed below in Table 6.3.

Table 6.3: Topics related to DT1

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Physical infrastructure should align with digital systems: roadside speed signs, lane closure signs and traffic control devices, should reflect real-time digital updates.
PT3	Ensuring compatible road and traffic design for AV navigation and operations	Road geometry affects and is affected by temporary detour implementation.
DT2	Ensuring data accuracy and validation for AV navigation	Digital representation of signage should align with physical placement for AV interpretation.
DT5	Ensuring CAV compliance with dynamic road regulations	Compliance with temporary rules depends on accurate and timely digital feeds.
DT13	Supporting CAV interpretation and compliance with traffic signal infrastructure	Integration of CAV digital maps with road agency operational control/traffic control systems for detour routing.

6.1.3 Principles

Principles derived from the above evidence that relate to DT1 are shown in Table 6.4 below.

Table 6.4: Principles related to DT1

Principle	Description
Plan beyond AV ‘normal behaviour’ assumptions	AVs operate using behavioural models (e.g. IEEE 2846) that assume typical, lawful road user behaviour in predictable environments. Infrastructure can be used support scenarios outside these assumptions (e.g. temporary traffic control changes, hazards) through digital data feeds.
Change it physically, update it digitally	Physical changes to the network (e.g. lane closures, speed zones, detours) should be reflected digitally to support CAV situational awareness and prevent reliance on outdated information.
Standardised, machine-readable digital updates	Digital road data should follow recognised standards (e.g. DATEX II, WZDx) to ensure machine readability and consistency across jurisdictions and platforms.
Data quality and metadata management	Digital messages should meet baseline standards for accuracy, latency, and completeness. Metadata (e.g. timing, location, regulatory context, lifecycle state) should support reliable CAV interpretation.
Digital–physical synchronisation	Signage, signals, and temporary control devices should be visually and digitally aligned to avoid conflicts or ambiguity in AV responses.
Technology-neutral data provision	Event-based road updates should support delivery across a range of communication channels (e.g. DSRC, 5G, APIs) to support redundancy and cross-platform access.
Agency-to-platform provision	Road agencies play a central role in distributing digital road condition data through structured interfaces with ISPs and navigation providers.
Real-time feedback loops	CAVs and connected platforms can support data quality improvement by reporting inconsistencies or fallbacks, enabling iterative data validation by agencies.

6.1.4 Future research areas

Whilst there is some coverage of the DT1 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.5 below.

Table 6.5: Potential research topic areas related to DT1

Research topic area	Description
Emergency override harmonisation	Determine how emergency-only overrides (e.g. police traffic control) should be recognised, prioritised, and interpreted by AV systems.
Real-time detection and digital map correction	Investigate mechanisms for AVs and third-party systems to detect discrepancies and support automated correction of digital maps in real time.
Data exchange standards	Develop structured protocols for exchanging road condition data between government platforms and commercial navigation providers.
AV behaviour in sudden road closures	Understand appropriate CAV response to unplanned events such as hard barriers or temporary manual detours.
Predictive models for temporary traffic disruptions	Improve agency ability to model, simulate, and pre-empt impacts of planned traffic disruptions or work zones on AV routing.
Dynamic speed limit interpretation	Refine how AVs process and act on dynamically changing speed zones (e.g. weather-triggered or time-of-day).
Investment models for digital infrastructure	Evaluate funding strategies and cost–benefit models for roadside digital infrastructure (e.g. RSUs, SPaT broadcasters).

References for DT1

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NCHRP (2024) *Infrastructure Modifications to Improve the Operational Conditions of Automated Vehicles: Phase 1 Executive Summary* (NCHRP Project 20-102[24]), Transportation Research Board, National Academies of Sciences, Engineering, and Medicine.

Queensland Department of Transport and Main Roads (2020a) *Ipswich Connected Vehicle Pilot – Project Specific Technical Specification PSTS015: Roadworks Warning Use Case*, Queensland Government, Brisbane, Qld.

Queensland Department of Transport and Main Roads (2020b) *Ipswich Connected Vehicle Pilot – Project Specific Technical Specification PSTS016: Road Hazard Warning Use Case*. Queensland Government, Brisbane, Qld.

Tengilimoglu O, Carsten O and Wadud Z (2023) Infrastructure requirements for safe CAV operations. *Transport Policy*, 134, 33–44.

6.2 Ensuring data accuracy and validation for AV navigation (DT2)

This topic focuses on agency-side governance, validation, and certification to ensure both static (e.g. lane geometry, regulations) and dynamic (e.g. roadworks feeds, speed limits) datasets are accurate, complete, and harmonised before and during distribution. Transport agencies are no longer solely stewards of physical infrastructure; they are becoming custodians of digital data environments. To support CAV readiness, agencies should also implement robust data publication, quality validation, and ongoing lifecycle governance processes.

CAVs depend on accurate, validated, and harmonised digital representations of the road environment to operate safely and in accordance with traffic laws. This includes geospatial references, regulatory overlays, road topology, and structured metadata made available by road authorities. If this information is incomplete, outdated, or inconsistently structured, CAV systems may misinterpret road conditions, leading to navigation errors, unsafe manoeuvres, or legal non-compliance. Examples include inappropriate lane selection, invalid turn behaviour, or misalignment between digital and physical speed limits.

Both static datasets (such as road geometry, speed zones, and permitted movements) and dynamic datasets (such as roadworks, temporary lane closures, and incident-based restrictions) play a critical role in AV decision-making. CAVs integrate these data sources with onboard perception to form a live model of their surroundings. Errors or ambiguities in the digital layer may prompt unnecessary system disengagements, conservative fallback behaviours, or degraded network performance, particularly in semi-structured or transitional environments.

The Infrastructure Support Levels for Automated Driving (ISAD) framework (INFRAMIX 2019) highlights that digital infrastructure readiness requires both availability and quality of base mapping and regulatory data. Meeting higher readiness levels demands harmonised, validated datasets that are machine-readable and semantically clear. Without this, the digital environment becomes a limiting factor in CAV deployment, particularly at intersections, school zones, and jurisdictional boundaries.

Recent studies underscore the operational risks posed by low-quality digital data. Misaligned lane geometry, outdated speed limits, and incomplete metadata (e.g. lifecycle status or regulatory authority) can disrupt AV localisation, planning, and behavioural decisions (Mihalj et al. 2022, Cucor et al. 2022). Without robust data validation and governance frameworks, even highly automated systems may misinterpret their environment or default to suboptimal behaviours. These findings are reinforced by broader EU quality efforts, such as the EU EIP Real-Time Traffic Information (RTTI) Guidelines (EU EIP 2019) and the C-ITS Quality Package (EU EIP 2022), which define baseline quality indicators and measurement practices for digital road data.

To address these risks, the EU Delegated Regulation 2022/670 requires that road condition and regulatory data be machine-readable and published via NAPs. These datasets are increasingly structured according to internationally recognised schemas such as DATEX II, which support machine-readability and semantic consistency across platforms.

These priorities are also reflected in the RADCAV framework (Austroads 2021), which sets out quality indicators such as timeliness, completeness, and metadata consistency, and identifies agency-side responsibilities for lifecycle governance and validation of road data used by automated vehicles. In particular, RADCAV defines reference architectures for the provision of six critical datasets delivered via vehicle-to-infrastructure (V2I) and cloud-based mechanisms: roadworks, incidents, static speed limits, VSLS and LCS, traffic signals, and vehicle height/load restrictions. This structured approach enables cross-jurisdictional interoperability and real-time information flows essential for CAV operation. It reinforces the need for machine-readable, semantically unambiguous datasets and is similar to other initiatives such as NAPCORE and the EU Delegated Regulation 2022/670.

NAPCORE (2025) further strengthens this by providing modular quality assessment methods across ITS domains. In the local context, the HAP concept from Austroads (2025) is one possible way road agencies can provide CAVs with access to access structured, certified datasets covering speed zones, regulatory signage, and roadwork events across jurisdictions.

These foundational frameworks are closely aligned with the principles set out by Thonhofer et al. (2023), who propose a digital twin-based model for infrastructure data quality to support automated driving systems. They argue that machines require data to be not only accurate and current, but also formally structured, semantically unambiguous, and universally interpretable. Their proposed model defines six core data quality principles: source agnosticism, receiver agnosticism, self-contained structure, semantic unambiguity, context independence, and universal applicability. These extend traditional data validation by addressing the interpretability and reliability of digital road information from the perspective of autonomous decision-making.

While EU ITS, C-ITS, and NAPCORE frameworks provide well-established data quality indicators (such as timeliness, accuracy, completeness, latency, and error rate), they primarily focus on service performance and update cycles. By contrast, Thonhofer et al. (2023) highlight that automated systems require data that is structurally and semantically robust, not just timely or accurate. Their critique of frameworks like ISAD underscores the need to move beyond availability metrics and toward enforceable quality standards embedded in the ODDs of CAVs. Together, these approaches offer complementary dimensions of data quality: one focused on measurable service performance, the other on machine-level interpretability and functional safety.

Additionally, there is a need to validate real-world conditions and performance using feedback from vehicles. This data can include location reporting errors, unexpected vehicle behaviours, or frequent automated control disengagements that indicate data problems. Establishing a safety data feedback loop that incorporates structured reporting from vehicle manufacturers or fleet operators could allow agencies to triage and correct digital errors more proactively. This approach mirrors proposals under international frameworks (e.g. UNECE WP.29).

6.2.1 Key challenges

The core challenge involves ensuring that CAVs receive accurate, validated and up-to-date digital road data to support lawful and effective operation. CAVs rely on structured information about road geometry, regulations and permitted movements, but inconsistencies in agency datasets, outdated base maps or missing metadata can lead to misalignment with physical infrastructure. These issues increase the risk of non-compliance, navigation errors or degraded system performance. Table 6.6 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.6: Key challenges that impact data accuracy and validation for AV navigation

Key challenges	Example scenario	Impact on CAV operations	References
Delayed update of road conditions	A new road closure is implemented but not reflected in digital maps for 48 hours.	The CAV attempts to enter a closed road, requiring sudden braking or rerouting.	• EU EIP (2019) • NAPCORE (2025)
Inconsistent data formats across jurisdictions	Agency A provides DATEX II feeds, Agency B provides unstructured shapefiles.	CAV systems cannot interpret cross-boundary data consistently, leading to degraded behaviour.	• NAPCORE (2025) • Thonhofer et al. (2023)
Conflict between physical signs and digital data	A speed limit sign displays 60 km/h, but the digital map shows 80 km/h.	The CAV may oscillate between speeds or fail to apply the correct regulatory rule.	• Mihalj et al. (2022) • EU EIP (2022)
Unverified third-party data inputs	A commercial navigation provider reports incorrect access restrictions.	AVs may plan illegal or unsafe routes based on unvalidated information.	• Cucor et al. (2022) • Thonhofer et al. (2023)
Incomplete or missing metadata	Speed limit is provided, but no validity time is defined (e.g. school zone hours).	CAV misinterprets the data and applies the speed incorrectly.	• Thonhofer et al. (2023) • Cucor et al. (2022)
No structured error reporting or correction tracking	Known mapping error is not logged, verified, or flagged as resolved.	CAVs repeatedly encounter the same issue, increasing risk and eroding trust.	• NAPCORE (2025) • EU EIP (2022) • Thonhofer et al. (2023)

6.2.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency related to DT2 are provided below in Table 6.7.

Table 6.7: Road and infrastructure design considerations related to DT2

Design consideration	Description	References
Structured data validation and metadata governance	Establish structured validation workflows for spatial and regulatory datasets. Include metadata such as source, timestamp, and verification status to support traceability and machine interpretation.	• CSA Group (2020) • Austroads (2021) • Thonhofer et al. (2023) • NAPCORE (2025)
Capability and Readiness	Agencies should use Austroads' phased model and reference architecture (Day 0.5 to Day 4) to benchmark readiness, identify gaps and guide improvements in data provision to CAVs.	• Austroads (2021)
Use of open data standards and interoperable formats	Adopt harmonised, machine-readable formats such as DATEX II or Traffic Management Data Dictionary (TMDD) to support cross-jurisdictional interoperability and reduce integration complexity for CAV systems.	• NAPCORE (2025) • EU EIP (2019) • Austroads (2021) • Thonhofer et al. (2023)
Alignment between physical and digital infrastructure	Ensure physical road elements (signs, lane markings, speed limits) are accurately reflected in digital datasets. Include update tracking and lifecycle status to prevent discrepancies.	• Mihalj et al. (2022) • EU EIP (2022) • Thonhofer et al. (2023)
Certification and accreditation of data providers	Define performance metrics (e.g. update frequency, accuracy) for internal and third-party data sources. Use these to assess suitability and maintain digital data trustworthiness.	• CSA Group (2020) • Austroads (2021) • NAPCORE (2025)
Infrastructure-supported CAV positioning resilience	Use surveyed digital infrastructure anchors (e.g. fixed reference points, lane anchors, signage locations, Bluetooth low energy (BLE) beacons) to support AV localisation in environments with limited Global Navigation Satellite System (GNSS) reliability, such as tunnels, urban canyons, or dense tree cover.	• CSA Group (2020) • Thonhofer et al. (2023)
Establish vehicle-sourced error reporting pathways	Enable CAV systems to report data mismatches (e.g. misaligned signage, out-of-date geometry) to agencies for correction and quality improvement.	• UNECE (2024) WP.29/2024/39

6.2.3 Related topics

Topics related to DT2 include those listed below in Table 6.8.

Table 6.8: Topics related to DT2

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Data should reflect signage and lane conditions for AV rule compliance.
DT1	Ensuring CAV Awareness of Temporary and Dynamic Traffic Conditions	Accurate data supports CAV response to temporary traffic conditions and traffic management arrangements.
DT5	Ensuring CAV compliance with dynamic road regulations	Validated data ensures AVs can interpret and act on dynamic road regulations.

6.2.4 Principles

Principles derived from the above evidence that relate to DT2 are shown in Table 6.9 below.

Table 6.9: Principles related to DT2

Principle	Description
Authoritative data ownership and validation	Agencies should validate both public and third-party infrastructure data before deployment.
Data provenance and metadata	All digital infrastructure updates should include metadata indicating their source, timestamp, and verification status.
Standards-based interoperability	Agencies should adopt international standards (e.g. DATEX II, TMDD) for encoding and sharing regulatory and spatial data to ensure machine readability and cross-jurisdictional consistency.
Alignment between physical and digital infrastructure	Signs, lane markings, and road geometry should be correctly georeferenced and synchronised with digital maps.
Feedback-driven data maintenance	Road authorities should incorporate error reports and observations from CAVs or probe vehicles into digital infrastructure databases.
Physical infrastructure to support safe AV fallback	Road agencies should ensure that physical signs, lane markings, and other regulatory features are clearly visible, consistently placed, and maintained to support safe AV fallback in degraded environments.
Data quality principles for machine interpretability	Infrastructure data should meet the six core quality principles defined by Thonhofer et al. (2023): source agnosticism, receiver agnosticism, self-contained structure, semantic unambiguity, context independence, and universal applicability. These principles go beyond traditional accuracy and timeliness metrics by focusing on machine interpretability, enabling safe and consistent AV decision-making across contexts and jurisdictions.
Performance-based data quality metrics	Agencies should measure and report digital infrastructure data using operational quality indicators such as timeliness, accuracy, completeness, latency, and error rate. These indicators are foundational to EU C-ITS and NAPCORE frameworks for evaluating and improving data trustworthiness.

6.2.5 Future research areas

Whilst there is some coverage of the DT2 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.10 below.

Table 6.10: Potential research topic areas related to DT2

Research topic area	Description
Automated change detection	Investigate use of satellite imagery, CAV fleets, and probe vehicle data to detect infrastructure changes in real time. Real-time updates improve reliability and awareness.
Confidence scoring of data	Develop frameworks to score data quality based on latency, accuracy, source credibility, and update frequency, helping AVs prioritise reliable information sources.
Digital twin trials	Conduct simulation-based testing of infrastructure changes in digital twins to assess AV behaviour before physical implementation.
Map certification frameworks	Develop national or regulatory accreditation systems to ensure maps and regulatory datasets meet accuracy, update, and coverage standards.
Cross-jurisdictional harmonisation	Pilot standardised regulatory feeds (e.g. speed zones) across jurisdictions to minimise fragmentation and enhance AV scalability.
Feedback loop effectiveness and reporting pathways	Develop structured processes for agencies to receive, validate, and act on map/data errors reported by CAVs or probe fleets.
Semantic interoperability testing	Assess whether digital rules (e.g. speed zones, turn restrictions) retain meaning when transferred across schemas or jurisdictions.

References for DT2

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6.3 Ensuring reliable CAV communications for continuous data exchange (DT3)

This topic addresses the communications infrastructure and digital systems required to support continuous, reliable, and secure data exchange between CAVs and road agencies. It focuses on infrastructure-side planning and design for V2X communications (e.g. RSUs, low-latency edge processing, backhaul networks, and protocol support) to enable time-critical message delivery.

While CAVs may be capable of safe operation using only onboard sensors and behavioural models (e.g. IEEE 2846), infrastructure-based vehicle-to-everything (V2X) communications can enhance situational awareness, support cooperative behaviours (e.g. merging, platoons), and improve traffic efficiency in complex, occluded or unpredictable environments. This communication ecosystem enables vehicle systems to receive and transmit messages related to signal phase and timing (SPaT), road conditions, hazard alerts, speed limits, and cooperative traffic behaviours.

IEEE 2846 (IEEE 2022), a standard developed by a coalition including Waymo, Mobileye and Honda, defines a set of reasonable behavioural assumptions that AVs may adopt when predicting the actions of other road users. These assumptions help inform motion planning under typical traffic conditions using only vehicle-side inputs. However, these models may be limited in their ability to interpret irregular or temporary scenarios (e.g. roadworks, incidents, detours, jaywalking). In these cases, V2X communications can still assist CAVs with increased awareness, and support cooperative vehicle behaviours (e.g. platooning, cooperative traffic management such as Traffic Management 2.0 (TM2.0) mentioned in DT10) that improve safety and traffic efficiency.

To support these functions, it is important that road and transport networks are underpinned by a robust and interoperable communications backbone across a range of road environments. This may involve a mix of solutions including RSUs, fibre-optic backhaul, and support for multi-protocol V2X communication (e.g. DSRC, C-V2X, 5G/6G), depending on context and available technologies. Without appropriate connectivity, CAVs may experience degraded performance in areas with limited communications, high communications congestion, or non-standard messaging environments.

As highlighted in the 5GAA (2021) white paper, current V2X technologies are not designed to fulfil safety-critical requirements under ISO 26262 (ISO 2018), which is the international standard for functional safety of electrical and electronic systems in road vehicles. They state that most C-ITS functions are intended to provide driver information or assistance, rather than directly controlling the vehicle. Therefore, these V2X functions are not considered part of the functional safety concept underpinning automated driving systems.

Extending current V2X applications to safety-critical scenarios like vehicle platooning will require substantial revisions to existing message formats to ensure reliability. It will also require additional radiofrequency spectrum, as current allocations are unlikely to be sufficient to support these types of use cases. In response to this evolution, Europe has partially reserved the 63.72–65.88 GHz band for ITS use (CAR 2 CAR Communication Consortium 2023). The USA and Australia have not allocated spectrum for these types of safety-critical road transport applications.

However, 5GAA notes that existing C-ITS implementations (such as Day 1 Emergency Brake Warning) may influence driver behaviour in time-critical situations and could warrant safety engineering consideration, depending on their use context. They also note that these implementations do not currently meet Automotive Safety Integrity Level (ASIL) requirements (a central concept in ISO 26262), and currently fall below ASIL A (the lowest integrity level). Similarly, Zimmermann et al. (2025) conclude that C-ITS is better suited to driver assistance than as a basis for safety-critical automated driving behaviour. This suggests that V2X should support, but not replace, vehicle safety systems.

This perspective is consistent with recent international regulatory work, including the UNECE (2025) *Automated Driving Systems Framework Document* (ADS/1807039) that provides complementary insights to the need for V2X. Paragraph 75 presents global accident-rate data for automated driving modes, showing lower at-fault crash rates compared to manual driving, but does not explicitly specify whether those results were achieved with or without V2X support. The subsequent discussion implies that these outcomes largely reflect systems operating on onboard perception and behavioural models, with V2X noted primarily as a means of improving efficiency through reduced headways and cooperative manoeuvres. This indicates that V2X is not currently essential for achieving ADS safety outcomes but can substantially enhance traffic flow and coordination when deployed in parallel.

In parallel, vehicle-side development is demonstrated by real-world deployments such as Waymo's rider-only AVs that operate without infrastructure-based V2X support. Kusano et al. (2025) reviewed more than 56 million kilometres (35 million miles) of rider-only travel by Waymo vehicles and found that crash rates are significantly lower than human-driven benchmarks. These findings align with the UNECE framework's observation that baseline ADS safety outcomes can be achieved primarily through onboard perception and behavioural models. Such evidence illustrates that infrastructure-based communications can benefit network coordination and support edge cases; however, they are not essential for core ADS motion planning in known operational domains.

Real-world projects such as the Ipswich Connected Vehicle Pilot (TMR 2022) have demonstrated the impacts of terrain, infrastructure placement, and network interference on V2X performance. Dropouts and latency variation (especially in tunnels, hilly terrain, and built-up environments) resulted in message loss and degraded CAV function. Similar challenges have been identified in rural contexts, where gaps in cellular coverage and sparse RSU placement prevent timely delivery of safety-critical information (Tavasoli et al. 2025). In urban settings, increasing volumes of data from AVs, infrastructure, and connected devices place pressure on available bandwidth, creating congestion and interference that can delay or degrade message transmission (Ahmed et al. 2023).

The Australian Government (The Department of Infrastructure, Transport, Regional Development, Communications, Sport and the Arts 2025) has proposed expanding the Universal Service framework to include a Universal Outdoor Mobile Obligation (UOMO), which would require mobile network operators to provide reasonable and equitable access to baseline (voice and SMS) outdoor mobile coverage across Australia. While this obligation is still under development, it may help strengthen baseline connectivity in regional and remote areas.

Fibre optic backhaul is a critical enabler of low-latency, high-reliability V2X connectivity, particularly for RSUs and signal systems located at high-volume or safety-critical intersections. The ITS America National V2X Deployment Plan recommends embedding fibre and high-speed wired backhaul into signalised intersections and along arterial corridors to ensure scalable, future-proof communications infrastructure (ITS America 2023). Additionally, reliable wireless connectivity between the vehicle and roadside infrastructure remains essential, as this 'last mile' link directly affects message delivery and system performance.

Emerging technologies such as 5G, edge computing, and intelligent message prioritisation improve system performance by reducing communication delays, increasing message reliability, and ensuring that safety-critical data is transmitted ahead of less urgent traffic (Ficzere et al. 2023, ITS America, 2023). These capabilities are critical for enabling fast response times and stable AV operation, particularly in high-demand environments such as intersections, merging zones, and dense traffic corridors (Ficzere et al. 2023, Tavasoli et al. 2025). They also help manage the growing volume of data exchanged between CAVs and infrastructure, alleviating bandwidth congestion and preserving communication integrity (Ahmed et al. 2023). As noted by Ficzere et al. (2023), achieving ultra-low latency is essential for executing movements such as cooperative merging, yielding, and collision avoidance.

Message interoperability is another key issue. Different jurisdictions have adopted varied V2X communication stacks, including DSRC (based on IEEE 802.11p) and C-V2X (based on LTE and 5G technologies). Without protocol translation mechanisms or dual-mode RSUs, CAVs may misinterpret or fail to receive messages when crossing borders, undermining national-scale deployment (Dettinger et al. 2024).

CAVs rely on accurate, authentic messages from infrastructure to make safe decisions and thus message security is important. Nayak and Barth (2025) emphasise the need for inbuilt integrity monitoring, authentication, and real-time validation, particularly for infrastructure-originated messages that affect lane selection, navigation, or route compliance. These principles are reinforced in the Principles for a National Approach to Co-operative Intelligent Transport Systems (C-ITS) in Australia (Infrastructure and Transport Ministers 2024), which highlights the need for trusted, timely, and standardised data exchange between public infrastructure and vehicles.

6.3.1 Key challenges

The core challenge involves delivering reliable, interoperable and secure V2X communications to support continuous data exchange across varied road environments. Agencies should manage protocol inconsistencies, communications congestion and coverage while ensuring cybersecurity and failover mechanisms are in place. Gaps in communication performance can reduce system trust, degrade safety, or force CAVs into fallback modes. Table 6.11 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.11: Key challenges that impact ensuring reliable CAV communications for continuous data exchange

Key challenges	Example scenario	Impact on CAV operations	References
Reliability in urban and rural environments	AV enters tunnel or rural corridor with low signal availability.	Signal loss leads to fallback operation or missed hazard alerts.	• Ahmed et al. (2023) • Tavasoli et al. (2025)
Protocol fragmentation and incompatibility	AV crosses from a C-V2X region into a DSRC-only zone.	Message mismatch or failure due to incompatible protocol stacks.	• Dettinger et al. (2024)
Message congestion and prioritisation	20+ vehicles interact near a signalised intersection.	Safety-critical messages delayed or dropped due to channel congestion.	• Ficzere et al. (2023)
Cybersecurity and data integrity threats	Malicious actor sends spoofed ‘lane closure’ message via RSU.	AV reroutes unnecessarily or enters fail-safe mode.	• Nayak and Barth (2025)
System failover and redundancy needs	Brief V2X outage during lane merge.	Without redundancy or fallback to on-board sensors, AV fails to merge safely.	• Ficzere et al. (2023) • Ahmed et al. (2023)
Backhaul and infrastructure bottlenecks	RSU located at intersection with limited fibre or congested cellular backhaul.	Safety-critical messages delayed due to slow uplink or packet loss in low-capacity areas.	• ITS America (2023)
RSU placement and site-specific design	RSUs omitted from tunnel exit or merge lane.	AVs receive outdated or no messages at high-risk locations, increasing safety risk.	• Ficzere et al. (2023) • ITS America (2023)
Jurisdictional consistency and integration	CAV crosses into a state or council region using different message formats.	Message interpretation errors or dropouts due to inconsistent deployment standards.	• Dettinger et al. (2024) • Infrastructure and Transport Ministers (2024)

6.3.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to ensure reliable CAV communications for continuous data exchange are provided below in Table 6.12.

Table 6.12: Road and infrastructure design considerations related to DT3

Design element considerations	Description	Supporting references
Fibre-optic and hybrid backhaul integration	Signalised intersections upgraded with fibre-optic links and RSUs for high-volume zones.	• ITS America (2021)
Dual-mode RSUs and protocol gateways	Deploy RSUs that can support multiple V2X protocols (e.g. DSRC and C-V2X), to ensure seamless communication with all equipped vehicles, regardless of jurisdiction or technology.	• Dettinger et al. (2024)
Strategic RSU siting at high-risk locations	RSUs deployed at merges, tunnels, intersections, and near public transport hubs.	• Ahmed et al. (2023) • Ficzere et al. (2023)
Edge computing at infrastructure nodes	Signal phase and safety data processed locally on RSUs to reduce latency.	• Ficzere et al. (2023)
Message prioritisation algorithms	Systems rank V2X messages by urgency (e.g. SPaT and hazard alerts before infotainment).	• Ficzere et al. (2023)
Standards-based messaging	Use of SAE and ISO message formats (e.g. SPaT, MAP) to ensure interoperability across platforms.	–
Encryption and authentication of RSU messages	RSUs sign outgoing messages using verifiable certificates to ensure trust.	• Nayak and Barth (2025)
Fail-safe defaults for communication shadow zones	RSUs trigger fallback signal phases or lane behaviours during signal loss.	• Tavasoli et al. (2025)
Integration with SCATS/STREAMS systems	RSUs synchronise with traffic signal control platforms to broadcast real-time SPaT.	–

6.3.3 Related topics

Topics related to DT3 include those listed below in Table 6.13.

Table 6.13: Topics related to DT3

Related topic (code)	Related topic title	Reason for cross-reference
DT4	Protecting CAV and transport data from cybersecurity threats	Reliable communications must be secure.
DT7	Ensuring digital resilience and failover mechanisms for CAV operations	Failover scenarios rely on communication continuity and fallback.

6.3.4 Principles

Principles derived from the above evidence that relate to DT3 are shown in Table 6.14 below.

Table 6.14: Principles related to DT3

Principle	Description
Plan for the limits of AV behavioural models	Although AVs may safely plan motion using behavioural assumptions (e.g. IEEE 2846), these models do not currently account for irregular or dynamic events. Communication between infrastructure and CAVs will assist with improved response in these contexts (e.g. traffic signal priority preemption, incident notifications, cooperative manoeuvres).
Continuous communications backbone	Ensure reliable, uninterrupted V2X coverage across priority corridors using fibre, RSUs, and cellular.
Redundancy through hybrid protocols	Support the use of multiple V2X communication types (e.g. DSRC, C-V2X, and 5G) to provide communications redundancy between vehicles and infrastructure. This helps maintain continuity in case of protocol failure or coverage gaps and supports interoperability across jurisdictions with different V2X standards.
Latency-critical local processing	Use edge computing and localised RSU processing to reduce decision delay for safety-critical functions.
Security-by-design	Embed encryption, message authentication, and validation at infrastructure level to ensure trust.
Interoperability across jurisdictions	Align RSU and messaging systems with ETSI, ISO, and SAE standards to support cross-border compatibility.
Deployment of communications networks by risk and utility	Prioritise deployment of communications networks based on CAV ODDs, traffic and hazard risks.
Data prioritisation and filtering	Implement V2X message filters that prioritise urgent safety information over low-priority data.
Fail-safe defaults in coverage shadow zones	Ensure infrastructure enables safe AV operation in known V2X outage areas via fallback signals or logic.

6.3.5 Future research areas

Whilst there is some coverage of the DT3 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.15 below.

Table 6.15: Potential research topic areas related to DT3

Research topic area	Description
Protocol conversion for DSRC/C-V2X environments	Develop translation gateways to allow interoperability across different V2X stacks.
Cyber resilience benchmarks for RSU infrastructure	Define measurable resilience indicators and acceptable failover times for V2X systems.
RSU deployment simulation tools	Create scenario tools that optimise RSU siting based on coverage gaps, investment levels, and AV need.
Standardised V2X performance metrics across platforms	Establish unified measures for message success rate, latency, and reliability across CAV systems.
Legacy traffic system integration	Develop interfaces between legacy traffic control systems (e.g. SCATS/STREAMS) and V2X broadcast logic.
Wireless reliability thresholds and failover planning	Define performance thresholds, latency tolerances, and communication failover protocols tailored to various conditions (e.g. urban congestion, regional coverage gaps, and tunnel signal loss).

References for DT3

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6.4 Protecting CAV and transport data from cybersecurity threats (DT4)

This topic covers protection of CAV-related data from cyber threats. It focuses on authentication, message integrity, and secure update systems. As CAVs become increasingly reliant on digital infrastructure and data exchange, the transport system's exposure to cybersecurity risks also increases. These systems interact across a broad range of communication surfaces, including vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and cloud-based traffic and mapping platforms. Road agencies and infrastructure managers must now account for cyber threats affecting RSUs, traffic signal control APIs, map update services, and data-sharing services that support CAVs.

Key threats include message spoofing (e.g. false hazard alerts or signal data), GPS jamming or manipulation, and breaches of cloud-connected systems that manage traffic logic, firmware updates, or route information. These can result in unsafe CAV decisions such as incorrect lane selection, unsafe manoeuvres, unnecessary rerouting, or system failures (Ficzere et al. 2023, Yadav and Alhabib 2024, NHTSA 2022). Without adequate protection, public infrastructure may become a target for message compromise, affecting safety-critical decisions made by CAVs.

Several international frameworks now call for secure, end-to-end data governance. The US National Highway Traffic Safety Administration (NHTSA 2022) and the European Commission's C-ITS Security Policy (JRC 2023) outline requirements for trusted vehicle–infrastructure communications, including message signing, encryption, credential management, and real-time anomaly detection. The Principles for a National Approach to Co-operative Intelligent Transport Systems (C-ITS) in Australia (2024) also emphasise the need for trusted, timely, and secure exchanges between CAVs, roadside infrastructure, and road agencies.

Transport agencies are increasingly expected to align with foundational information security frameworks such as ISO/IEC 27001 (Information Security Management Systems) and the NIST (2020) Cybersecurity Framework. These standards provide lifecycle controls for risk classification, asset protection, credential handling, over-the-air (OTA) update governance, audit logging, and incident response. Adoption of these standards helps long-term digital resilience and operations security.

Guidance from CSA Group (2023) further supports this approach, encouraging infrastructure operators and public agencies to embed security-by-design, implement certificate-based trust systems, and manage cyber risk holistically across roadside and digital platforms. While some responsibilities remain with OEMs and third-party suppliers, message integrity, access control, firmware verification, and public key infrastructure (PKI) governance increasingly fall within agency-managed infrastructure systems.

6.4.1 Key challenges

The core challenge involves securing all CAV-related data and communications against interference, unauthorised access and operational misuse. Agencies must protect V2X messages, roadside systems, cloud APIs and OTA platforms while managing risks such as spoofing, jamming and credential compromise. Failure to maintain data integrity and system trust can degrade safety, disrupt operations or expose infrastructure to attack. Table 6.16 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.16: Key challenges that impact protection of CAV and transport data from cybersecurity threats

Key challenges	Example scenario	Impact on CAV operations	References
Unsecured V2X message channels	Spoofed ‘accident ahead’ message causes a CAV to reroute unnecessarily.	Traffic inefficiency, increased vulnerability to coordinated or spoofed alerts.	• Ficzere et al. (2023) • Yadav and Alhabib (2024)
Delayed or absent firmware updates	Missed OTA update leaves known vulnerability unpatched.	Malicious command injection via known exploit path.	• Yadav and Alhabib (2024) • NHTSA (2022)
GPS spoofing or jamming	AV is lured off-route by a spoofing device near a tunnel.	Navigation error, unsafe routing and potential collision risk.	• Ficzere et al. (2023) • Tavasoli et al. (2025)
Insufficient authentication (Cloud/API)	Hacker gains access to traffic control APIs and sends false green-light messages.	Conflicting signal logic, elevated crash risk at intersections.	• NHTSA (2022) • Nayak and Barth (2025)
Sensor manipulation	LiDAR-reflective device simulates phantom obstacle.	CAV overreacts - abrupt stop or unsafe lane change.	• Yadav and Alhabib (2024)
Compromised RSU hardware	RSU is tampered with and distributes invalid SPaT messages.	AVs receive incorrect signal timing, operational instability across multiple vehicles.	• Ficzere et al. (2023) • Yadav and Alhabib (2024)
Insider or supply chain threats	Third-party service contractor installs malware or backdoor into RSU firmware.	Persistent remote access or message tampering capability introduced into system.	• NHTSA (2022)

6.4.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency related to protecting CAV and transport data from cybersecurity threats are provided below in Table 6.17.

Table 6.17: Road and infrastructure design considerations related to DT4

Design element considerations	Description	Supporting references
Secure V2X communication architecture	RSUs and infrastructure should use digitally signed and authenticated messages (e.g. SPaT, MAP) via IEEE 1609.2 (used primarily in North America) or ETSI ITS standards (used in Europe).	• Ficzere et al. (2023) • Yadav and Alhabib (2024)
Credential management and trust frameworks	Agencies should implement certificate-based systems (e.g. Security Credential Management System (SCMS)) to govern key issuance, revocation, and trust validation for all infrastructure communications.	• CSA (2023)
Physically secure roadside infrastructure	RSUs and field devices require physical protection (e.g. tamper-proof housings, access control, secure firmware) and system integrity verification.	• Ficzere et al. (2023) • CSA (2023)
OTA update governance	Infrastructure firmware and traffic system software should be maintained through secure OTA updates with rollback capability, version control, and logging.	• NHTSA (2022) • CSA (2023)
Sensor fusion resilience and fail-safe logic	AVs should respond safely to conflicting or missing data using sensor fusion, fallback systems, and conservative safety behaviours (e.g. stop, yield).	• Yadav and Alhabib (2024) • Tavasoli et al. (2025)
Cyber threat detection and monitoring	RSUs and cloud platforms should incorporate real-time intrusion detection, anomaly logging, and machine-learning-based spoofing detection.	• Ficzere et al. (2023)
Cross-sector cybersecurity collaboration	Road agencies, OEMs, telcos, and cybersecurity authorities should coordinate on shared threat intelligence, incident response, and joint testing protocols.	• NHTSA (2022) • CSA (2023)

6.4.3 Related topics

Topics related to DT4 include those listed below in Table 6.18.

Table 6.18: Topics related to DT4

Related topic (code)	Related topic title	Reason for cross-reference
DT3	Ensuring reliable CAV communications for continuous data exchange	Depends on continuous, authenticated V2X message exchange infrastructure.
DT7	Ensuring digital resilience and failover mechanisms for CAV operations	Security compromises may trigger fallback and degraded mode operations.

6.4.4 Principles

Principles derived from the above evidence that relate to DT4 are shown in Table 6.19 below.

Table 6.19: Principles related to DT4

Principle	Description
Security-by-design	Cybersecurity should be embedded from the outset across roadside and digital systems, including RSUs, APIs, and OTA services.
Authenticated communications	All V2X messages should be digitally signed and verified using standardised protocols.
Lifecycle credential management	Agencies should govern certificate issuance, revocation, and validation to maintain trust and mitigate unauthorised access.
Tamper-proof infrastructure	Physical security and integrity checks for roadside infrastructure (e.g. RSUs) are essential to prevent localised system compromise.
Secure update governance	OTA software and firmware updates should be governed by secure, auditable processes with rollback and version control.
Anomaly and intrusion detection	Systems should include real-time monitoring for spoofing, jamming, and unauthorised access to enable rapid response.
Cross-agency collaboration	Agencies should coordinate with other agencies, OEMs, telcos, and national security bodies for shared threat intelligence and incident response.

6.4.5 Future research areas

Whilst there is some coverage of the DT4 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.20 below.

Table 6.20: Potential research topic areas related to DT4

Research topic area	Description
RSU compromise simulations	Simulate cyber-physical impacts of rogue or compromised roadside infrastructure on CAV behaviour.
AI for threat detection	Explore AI/ML anomaly detection systems for real-time message spoofing and intrusion signals in V2X networks.
Cyber-physical integration testing	Study failure propagation between cyberattacks (e.g. GPS jamming) and physical vehicle outcomes (e.g. unsafe lane change).
Security update governance models	Evaluate governance structures, policy frameworks, and industry best practices for consistent OTA security patches.
Trust frameworks for decentralised infrastructure	Design scalable certificate revocation systems and zero-trust architectures across multi-agency networks.

References for DT4

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6.5 Ensuring CAV compliance with dynamic road regulations (DT5)

This topic addresses how CAVs comply with dynamic and time-based road regulations, focusing on regulation encoding, machine-readable rule delivery, and compliance logic.

CAVs must operate within complex and evolving regulatory environments. Unlike human drivers, who rely on visual cues and situational judgment, CAVs require digitally encoded, machine-readable rules to interpret time- and location-based changes such as temporary speed zones, reversible lanes, and event-driven access restrictions. These rules should be communicated in real time, using interoperable and standardised data formats, to support lawful and safe vehicle behaviour.

The lack of synchronised, structured regulation data has been identified as a critical barrier to the safe operation of CAVs. Studies such as NCHRP (2024) and CROW (2023) highlight the operational risks that arise when temporary or dynamic regulations are not accurately encoded in digital formats. For example, discrepancies between digital maps, physical signage, and V2X messages can lead to non-compliance, unsafe manoeuvres, or unnecessary system disengagement. INFRAMIX (2019) reinforces this need by defining digitally cooperative road environments as a foundational requirement for managing dynamic conditions through real-time regulatory overlays.

In the EU, regulatory frameworks and infrastructure initiatives have emerged to address this digital gap. EU Delegated Regulation 2022/670 (EC 2022) requires that traffic rules (e.g. dynamic speed limits, temporary access restrictions, lane reassignments) be published via National Access Points (NAPs) in machine-readable formats. The NAPCORE (n.d.) initiative further supports this by promoting standardisation and cross-border harmonisation of regulatory data, creating a common framework for rule handover, versioning, and data governance.

Parallel to this, the ISO 24315 Management of Electronic Traffic Regulations (METR) standard, under development by ISO Technical Committee 204 (ISO TC204 2024), proposes a global framework for encoding traffic rules in structured digital formats. METR defines lifecycle states (e.g. active, revoked), geospatial parameters, and governance roles for rule publication. It aims to ensure consistency and trustworthiness across jurisdictions, while allowing local flexibility for rule interpretation and emergency response. However, as noted by OECD/ITF (2023), the challenge remains in balancing interoperability with the need for regulatory adaptability at local and regional levels.

Research by Shi and Wang (2025) further illustrates that many traffic rules globally remain human-oriented and semantically ambiguous, particularly at intersections where complex manoeuvres like turning, yielding, or stopping lack consistent digital definitions. Their cross-country analysis confirmed that without regulatory digitisation, AVs face persistent uncertainty in interpreting legal intent, especially under jurisdictional fragmentation.

6.5.1 Key challenges

The core challenge involves enabling CAVs to comply with dynamic road regulations that vary by time, location, or conditions such as traffic, weather or emergencies. Examples include temporary speed limits, reversible lanes and freight-only zones. Without timely, synchronised and machine-readable updates, CAVs may behave illegally or unsafely, reducing public trust and increasing operational risk. Table 6.21 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.21: Key challenges that impact CAV compliance with dynamic road regulations

Key challenges	Example scenario	Impact on CAV operations	References
Delayed digital updates to speed limits or access zones	A school zone reduces the speed limit to 40 km/h from 8–9 AM, but the digital feed is not updated in time.	The vehicle continues at 50 km/h, violating applicable law and increasing pedestrian risk.	• NCHRP (2024)
Lack of integration between physical signs and digital data	A reversible bus lane opens to general traffic during off-peak hours, but the system still marks it as restricted.	The vehicle avoids the lane unnecessarily, contributing to congestion and suboptimal routing.	• iMOVE (2023)
Jurisdictional inconsistency in regulation encoding	One region provides rules in DATEX II, while another relies on PDF-based sign documents.	The vehicle fails to interpret regional rules correctly, leading to inconsistent or unsafe behaviours.	• CROW (2023)
Absence of geofencing for regulation context	A temporary turn restriction is issued near a stadium during an event, but lacks spatial metadata.	The vehicle cannot determine where the rule applies and either overreacts or disregards it.	• INFRAMIX (2019)
Conflicting updates from map providers vs agency feeds	A road agency reports a temporary closure, but the AV's high-definition map does not yet reflect it.	The vehicle attempts a restricted manoeuvre, increasing the risk of non-compliance or emergency stops.	• NCHRP (2024)
Lack of enforcement signal integration	A temporary speed camera is installed, but enforcement parameters are not broadcast digitally.	The vehicle does not slow down, risking legal violations and weakening the deterrent effect of automated enforcement.	• CSA Group (2024) • iMOVE (2023)

6.5.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to ensure CAV compliance with dynamic road regulations are provided below in Table 6.22.

Table 6.22: Road and infrastructure design considerations related to DT5

Design element considerations	Description	Supporting references
Real-time digital regulation feeds	Road agencies should publish machine-readable updates for access rules, speed limits, and restrictions using standardised formats (e.g. DATEXII) with metadata (e.g. geolocation, time validity).	• Rana and Hossain (2023) • EC (2022)
Interoperable regulation encoding (METR)	The ISO 24315 METR standard defines how traffic regulations can be digitally encoded, governed, and interpreted by AV systems, including rule lifecycle states (e.g. active, revoked).	• ISO TC204 (2024b)
Integration with V2X and enforcement systems	Digital regulation feeds should be broadcast via DSRC or C-V2X protocols and integrated with roadside units and enforcement infrastructure (e.g. cameras, speed displays).	• CSA Group (2024) • iMOVE (2023)
Machine interpretability and validation logic	Regulation messages should include enforcement tolerances, fallback rules, and signage references. AVs must be able to validate digital inputs using sensor fusion.	• Reed et al. (2021) • INFRAMIX (2019)
Geospatial and temporal granularity	Regulations should contain clear location boundaries and time-based applicability (e.g. school zones, weekday turn bans, event-based detours).	• INFRAMIX (2019) • NCHRP (2024)
National Access Point (NAP) publication and harmonisation	In the EU, traffic regulations must be published via NAPs. The NAPCORE initiative supports harmonisation of formats and geotagging across borders.	• EC (2022) • NAPCORE (n.d.)

6.5.3 Related topics

Topics related to DT5 include those listed below in Table 6.23.

Table 6.23: Topics related to DT5

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Signage interpretation impacts rule adherence.
DT12	Standardising digital road regulations for CAV and EV charging zones	Digital regulation encoding should extend to EV zones and kerbside.

6.5.4 Principles

Principles derived from the above evidence that relate to DT5 are shown in Table 6.24 below.

Table 6.24: Principles related to DT5

Principle	Description
Machine readability	All relevant regulatory information (such as time-dependent speed limits, access restrictions, detours, and geofences) should be encoded in machine-readable formats that are geospatially and temporally precise.
Redundancy with clarity	Physical and digital representations of traffic regulations should co-exist with clearly defined prioritisation logic to avoid ambiguity in CAV interpretation.
Uniformity and simplicity	Road rules and digital regulation formats should be as uniform and semantically clear as possible to reduce compliance complexity across jurisdictions.
Real-time update capability	Road regulations, particularly temporary or event-driven rules, should be capable of being issued, revoked, or revised in real time, with dependable distribution mechanisms.
Provenance, lifecycle and trust	Regulatory data should include detailed metadata (such as origin, version, timestamp, confidence level, and lifecycle status (e.g. proposed, active, revoked)) to ensure decision traceability, legal auditability, and AV trust in rule validity.
Jurisdictional compatibility	Data formats and rule encoding should support local flexibility while enabling cross-border and cross-agency harmonisation.

6.5.5 Future research areas

Whilst there is some coverage of the DT5 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.25 below.

Table 6.25: Potential research topic areas related to DT5

Research topic area	Description
Trust scoring of regulation feeds	Develop frameworks to assess the reliability of regulatory data feeds using indicators such as source credibility, update frequency, latency, and validation history.
Metadata standards for regulation provenance	Advance metadata standards for digital rules to include consistent timestamps, geo-tagging, issuer information, and version control.
Conflict resolution between physical and digital rules	Define and test fallback strategies for AVs when physical signage and digital regulation feeds diverge.
Dynamic regulation handover governance	Investigate models for real-time handover of rule authority between transport agencies, map providers, and traffic management centres, ensuring auditability and control.
Physical–digital alignment audits	Develop tools and processes to audit the alignment of physical infrastructure (e.g. signs, lane markings) with their digital counterparts (e.g. WZDx, DATEX II feeds).
Machine interpretability of legacy rules	Examine how AVs can process ambiguous, qualitative, or non-standard traffic rules (e.g. ‘yield when safe’) in diverse jurisdictions and contexts.

References for DT5

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6.6 Supporting multimodal and CAV integration (DT6)

This topic addresses the digital coordination of highly-automated CAVs with other transport modes, including public transport, micromobility, and shared mobility services. It focuses on enabling multimodal journey planning, real-time data exchange, and dynamic kerbside access management.

Cities are looking to integrate highly- automated CAVs into multimodal transport networks as part of broader efforts to deliver more sustainable and efficient urban mobility. While CAVs offer flexibility and responsiveness, their potential can only be realised when they operate in coordination with established transport modes, including public transport (e.g. buses, trains, light rail), shared mobility services (e.g. ride-share, demand-responsive public transport), and micromobility options (e.g. e-scooters, bike-share).

Without alignment, highly-automated CAVs risk creating inefficiencies at key transfer points, exacerbating kerbside congestion, and disrupting network equity goals. Integration challenges range from poor data exchange between systems to incompatible kerbside allocation policies.

International frameworks reflect this focus. The EU ITS Directive promotes standardised data sharing, such as real-time public transport and traffic information, to support routing and coordination between AVs, public transport services, and mobility platforms (European Commission 2022). The National Association of City Transportation Officials’ Blueprint for Autonomous Urbanism (NACTO 2021) advises transport agencies to redesign physical infrastructure by introducing AV drop-off zones, reallocating kerb space, and prioritising high-capacity and low-emission modes such as public transport and micromobility. Complementing this, NACTO’s Principles for Autonomous Vehicles on City Streets advocate for city-led regulation of AV operations, control over kerbside access, and open standards for mobility data sharing (NACTO 2024).

Australian and New Zealand agencies are also recognising these imperatives, with Austroads (2024) providing guidance for local governments on integrating CAVs into land use and mobility plans, including digital kerb coordination and shared mobility integration.

In the US, NASEM (2024) provides guidance on updating travel demand models to incorporate AVs, shared mobility, and micromobility. The International Transport Forum (ITF 2023) reinforces this approach, noting that AVs will increasingly operate within environments shared with public transport, micromobility, freight, and pedestrians. It recommends that transport agencies adopt integrated physical and digital strategies to prevent conflict at transfer points and enable reliable multimodal coordination. Without such integration, the report warns, AV deployment may exacerbate existing urban challenges rather than alleviate them.

Researchers further highlight the risks of poor integration. Appleyard and Riggs (2023) show that without coordinated planning, CAV operations may conflict with public transport, pedestrian flows, and micromobility, leading to street-level inefficiencies and declining multimodal accessibility. Guo and Zhao (2024) demonstrate that uncoordinated CAV–public transport systems can increase passenger disutility, kerbside demand, and operational inefficiencies.

As kerb space becomes increasingly contested between AVs, freight, public transport, and micromobility, agencies are beginning to adopt dynamic kerbside management strategies. Pilot programs, digital kerb inventories, and time-based access systems are already being tested to balance access, safety, and operational efficiency (Appleyard and Riggs 2023, NACTO 2021, NASEM 2022).

In parallel, transport agencies are being encouraged to adapt their planning and forecasting tools to support this new multimodal situation. These tools enable road agencies to better anticipate kerbside demand, modal interactions, and infrastructure requirements, strengthening the foundations for coordinated digital and physical planning in CAV-ready networks (NASEM 2024).

6.6.1 Key challenges

The core challenge involves integrating highly-automated CAVs into multimodal transport systems where they must operate alongside public transport, micromobility, and freight services. Gaps in real-time data exchange, standardised protocols, and kerbside coordination limit CAV effectiveness in shared environments. These issues contribute to service inefficiencies, competition for space and reduced accessibility, especially in high-demand urban areas. Table 6.26 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.26: Key challenges that impact multimodal and CAV integration

Key challenges	Example scenario	Impact on CAV operations	References
Lack of real-time public transport coordination	A CAV taxi arrives after the last train has departed due to no access to public transport schedule data.	Passengers miss connections, undermines first/last mile viability.	• Guo and Zhao (2024) • Appleyard and Riggs (2023)
Uncoordinated kerbside demand	An AV, bus, and e-scooters all attempt to use the same kerb space near a station.	Creates congestion and unsafe conditions.	• NACTO (2021)
Fragmented shared mobility services	Ride-share AVs are routed through protected bike-share zones.	Disrupts micromobility safety and priority networks.	• Appleyard and Riggs (2023) • NACTO (2024)
No common API or data standard	CAVs and buses cannot exchange live occupancy or Estimated Time of Arrival (ETA) data.	Results in inefficient routing and missed opportunities.	• EC (2022)
Static kerbside allocation rules	AVs are forced to stop mid-road due to fixed access time rules.	Reduces safety and increases obstruction.	• NCHRP (2022)

6.6.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to support multimodal and CAV integration are provided below in Table 6.27.

Table 6.27: Road and infrastructure design considerations related to DT6

Design element considerations	Description	Supporting references
Smart multimodal hubs	Integrated stations with CAV drop-off bays, micromobility docks, real-time public transport info, and dynamic signage.	• Appleyard and Riggs (2023) • NACTO (2021)
Standardised AV– public transport APIs	Shared data platforms that enable CAVs to access real-time public transport schedules, ETAs, and occupancy.	• EC (2022)
Time-geofenced kerb access	Use of geofencing and time-based rules to manage AV access to kerb areas shared with public transport or micromobility.	• NACTO (2024) • NASEM (2022)
CAV priority near stations	Smart signals or intersection control that prioritise AVs during passenger pick-up and transfer periods.	• Appleyard and Riggs (2023)
Digital signage with modal updates	Real-time digital or V2X-enabled signage to inform CAVs and passengers about real-time public transport arrival, service changes, and local demand.	• NACTO (2021)
Dynamic kerbside allocation platforms	Systems that allocate kerb space dynamically based on live demand, user type, and modal priority.	• NASEM (2022) • ITF (2023)
Local government-driven AV integration	Local councils coordinate kerb planning, CAV infrastructure retrofits, and policy alignment with land use and mobility plans.	• Austroads (2024)

6.6.3 Related topics

Topics related to DT6 include those listed below in Table 6.28.

Table 6.28: Topics related to DT6

Related topic (code)	Related topic title	Reason for cross-reference
PT8	Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs	Physical kerbside design supports AV/public transport coordination.
DT9	Optimising CAV and EV fleet management and staging	Staging, loading, and kerb allocation require real-time digital systems.

6.6.4 Principles

Principles derived from the above evidence that relate to DT6 are shown in Table 6.29 below.

Note**:** While some DT6 principles are mode-integration oriented, they are included due to the enabling role of road agencies in supporting multimodal coordination. This includes through physical design, signal operations, and infrastructure-enabled data exchange.

Table 6.29: Principles related to DT6

Principle	Description
Modal-aware routing	CAV routing systems should incorporate real-time data from public transport and shared mobility services to optimise user journey coordination and minimise missed transfers.
Standardised data exchange interfaces	Use open and interoperable standards (e.g. GTFS-RT, APIs) to enable seamless digital integration between AVs, public transport, and mobility platforms.
Dynamic kerb access management	Implement demand-based and time-specific kerbside access controls that prioritise shared, efficient, and low-emission modes.
Public transport–CAV coordination	Align AV routing and scheduling logic with public transport operations to reduce service duplication and enhance first/last mile access.
Equitable kerb access management	Prioritise high-capacity and sustainable modes (e.g. public transport, walking, micromobility) over private AVs in kerb design and access policies, and empower local governments to manage conflicts.

6.6.5 Future research areas

Whilst there is some coverage of the DT6 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.30 below.

Table 6.30: Potential research topic areas related to DT6

Research topic area	Description
CAV–public transport synchronisation algorithms	Development of predictive AV routing tools that align pick-up and drop-off timing with real-time public transport operations.
CAV–micromobility interoperability standards	Design and operational standards for safe, predictable interaction between AVs, micromobility users, and kerbside environments.
Multimodal hub simulation frameworks	Tools to model and optimise the physical and digital design of interchanges serving CAVs, public transport, and shared mobility.
End-to-end journey coordination for AV passengers	Methods for coordinating full end-to-end trips across CAVs, micromobility, and public transport, accounting for user preferences and delays.
Dynamic multimodal forecasting	Real-time prediction models for kerbside demand, AV dispatching, and intermodal traffic coordination.

References for DT6

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6.7 Ensuring digital resilience and failover mechanisms for CAV operations (DT7)

This topic addresses digital resilience and failover mechanisms required to support CAV operations during infrastructure-related disruptions. It focuses on the role of transport and road agencies in ensuring continuity through redundant communications, localised edge processing, and digital–physical fallback strategies. The topic covers scenarios such as RSU outages, signal loss, and degraded V2X messages.

CAVs are likely to rely on digital infrastructure, including Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), and cloud-based platforms, to support driving functions such as perception, routing, compliance, and coordination. However, these systems are prone to degradation or failure caused by sensor or RSU malfunction, temporary coverage loss, or disruptions to cloud-based services.

Research shows that operational continuity can still be maintained under degraded conditions, provided appropriate failover mechanisms are in place. Murali et al. (2025) demonstrate that even in scenarios with 30% communication failure and 20% lane closures, connected AVs will outperform conventional traffic systems. This highlights the importance of redundancy and degraded-mode safety across systems. Sukhu et al. (2023) similarly show that V2X systems heavily dependent on infrastructure can suffer performance drops when network connectivity fails, supporting the need for infrastructure-led failover capabilities and local fallback behaviour.

Industry guidance calls for resilience-by-design approaches to digital infrastructure. The CSA Group (2024) recommends building in fallback protocols, redundant communication channels, and physical-digital integration to ensure system continuity during disruptions. These principles are similar in transport agency guidance. NASEM (2024) highlights that infrastructure failures such as RSU breakdowns or firmware issues require rapid response. They emphasised the importance of systems engineering, localised edge processing, and having multiple maintenance pathways (e.g. remote monitoring, spare parts, and trained response teams) to ensure continuity during digital infrastructure failures.

Australian and New Zealand transport agencies already apply similar resilience strategies in the management of ITS. TMCs have adopted contingency plans that include manual signal overrides, backup communication layers, and disaster recovery processes (Austroads 2025). While these procedures were not designed specifically for CAVs, they highlight the foundational importance of resilience, redundancy, and fallback planning as digital systems expand into vehicle coordination and automation.

6.7.1 Key challenges

The core challenge involves ensuring that AVs can continue safe and lawful operation when digital infrastructure is disrupted. Loss of connectivity, corrupted V2X signals, or failures in RSU or signal coordination systems can impair navigation, intersection handling or routing. Overreliance on digital-only systems without physical redundancy increases the risk of degraded or unsafe AV behaviour. Table 6.31 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.31: Key challenges that impact digital resilience and failover mechanisms for CAV operations

Key challenges	Example scenario	Impact on CAV operations	Reference
Network connectivity outage	A 5G network node serving a highway segment goes offline.	AVs revert to conservative fallback logic, causing erratic or overly cautious driving.	Sukhu et al. (2023)
RSU equipment failure	Roadside unit fails at a major signalised intersection.	No digital signal or MAP/SPaT broadcast; AVs misjudge intersection timing.	NASEM (2024)
Cloud service disruption	AV navigation provider experiences a server outage.	AVs lose routing updates or traffic intelligence; reroute inefficiently.	Murali et al. (2025)
No localised failover capability	An AV receives corrupted data but cannot detect or override it.	Vehicle accepts invalid V2X input, leading to poor manoeuvring or unsafe decisions.	CSA Group (2024)
Lack of physical redundancy for digital messages	A dynamic VSL or digital construction warning fails without backup signs or cones.	AV misinterprets speed limit or situation; may hesitate, reroute, or stop abruptly.	CSA Group (2024)

6.7.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to ensure digital resilience and failover mechanisms for CAV operations are provided below in Table 6.32.

Table 6.32: Road and infrastructure design considerations related to DT7

Design element considerations	Description	Supporting references
Redundant communication layers	Maintain multiple V2I communication channels (e.g. DSRC, 4G/5G, Wi-Fi) to ensure fallback when primary networks fail.	CSA Group (2024)
Localised edge processing	Deploy edge computing at RSUs to maintain core AV support (e.g. signal interpretation, routing) during cloud disruptions.	NASEM (2024)
V2X failover protocols	Configure infrastructure to detect invalid or corrupted V2X messages and trigger default rule-based responses or fallback scenarios.	-
Physical–digital redundancy	Retain physical infrastructure (e.g. signage, road markings) to support AV perception during digital message loss or degradation.	-
Resilience testing of RSUs	Apply failure mode analysis and simulation testing to assess RSU reliability and support recovery planning.	CSA Group (2024)

6.7.3 Related topics

Topics related to DT7 include those listed below in Table 6.33.

Table 6.33: Topics related to DT7

Related topic (code)	Related topic title	Reason for cross-reference
PT3	Ensuring compatible road and traffic design for AV navigation and operations	Physical infrastructure should support AV operation in degraded mode.
PT11	Maintenance and asset management for CAV and EV infrastructure	Degraded infrastructure triggers reliance on backup maintenance systems.
DT3	Ensuring reliable CAV communications for continuous data exchange	Fallback behaviour is activated by communication loss or signal dropout.
DT4	Protecting CAV and transport data from cybersecurity threats	Platforms must be protected from data cyber threats.

6.7.4 Principles

Principles derived from the above evidence that relate to DT7 are shown in Table 6.34 below.

Table 6.34: Principles related to DT7

Principle	Description
Digital–physical redundancy	Critical messages (speed limits, merges, closures) delivered through both physical and digital means to ensure continuity.
Resilient-by-design infrastructure	RSUs, signage, and networks must be designed to tolerate and recover from component failures.
AV decision continuity	AVs must safely operate with onboard logic when disconnected from digital infrastructure.
Failover validation	Regular testing of RSU and fallback behaviours under disruption scenarios.

6.7.5 Future research areas

Whilst there is some coverage of the DT7 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.35 below.

Table 6.35: Potential research topic areas related to DT7

Research topic area	Description
Cross-network failover simulations	Modelling AV behaviour across communications transitions between DSRC, C-V2X, 4G/5G cellular networks.
RSU failure mode testing frameworks	Develop agency-led frameworks to validate RSU and signal infrastructure under degraded and failure scenarios.
Edge AI for decentralised control	Explore use of roadside computing to support AV decision-making during cloud outages or communication loss.

References for DT7

Austroads (2025) *Transport Management Centre Responses to Intrusive System Change Outages*, AP-R741-25, Austroads, Sydney, NSW.

CSA Group (2024) *EXP150.1:23 – Guidelines for connected and automated vehicles: Digital infrastructure*. CSA Group, Toronto, Canada.

Murali P S, Mohebbi S and Zaman M (2025) ‘Resilience of connected and autonomous vehicles to cyber–physical disruptions’, *SIMULATION*, https://doi.org/10.1177/00375497241308575.

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Sukhu J B, Yang H, Abdulsattar H and Razavi S (2023) Assessment of the Impact of Network Infrastructure Failure on Infrastructure-supported vs. Infrastructure-Less V2X Systems, *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, 2030–2037. https://doi.org/10.1109/ITSC57777.2023.10422560.

6.8 Improving CAV interaction with emergency vehicles and vulnerable road users (DT8)

This topic outlines how digital infrastructure enhances safe and predictable interactions between CAVs and emergency vehicles, along with vulnerable road users (VRUs), including pedestrians and cyclists. It focuses on digital alert systems, behavioural interpretation aids, and situational awareness technologies that operate independently of traditional traffic signal systems.

CAVs must respond appropriately to emergency vehicles and VRUs to operate safely in mixed traffic environments. Key behaviours include yielding, recognising external cues such as lights and sirens, and navigating situations without formal rules or communication. These tasks rely on a vehicle’s sensor data and programmed decision logic, which may be insufficient in environments where cues are informal, obstructed, or ambiguous.

Digital infrastructure plays a critical role in supporting CAV performance under these conditions. By delivering timely, standardised alerts and enhancing perception in complex settings, road agencies can improve CAV situational awareness and support consistent, compliant behaviour when interacting with emergency services and vulnerable users.

The NACTO Blueprint outlines an expectation that AVs should be able to navigate urban environments safely and yield to VRUs without relying on external devices or infrastructure-based signalling (NACTO 2021). While this sets an important policy goal, AV systems still face challenges in interpreting informal human behaviours and predicting VRU intent in mixed-use settings. This gap between expected and actual system capability reinforces the need for supporting digital infrastructure to assist AV decision-making in mixed environments.

For example, pedestrian behaviour is often shaped by group dynamics or social context (e.g. waiting for others to cross), which AVs may not interpret accurately. A recent study showed that pedestrian decision-making in the presence of AVs may not align with vehicle behaviour, especially when users are unfamiliar with AV systems (Zhao et al. 2024). Similarly, CAVs may brake too late or overreact in response to unpredictable situations.

This situation is further complicated for pedestrians with sensory, cognitive, or mobility impairments, who may not understand vehicle intent in the absence of human driver gestures. El Hamdani et al. (2020) emphasise that inclusive pedestrian design such as tactile pavements, audible kerbside signals, or simplified visual indicators can support safer interaction between AVs and pedestrians. This highlights the need for human-centred infrastructure that accommodates a range of VRUs.

Emergency vehicle detection and response is another critical aspect of CAV readiness. This is seen through the NordicWay 3 project that demonstrated Emergency Vehicle Approaching (EVA) warnings improve driver yielding behaviour and reduce emergency access delays. These digitally broadcast warnings are based on real-time routing data from emergency dispatch centres, and are transmitted using standard V2X channels (Weibull 2024). The study showed that EVA infrastructure-based messaging can pre-emptively inform AVs of high-priority vehicles before traditional signals (e.g. sirens or lights) are perceived, improving safety and compliance in occluded or dynamic environments.

In the Netherlands, the Safety Priority Services (SPS) project digitally alerts drivers about approaching emergency vehicles through commercial navigation apps such as Flitsmeister, and systems from KIA, Hyundai, and TomTom, integrating real-time safety messaging into consumer platforms (Rijkswaterstaat 2022). Weibull (2024) also notes similar EVA-style digital alerting by the HAAS Alert Safety Cloud platform that broadcasts emergency vehicle presence to nearby civilian vehicles via connected apps (e.g. Waze, Apple Maps), vehicle systems, and government traffic platforms.

Australian research also confirms that AVs may respond inconsistently to ambiguous merging, yielding, or informal road behaviour. These scenarios expose the limits of rule-based AV logic and highlight the need for clearer digital support systems that interface directly with AV decision processes (iMOVE 2023).

6.8.1 Key challenges

The core challenge involves enabling CAVs to interact safely with emergency vehicles and vulnerable road users in environments where cues are informal, partial or digitally unavailable. Without infrastructure-supported alerts, real-time messaging or standardised intent signalling, AVs may hesitate, fail to yield or misinterpret human behaviour. These limitations reduce coordination, especially in unsignalised or mixed-use areas. Table 6.36 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.36: Key challenges that impact CAV interaction with emergency vehicles and vulnerable road users

Key challenges	Example scenario	Impact on CAV operations	References
Poor detection of emergency vehicles	AV does not yield to an ambulance approaching from behind due to occlusion or noise.	Safety risk; non-compliance with yielding rules; delays to emergency response.	• Weibull (2024) • Rijkswaterstaat (2022)
Unpredictable VRU behaviour	A pedestrian steps into traffic mid-block, following the lead of another pedestrian.	AV overreacts or hesitates; increased risk of collision in the absence of clear cues.	• Zhao et al. (2024)
Lack of AV-to-human signalling	A pedestrian waits at a kerb without knowing if the AV intends to stop.	Missed crossing opportunity or unsafe decision due to lack of non-verbal cues.	• El Hamdani et al. (2020)
Absence of emergency vehicle digital alerts	AVs receive no pre-warning about emergency vehicle routing.	No time to prepare yielding; delayed response; blocked access for emergency vehicles.	• Weibull (2024) • Rijkswaterstaat (2022)
Sensor occlusion or ambiguous signals	A pedestrian warning light or vehicle hazard light is misclassified as ambient lighting.	AV proceeds without caution or fails to yield; VRU safety compromised.	-
Limited deployment of cooperative awareness infrastructure	No RSUs or V2X feeds exist in rural or mid-block segments.	AVs rely solely on perception; no support for hidden or dynamic VRU/emergency scenarios.	• iMOVE (2023)
Privacy or security restrictions on emergency data	Police vehicle chooses not to broadcast EVA location or intent.	AVs lack pre-emptive context; may not yield or adjust appropriately.	• Weibull (2023)
Inconsistent AV responses	One AV model yields to siren proximity; another does not due to different logic rules.	Unpredictable traffic flow; increased safety risks and reduced trust.	-

6.8.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to improve CAV interaction with emergency vehicles and vulnerable road users are provided below in Table 6.37.

Table 6.37: Road and infrastructure design considerations related to DT8

Design element considerations	Description	Supporting references
Emergency Vehicle Alert (EVA) infrastructure	Deploy roadside and/or or cloud-based systems that broadcast standardised digital alerts of emergency vehicle approach to CAVs, improving pre-warning and yielding behaviour.	• (Weibull 2024) • (Rijkswaterstaat 2022)
AV-VRU interaction zones in design guidelines	Update road design manuals to include visual or spatial cues that guide AVs and support predictable VRU crossing behaviour.	• NACTO (2021)
Human–CAV communication support infrastructure	Consider kerbside indicators (e.g. lights, sounds) or low-complexity digital signs to help pedestrians interpret AV intention where eye contact or gestures are missing.	• (Zhao et al. 2024)
Emergency routing support from TMCs	Link road agency TMC systems with emergency vehicle dispatch feeds to provide timely, digitally delivered routing information to AVs.	• (Weibull 2023)
Privacy-sensitive emergency broadcast protocols	Coordinate with emergency services to allow alert broadcasting without compromising sensitive location or identity data.	• (Weibull 2023)
Focus on high-risk or underserved segments	Prioritise deployment of digital safety infrastructure in areas with limited visibility, no signals, or higher VRU exposure (e.g. rural roads, midblocks, schools).	• (iMOVE 2023)

6.8.3 Related topics

Topics related to DT8 include those listed below in Table 6.38.

Table 6.38: Topics related to DT8

Related topic (code)	Related topic title	Reason for cross-reference
PT7	Managing AV interactions with e-scooters, cyclists and personal mobility devices.	Relates to physical response patterns and visibility to VRUs.
DT13	Supporting CAV interpretation and compliance with traffic signal infrastructure.	Overrides normal signal operation and should be synchronised with digital feeds.

6.8.4 Principles

Principles derived from the above evidence that relate to DT8 are shown in Table 6.39 below.

Table 6.39: Principles related to DT8

Principle	Description
Emergency vehicle priority by design	Deploy and manage digital alert systems (e.g. EVA) that broadcast emergency vehicle approach data to CAVs, enabling early yielding and route adaptation.
Support for human–road user communication	Implement kerbside signals or signage (e.g. light indicators, sound cues) in crossing environments to help pedestrians interpret CAV behaviour where driver gestures are absent.
Infrastructure-augmented VRU detection	Deploy smart roadside infrastructure (e.g. midblock sensors, RSUs) in occluded or unsignalised zones to digitally support AV detection of hidden VRUs.
Interoperable priority data feeds	Standardise digital message formats (e.g. SPaT, MAP, EVA) for emergency vehicle and VRU systems to ensure direct compatibility with digital alert feeds used in AV navigation and decision-support systems.

6.8.5 Future research areas

Whilst there is some coverage of the DT8 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.40 below.

Table 6.40: Potential research topic areas related to DT8

Research topic area	Description
Infrastructure-supported yielding for emergency vehicles	Investigate how digital alert systems (e.g. EVA) can be optimised for early detection, improved response times, and integration with AV behaviour through agency-managed systems.
Pedestrian communication interfaces at crossings	Trial kerbside signals, auditory cues, or visual displays that help pedestrians interpret AV intent, particularly in school zones, midblocks, or areas with high VRU density.
Simulation of emergency-CAV interactions	Use traffic simulation and co-simulation tools to model emergency vehicle routing, CAV yielding behaviour, and the effects of digital alert infrastructure on safety and response times.
Sensor support standards in high-risk areas	Develop guidance on placement, sensitivity, and integration of roadside sensors (e.g. thermal, LiDAR, radar) that assist AVs in detecting VRUs where visibility is limited.
Smart infrastructure for uncontrolled environments	Explore use of deployable V2X units, passive detection devices, or smart signage in uncontrolled road segments (such as roundabouts, shared spaces, or rural roads) to improve AV awareness of VRUs and emergency vehicles where traditional signals are absent.
Inclusive design	Investigate kerbside tools (e.g. tactile, auditory, and visual cues) to help pedestrians with sensory, cognitive, or mobility impairments interpret AV behaviour and cross safely.

References for DT8

El Hamdani S, Benamar N and Younis M (2020) ‘Pedestrian support in intelligent transportation systems: Challenges, solutions and open issues’, *Transportation Research Part C: Emerging Technologies, 121*, 102856. https://doi.org/10.1016/j.trc.2020.102856.

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NACTO (National Association of City Transportation Officials) (2021) *Blueprint for Autonomous Urbanism (2nd Edition)*, NACTO, New York.

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Zhao X, Li X, Rakotonirainy A, Bourgeois-Bougrine S, Zhu Z and Delhomme P (2024) ‘Crossing roads in a social context: How behaviors of others shape pedestrian interaction with automated vehicles’, *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 102, pp. 88–106, https://doi.org/10.1016/j.trf.2024.02.008

6.9 Optimising CAV and EV fleet management and staging (DT9)

This topic covers digital strategies for managing CAV and EV fleets at the network and kerbside level. It focuses on tools that support dynamic dispatch, digital staging, idle-time regulation, and coordinated access to charging infrastructure. These systems help transport agencies reduce congestion, improve kerbside efficiency, and integrate fleet operations with broader mobility objectives.

As CAV and EV adoption increases, especially in urban environments, fleet-based operations such as ride-hailing, autonomous taxis, and delivery AVs are expected to account for a significant proportion of vehicle kilometres travelled. Without coordinated approaches to fleet staging, dispatch, and charging, these fleets risk increasing congestion and kerbside conflicts, and creating empty vehicle circulation inefficiencies.

Fleet behaviour modelling and early trials have highlighted the risks posed by unmanaged fleets. NASEM (2022) identifies that AVs may circulate endlessly while waiting for a passenger, especially in the absence of dynamic kerb access rules. This raises concerns about congestion and emissions impacts. Millard-Ball (2019) similarly finds that AVs are likely to cruise slowly to avoid parking charges, a behaviour known as ‘zombie miles’, which can double vehicle travel in urban cores.

Public infrastructure constraints, particularly at the kerb, further compound these issues. NASEM (2022) warns that fixed EV charging infrastructure can reduce the flexibility of kerbside management and may not align with broader mobility goals if fleets monopolise space beyond their charging period. It also notes that smaller operators, including shared fleets and delivery services, face uncertainty about where and how to charge vehicles, due to a lack of suitable staging and charging areas.

CROW (2023) highlights the role of machine-readable infrastructure and access control tools in supporting automated fleet coordination. By enabling digital kerb access permissions, V2X integration, and predictable staging zones, infrastructure can reduce idle AV circulation and improve the efficiency of dispatch and charging operations.

Without intervention, AV fleets may interfere with active and public transport modes by occupying kerbside or traffic lanes during idle periods. For example, a pilot in the South Lake Union neighbourhood of Seattle USA found that adding passenger loading zones supported by geofencing decreased in-lane pickup stops from 20% to 14%, demonstrating the value of digital kerb enforcement tools (NASEM 2022).

According to the OECD/ITF (2023), a lack of coordinated digital rules (e.g. access time restrictions, staging zones (off-street areas where fleet vehicles wait for dispatch instructions or charging access)) can lead AVs to idle in sensitive areas or circulate unnecessarily, undermining efficiency and safety.

Finally, the infrastructure and policy responses required to manage these challenges should be coordinated across jurisdictions. As noted in NASEM (2022), delivering effective AV and EV kerb management strategies depends on strong alignment between local, state and national agencies, particularly in the planning and deployment of shared-use charging infrastructure.

6.9.1 Key challenges

The core challenge involves managing the movement, staging and charging of CAV and automated EV fleets to prevent kerbside congestion and inefficient use of road and energy infrastructure. Without coordinated digital integration, fleets may cluster in high-demand areas, circulate inefficiently or block charging bays. Gaps in geofencing, idle-time enforcement and platform interoperability further limit the effectiveness of fleet management. Table 6.41 presents these key challenges, example scenarios and their impacts on CAV and automated EV operations.

Table 6.41: Key challenges that impact optimisation of CAV and EV fleet management and staging

Key challenges	Example scenario	Impact on CAV and EV operations	References
Lack of designated staging areas	Fleets of ride-hail AVs congregate near a train station awaiting trips.	Increased kerbside congestion; passenger confusion; and AV–AV interaction complexity.	• NASEM (2022) • OECD/ITF (2023)
Charging point bottlenecks	A shared charging site remains occupied by AVs beyond their charging period.	Other EVs experience long delays; operators must reroute or idle elsewhere.	• NASEM (2022) • CROW (2023)
Poor fleet dispatch coordination	AV fleet is deployed to areas without real-time demand insights.	Idle vehicle congestion; missed trip opportunities; and inefficient fleet utilisation.	• Millard-Ball (2019) • OECD/ITF (2023)
Absence of geofencing or idle-time logic	Unoccupied AVs circulate in the CBD to avoid parking costs or enforcement.	Higher emissions; traffic disruption; and degraded network performance.	• NASEM (2022) • NACTO (2021)
No integration with digital kerb management	AV fleets are unaware of time-limited kerb access rules or priority zones.	Non-compliance with local rules, fines; or AV fallback behaviours.	• NASEM (2022) • CROW (2023)
Fragmented platform and infrastructure systems	Lack of API-based access between public kerbside management systems and fleet platforms reduces coordination and limits enforcement capabilities.	Reduced coordination across operators; poor access timing; underuse of staging infrastructure.	• CROW (2023) • OECD/ITF (2023)

6.9.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to optimise CAV and EV fleet management and staging are provided below in Table 6.42.

Table 6.42: Road and infrastructure design considerations related to DT9

Design element considerations	Description	Supporting references
Digitally managed fleet staging hubs	Digitally assigned kerbside or off-street zones, coordinated via real-time APIs and platform integration.	• NASEM (2022) • OECD/ITF (2023)
Geofenced idle-time enforcement	Use of digital geofencing and access timers to regulate how long AVs can dwell or circulate in high-demand zones.	• NACTO (2021) • NASEM (2022)
Fleet–kerb API integration	Standardised digital interfaces that connect AV fleet platforms to city kerb management systems for scheduling, compliance, and data exchange.	• OECD/ITF (2023) • CROW (2023)
AI-driven dispatch and load balancing	Predictive algorithms that rebalance fleets and assign vehicles to areas of forecasted demand, reducing idle circulation.	• Millard-Ball (2019) • OECD/ITF (2023)
Digitally coordinated fleet EV charging	Public or shared-use EV charging zones managed through real-time booking, prioritisation logic, and integration with fleet V2G systems.	• NASEM (2022) • CROW (2023)

6.9.3 Related topics

Topics related to DT9 include those listed below in Table 6.43.

Table 6.43: Topics related to DT9

Related topic (code)	Related topic title	Reason for cross-reference
PT8	Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs.	Kerbside access design should support digital rules and management.
PT9	Minimising urban congestion from AV fleet staging, parking and idle circulation.	Staging zones should be planned in conjunction with digital dispatch systems.
DT10	Integration of CAV and EV operations into smart city and traffic management platforms.	Vehicle fleet coordination is enhanced by integration with traffic control and management platforms.

6.9.4 Principles

Principles derived from the above evidence that relate to DT9 are shown in Table 6.44 below.

Table 6.44: Principles related to DT9

Principle	Description
Digitally managed staging zones	Road agencies should enable dedicated, digitally coordinated spaces for AV/automated EV fleets to idle or charge without disrupting traffic flow.
Demand-responsive dispatch	Infrastructure systems should support fleet platforms with real-time data to enable dispatch aligned to demand and staging capacity.
Digital–physical kerb integration	AV and automated EV fleet operations should align with digitally defined kerb rules and physical kerb infrastructure to ensure compliance and safety.
Time-windowed optimisation	Road agencies should apply time-based access and dispatch rules to reduce idle circulation and improve kerbside availability.
Interoperability by default	Public infrastructure systems should adopt open APIs and data standards to ensure equal access and coordination across fleets.
Govern data	Establish policies and digital interfaces that ensure fleet data (e.g. dispatch events, kerb use) is accessible for planning and enforcement, while protecting operator and user privacy.

6.9.5 Future research areas

Whilst there is some coverage of the DT9 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.45 below.

Table 6.45: Potential research topic areas related to DT9

Research topic area	Description
Integrated AV–kerb management platforms	Tools and standards to align kerb use, staging, and charging across multiple fleet operators.
Dynamic fleet heatmapping and congestion control	Predictive systems that optimise fleet movement using real-time demand and kerb occupancy data along with congestion hotspots.
Idle-time pricing and access incentives	Urban pricing or access control models that discourage unnecessary AV dwelling in sensitive zones.

References for DT9

CROW (2023) *Future-Proof Road Infrastructure for Automated and Connected Vehicles,* CROW Knowledge Platform, Netherlands.

Millard-Ball A (2019) 'The autonomous vehicle parking problem', *Transport Policy*, vol. 75, pp. 99–108, https://doi.org/10.1016/j.tranpol.2019.01.003.

NASEM (National Academies of Sciences, Engineering, and Medicine) (2022) 'Dynamic Curbside Management: Keeping Pace with New and Emerging Mobility and Technology in the Public Right-of-Way', *Part 1: Dynamic Curbside Management Guide and Part 2: Conduct of Research Report* (NCHRP Project 20-102(26), The National Academies Press, Washington, DC, https://doi.org/10.17226/26718.

OECD/ITF (2023) *Preparing Infrastructure for Automated Vehicles*, International Transport Forum, Paris.

6.10 Integration of CAV and EV operations into smart city and traffic management platforms (DT10)

This topic addresses how traffic and transport agencies can integrate CAVs and EVs into traffic management and smart city platforms. It focuses on enabling real-time, two-way communication between public systems and connected vehicles to support signal coordination, demand management, and infrastructure responsiveness.

Modern traffic management increasingly depends on real-time, data-driven decision-making to optimise network performance, reduce congestion, and improve system responsiveness. CAVs will generate valuable operational data (such as speed, routing, hazard events and vehicle state) that offer new opportunities for cooperative and coordinated adaptive traffic control, predictive modelling, and infrastructure efficiency.

Despite this, most road agencies locally and internationally lack the system-level capability to ingest and act on CAV-generated data. Legacy traffic control systems, such as SCATS and STREAMS, were not designed to interface with vehicle-based data feeds and continue to rely heavily on in-ground loop detectors and closed-system inputs. Austroads (2021) RADCAV notes that while CAVs can provide granular, real-time data (vehicle-generated data), most traffic platforms lack the ingestion and processing capabilities to use it. It highlighted the absence of interface standards and ingestion protocols as a major barrier to integration. This limits agency situational awareness (e.g. knowledge of delays, hazards) and reduces opportunities for proactive network optimisation and prediction.

However, as agencies move to ingest vehicle-generated data, governance frameworks become a concern. Austroads (2021) highlights that access, security, and privacy standards are needed to govern data sharing between government platforms and CAV systems. Without clear protocols and agreements, commercial sensitivity and legal uncertainty may limit data integration, particularly concerning real-time, individual vehicle feeds.

Emerging frameworks such as Traffic Management 2.0 (TM2.0) and Europe's NAPCORE initiative propose a cooperative, bidirectional model for managing traffic between vehicles and infrastructure. TM2.0 outlines a future where traffic management centres broadcast conditions along with ingesting real-time data from connected vehicle fleets to improve responsiveness, coordination, and safety. This vision is being actively operationalised through NAPCORE, which has initiated technical and policy dialogues to support implementation.

A 2023 NAPCORE workshop involving public and private sector stakeholders (including TomTom, Google, national road authorities, and city governments) highlighted critical challenges around integrating traffic circulation rules and road hierarchies into in-vehicle navigation platforms. Cities raised concerns about routing practices contributing to rat-running, local congestion, and safety risks, particularly on roads unsuited for heavy or through-traffic. These discussions surfaced concepts such as 'societal routing' and multimodal network management, underscoring the need for digital systems that align vehicle routing with civic priorities like pedestrian safety, emissions reduction, and equitable road use (POLIS 2023).

The NAPCORE activities see TM2.0 in action and reinforces the growing imperative for shared, dynamic, and standards-based integration between public traffic platforms and connected mobility services. Without integration, CAV data will remain untapped, limiting situational awareness, increasing system rigidity, and undermining the strategic value of emerging vehicle fleets in urban traffic optimisation.

Recent research underscores the operational benefits of integrating CAV data into traffic systems. Wu et al. (2024) propose a participatory traffic control framework, where CAVs act as 'traffic stream regulators', subtly influencing human drivers' departure times and route choices to rebalance demand and improve system efficiency. Their model-free, scalable control architecture supports real-time and decentralised adjustments, which are key attributes for future-ready smart platforms.

Similarly, Avedisov, Bansal and Orosz (2022) demonstrate that even low CAV penetration (e.g. 25%) can deliver a 25% improvement in traffic flow, provided vehicles leverage long-range V2X communication. Their findings validate the critical role of connected vehicle data in improving traffic patterns and enhancing throughput, even in mixed-fleet conditions.

In parallel with real-time optimisation and cooperative traffic control, CAV-generated data can support a safety feedback function, enabling agencies to detect infrastructure-related issues that may not be visible through traditional sensors or inspection. Disengagements and perception-related fallback events recorded by CAVs can provide early indicators of confusing layouts, unclear signage, or unreliable data conditions. If structured appropriately, this vehicle-originated safety feedback loop could complement traffic efficiency goals by highlighting where digital or physical infrastructure may require attention — improving both performance and safety. This aligns with emerging international guidance (e.g. UNECE WP.29/2024/39) that recognises infrastructure as a contributor to safe vehicle operation.

6.10.1 Key challenges

The core challenge involves integrating CAV and EV operations into smart city and traffic management platforms, including the use of vehicle data for real-time coordination and system optimisation. Beyond data exchange, agencies should ensure that CAVs can interact with traffic management systems in real time, including responding to signal controls, priority rules and dynamic routing strategies. Without interoperability, standardised interfaces and system upgrades, these platforms may fail to accommodate or leverage CAV behaviours, limiting their value for network efficiency and planning. Table 6.46 presents these key challenges, example scenarios and their impacts on CAV operations and agency traffic control systems.

Table 6.46: Key challenges that impact integration of CAV and EV operations into smart city and traffic management platforms

Key challenges	Example scenario	Impact on Vehicle operations	References
Proprietary vehicle data silos	A ride-hail AV fleet does not share routing or location data with city systems.	Traffic models fail to account for vehicles in congestion planning.	• POLIS (2023)
Incompatibility with legacy traffic platforms	AV-generated hazard alerts cannot be ingested by SCATS or STREAMS.	Delayed incident detection.	• Austroads (2021)
No feedback loop between AVs and traffic control systems	AVs encounter frequent congestion but agency traffic control systems do not receive delay signals.	Predictive traffic control models underperform, increasing congestion and travel times.	• Wu et al. (2024) • Avedisov et al. (2022)
Agencies cannot influence or constrain CAV routing preferences	Navigation systems route through residential streets not designed for high volumes.	Inefficient use of strategic corridors, increased congestion, noise, and safety concerns.	• POLIS (2023)
Fragmented data standards and APIs	A CAV sends event data in a format not recognised by a traffic control system (e.g. SCATS).	Event data is lost or ignored by the traffic control system.	• Austroads (2021)

6.10.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency related to integration of CAV and EV operations into smart city and traffic management platforms are provided below in Table 6.47.

Table 6.47: Road and infrastructure design considerations related to DT10

Design element considerations	Description	Supporting references
Standardised vehicle-to-platform data formats	Use of common data standards (e.g. DATEX II, TMDD) enables traffic management platforms to interpret and integrate vehicle-generated data (e.g. routing, event alerts) in a consistent schema across fleets and jurisdictions.	• POLIS (2023)
CAV-compatible traffic management logic	Legacy systems like SCATS and STREAMS cannot process CAV generated data. Updates to signal logic and system architecture are required to process and respond to vehicle-sourced inputs in real time.	• Austroads (2021) • Avedisov et al. (2022)
Capability and readiness	Agencies should use Austroads' phased model and reference architecture (Day 0.5 to Day 4) to benchmark readiness, identify gaps and guide improvements in data exchange with CAVs.	• Austroads (2021)
Real-time feedback integration with CAVs	Advanced traffic control frameworks allow traffic systems to continuously adjust based on real-time CAV feedback (e.g. vehicle speeds, delays). This supports dynamic signal coordination, congestion prediction, and proactive traffic control.	• Wu et al. (2024)
Routing alignment with road hierarchy and policy	In-vehicle navigation should reflect public network management priorities, avoiding unsuitable routes (e.g. residential streets, school zones) and aligning with modal and functional hierarchies managed by agencies.	• POLIS (2023)
Two-way data exchange between CAVs and platforms	Traffic management platforms should be designed to both ingest real-time vehicle data (e.g. hazard events, position, delay) and broadcast traffic information back to CAVs (e.g. signal phase, detours, incidents), enabling cooperative operations.	• Austroads (2021) • Wu et al. (2024)
Use of CAV operational data to identify infrastructure weaknesses	Agencies should analyse disengagements, fallback events, or localisation errors reported by CAVs to detect problematic infrastructure elements and inform future road design or upgrades.	• UNECE WP.29 (2024)

6.10.3 Related topics

Topics related to DT10 include those listed below in Table 6.48.

Table 6.48: Topics related to DT10

Related topic (code)	Related topic title	Reason for cross-reference
DT4	Protecting CAV and transport data from cybersecurity threats	Traffic system platforms should be protected from data manipulation threats.
DT9	Optimising CAV and EV fleet management and staging	Staging, loading, and kerb allocation require integrated real-time digital systems.
DT11	Ensuring real-time EV charging availability and status updates	Real-time EV charging status feeds into routing decisions and network planning.

6.10.4 Principles

Principles derived from the above evidence that relate to DT10 are shown in Table 6.49 below.

Table 6.49: Principles related to DT10

Principle	Description
Standardised data interfaces	Use shared data structures (e.g. DATEX II, TMDD) to support compatibility across traffic systems and connected services, while acknowledging their limits for direct vehicle data ingestion.
Real-time operational responsiveness	Ensure traffic platforms can ingest and act on live CAV/EV data to support predictive modelling, adaptive signal control, and network optimisation.
Two-way vehicle–infrastructure communication	Build systems that enable continuous bidirectional exchange—traffic platforms ingest vehicle data, and broadcast traffic information back to fleets.
Policy-aligned routing integration	Ensure in-vehicle navigation reflects agency-defined network priorities such as road hierarchy, restricted access zones, and safety requirements.
Agency–industry data coordination	Establish shared protocols, roles, and technical standards across transport agencies, OEMs, platform providers, and fleet operators to enable secure and consistent data exchange.

6.10.5 Future research areas

Whilst there is some coverage of the DT10 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.50 below.

Table 6.50: Potential research topic areas related to DT10

Research topic area	Description
Real-time AV–traffic system feedback loops	Development of scalable, bidirectional interfaces between CAVs and platforms to support congestion detection and cooperative response.
Models for data access and use	Design of frameworks (e.g. MOUs, protocols) for secure, consistent CAV data exchange between industry and agencies.
Use of CAV data in traffic prediction and simulation	Applying vehicle-generated inputs to improve accuracy of urban traffic forecasting and simulation models.
Standardised vehicle–platform communication protocols	Research on real-time message structures and API implementation between fleets and traffic management systems.
Platform adaptation for mixed-fleet environments	Ensuring platforms function effectively with limited CAV penetration, legacy vehicles, and incomplete data streams.
Adaptive traffic control systems using CAV data	Development of signal control systems that respond dynamically to real-time CAV inputs for phase timing, coordination, and flow management.
Platform-to-vehicle traffic coordination models	Research into TM2.0-style systems where platforms guide vehicle routing and behaviour to support public network priorities and demand balancing.

References for DT10

Austroads (2021) *Road Authority Data for Connected and Automated Vehicles: Guidance for Agency Data Provision to Connected and Automated Vehicles*, AP-R662-21, Austroads, Sydney, NSW.

Avedisov S, Bansal G and Orosz G (2022) 'Impacts of Connected Automated Vehicles on Freeway Traffic Patterns at Different Penetration Levels', *IEEE Transactions on Intelligent Transportation Systems*, 23, 4305-4318. https://doi.org/10.1109/tits.2020.3043323.

ERTICO – ITS Europe (n.d.) *Traffic Management 2.0 Enabling vehicle interaction with traffic management*, Brussels, Belgium.

Makridis M and Kouvelas A (2023) 'An adaptive framework for real-time freeway traffic estimation in the presence of CAVs', *Transportation Research Part C: Emerging Technologies*, vol. 154, 104066, , https://doi.org/10.1016/j.trc.2023.104066.

NAPCORE (National Access Point Coordination Organisation for Europe) (2023) *About NAPCORE*, NAPCORE website.

POLIS (2023) POLIS members attend NAPCORE Workshop on driver information services, *POLIS Network website*, accessed 30 June 2025.

Wu M, Wang B, Yin Y and Lynch J (2024) 'Participatory traffic control: Leveraging connected and automated vehicles to enhance network efficiency', *Transportation Research Part C: Emerging Technologies*, 166. https://doi.org/10.1016/j.trc.2024.104757.

6.11 Ensuring real-time EV and electric CAV charging availability and status updates (DT11)

This topic addresses the role of transport and road agencies in enabling real-time visibility of EV charge status and availability through open, interoperable digital systems. It focuses on the provision, integration, and standardisation of live data feeds (including covering charger occupancy, queue conditions, power ratings, connector types, and operational status) to support EV operators (both for human operated vehicles and electric-powered CAVs).

Road and transport agencies play a critical role in ensuring that public EV charging infrastructure supports real-time access to data. This data is needed to support efficient EV and electric CAV movements that will involve trip planning, routing, and idle-time optimisation. These requirements are especially important for fleet-based electric CAVs, such as autonomous taxis and delivery services, which should dynamically plan routes based on remaining charge and charger accessibility (Verma et al. 2024, Kim 2024).

Despite this need, many charging networks operate on fragmented data formats and proprietary access protocols, which limits cross-platform visibility and vehicle-system integration. Accordingly, vehicles are frequently routed to charging stations that are full, offline or incompatible, reducing system efficiency and undermining service reliability (Bauer et al. 2022).

To address these challenges, several national guidelines have begun mandating open access to live charger data. The Department of Climate Change, Energy, the Environment and Water (DCCEEW 2024) requires all government-supported public charging infrastructure to publish real-time availability data for use by both consumers and government platforms. Similarly, Austroads (2022) recommends that all public charging installations adopt open communication protocols such as the Open Charge Point Interface (OCPI) and Open Charge Point Protocol (OCPP) to enable interoperability between charging infrastructure and digital mobility platforms.

New Zealand’s approach to public EV charging infrastructure reinforces the role of road agencies and governments in enabling real-time data visibility. Charging station operators can voluntarily submit location, availability and status data to the EVRoam platform, which acts as the national access point for EV charging information. Data sharing with EVRoam is mandatory when infrastructure is co-funded by government programs. EVRoam data is freely distributed to third-party apps and navigation systems, enabling route planners and fleet services to access real-time operational insights. The platform is managed by the Energy Efficiency and Conservation Authority (EECA 2024) and aligned with the New Zealand Transport Agency’s national guidance for charging infrastructure (NZTA 2024).

International standards reinforce the importance of open and accessible real-time charger data. Under the European Union’s Alternative Fuels Infrastructure Regulation (AFIR) ((EU) 2023/1804), charging station operators must provide real-time information on charger availability, operational status, waiting times and pricing through open-access APIs and submit this information to National Access Points (NAPs), which are national digital platforms designed to support public access and data reuse across transport services (European Commission 2023).

6.11.1 Key challenges

The core challenge involves providing EVs (including electric CAVs) with reliable, real-time access to EV charging availability across diverse public and commercial networks. Incomplete status updates, incompatible data protocols, and restricted APIs limit the ability of EV operators and electric CAVs to locate suitable chargers, estimate wait times or plan efficient routes. These constraints reduce situational awareness, increase the risk of failed charging stops and disrupt service reliability. Table 6.51 presents these key challenges, example scenarios and their impacts on EV and electric CAV operations.

Table 6.51: Key challenges that impact real-time EV charging availability and status updates

Key challenges	Example scenario	Impact on EV and electric CAV operations	References
No live charger status feed	A CAV is routed to a charger under maintenance, unaware due to a stale or absent feed.	Re-routing mid-trip increases risk of battery depletion.	• Bauer et al. (2022) • DCCEEW (2024)
No real-time queuing or wait time data	A fleet vehicle arrives at a listed 'available' charger but faces a five-vehicle queue.	Unplanned idle time reduces fleet utilisation and increases operational cost.	• Bauer et al. (2022) • Kim (2024)
Incompatible APIs across networks	AV system cannot ingest status data from a nearby network due to closed formats.	Navigation excludes viable chargers; route planning becomes less efficient.	• Austroads (2022) • European Commission (2023)
Lack of charger capacity metadata	A heavy EV is directed to a slow charger due to missing power rating data.	Slow recharging or aborted charge session disrupts service timeline.	• DCCEEW (2024)
Incomplete or non-standard metadata in public charger feeds	Government-supported charging platforms omit details like power rating or connector type.	Route planners or trip engines cannot confidently assess charger suitability.	• DCCEEW (2024)

6.11.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency related to real-time EV charging availability and status updates are provided below in Table 6.52.

Table 6.52: Road and infrastructure design considerations related to DT11

Design element considerations	Description	Supporting References
Use of open standard APIs	Require all government-supported charging infrastructure to implement open communication protocols, such as the Open Charge Point Interface (OCPI) or Open Charge Point Protocol (OCPP), to enable consistent access to real-time charger availability, status and fault data across networks.	• Austroads (2022) • European Commission (2023)
Real-time charger health and queue reporting	Mandate that stations report charger uptime, maintenance status, and queuing conditions through machine-readable feeds, enabling agencies and users to monitor infrastructure performance and anticipate delays.	• DCCEEW (2024) • Bauer et al. (2022)
Public platform integration requirements	Ensure all publicly funded charging infrastructure delivers live status and operational data through open-access digital platforms or National Access Points (NAPs), in line with policy standards.	• DCCEEW (2024) • European Commission (2023)
Data-driven planning conditions for approval	Include open data visibility, power metadata, and API compliance as mandatory conditions for planning approval, funding allocation or site access for EV charging deployments.	• Austroads (2022) • DCCEEW (2024)
Support for structured data to enable trip planning systems	Require charger data feeds to include structured, machine-readable metadata such as connector type, power output, and access constraints, to support integration with navigation and routing platforms.	• Kim (2024) • Verma et al. (2024)

6.11.3 Related topics

Topics related to DT11 include those listed below in Table 6.53.

Table 6.53: Topics related to DT11

Related topic (code)	Related topic title	Reason for cross-reference
PT9	Minimising urban congestion from AV fleet staging, parking and idle circulation	Staging and idle strategies rely on charger occupancy status.
DT9	Optimising CAV and EV fleet management and staging	Staging, loading, and kerb allocation require integration with real-time digital systems.
DT10	Integration of CAV and EV operations into smart city and traffic management platforms	Addresses the ingestion and coordination of digital inputs like charger availability within wider traffic and mobility systems.
DT12	Standardising digital road regulations for CAV and EV charging zones	EV zone access conditions should align with live charger data feeds.

6.11.4 Principles

Principles derived from the above evidence that relate to DT11 are shown in Table 6.54 below.

Table 6.54: Principles related to DT11

Principle	Description
Open data access by design	Publicly supported EV charging systems should be developed with real-time data visibility as a default capability, not a retrofit.
Real-time data availability	Charging station status, availability and outage information should be published in real time and continuously updated to support dynamic trip planning.
System interoperability through open protocols	Charging infrastructure should use standardised, open protocols (e.g. OCPI, OCPP) to ensure seamless data exchange across networks, vendors, and public platforms.
User-relevant granular data	Data feeds should include detail such as queue length, connector type, power output and access constraints to enable efficient vehicle and fleet decision-making.
Structured data for platform integration	Charger should include machine-readable fields (e.g. connector type, power level, access status, and location) provided in agreed data schemas. This supports integration with navigation tools and digital infrastructure platforms.
Public data infrastructure enablement	Agencies should treat real-time charger data as critical digital infrastructure and ensure integration with national access platforms and open systems.

6.11.5 Future research areas

Whilst there is some coverage of the DT11 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.55 below.

Table 6.55: Potential research topic areas related to DT11

Research topic area	Description
Implementation and coverage of open charging APIs	Research should assess how widely open protocols like OCPI and OCPP are adopted across public and commercial networks, identify coverage gaps, and explore policy mechanisms to enforce consistent, nationwide implementation.
Integration of real-time charger data with public traffic and planning platforms	Future studies should explore models for embedding charger availability and queue data into public transport planning and network management systems.
Standardised metadata schemas for charger visibility	Further work is required to define consistent metadata fields (e.g. plug type, power level, access type) to ensure route planners and digital systems can consume charger feeds effectively.
Predictive queue modelling for high-demand sites	Research into data-driven queue forecasting using historical and real-time demand would support dynamic AV charging strategies and reduce idle time.
Data sharing governance for public charger networks	There is a need for consistent models (e.g. mandates, incentives, platform standards) for secure and equitable charger data sharing between operators and public agencies.

References for DT11

Austroads (2022) *Guidelines for low and zero emission vehicle charging infrastructure installation*, AP-G98-22, Austroads, Sydney, NSW.

Bauer G S, Zheng C, Shaheen S and Kammen D M (2022) ‘Leveraging big data and coordinated charging for effective taxi fleet electrification: The 100% EV conversion of Shenzhen, China’, *IEEE Transactions on Intelligent Transportation Systems, vol. 23*, no. 10, pp. 10343–10353, https://doi.org/10.1109/TITS.2021.3092276.

DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2024) *Minimum operating standards for government-supported public electric vehicle charging infrastructure: Guidance document*, Australian Government, Canberra, accessed April 2025.

European Commission (2024) *Alternative Fuels Infrastructure Regulation: QandA on operating recharging infrastructure*, Brussels, Belgium.

EECA (Energy Efficiency and Conservation Authority) (2024) EVRoam: National database of public EV charging stations, EVRoam website, accessed April 2025.

Kim G (2024) ‘Electric vehicle routing problem with states of charging stations’, *Sustainability*, vol. 16, no. 8, article 3439, https://doi.org/10.3390/su16083439.

NZTA (New Zealand Transport Agency) (2024) *National guidance for public electric vehicle charging infrastructure*, New Zealand Government, accessed April 2025.

Verma S, Patel O, Kush and Singh O (2024) ‘Predictive Routing For EV Charging Stations’, *International Journal of Science, Engineering and Management (IJSEM)*, 11(1), 80–85.

6.12 Standardising digital road regulations for EV and electric CAV charging zones (DT12)

This topic addresses the development and standardisation of machine-readable regulations for EV charging zones. It focuses on the role of transport and road agencies in ensuring that access rules (e.g. time limits, eligibility conditions, signage logic) are digitally encoded, structured, and aligned across jurisdictions. These digital rules support CAV compliance with kerbside restrictions and enable integration with vehicle routing and trip-planning systems.

CAVs require access to digital representations of road rules, including for EV charging infrastructure. This includes understanding when and where kerbside charging zones are accessible, interpreting signage conditions, and complying with dynamically enforced time or permit restrictions.

While real-time charger availability data (as addressed in DT11) supports efficient CAV routing and planning, this is complemented by machine-readable regulatory data governing access and timing. This ensures CAVs comply with system status and local road rules.

Some AV developers, such as Waymo (Google for Developers 2025), have demonstrated the ability to interpret kerbside signage and restrictions using perception-based models and real-time sensor input. While this approach enables context-specific compliance, it does not eliminate the need for structured digital regulations. Machine-readable data provides authoritative access logic, improves consistency across jurisdictions, and reduces interpretive errors in edge cases, especially where signage is ambiguous, obstructed, or conditionally enforced.

However, there is currently no nationally standardised framework for either physical signage or digital rule encoding related to EV charging zones. Jurisdictional differences in signage language, regulatory logic, and conditional access formats present significant challenges for CAV compliance. Road agencies and local governments are currently deploying charging infrastructure without consistent signage guidance, increasing the risk of confusion for drivers, and enforcement challenges for authorities (Austroads 2022a).

While Austroads (2022b) has provided national guidance on the installation of EV charging infrastructure, these guidelines focus on physical layout and infrastructure design, and do not address machine-readable rule encoding or public APIs for access restrictions. International efforts, including the development of ISO 24315 series on the Management of Electronic Traffic Regulations (ISO TC204 2024), provide structured approaches to digital rule publication, but are still in development.

As the number of EV-only parking zones expands across urban areas, CAVs must be able to interpret access restrictions consistently across councils, signage types, and regulation formats. In the absence of structured digital rule data feeds, CAVs risk entering restricted bays during prohibited hours or failing to make use of eligible infrastructure. For agencies, this creates enforcement challenges, public confusion, and inconsistency between digital trip planning and actual on-road regulations. Addressing this requires both a national schema for digital rule encoding and mechanisms for local authorities to publish and maintain machine-readable regulation data.

Although some CAV platforms may interpret signage visually or infer rules from context, this does not ensure compliance with nuanced local regulations. A nationally consistent schema for digital rule encoding remains essential for reliable, scalable CAV operations. This is especially the case across different jurisdictions with different signage standards.

6.12.1 Key challenges

The core challenge involves ensuring that CAVs can interpret and comply with digital access rules for EV charging zones across jurisdictions. Many councils lack structured data feeds for time limits, access conditions or signage logic, and use inconsistent rule formats. Without harmonised, machine-readable regulations, CAVs risk non-compliance, enforcement conflicts or missed charging opportunities. Table 6.56 presents these key challenges, example scenarios and their impacts on CAV and EV operations.

Table 6.56: Key challenges that impact standardising digital road regulations for CAV and EV charging zones

Key challenges	Example scenario	Impact on CAV and EV operations	Reference
Lack of machine-readable access rules	An AV parks in an EV-only bay outside permitted hours due to lack of digital restriction data.	Risk of non-compliance, enforcement, or service disruption.	-
Jurisdictional differences in signage	Different councils mark EV-only access with different icons, colours, or conditions.	CAV path planning may misinterpret or wrongly avoid charging infrastructure.	Austroads (2022a)
Lack of digital feed for time restrictions	A council designates a 2-hour EV charging window but does not publish a structured data feed.	AV cannot manage charging session duration or identify time-based constraints.	-

6.12.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency related to standardising digital road regulations for CAV and EV charging zones are provided below in Table 6.57.

Table 6.57: Road and infrastructure design considerations related to DT12

Design element considerations	Description	Supporting references
National digital regulation schema	Develop a national format for encoding kerbside access and time-based EV rules in machine-readable formats.	ISO TC204 (2024)
Digital kerbside access metadata	Include structured metadata (e.g. access type, user eligibility, time windows) in all EV zone definitions.	ISO TC204 (2024)
Digital–physical rule consistency	Ensure that digital rule encodings mirror signage logic and enforceable legal conditions.	ISO TC204 (2024)
Inter-jurisdictional encoding alignment	Standardise how digital rules are structured and shared across councils and states.	ISO TC204 (2024)
Public access APIs for regulation feeds	Provide structured, open APIs to publish local digital signage and EV access rules.	ISO TC204 (2024)

6.12.3 Related topics

Topics related to DT12 are listed below in Table 6.58.

Table 6.58: Topics related to DT12

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Physical sign readability.
PT8	Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries) and EVs	Kerbside access design should reflect digital eligibility rules.
DT5	Ensuring CAV compliance with dynamic road regulations	Should conform to broader dynamic regulation encoding frameworks.
DT11	Ensuring real-time EV charging availability and status updates	Focuses on real-time operational status of EV chargers — whether a site is usable, functioning, and has availability.

6.12.4 Principles

Principles derived from the above evidence that relate to DT12 are shown in Table 6.59 below.

Table 6.59: Principles related to DT12

Principle	Description
Digital–physical consistency	AVs should interpret kerbside access rules provided in digital data as is shown on signage, including icons, rules, and time limits.
Harmonised rule encoding across jurisdictions	Road agencies at all levels should align digital rule formats to ensure machine-readable consistency.
Machine-readable regulation as default	Digital rule feeds should be structured (e.g. JavaScript Object Notation (JSON)/Extensible Markup Language (XML)), validated, and publicly accessible where appropriate.
Public infrastructure data for navigation	Charging zone data should support trip planning and compliance for AV systems via infrastructure-side data sharing.

6.12.5 Future research areas

Whilst there is some coverage of the DT12 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.60 below.

Table 6.60: Potential research topic areas related to DT12

Research topic area	Description
AV rule compliance simulation	Develop and test how AVs interpret and respond to digital kerbside access rules across varied conditions.
Standardised signage encoding formats	Define machine-readable rule formats and metadata libraries for digital signage elements.
Cross-jurisdiction alignment pilots	Pilot standardised digital rule encoding across multiple councils/states to harmonise formats.

References for DT12

Austroads (2022a) *Standardised signage and pavement symbols for low and zero emission vehicles*, AP-R667-22, Austroads, Sydney, NSW.

Austroads (2022b) *Guidelines for low and zero emission vehicle charging infrastructure installation*, AP-G98-22, Austroads, Sydney, NSW.

ISO TC204 (2024) *ISO 24315 – Management of Electronic Traffic Regulations (METR),* https://iso-tc204.github.io/iso24315

6.13 Supporting CAV interpretation and compliance with traffic signal infrastructure (DT13)

This topic investigates how CAVs interpret traffic signal infrastructure using digital signal data and logic-based control rules. It focuses on digital communication, signal compliance under degraded conditions, and agency digital service responsibilities.

CAVs must interpret and comply with traffic signal infrastructure under real-world conditions. This includes complex traffic signal phasing and priority overrides for emergency or public transport vehicles. Accurate interpretation is essential to ensure legal compliance, safety, and integration into mixed traffic environments.

CAVs need a combination of onboard perception systems (e.g. vision, LiDAR) and digitally broadcast signal messages, particularly SPaT (Signal Phase and Timing) and MAP (intersection geometry and lane-level movement authority) data to interpret traffic signals. However, both physical and digital signal elements present operational challenges for road agencies seeking to support AV functionality. Additional jurisdiction-specific rules, including hook turns in Victoria or turn-on-red permissions in some jurisdictions, present further challenges for AVs relying solely on perception.

US research by NASEM (2024) also highlights how non-standardised placement, height, and orientation of signal heads can impact CAV interpretation. The report recommends that infrastructure owners provide real-time digital signal data, reduce physical variability, and adopt design standards explicitly tailored to support automated systems.

Standards such as ISO 19091 (ISO 2019) and SAE J2735 (SAE International 2023) define the structure of SPaT and MAP messages to facilitate consistent digital communication. However, deployment across Australian and New Zealand jurisdictions remains limited. Austroads (2021a) confirmed that no road agency currently provides digital traffic signal data in a format suitable for operational AV use, with current capability ranging from ‘not available’ to ‘in trial’. Additionally, signal pre-emption (or vehicle priority) logic used by systems such as SCATS and STREAMS is often not reflected in outbound digital feeds. These systems typically rely on automated vehicle location (AVL), GPS, and localised signal control, which are not visible to AVs unless explicitly broadcast.

Austroads (2021b) reinforces that traffic signal data is safety-critical and that digital provision should meet defined service quality and governance standards. It outlines a comprehensive framework comprising a Capability Model, Reference Architecture, and Implementation Guidance to help agencies assess readiness and plan improvements. The framework supports agencies to identify gaps, manage delivery across API and RSU channels, and progress from Day 0.5 to Day 4 capability levels, depending on the maturity of their digital signal data systems (Austroads 2021b).

Austroads (2021b) also details key service level criteria, such as data refresh rate, location accuracy, latency, and classification correctness, which are essential to ensuring SPaT/MAP messages are safe and reliable for AV use. These criteria align with international guidance, such as the EU ITS Platform, and are necessary to build AV trust in digital messages (Austroads 2021b).

In Europe, the C-Roads Platform promotes harmonised deployment of C-ITS, including the use of SPaT/MAP and signal priority messages. It publishes a set of baseline profiles to support a range of traffic signal use cases. Their roadmap indicates these services to be operational by 2026 (C-Roads Platform 2024).

6.13.1 Key challenges

The core challenge involves enabling CAVs to reliably interpret and comply with traffic signal infrastructure under diverse conditions. Agencies should ensure that signal systems support both visual detection and digitally encoded logic (e.g. SPaT/MAP messages). Gaps in visibility, message quality, or alignment with adaptive behaviours can result in AV hesitation, misinterpretation or non-compliance. Table 6.61 presents these key challenges, example scenarios and their impacts on CAV operations.

Table 6.61: Key challenges that impact CAV interpretation and compliance with traffic signal infrastructure

Key challenges	Example scenario	Impact on CAV operations	Reference
Lack of SPaT/MAP broadcast	Intersection lacks any digital signal message.	AV operates in perception-only mode; no redundancy.	Austroads (2021b)
Erroneous lane-phase mapping	Overlapping arrows apply to multiple lanes without digital distinction.	AV misinterprets signal relevance; wrong path or indecision.	Austroads (2023)
Inadequate signal data governance	No agency-defined quality criteria for SPaT message latency or accuracy.	CAV systems cannot verify or trust digital signal data.	Austroads (2021b)
Controller-only vehicle pre-emption logic	Emergency signal override is triggered locally but not broadcast.	AV unaware of override; proceeds on outdated phase assumption.	Austroads (2021b)
Unmapped temporary signal	Portable signals during roadworks not included in digital infrastructure.	AV ignores valid signal; incorrect or unsafe movement.	NASEM (2024)
Region-specific traffic rules	Hook turn or turn-on-red permission not indicated or encoded.	AV fails to execute legal movement or makes invalid decision.	NASEM (2024)

6.13.2 Road and Infrastructure design considerations

Potential road and infrastructure design considerations for an agency to support CAV interpretation and compliance with traffic signal infrastructure are provided below in Table 6.62.

Table 6.62: Road and infrastructure design considerations related to DT13

Design element considerations	Description	Supporting references
SPaT/MAP message broadcast	Signal controllers should be connected to RSUs capable of broadcasting SPaT and MAP messages using ISO 19091 and SAE J2735 formats.	• Austroads (2021b) • ISO (2019) • SAE International (2022)
Digital reflection of priority logic	Local signal systems (e.g. SCATS, STREAMS) should integrate priority overrides (e.g. for emergency/public transport vehicles) into broadcasted SPaT messages.	• Austroads (2021b)
Capability and readiness	Agencies should use Austroads' phased model and reference architecture (Day 0.5 to Day 4) to benchmark readiness, identify gaps and guide improvements in traffic signal data delivery.	• Austroads (2021b)
Reference conceptual architecture	Agencies should adopt a high-level signal data architecture (as outlined in Austroads 2021b) to define roles, data flows, and system interfaces across physical and digital signal assets. It supports strategic planning and integration without locking in specific technologies.	• Austroads (2021b)
Data quality criteria for SPaT/MAP	Agencies should define service levels (e.g. refresh rate, positional accuracy, latency, classification error) to support AV trust.	• Austroads (2021b)
Fallback and redundancy enablement	Signal infrastructure should support seamless fallback between physical visibility and digital feeds. AVs should be able to rely on digital messages where physical signals are obstructed and revert to perception when SPaT/MAP data is unavailable, delayed, or non-authoritative—ensuring safe and lawful operation across all conditions.	–

6.13.3 Related topics

Topics related to DT13 are listed below in Table 6.63.

Table 6.63: Topics related to DT13

Related topic (code)	Related topic title	Reason for cross-reference
PT2	Ensuring readability of lane markings and road signage by vehicles	Builds on physical signal visibility issues by introducing digital signal interpretation logic and broadcast requirements.
PT3	Ensuring compatible road and traffic design for AV navigation and operations	Signal visibility and placement depend on road design standards.
DT5	Ensuring CAV compliance with dynamic road regulations	CAV compliance logic integrates with digital signal interpretation.
DT8	Improving CAV interaction with emergency vehicles and vulnerable road users	Behavioural response to priority signals, including digitally triggered overrides.
DT10	Integration of CAV and EV operations into smart city and traffic management platforms	Vehicle fleet coordination is enhanced by integration with traffic management and control platforms.

6.13.4 Principles

Principles derived from the above evidence that relate to DT13 are shown in Table 6.64 below.

Table 6.64: Principles related to DT13

Principle	Description
Digital-physical signal redundancy	Physical signals and digital SPaT/MAP broadcasts should align to support interpretation under diverse conditions.
Inclusion of priority events in SPaT	Signal pre-emption events (e.g. for emergency or transit vehicles) should be included in digital feeds where supported.
Standard-compliant digital formats	SPaT/MAP messages should be complete, accurate and interoperable using harmonised formats such as ISO 19091 and SAE J2735.
Data governance for safety-critical feeds	Agencies should treat SPaT/MAP as safety-critical and apply structured governance for data quality including accuracy, availability, and timeliness.

6.13.5 Future research areas

Whilst there is some coverage of the DT13 topic area, there are still knowledge gaps and limitations in current literature. Focus areas for future research have been identified in Table 6.65 below.

Table 6.65: Potential research topic areas related to DT13

Research topic area	Description
Deployment learnings from trial sites	Review outcomes from local trials (e.g. iMOVE 2024) to identify practical barriers to consistent SPaT/MAP message deployment.
Mapping and encoding of jurisdiction-specific signal rules	Investigate how localised exceptions (e.g. hook turns, turn-on-red permissions) can be incorporated into signal infrastructure and digital feeds.
Application of the RADCAV Capability Model	Evaluate how agencies are applying the Capability Model to benchmark and improve signal data readiness.

References for DT13

Austroads (2021a) *Road Authority Data for Connected and Automated Vehicles – Summary Report*, AP-R662H-21, Austroads, Sydney, NSW

Austroads (2021b) *Road Authority Data for Connected and Automated Vehicles Module 5 Guidance for Traffic Signal Data Provision to Connected and Automated Vehicles*, AP-R662E-21, Austroads, Sydney, NSW.

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7. Cross-Cutting Design Considerations

This section identifies recurring high-level infrastructure considerations across the physical and digital topic areas. They reflect common design themes and enabling conditions for CAV and EV readiness observed across the design principles contained in sections 5 and 6.

The 24 digital and physical topics were analysed to derive a set of cross-cutting road and infrastructure design considerations. This analysis presents a set of recurring themes that apply across multiple design areas and collectively inform the development of the design principles, as outlined below:

Infrastructure should support AV readability and control transitions

Line markings, signage, and road geometry should remain clear, consistent, and interpretable by automated driving systems. Infrastructure also needs to support safe transitions between automated and manual driving modes. This does not imply widespread infrastructure changes. Rather, it highlights the need for clear, consistent environments to help ensure smooth, safe driver handover where transitions occur.

Pavement design should account for emerging EV and AV use patterns

Increased EV axle loads and AV lane discipline may accelerate pavement wear. This affects design, maintenance strategies, and lifecycle assumptions, particularly on high-volume corridors.

Road and traffic designs should reduce ambiguity in mixed traffic environments

Infrastructure should support safe interaction between AVs, human drivers, micromobility users, and vulnerable road users through clear lane design, intersection treatments, and shared space markings.

Kerbside environments require reconfiguration for new functions

Kerbside areas may need to be reconfigured to support emerging functions such as AV pick-up/drop-off, unattended deliveries, and EV charging. This includes enabling dynamic space allocation, time-based access, and integration with digital management platforms.

Digital infrastructure should enable real-time operational awareness

CAVs will benefit from timely access to dynamic information such as roadworks, lane closures, and signal states. Machine-readable formats could help support safe and lawful AV operation.

Infrastructure should support the provision and maintenance of machine-readable data

Road infrastructure should enable consistent generation, storage, and distribution of digital asset and operational data. This includes geospatial files, sign inventories, and updates for AV mapping systems.

Consistent, structured data can help AV decision-making

Road rules, geometry, and access permissions should be encoded in standardised and verifiable digital formats to support localisation, navigation, and compliance.

Cybersecurity should be addressed at the infrastructure level

Agency systems should incorporate protections against interference, spoofing, and unauthorised access to ensure secure and reliable CAV operations.

Digital fallback mechanisms are required to manage degraded operations

Infrastructure should support minimum-risk manoeuvres and safe transitions when communications or digital systems fail, enabling CAVs to continue or stop safely.

Staging and fleet behaviour should be considered in design

AV and EV fleets require infrastructure support for traffic management, staging, parking, and queue management to avoid kerbside congestion and inefficiencies in high-demand environments.

Infrastructure should align with traffic management and control logic suitable for CAVs

Digital infrastructure should support government/agency policy-aligned travel routing, integration with road hierarchies, movement and place considerations, and real-time feedback loops between CAVs and traffic management and control systems.

The considerations complement the detailed principles, and inform their application in section 8. Together, they support a consistent and future-focused approach to infrastructure adaptation for CAVs and EVs.

8. Applying the Principles

This section provides guidance on how to use the principles identified in sections 5 and 6 to support road and infrastructure planning, design, and evaluation across a range of project types.

A core consideration in applying these principles is to treat CAVs, ADAS, and ADS as legitimate road users. Like human drivers, cyclists, and pedestrians, these systems have distinct capabilities, limitations, and behaviours that road infrastructure should support. This perspective ensures that infrastructure design is proactive rather than reactive to emerging vehicle technologies. It also ensures that roads remain adaptable to a diverse and evolving mix of users.

These principles are designed to function as a *menu-style reference tool* — helping agencies select only what is relevant for their current need, whether for a trial, upgrade, long-term planning, or internal gap analysis. This allows road managers to draw from the same principles flexibly, rather than treating them as a checklist for blanket implementation.

The topic-based principles in sections 5 and 6 provide a flexible toolkit that agencies can apply based on project objectives, local context, and technology readiness. Practitioners may apply the principles as follows:

- **Corridor or precinct planning**

  Agencies can assess infrastructure needs and readiness in defined locations by selecting topic principles that align with intended use cases or future scenarios.

- **Design and procurement**

  Principles may inform physical treatments (e.g. line markings, signage, kerbs), digital system requirements (e.g. SPaT messages, V2X data), or interface specifications within projects wanting to support future vehicle technologies.

- **Gap analysis and risk identification**

  The topic-level principles can help identify infrastructure limitations, policy misalignments, or implementation risks in current or proposed road designs when compared with expected vehicle (and technology) demands using those roads.

- **Support for guideline development**

  The principles provide a foundation for developing or updating agency and/or Austroads guidance and other national frameworks as vehicle technology evolves.

The principles are not intended for blanket implementation. A systems engineering or planning-based approach should be used to determine which principles are relevant for a given context. Implementation should be guided by defined objectives, such as enabling improved real-time safety and traveller information, maximising support for AV operation in selected road environments, supporting EV adoption, or enabling C-ITS messaging in selected corridors; coupled with a realistic understanding of technology maturity. Infrastructure support should only be applied where CAV and EV systems are sufficiently developed or deployed to benefit from it, ensuring that investment is timely, effective, and aligned with readiness.

Application decisions should consider local demand, technology availability, costs, benefits and operational readiness. For example, there is little benefit in deploying roadside C-ITS infrastructure if no compatible vehicles are present, or in allocating kerbside charging if EV uptake is not expected. Selecting and applying only the relevant principles ensures agency resources are targeted, outcomes are aligned to road user needs, and agency infrastructure adapts effectively to changing conditions with optimal resource use.

This helps avoid wasted effort on unnecessary deployments and ensures alignment with real-world user needs and technology conditions.

The application approaches outlined in this section also reflect the broader understanding that agencies will vary in how actively they modify their infrastructure in response to emerging vehicle technologies. This variability is reflected in the *infrastructure support spectrum* introduced in section 2.3.1, which ranges from low-effort adaptations (e.g. improved signage) to more significant upgrades like vehicle-infrastructure communications or redesign of road geometry. Some agencies may choose to focus on foundational changes, while others may invest in advanced infrastructure integrations depending on their goals, resourcing, and level of technology support desired.

Ultimately, the design principles serve as a *scalable toolkit* — a shared menu of physical and digital infrastructure considerations. Agencies can use these principles as needed to support what is relevant to their project scope, context, and role in enabling new vehicle technologies.

Near-term opportunities for application

This subsection identifies near-term opportunities to apply the design principles identified in sections 5 (Physical Infrastructure Topics (PTs)) and 6 (Digital Infrastructure Topics (DTs)) using existing agency approaches. These actions are primarily suited to supporting ADAS, connected vehicles (including C-ITS), and human-operated EVs, while also establishing foundations for increasingly automated vehicles. Each opportunity listed is linked to its corresponding topic area (PT or DT code) for clear reference to the relevant design principles.

Two tables are presented:

- Table 8.1 contains near-term physical infrastructure opportunities
- Table 8.2 contains near-term digital infrastructure opportunities.

Note on topic codes and overlaps:

The examples draw directly from the topic principles introduced in sections 5 and 6. Where near-term opportunities span multiple topic areas, the relevant PT and DT codes have been listed to reflect their shared applicability. This cross-referencing approach provides a mapping to the design principles without duplicating similar actions in multiple rows.

The examples are limited to actions deliverable through existing agency capabilities and do not include long-term design changes or emerging policy recommendations, which are addressed separately in section 9.1.

Table 8.1: Examples of near-term physical infrastructure applications

Physical design topic	Design principles (from section 5)	Near-term opportunities for application
PT2 – Ensuring readability of lane markings and road signage by vehicles	• Design for human and machine vision • Favour consistency over innovation • Prioritise critical use locations • Support with digital redundancy • Maintain visibility under all conditions • Phase implementation based on use and risk	• Incorporate high-contrast edge lines into routine resealing programs. • Replace faded signage with ADAS/AV-camera readable signs. • Prioritise ADAS/AV-camera supportive line marking where high-volumes of camera equipped vehicles are expected. • Ensure consistency between physical signage and digital datasets made available to ISPs. • Eliminate in-pavement visual inconsistencies (e.g. crack seals, longitudinal joints, ghost line marking) during maintenance and pavement design.
PT3 – Ensuring compatible road and traffic design for AV navigation and operations	• Consistent designs • Simple designs • Legible designs • Physical designs complemented by digital infrastructure • Mixed-fleet compatible design	• Assess signal lantern positions to improve ADAS/AV camera visibility during site rebuilds/refits/upgrades. • Apply simplified geometry and line treatments during intersection upgrades. • Ensure AV-interpretable digital datasets made available to ISPs align with physical geometry.
PT6 – Supporting CAV readability of digital roadside signage	• Sensor-aligned visibility standards • Failover-safe message sequencing • Cross-modality redundancy • Standardisation across jurisdictions • Digital–physical synchronisation	• Ensure new/replaced digital signage (e.g. VMS, VSLS) have ≥200 Hz refresh rates for LEDs. • Ensure sign luminance and placement is suitable for ADAS/AV camera-based detection. • Work with sign manufacturers to verify message sequencing/display requirements for VMS messages. • Ensure AV-interpretable and consistent digital datasets made available to ISPs align with roadside signage.

Physical design topic	Design principles (from section 5)	Near-term opportunities for application
PT8 – Kerbside management for AVs (passenger pick-up, drop-off and automated deliveries)	• Use existing human-driven vehicle design guidance as a foundation • Prioritise solutions that address growing demand • Apply time-based management approaches • Leverage digital infrastructure to complement physical access • Ensure physical access points are available, visible, and sufficient • Design for safe passenger and goods exchange • Plan for unstaffed vehicle operations • Support integration of kerbside EV charging into local street environments	• Trial designated pick-up/drop-off zones for ride-hail vehicles as a proxy for future AV operations, using existing signage and time-based access rules. • Use painted markings and standard signs to define stopping zones and time windows, supporting eventual automation of kerbside access and enforcement. • Integrate dynamic time-of-day access rules via smart parking or kerbside apps to test digital coordination mechanisms that will be essential for CAV fleets. • Pilot geofenced staging guidance for delivery vehicles to simulate future automated delivery behaviour and explore integration with navigation platforms. • Design kerbside zones with sufficient space and separation for safe loading activities, anticipating future use by driverless shuttles or unattended delivery bots. • Trial extended dwell times for supervised deliveries to understand operational needs of future unattended services (e.g. AVs without passengers). • Ensure EV charger installations are clearly marked, signposted, and integrated into kerbside designs, supporting visible, accessible EV charging as part of multimodal kerbside use.
PT9 – Minimising urban congestion from AV fleet staging, parking and idle circulation	• Efficient use of kerb and road space • Support physical–digital infrastructure integration • Adaptability and scalability • Design for physical safety and user coexistence • Design to reduce emissions and idle travel • Equitable access to AV infrastructure • Collaborative stakeholder engagement	• Repurpose parking or loading zones for human-driven ride-hail and delivery vehicle staging, using time-based access signage. • Mark and sign designated loading zone time windows in dense commercial or mixed-use areas to avoid kerbside conflict. • Trial integration with kerbside management apps or digital platforms to support access coordination for delivery and service fleets. • Design staging zones with modular layouts to allow future reconfiguration. • Prioritise ride-hail and taxi vehicle staging near high-demand areas to reduce idle travel and minimise congestion. • Ensure trials include sites across a variety of urban areas to support equitable access. • Collaborate with local governments and fleet operators to co-design loading and staging zones and signage strategies.
PT11 – Maintenance and asset management for AV and EV infrastructure	• Design for lifecycle • Enable predictive maintenance • Assign clear ownership • Integrate with asset systems • Design for maintainability • Upskill the workforce	• Include ADAS/AV camera visibility and readability metrics in routine line marking and signage audits. • Add night-time and poor weather reflectivity assessments to condition inspections. • Integrate sign clarity and marking durability into asset renewal prioritisation. • Ensure responsibility for new maintenance and asset management functions are assigned within the agency. • Obtain sensor data from CVs (e.g. degraded line detectability) to assist with sign and pavement marking condition audits. • Ensure staff are trained on added maintenance and asset management requirements.

Table 8.2: Examples of near-term digital infrastructure applications

Digital design topic	Design principles (from section 6)	Near-term opportunities for application
DT1 – Ensuring CAV awareness of temporary and dynamic traffic conditions	• Change it physically, update it digitally • Standardised, machine-readable digital updates • Data quality and metadata management • Digital–physical synchronisation • Technology-neutral data provision • Agency-to-platform provision • Real-time feedback loops	• Publish real-time temporary traffic condition updates (e.g. roadworks, incidents) to ISPs using agency and third-party apps. • Align digital messages with physical signage (e.g. roadwork zones, VMS). • Ensure metadata fields (e.g. timestamps, source, regulatory status) are included in updates. • Use CAV or ISP feedback (e.g. error reports, fallback behaviours) to identify data errors and gaps.
DT2 – Ensuring data accuracy and validation for AV navigation	• Authoritative data ownership and validation • Data provenance and metadata • Standards-based interoperability • Alignment between physical and digital infrastructure • Feedback-driven data maintenance • Performance-based quality metrics	• Implement structured metadata and quality assurance (QA) in agency GIS/asset platforms. • Publish validated digital datasets (e.g. roadworks, speed zones) through Harmonised Access Points (HAPs). • Use AV or probe vehicle reports to identify and validate digital errors.
DT3 – Ensuring reliable CAV communications for continuous data exchange	• Continuous communications backbone • Redundancy through hybrid protocols • Latency-critical local processing • Security-by-design • Interoperability across jurisdictions • Deployment by risk and utility • Data prioritisation and filtering • Fail-safe defaults in coverage shadow zones	• Ensure road designs include communications-ready features such as power supply, conduit, and mounting infrastructure to support future connectivity deployments. • Identify high-priority locations (e.g. tunnels, intersections) where cellular coverage gaps may limit app-based connected traffic and safety data delivery, and work with telecommunications providers to address these gaps. • Support hybrid connectivity models (e.g. cellular network + road infrastructure-based message delivery) to ensure coverage for CAV, fleet, connected vehicle platforms and infotainment systems (e.g. Apple CarPlay, Android Auto).
DT4 – Protecting CAV and transport data from cybersecurity threats	• RSU compromise simulations • AI for threat detection • Cyber-physical integration testing • Security update governance models • Trust frameworks for decentralised infrastructure • Adversarial attacks on sensor fusion	• Apply NIST/ISO-aligned security specifications when procuring digital data provision/exchange systems and connected roadside infrastructure (see also Austroads 2025b). • Require secure OTA update capabilities in digital roadside infrastructure. • Initiate audits of digital asset integrity (e.g. firmware version control, security). • Monitor infrastructure logs for anomalous data or security events.

Digital design topic	Design principles (from section 6)	Near-term opportunities for application
DT7 – Ensuring digital resilience and failover mechanisms for CAV operations	• Digital–physical redundancy • Resilient-by-design infrastructure • AV decision continuity • Failover validation	• Align digital safety and traffic messages (e.g. roadwork speed limits, detours) with physical signage to ensure continuity during connectivity outages. • Ensure digital messages (e.g. lane closures, speed changes) are supported by visible physical signage in areas with poor or no communications connectivity, to maintain continuity for AV/ADAS systems. • Embed failover scenarios into agency business continuity planning and incident response plans (e.g. VSLS or traffic signal malfunction).
DT8 – Improving CAV interaction with emergency vehicles and vulnerable road users	• Emergency vehicle priority by design • Support for human–road user communication • Infrastructure-augmented VRU detection • Interoperable priority data feeds	• Enable real-time emergency vehicle approaching alerts (EVA) to connected vehicles using third-party platforms (e.g. Apple Maps, Waze). • Trial traffic control systems-to-connected vehicle platform data integration to deliver incident-based rerouting to connected vehicle operators.
DT9 – Optimising CAV and EV fleet management and staging	• Digitally managed staging zones • Demand-responsive dispatch • Digital–physical kerb integration • Time-windowed optimisation • Interoperability by default • Govern data	• Support use of app-based geofencing tools to manage staging for human-operated fleets, including ride-hail and EVs. • Pilot real-time access windows using signage and dynamic allocation platforms for commercial and delivery fleets. • Align physical zone design with digital access rules (e.g. signage, time limits, enforcement zones).
DT10 – CAV and EV integration into smart city and traffic management platforms	• Standardised data interfaces • Real-time operational responsiveness • Two-way vehicle–infrastructure communication • Policy-aligned routing integration • Agency–industry data coordination	• Integrate vehicle-derived probe data (e.g. speed, congestion, hazard events) into traffic control platforms (e.g. SCATS, STREAMS) to enhance situational awareness. • Begin aligning agency data systems with TMDD/DATEX II or other traffic data standards to support future two-way CAV coordination. • Trial simple feedback mechanisms using connected vehicle alerts (e.g. Waze, ISP apps) to adjust traffic signal timing or incident response.
DT11 – Ensuring real-time EV charging availability and status updates	• Open Data Access by Design • Real-Time Data Availability System Interoperability Through Open Protocols • User-Relevant Granular Data • Structured Data for Platform Integration • Public Data Infrastructure Enabeent	• Mandate real-time OCPI/OCPP-compatible feeds for publicly funded EV chargers. • Require EV charger data feeds to include status, connector type, access constraints, and power output. • Integrate public charger data with ISP routing/navigation platforms and agency traffic control/management systems.

9. Conclusions and Recommendations

This section presents overarching conclusions and strategic recommendations based on the design principles outlined across the 24 physical and digital infrastructure topic areas. These findings support road agencies in planning and designing infrastructure that is compatible with emerging technologies, including AVs, CAVs, EVs, ADAS, and C-ITS.

This report looked at the key challenges, road and infrastructure considerations and related topics for each physical and digital infrastructure topic area to derive a set of respective principles. As such, 135 design principles were identified throughout this report, demonstrating that many infrastructure improvements are required to support emerging vehicle technologies. These can be achieved using current programs, standards, and practices. Near-term opportunities as summarised in section 8, highlighting how agencies can begin applying supportive treatments in the near term while laying the groundwork for more advanced vehicle technologies.

As these transport technologies continue to evolve, it is essential that infrastructure investments embed future-ready principles and that agencies adopt adaptive planning approaches. This report offers a nationally consistent, evidence-based foundation to support the transition toward a safe, resilient, and adaptable network for both human drivers and increasingly automated and connected vehicles.

However, realising these objectives requires a staged and risk-managed approach to guidance development. Some areas are ready for immediate development, while others will require targeted future research to underpin safe and effective guidance.

9.1 Recommendations for guidance development and research priorities

This subsection identifies priority areas where Austroads should develop formal guidance to address gaps in current infrastructure practice, specification, and policy coverage. These guidance opportunities are grouped into two categories:

- Section 9.1.1, Guidance Development Opportunities: Areas where Austroads can proceed with formal guidance development based on existing evidence, international practice, or adaptations of current Australian standards.
- Section 9.1.2, Future Research Priorities to Enable Guidance Development: Areas where further investigation, piloting, or technology validation is required before safe and effective guidance can be confidently developed.

To ensure a safe, scalable, and nationally consistent transition toward CAV- and EV-compatible infrastructure, Austroads and its member agencies should use the content in this subsection to:

- prioritise immediate development of guidance in areas where sufficient evidence already exists
- initiate a coordinated research program targeting critical evidence gaps that currently prevent responsible guidance development
- embed adaptive review cycles into all guidance to allow updates in response to evolving technology and operational experience
- coordinate international engagement to align emerging Australian and New Zealand guidance with best practice developments from regions such as Europe, North America, and Asia
- maintain strong agency and industry consultation during research and guidance development to ensure operational practicality and national harmonisation.

This staged approach will ensure that infrastructure guidance remains evidence-based, future-ready, and trusted by both agency and industry stakeholders.

9.1.1 Guidance development opportunities

This subsection summarises the priority guidance topics that can be developed based on current knowledge. These include areas such as pavement and line marking standards, digital roadside signage, communications-ready infrastructure, and governance frameworks for digital road data to support current and near-term vehicle characteristics. The guidance areas are presented in two tables:

- Table 9.1 - Physical Infrastructure and Road Design: Identifies gaps in line marking, surface treatments, signal visibility, signage, fallback design, safety assessments, EV charger zone design, and kerbside access. These also include addressing selected digital topics where they are complementary in nature.
- Table 9.2 - Digital Infrastructure, Data and Governance: Highlights areas needing structured guidance for machine-readable rules, data provision, data governance, and cybersecurity.

The recommendations are intended to guide both immediate and long-term planning. Each item references relevant topic areas from sections 5 and 6, and includes suggested review cycles to align with technology maturity and operational deployment timelines.

Table 9.1: Physical infrastructure and road design guidance development opportunities

Guidance area	Relevant topic	Guidance gap or limitation	Suggested review cycle
Line marking and signage standards for ADAS/AV readability	PT2	Guidance can proceed for minimum line marking width, dry retroreflectivity, and static signage placement to support ADAS/AV system readability. Further research is needed for wet visibility, contrast thresholds, and temporary works readability.	Initiate development within 1–2 years; review every 3–5 years.
Physical traffic signal design for ADAS/AV readability	PT2	Guidance can proceed for LED refresh rates and basic placement standards. Further research needed for mounting height optimisation, fallback visibility in occluded conditions, and dynamic environment handling.	Initiate development within 1–2 years; review every 2–3 years.
Digital roadside signage design standards for ADAS/AV readability	PT3, PT6	Immediate guidance can proceed for minimum luminance, refresh rates, placement, and symbol consistency for permanent electronic signs (e.g. VSLS, LCS). Further research is needed to optimise dynamic messaging formats and fallback readability under variable conditions (e.g. portable and vehicle-mounted VMS and VSLS in roadwork zones).	Initiate development within 1–2 years; review every 3–5 years.

Guidance area	Relevant topic	Guidance gap or limitation	Suggested review cycle
Temporary traffic guidance schemes for ADAS/AV compatibility (partial)	PT1, PT2, DT1	Partial guidance can proceed for temporary sign placement, visibility standards, and removal of redundant markings to ensure machine readability. Further research is needed to optimise full temporary traffic guidance layouts and ensure reliable ADAS/AV interpretation in complex work zones.	Initiate development within 1–2 years; review every 3–5 years.
Communications-ready infrastructure for new projects	PT6, DT3, DT4	No guidance to embed communications infrastructure (e.g. RSU mounting points, power, fibre) into new builds or corridor upgrades.	Initiate development within 1–2 years; review every 3–5 years.
Kerbside access, coordination, and fleet staging	PT8, PT9, DT9	No coordinated guidance for kerbside use across CAV and non-CAV fleets, public transport, micromobility, or general access control; includes gaps in staging zone design and geofencing.	Initiate development within 1–2 years; review every 2–3 years.
EV charger zone design and recognition standards	PT9	No national guidance on consistent signage, kerbside placement, or layout for public EV chargers to support accessibility, visibility, and wayfinding for human-driven EVs and routing systems.	Initiate development within 1–2 years; review every 3 years.
Audit-style ADAS/AV route and infrastructure safety assessment (as an extension to road safety audits)	PT2, PT3, PT11, DT1, DT2, DT5, DT8	Traditional road safety audit and inspection processes do not address CAV-specific risks, including digital infrastructure presence, signage-machine alignment, and transitional ODD boundaries. An audit tool or checklist will help evaluate routes for CAV suitability, especially in trials or early deployment situations.	Commence development now; review every 3–5 years.

Table 9.2: Digital infrastructure, data and governance guidance development opportunities

Guidance area	Relevant topics	Guidance gap or limitation	Suggested review cycle
Digital road data, rules and access signage harmonisation	DT1, DT2, DT5, DT12	No national schema, certification process, or update model for machine-readable traffic rules, regulatory signage, hazard alerts, or road access logic.	Initiate development within 1–2 years; review annually.
Dynamic traffic regulation encoding and update governance	DT5	No guidance exists on managing lifecycle, validity, and semantic structure of digitally encoded traffic rules (e.g. dynamic speed zones, event-based restrictions). No national metadata framework for rule confidence, time applicability, or geofencing.	Initiate development within 1–2 years; review every 2–3 years.
Digital road data validation, metadata and lifecycle governance	DT2	No nationally consistent workflows for validating road geometry, regulatory overlays, or metadata (e.g. timestamp, version, source authority). Agencies lack lifecycle governance frameworks for data maintenance, certification, or cross-jurisdiction consistency.	Initiate development within 1–2 years; review every 2–3 years.
Publishing validated digital road data via HAP	DT2, DT12	No consistent national approach for publishing certified datasets (e.g. roadworks, speed limits, regulatory signs) to a Harmonised Access Point (HAP) for use by ISPs and OEMs. Requires definition of schema, metadata standards, and agency publishing responsibilities.	Initiate development within 1–2 years; review every 2–3 years.
Ownership and governance of digital infrastructure layers	DT12	No clear agency accountability for maintaining digital rules, regulatory overlays, access zones, and update schedules.	Initiate development within 1–2 years; review every 3 years.

9.1.2 Future Research to Inform Guidance Development

While several road and infrastructure design areas have been identified as ready for near-term guidance development in section 9.1.1, other areas require further research before guidance can be produced. These research priorities are summarised in Table 9.3 and are drawn from the topic analyses in sections 5 and 6. The table highlights key research areas that should be addressed to support the next phase of infrastructure evolution for automated, connected, and electric vehicles.

Note that lower-priority research topics identified across sections 5 and 6, such as emerging micromobility coordination models, evolving RSU hardware improvements, and signage material resilience trials are acknowledged. However, these can be monitored and incorporated into future Austroads research programming as appropriate.

Table 9.3: Future research priorities to inform guidance development

Future guidance area	Relevant topics	Research focus	Reason
AV-compatible geometric road design	PT3, PT5	Validation of AV-specific curve radii, SSD/DSD parameters, gradient transitions, and merge/lane drop treatments.	Current road standards based on human drivers; safety-critical to validate CAV requirements.
AV sensor visibility and perception thresholds	PT2, PT5, PT6	Empirical studies on AV perception performance for signs, markings, and signals under adverse weather, low light, and glare.	No nationally agreed sensor visibility thresholds yet exist.
Crash barrier suitability for EVs	PT10	Research into crash performance of existing W-beam, concrete, and wire-rope barriers for heavier EVs and light trucks.	Current crash barrier designs based on lighter legacy vehicle fleets; impact performance for heavier EVs remains uncertain.
Pavement resilience under increased EV loading	PT4	Research into pavement wear patterns, maintenance cycles, and structural resilience under heavier EV axle loads and lane discipline patterns.	Existing pavement designs are based on legacy vehicle fleet loads; increased EV mass and different loading patterns may accelerate wear and require adaptive maintenance strategies.
Automated vehicle control fallback and handover infrastructure design	PT1, DT7	Concept development and trials for degraded-mode zones, ODD exits, emergency pullover zones, and signage integration.	No existing national designs or best practice templates.
Emergency Vehicle Priority (EVP) and CAV interaction	DT8, DT13, DT4	Development and field testing of standardised C-ITS messaging for emergency vehicle alerts and pre-emption behaviour.	No operational standards yet set nationally.
Infrastructure support for AV/ADAS and GNSS-dependent vehicle positioning resilience	PT2, DT2, DT12	Research into enabling reliable AV/ADAS positioning in GNSS-constrained areas (e.g. tunnels, urban canyons) using infrastructure-supported methods like surveyed signage, high-contrast markings, and BLE beacons.	GNSS signal weakness affects AVs, ADAS-equipped vehicles, and navigation-reliant human-driven vehicles.
Connected vehicle–platform data integration to support traffic control	DT10	Pilot two-way data exchanges between CAVs and agency traffic management platforms (e.g. SCATS, STREAMS).	Models (TM2.0, NAPCORE) still evolving; need local validation.
Digital augmentation of physical infrastructure	DT3, DT4	Trials of V2X broadcast overlays and CAV-readable infrastructure messaging to supplement physical signs, signals, and road markings.	Deployment models for V2X augmentation are immature; operational validation is needed to ensure safety and redundancy in mixed-fleet conditions.

Future guidance area	Relevant topics	Research focus	Reason
Machine-readable messaging for VMS	DT1	Field validation of optimal dwell times, sequencing, and fallback text/image formats for ADAS/AV camera interpretation.	Lack of local studies that validate camera readability standards for dynamic VMS.
SPaT/MAP message deployment	DT13	Trial deployments to validate lane mapping logic, RSU upgrades, prioritisation messaging quality (e.g. public transport, EVP).	No coordinated national deployment or validation of SPaT/MAP for CAV use.
Cybersecurity, message integrity, and credential governance	DT4	Design and testing of SCMS/PKI credential frameworks, OTA lifecycle updates, anomaly detection protocols for RSUs and digital systems.	National approach not determined; critical for CAV trust and safety in certain use cases.
EV charger data interoperability	DT11	Research into harmonised metadata fields, standard APIs (e.g. OCPI), and availability feed consistency.	Deployment fragmentation across jurisdictions; user trust and EV routing rely on data.
Safety data feedback loop for CAV infrastructure performance	PT1, PT2, PT5, DT1, DT2, DT10	Develop a structured, nationally coordinated feedback loop to collect, analyse, and respond to real-world safety and performance data from CAV operations — including AV disengagements, hesitation events, fallback manoeuvres, and machine perception failures linked to road design or digital infrastructure.	Enables evidence-based infrastructure improvement and adaptive design standards. Supports cross-topic validation of physical and digital treatments, aligned with international safety assurance frameworks

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Appendix A Relevant CAV and EV Infrastructure Guidance

This appendix tabulates key publications reviewed to identify relevant infrastructure guidance for CAV, AV, EV, ADAS, and C-ITS systems produced by Austroads, Australian and New Zealand jurisdictions. These documents contain varying levels of design-related insight, from strategic intent to infrastructure considerations and technical specifications.

Table A.1: Relevant Austroads publications

Title	Date published	Category	Summary	Relevance to road and infrastructure design	Design guidance present
Zero Emission Heavy Vehicles and Road Pavements	Feb 2025	EV	Pavement implications for heavy EVs	Relevance to road materials and asset design	Yes
Minimum Requirements for Traffic Signs, Traffic Signals and Line Markings	Oct 2023	CAV	Design principles for signs, lines, and signal infrastructure	Physical infrastructure recommendations	Yes
Preparing for Connected and Automated Vehicles: Resources for Local Government	Jun 2024	CAV, ADAS	Guidance for councils on CAV planning, including infrastructure and land use	Physical and digital infrastructure actions	Yes
Guidelines for Trials of Automated Vehicles in Australia	Sep 2023	AV	Requirements for trial participants	Trial context only	No
Best Practice in Smart Motorways Operations	Mar 2023	CV	Focus on operations, with mention of C-ITS	Conceptual relevance only	No
Standardised Signage and Pavement Symbols for Low and Zero Emission Vehicles	Dec 2022	EV	Iconography and signage for EV bays	Road user information design	Yes
Guidelines for Low and Zero Emission Vehicle Charging Infrastructure Installation	Sep 2022	EV	Planning, design, installation, and decommissioning of EV chargers	Focus on charger infrastructure design	Yes
Supporting Cloud Connected Road Users	Jun 2022	CV	Agency-side support for data delivery to vehicles	Digital infrastructure guidance	Yes
Minimum Physical Infrastructure Standard for Operation of Automated Driving	Jan 2022	CAV	Infrastructure upgrades for safe AV operations	Line marking and geometry guidance	Yes
Agency Business Capability Model to Support Connected Vehicles	Jan 2022	CV	Capability model for data and system readiness	Focus on digital capability, not design	No
Road Authority Data for Connected and Automated Vehicles (RADCAV) – Modules 1–8	Dec 2021	CAV	Data types and quality measures for digital AV support	Strong relevance to digital readiness	Yes

Title	Date published	Category	Summary	Relevance to road and infrastructure design	Design guidance present
Future Vehicles Forecasts Update 2031	Sep 2021	CAV, EV	Uptake forecasts for planning	Contextual only	No
Implications of Pavement Markings for Machine Vision	Sep 2020	AV, ADAS	Marking design and visibility for machine vision	Some operational guidance	Partial
Guidance and Readability Criteria for Electronic Signs	Aug 2020	CAV	AV camera readability of electronic signs	Some implications for sign placement	Partial
Future Vehicles 2030	Jun 2020	CAV, EV	Technology uptake and policy implications	Context only	No
Assessment of Road Operator Actions to Support EVs	Feb 2020	EV	Strategic actions for road operators	Action recommendations, not standards	No
Infrastructure Changes for Automated Vehicles – Modules 1–5	Nov 2019	CAV	Line marking, signage, and connectivity audit	Field-based recommendations	Yes
Evaluation of the European C-ITS Platform	Oct 2018	C-ITS	Security risk model for DSRC	Relevant to DSRC-based infrastructure	Potentially
C-ITS Compliance Assessment Framework	Oct 2018	C-ITS	CAF review for AU/NZ	Strategic only	No
Operations of Automated Heavy Vehicles in Regional Areas	Aug 2018	AV	CAV infrastructure findings for heavy freight	Highlights road needs	Potentially
CAV Open Data Recommendations	Aug 2018	CAV	Strategic open data and digital exchange	Influenced later guidance	Potentially
Implications of TSR for Road Operators	Aug 2018	ADAS	AV/ADAS camera performance on signs	Some visual and format guidance	Potentially

Table A.2: State, Territory and Local Government Strategies and Guidance Related to CAV and EV Infrastructure

Jurisdiction	Document title	Year	Scope/focus	Design-related content
Australia (National)	Principles for a National Approach to C-ITS	2024	Cooperative ITS, interoperability, national consistency	High-level guidance on data exchange and digital infrastructure alignment
	Commonwealth EV Charging Infrastructure Standards (DCCEEW)	2024	Minimum operating standards for public EV chargers	Includes real-time data visibility and accessibility requirements
NSW	NSW CAV Readiness Strategy	2022	CAV readiness and infrastructure planning	Covers physical and digital infrastructure needs (e.g. C-ITS, lane markings, 5G)
	NSW Electric Vehicle Strategy	2021	EV uptake and infrastructure rollout	Includes charging network deployment and support programs
	NSW EV Charging SEPP Guidance	2024	EV charging units in planning controls	Supports integration of EV infrastructure in development assessments

Jurisdiction	Document title	Year	Scope/focus	Design-related content
Queensland	Cooperative and Automated Vehicle Initiative (CAVI)	2018–2022	Pilots, trials, and infrastructure development	Field trials, digital infrastructure testing (e.g. ICVP use cases and specifications)
	Ipswich Connected Vehicle Pilot (ICVP) Specifications	2020	Technical standards for V2X deployment	Includes detailed infrastructure, system architecture, and message protocol design
	Road Safety Strategy 2022–31	2022	Safe system and future mobility planning	References C-ITS and digital infrastructure roles in safety
Victoria	Victoria’s Zero Emissions Vehicle Roadmap	2021	EV rollout and policy	Includes infrastructure needs for EV access and regional availability
	Infrastructure Strategy 2021–2051	2021	State-wide infrastructure planning	Highlights need for adaptable design standards and infrastructure flexibility
Western Australia	State Infrastructure Strategy	2022	Long-term transport infrastructure trends	Recognises integration of CAV and EV needs by 2032
South Australia	20-Year State Infrastructure Strategy	2020	Future mobility and AV integration planning	Recommends infrastructure flexibility and alignment with future tech uptake
New Zealand	NZ Long-Term Insights Briefing – AVs on NZ Roads	2022	AV impacts and infrastructure needs	Identifies physical and digital readiness gaps; recommends practical interventions
	EVRoam and NZTA EV Guidance	2024	Real-time EV data and charger deployment	Supports open data, charger metadata, and access consistency
Local government examples	City of Parramatta – EV Charging Guidelines	2022	Infrastructure deployment on council land	Contains practical layout and planning conditions
	Hornsby Shire Council – EV Charging Guidance	2024	Local deployment and signage	Supports council-level charging deployment and coordination

Appendix B Consultation Findings

This appendix contains results of the consultation workshop.

B.1 Physical infrastructure design challenges raised by agency representatives

Table B.1: Physical infrastructure design challenges raised by agency representatives

Road and infrastructure design category	Physical infrastructure challenge identified	Author interpretation of the challenge	Relevance to road and infrastructure design
Vehicle design and road standard implications	Design vehicle changes (e.g. weight, skid resistance, curve radii impacts)	EVs and AVs have different weight distribution and handling, requiring potential updates to road design standards.	Relevant – Road geometry, surface material selection, and safety barrier standards may need adjustments.
	Larger, heavier vehicles (including EVs) breaching road safety barriers	Safety barriers may need reinforcement to account for the increased momentum of heavier EVs.	Relevant – Barrier design specifications must be updated to handle increased impact forces.
	Impact of heavier electric vehicles on safety and road structures	Bridges and pavements may need reinforcement due to increased axle loads from EV batteries.	Relevant – Structural load limits for roads, pavements, and bridges may require revisions.
	Impact of width of electric vehicles on road design aspects	Lane widths, parking bays, and intersection clearances may require adjustments to accommodate wider EVs.	Relevant – Standard lane width and intersection designs may need to be reviewed.
Road safety and visibility challenges	Vehicle blind spots and lack of direct vision	Larger vehicle blind spots raise safety risks at intersections; improved vehicle technology and road design adjustments may be needed.	Relevant – Road design elements such as intersection layouts, mirror placement, and visibility requirements must be considered.
	Identifying bikes and micromobility devices (e.g. scooters)	AV sensors struggle to detect smaller road users. Better road markings and C-ITS integration may help.	Relevant – Road markings, signage, and C-ITS integration may need adjustments to improve detection.
	School and other zones with more than just speed limit being recognised	AVs must detect hazards beyond speed signs, requiring enhanced visual cues in school and pedestrian zones.	Relevant – Additional road markings, flashing signals, and pedestrian warning systems may be needed.
	Guidance on pedestrian crossings and pedestrian refuge	AVs may require clearer pedestrian zones and adjusted crossing designs to ensure safety.	Relevant – Crosswalk design, refuge islands, and pedestrian detection measures may need enhancement.
	Where on-road cycleways and kerb ramps are located/start or end	Clearer standards may be needed for AVs to correctly interpret cycleway start/end points.	Relevant – Cycleway design and integration with AV-readable infrastructure may need updates.

Road and infrastructure design category	Physical infrastructure challenge identified	Author interpretation of the challenge	Relevance to road and infrastructure design
	Cost of implementing infrastructure to control vehicle speeds at conflict points with people walking and cycling	Establishing raised crossings may require drainage enhancements, which can be costly. Could C-ITS and Intelligent Speed Adaptation (ISA) reduce the need for infrastructure modifications?	Relevant – Road design may need to consider alternative solutions like C-ITS or ISA to reduce physical modifications.
Pavement markings, road signs, and traffic control devices	Ghost lines when road marking is wiped out	AVs may misinterpret faded/removed markings, requiring better removal techniques or AV software improvements.	Relevant – Pavement marking removal techniques must be improved for AV compatibility.
	Vienna convention on road signs for ADAS systems (e.g. no text under speed signs)	Signage may require alignment with ADAS system needs for better automated recognition.	Relevant – Signage should comply with human standards but remain consistent and clear to support ADAS recognition.
	Line marking requirements for ADAS in a new motorway	Standardisation needed for AV-readable line markings (width, contrast, reflectivity).	Relevant – Standardised lane markings improve AV performance and lane-keeping capabilities.
	What line marking width and retroreflectivity standard is needed for the design vehicle?	AVs may require higher retroreflectivity and consistent widths for accurate lane following.	Relevant – Retroreflectivity and line marking width should be optimised for AV sensors.
	Traffic signal lantern backing board standard	AVs rely on contrast for signal recognition; backing board visibility may need adjustments.	Relevant – Signal design should improve visibility for both human drivers and AVs.
	Poor line marking removal causing multiple visible lines in wet/sunny conditions	Human and AV drivers may struggle with unclear markings, requiring better line removal processes.	Relevant – Line removal must ensure clarity in various weather conditions for both AVs and humans.
	Refresh rate on VMS meant the signs cannot be read by cameras on vehicles	Slow refresh rates on Variable Message Signs (VMS) may prevent AVs from capturing full messages.	Relevant – VMS technology and refresh rates should be standardised for AV readability.
	Currently looking into the impact of wide centre-line markings on vision systems	AV camera and LiDAR systems may struggle with certain road marking styles, requiring evaluation.	Relevant – Road marking standards should consider AV perception requirements.
Resilience and reliability of roadside infrastructure	Impacts of vandalism. Ensure robust and fail-proof infrastructure	Tamper-resistant roadside sensors, C-ITS devices, and vandal-proof designs may be needed.	Relevant – Roadside technology must be designed to resist tampering and vandalism.
	Long maintenance time to reinstate ITS infrastructure	Prolonged ITS downtime can impact AV functionality. Faster maintenance protocols are needed.	Relevant – ITS infrastructure should be designed for quick repair and replacement.

Road and infrastructure design category	Physical infrastructure challenge identified	Author interpretation of the challenge	Relevance to road and infrastructure design
Digital and connected infrastructure considerations	Network and communication coverage across the network	Rural and remote areas lack connectivity, affecting AV and C-ITS functionality.	Relevant – Roadside infrastructure planning should include considerations for network coverage.
	C-ITS technology to support CAVs	Roadside C-ITS infrastructure to support Vehicle-to-Infrastructure (V2I) communication.	Relevant – Space and location for roadside C-ITS units.
Interactions with level crossings	Level crossings (non-separated or unprotected)	AVs may struggle to detect and respond to railway crossings without clear infrastructure cues.	Relevant – Railway crossings may need AV-friendly visual and sensor-based enhancements.
Active transport hub interactions	Transport interchanges with higher active transport use and buses	Interchange designs must integrate AVs with buses, cycling lanes, and pedestrian traffic.	Relevant – Road infrastructure should support mixed mobility interactions, including AVs.
Policy and governance considerations	Lack of standards for determining safety of AVs	Road-based infrastructure criteria for AV safety assessments are currently lacking.	Relevant – Safety assessment standards should include road-based AV performance metrics.
	Government’s lack of role in CAV and EV deployment	Stakeholders perceive a lack of clear government strategy for supporting infrastructure.	Not Relevant – Government CAV/EV policy is not a road design principle.
	Guidance required on how to ensure accuracy of information provided by infrastructure	Clearer methodologies are needed for ensuring the reliability of digital and physical infrastructure data.	Relevant – Infrastructure data quality standards should be developed to support AV decision-making.

B.2 Digital infrastructure design challenges raised by agency representatives

Table B.2: Digital infrastructure design challenges raised by agency representatives

Road and infrastructure design category	Digital infrastructure challenge identified	Author interpretation of the challenge	Relevance to road and infrastructure design
Data collection, sharing, and standardisation	Roadworks: Collecting and sharing detailed, quality, real-time data	Ensuring accurate, up-to-date roadworks data is available for CAVs and other digital systems.	Relevant – Real-time roadwork updates should match physical road elements (e.g. signage, lane closures, detours).
	Road disruptions: Collecting and sharing detailed, quality, real-time data	Providing accurate and timely digital representations of physical road disruptions, such as incidents.	Relevant – Disruptions (e.g. flooding, crashes) must be reflected in digital systems and matched with physical road barriers, signage, and lane guidance.
	Standardisation of data and quality validation for sharing with industry	Establishing common data formats and validation protocols for reliable industry-wide data use.	Relevant – Standardised data ensures road infrastructure effectively supports CAV operations.
	Digital representation of physical disruptions (e.g. flooding)	Improving how real-world disruptions are reflected in digital roadmaps and navigation systems.	Relevant – Road design should accommodate sensors and signage to support digital mapping of disruptions.
Connectivity and system resilience	Connectivity in remote areas	The operation of CAVs in regional areas may be impacted by available mobile connectivity and digital infrastructure.	Partially Relevant – Road design and transport infrastructure deployments should include consideration of telecom equipment (e.g. roadside units, C-ITS) issues during the planning stages. Also noting that network coverage is a telecommunications policy issue.
	Telecommunications network outages	Assessing the impact of major telecommunications failures on CAVs and digital traffic management systems.	Not Relevant – Network resilience is an IT and telecom issue, not a road design principle.
	Ensuring strong enough mobile coverage to enable CAVs	Involving telecommunication companies in road planning to support future mobility needs.	Partially Relevant – Road planning should account for infrastructure to support telecom integration but does not dictate network coverage.
	A strong digital connectivity backbone to support CAVs and EVs	Without robust digital infrastructure, the full benefits of CAV and EV applications may not be realised.	Partially Relevant – Roadside infrastructure should support connectivity such as C-ITS, but the core network is a telecom issue.
	Regional locations miss out on key opportunities due to poor coverage or low benefit-cost ratio (BCR) based on use/population	Improving digital infrastructure access in regional areas to prevent economic and technological disadvantages.	Not Relevant – This is a policy and telecom infrastructure issue, not a road design concern.

Road and infrastructure design category	Digital infrastructure challenge identified	Author interpretation of the challenge	Relevance to road and infrastructure design
Policy, governance, and privacy concerns	Protocols for open information sharing between agencies and CAVs	Defining rules and frameworks for secure and effective data exchange between agencies and CAVs.	Partially Relevant – Road agencies need structured CAV data, but this is a governance issue, not a road design principle.
	Privacy concerns surrounding the sharing of CAV location data	Ensuring location tracking policies balance safety benefits with privacy rights for vehicle owners and users.	Partially Relevant – Privacy is important for CAV data exchange systems, but privacy policy relates to governance.
	Vehicle manufacturers' willingness to share vehicle-generated data (VGD) with government (and consumer concerns)	Clarifying whether and how VGD can be shared with government agencies for transport management.	Relevant – Data sharing arrangements will influence how agencies design and operate digital infrastructure (e.g. data exchange platforms, and V2X integration).
	Government’s lack of role in CAV and EV deployment	Stakeholders perceive an unclear government strategy for integrating digital infrastructure for future mobility.	Not Relevant – This is a transport policy concern, not a road design issue.
	Cybersecurity of remote data sharing and access	Mitigating risks associated with remote access to traffic data, CAV networks, and government digital platforms.	Relevant – Cybersecurity is important for ITS and C-ITS devices and affects how supporting infrastructure is implemented.
	Policy required on how to manage traffic (e.g. vehicle priority system)	Defining policies for how CAVs interact within traffic management frameworks.	Partially Relevant – Traffic management systems need to support CAVs, but operations management is not part of road design principles.
Digital Applications for Transport Safety and Management	Understanding what digital applications are actually useful for industry advancements in safety technologies	Identifying which emerging digital applications provide tangible safety benefits to road users.	Partially Relevant – Road design should ensure integration with useful digital safety applications but does not control their development.
	Using mobile phones as a V2X device. Security, latency, and accuracy concerns	Ensuring C-ITS applications that use mobile phones provide accurate and reliable safety alerts to road users.	Relevant – Phone-based transport technology needs to integrate into the CAV digital environment.
	VMS and vehicle onboard CCTV recognition	Evaluating how vehicle cameras interpret VMS and whether current standards support AV recognition.	Relevant – Roadside VMS placement, size, contrast, and refresh rates must align with AV readability needs.
	Impacts of digital infrastructure system failure. Mitigations for failure	Developing contingency plans for digital transport systems in case of cyberattacks, data outages, or software failures.	Partially Relevant – Important aspects, but system redundancy is primarily an IT/network issue.
	Interruptions to signal sequence (Heavy Rail/Emergency Vehicle Priority (EVP)) needed for accurate signal timing	Ensuring accurate traffic signal phasing, particularly for emergency vehicles and rail crossings, within CAV systems.	Relevant – Road design should ensure traffic management systems and traffic signals interact properly with CAVs and emergency vehicle priority systems.
	EV charging locations – may be on map but current use and status not live	Enhancing real-time EV charger availability and status updates for navigation systems.	Relevant – Placement and signage for EV charging stations should be incorporated into road design.

B.3 Physical infrastructure design priority topic areas

Table B.3: Summary of physical infrastructure design topics of most interest to stakeholders

Topics areas of interest	Topics identified
Road safety and risk management	Road Safety Measures for Automation (5 votes): Investigate design adaptations to accommodate AV interactions with vulnerable road users, including safe pedestrian crossings (including koala crossing time), bicycle road use integration (including on-road use and lanes interaction).
	Redundancy for System Failures (4 votes): Explore physical infrastructure requirements to support safe fallback modes for automation (e.g. clear stopping areas, reliable roadside signage, redundant traffic control measures, low lighting).
	Micromobility and Vulnerable Road Users (5 votes): Assess design needs for safely integrating bicycles, e-scooters, prams, wheelchairs and other personal mobility devices into AV-adapted road environments.
	Safe System and Road-Based Risk Management Approaches (6 votes): Investigate how road-based safety frameworks such as Safe System principles, infrastructure risk assessments, and automation-adapted safety measures can inform physical infrastructure design for AVs. Originally, Safety Integrity Levels (SIL) were raised as a priority (6 votes), but SIL relates to functional safety in electronic and software systems, not physical road design. It is used to assess failure probabilities in safety-critical control systems (e.g. automated braking, signal control). Thus, to better align with infrastructure considerations, the topic has been reframed to focus on road-based safety risk management approaches more relevant to AV infrastructure, such as Safe System thinking, infrastructure redundancy, and risk-based design responses to AV–road user interactions.
Road and traffic design for automation	Road and Traffic Design for Automation (5 votes): Investigate AV-specific design considerations, such as lane widths, intersection design, and separation treatments.
	Safe Harbour Zones (3 votes): Determine spatial and operational needs for automated vehicle stopping zones in various road environments.
	Operating Speed Model in an Intelligent Speed Adaptation World (3 votes): Identify design implications of variable speed enforcement and adaptable speed management.
	AV Prioritised Treatments (2 votes): Investigate dedicated lanes for AVs, including consideration of capacity and congestion impacts.
	Physical Hacking/Mistakes of Signs/Lines (2 votes): Identify situations such as removal/ vandalism that confuse AVs.
Pavement and structural considerations	Lane-Keeping Wear Patterns (4 votes): Assess how automated lane discipline affects pavement wear and whether new materials or maintenance strategies are required.
	Pavement Design for EVs (3 votes): Investigate weight distribution, braking performance, structural and road surface friction needs for increasing EV adoption.
Traffic signal systems and connected infrastructure	Ambiguities in Traffic Signals (4 votes): Standardise treatments for hook turns, U-turns, and signal phasing variations to improve AV recognition.
	CAV Feedback into Traffic Signal Systems (4 votes): Investigate integration methods for real-time vehicle-to-signal communication to optimise network efficiency (including predictions).
	Traffic Signal Security (4 votes): Identify infrastructure-based cybersecurity protections for signal priority and data integrity.
	Digital-Physical Sign Synchronisation (4 votes): Consistency of digital VSLS/VMS/other message signs with physical counterparts.
	Temporary Road Restrictions (3 votes): Providing access to temporary and permanent road restrictions data to Vehicles: e.g. weight, height.
Lane markings and roadside infrastructure	Standardisation of Line Markings (4 votes): Determine minimum reflectivity, width, and durability standards for AV detection consistency.
	Feedback Loops for Lane Marking Issues (3 votes): Identify best practices for maintaining AV-compatible markings and addressing reported inconsistencies.

Topics areas of interest	Topics identified
Land use and transport planning for AVs	Kerbside Management (3 votes): Evaluate spatial design considerations for AV pick-up/drop-off zones in high-demand areas.
	AV Operation Zones and Transition Points (2 votes): Define requirements for safe transition areas between L4 AV-permitted and restricted zones.
	Vehicle parking areas (4 votes): Identify impacts on parking demands due to AV fleets.
Other Intelligent Transport Systems (ITS) and C-ITS Integration	Roadside C-ITS Infrastructure (2 votes): Explore placement and standardisation of roadside communication units in road design projects.
	Backbone Communications Infrastructure within road projects (2 votes): Identify physical infrastructure needs for supporting V2X connectivity.
	Does C-ITS rollout timeframe impact economic justifications? (3 votes): Consider whether upcoming C-ITS safety improvements could weaken the economic case for traditional road upgrades (e.g. barriers, hazard removal, grade separation) by reducing their useful life or safety benefits.
Other EV considerations	Tunnel fire safety for EVs (2 Votes): It is noted that this topic is being addressed by another Austroads project so is excluded from further investigation and discussion in this report.
Maintenance and asset management for future mobility	Traffic Device and Road Maintenance (5 votes): Determine AV-specific requirements for road maintenance, new technology maintenance, pothole detection, and signage legibility.
	Ownership and Responsibilities for New Asset Types (5 votes): Identify requirements for maintenance and asset management of new infrastructure supporting AVs and C-ITS.

B.4 Digital infrastructure design priority topic areas

Table B.4: Summary of digital infrastructure design topics of most interest to stakeholders

Topic areas of interest	Topics
Communications Networks	Communications Systems Supporting Data Exchange (5 votes): Investigate requirements for interoperable, high-reliability networks to facilitate real-time data transmission between connected vehicles, infrastructure, and road users.
	Connectivity for Regional and Rural Areas (3 votes): Examine challenges and potential solutions for ensuring consistent coverage in areas with limited network infrastructure.
	Competing Global Standards (2 votes): Assess the impact of different regional standards (US, Japan, EU, China) on connected vehicle interoperability.
	Role of 5/6 G Services (2 votes): Explore how next-generation mobile networks could support CAV and EV infrastructure.
Cybersecurity, Security, and Privacy	Privacy and Trust (6 votes): Explore issues relating to the complete CAV ecosystem, including how vehicle-generated data is managed by manufacturers and road agencies.
	Security Credential Management System (SCMS) for Connected Vehicles (4 votes): Examine the requirements for secure authentication and encryption to protect V2I communications from cyber threats.
Data Acquisition and Provision	Roadworks Data Improvement (4 votes): Explore how to improve real-time roadworks data to enhance CAV navigation and road user awareness.
	Digital Monitoring of Surrogate Safety Measures (2 votes): Assess the feasibility of using emerging technologies such as LiDAR and vehicle-generated data for network monitoring and predictive safety analysis.
	Vehicle-Generated Data for Road Agency Use (2 votes): Investigate how data from connected vehicles can inform proactive maintenance, operations and road safety.
	Providing Agency Data in General: Investigate agency data provision including road disruption, other data such as traffic signal phase and timing (SPaT) and incidents; including through a data platform (3 votes)
Data Management	Cross-Border Data Consistency and Sharing with Road Users (4 votes): Evaluate frameworks for standardising data formats and exchange mechanisms to ensure seamless access to transport information across jurisdictions and users.
ITS and Operational Technology Requirements	Standardisation of Traffic Signal Controller Data Formats (3 votes): Investigate the need for consistent formats and protocols for signal phase and timing data to support CAV interactions with traffic signals.
	ITS and Operational Systems Supporting Data Provision (2 votes): Assess how traffic management platforms, traveller information systems, and digital twins can be integrated with real-time data feeds to enhance transport network efficiency.

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