International Transport Forum

Preparing Infrastructure for Automated Vehicles

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The International Transport Forum

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Michael Dnes acted as principal author of the report. Martin Russ, Eetu Pilli-Sihvola and Aida Joaquin-Acosta authored individual chapters. Eetu Pilli-Sihvola and Aida Joaquin-Acosta also chaired Working Group sub-groups.

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The following countries participated in Working Group activities: Australia, Austria, Belgium, Canada, Finland, France, Germany, Japan, New Zealand, Norway, Poland, Singapore, Spain, Sweden, Switzerland, the United Kingdom and the United States.

For a list of Working Group participants and their affiliations, see the Annex.

Foreword

When automated vehicles were first unveiled, their potential to change the world appeared obvious. Driving is a task carried out by billions of humans daily. By handing it over to machines there was potential for a transformation of transport – greater safety, less drudgery and better outcomes for the cities and countries of the world. Furthermore, in those early days of optimism there was a hope that the rise of technology would be so fast, and its deployment around the world so rapid, that this process would be almost effortless for policy makers and drivers alike.

Today, we have a more realistic sense of the pace of progress. Automated vehicles are no fantasy – they exist, are being deployed in a growing range of contexts, and are becoming increasingly more capable as each year passes. But the arrival of the fully automated "Level 5" vehicle now appears many decades away. More modest applications of automation seem likely to dominate the near future, deployed in the environments that are most able to support them.

This changes the calculus of automation for industry and policy makers alike. For industry, the initial entry of automated vehicles will need to be integrated within the existing road network. Mixed modes of human and machine-operated systems impose challenges which must be considered and managed for the foreseeable future. For policy makers, it is no longer enough to wait passively for automated vehicles to appear. While both groups continue to see great value in automated vehicles, realising this involves looking at familiar infrastructure in new ways.

Since 2020, 17 countries have come together through the ITF to examine the implications of this shift, and to ask what immediate steps can be taken by those countries that wish to accelerate local developments. Experts from around the world have pooled their understanding of issues to do with the physical road, the "invisible infrastructure" that surrounds it (including digital infrastructure) and the institutional and legal systems that govern what may or may not be permitted to take place on the road.

Experts and industry representatives have generously helped to widen this picture further. Their contributions have stressed the practical and immediate challenges they must overcome and plan for now, in order to make progress, as opposed to at some indefinite point in the future. These developments suggest that the historical remits of infrastructure operators will not match the demands of the future. Infrastructure operators will need to learn new skills and understand topics unfamiliar to the classical roadway infrastructure community in order to maintain the standards we currently expect of them.

This report summarises the findings of this work. The actions set out here are intended to be immediate and practical, while at the same time respecting different international approaches to infrastructure management. Automated vehicles are set to be a growing part of the transport system. While the multiplicity of converging emerging technologies that enable automation in vehicles continues to shift as they progress, by continually maintaining our understanding of the needs of automated vehicles we can speed their arrival and harness their power for good.

Michael Dnes and Martin Russ, Working Group Co-Chairs

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Background

Many of those responsible for developing and managing the transport system remain enthusiastic about the potential for automation to make journeys better, save lives and streamline the management of the road network. Automated vehicles (AVs) are becoming more prevalent and more capable, and are likely to become more widespread in the decades ahead.

However, AVs represent a significant departure for road transport. Until now, all vehicles have been under the control of a human driver. This means that expectations about perception, safety requirements and legal compliance are all designed around human needs and limitations. AVs may have substantially different requirements and implications for the operation of road infrastructure. This, in turn, may require updating understanding of what infrastructure must deliver in order to serve the needs of its users.

Any difference could have significant implications. The operation of AVs to date has largely been within the context of testing and piloting initiatives. Developers and their sponsors have limited AVs' operation to particular geographical areas with well-defined types of roads and fairly predictable environments. This has helped ensure that trials lead to the repeated experience that enables the learning and continual improvements essential to the ability to unlock the benefits of automation. Yet it has also limited the area where developers are confident offering automated services, limiting their real-world spread.

While current AV implementations are designed to operate safely within the current infrastructure designs and ecosystem, there are also important questions about what kinds of infrastructure may enhance safety critical functions once AVs are present on more of the road network. These questions are made more complex by the way in which AVs are part of a connected and intelligent system of systems, whose architecture has not yet fully emerged. In the face of such changes, maintaining coherent oversight of the safety of the road network becomes more complex.

To explore these questions, and to examine the potential for immediate action to address the clearest needs, this report examines what kinds of support are most in demand from three policy-making areas: physical infrastructure, data and digital infrastructure, and institutional frameworks. While many studies have sought to understand how the long-term future of transport may be shaped by new technology, this report focuses on immediate obstacles to deployment and the extent to which governments can address them through specific actions.

Main findings

Progress to date in adopting AVs on public roads has been slower than originally expected in most countries, but AVs already exist and will become more widespread over the 2020s and beyond. Key questions for policy makers regarding infrastructure therefore relate not to whether AVs will be adopted, but *where* they can be used. Conventional thinking views the capabilities of an automated vehicle in terms of the technology on board but a vehicle's surroundings play an equally important part. Infrastructure is a crucial part of the operating environment of any AV, and partly determines where and how it can function.

In the near term, it is certain that AVs will need to use roads as they exist today. However, policy makers should prepare for a future that optimises the integration of AVs in the wider system, and take a cross-cutting approach that views the transportation system of the future as an integrated system of systems. There are also a number of other "invisible infrastructures" such as data, digital connectivity and institutional or legal factors, all of which may evolve to play a critical role in supporting the operations of automated vehicles.

As recent work by the US Department of Transportation on the analogous concept of "digital infrastructure" has shown, the real-world operations of these different elements mean that it is hard to assess any of them in isolation. Action by policy makers to address these different types of infrastructure in a co-ordinated way can make their countries more attractive for the development and arrival of AVs.

This report finds that these invisible infrastructures offer the greatest opportunities for near-term action, principally due to their adaptable nature. Their ability to produce high-value outcomes without the need for major construction means they offer more potential than changes to the physical road network itself.

Simultaneously, if AVs increase the importance of some types, features or capabilities of infrastructure, this challenges the established way in which roads are managed. Data connectivity, mapping and real-time data become significantly more important in maintaining the quality and safety of roads. The existing skills of infrastructure operators do not always cover these areas, and in some cases these new elements of infrastructure may be thought to be the responsibility of other bodies. The introduction of AVs does not relieve infrastructure operators of current responsibilities or lessen the need to serve existing users, but policy making must evolve in order to remain effective.

AVs will be a global technology. As a result, solutions which co-operate across borders will be more effective than purely national responses to challenges. This is especially true with evidence on safety: confidence about what is and is not safe will hinge on a volume of data that is far easier to gather and analyse on an international basis. The fastest route to unlocking the benefits of AVs will reflect this fact.

Different countries will approach these challenges using different methods, ranging from state-mandated action to market investment. A wide variety of approaches can resolve these problems, and there is no sense in which direct government investment is the only answer. However, a clear sense of an evolving strategy, and a need to embrace new challenges alongside traditional responsibilities, will be critical to success.

Policy insights

Policy makers need new skills and partners to optimise the function and benefits of automated vehicles on their roads

The deployment of AVs at scale has the potential to bring massive societal benefits, but also carries with it a degree of disruption and risk. The increasing assimilation of automation into both vehicles and infrastructure could fundamentally shift the relationship between them. Increasing automation in infrastructure and associated systems makes new demands, and may work in ways that are unfamiliar. Policy makers and infrastructure operators must engage with new stakeholders to understand the state of development of AVs and the critical issues in relation to their widespread adoption; and they must invest in unfamiliar skills and expertise to be intelligent partners. This requires significant new institutional capacity among policy makers. Engagement must be structured and sustained, and in most countries will require the development of new forums and processes.

Automated vehicles will use existing roads in the near term, and are supported by good maintenance to a defined standard

There are currently no calls from industry or developers to create special-purpose infrastructure solely for the use of AVs – their intention is to create vehicles capable of working on the existing physical road network. Nor is there a standard for designing or refitting roads for the benefit of AVs. While AVs may benefit from regular maintenance of existing roads – and particularly the provision of clear road markings and signs, and reliable surface quality – standards for such maintenance are not yet available. Live updates on changes as they occur are a key industry request, but are currently limited by the lack of global standards for sharing or communicating such information.

Developing “invisible infrastructures” offers greater opportunities for near-term benefits than upgrades to physical infrastructure

At present, there is still limited evidence on what makes a road ‘good’ for AVs, and technology is still developing. This means that there is limited scope to invest in physical upgrades to the road network until requirements are clearer. There is a better case for developing the “invisible infrastructures” of digital connectivity, data and institutional capacity on which AVs will rely. The clearest cases for action are for producing strategies to 1) ensure adequate connectivity to communications networks and infrastructure on key roads, 2) ensure the availability and reliability of high-definition maps for key sections of the road network, 3) ensure the availability of live data on road infrastructure, including all traffic regulations and 4) establish data standards, Concepts of Operations, and architectures for applicable digital infrastructures.

As invisible infrastructures are often privately operated, these strategies are more about providing leadership than spending money. These measures are valuable regardless of the future of AVs, but each materially improves the ability of AVs to operate on the road network.

A blueprint for co-operation can help traffic managers maximise the benefit of introducing automated vehicles as part of a wider transport network

AVs, particularly those designed to co-operate with other vehicles and talk to infrastructure, will offer traffic managers an unprecedented opportunity to understand and manage traffic flows in their cities. Achieving such capabilities and benefits will require co-operation, which can be facilitated through a global "blueprint" setting out how different parties can work together and support the arrival of new mobility services, and then customised to local circumstances. Drafting this blueprint requires co-operation between industry and policy makers worldwide.

Standardised testing procedures across jurisdictions can accelerate the spread of automated vehicles

Assessing the safety of AVs requires far more data than current laboratory-based and test track approaches. While different countries and jurisdictions are carrying out research, setting policy and developing validation testing procedures for safe operation of AVs on their roads, integrating international experience into standardised testing procedures can help introduce AVs across jurisdictions faster. In collaboration with industry, governments should work together to pursue complementary strategies to design, implement, and revise their measures, metrics, analytics, testing procedures, and test data and reporting methods. Similar arguments can be made for coordinating crash investigations internationally.

Traffic laws and behavioural norms must be ready for automated vehicles

As AV technology and operating conditions evolve, governments should continuously review and update their regulatory frameworks to remain consistent, accessible, and suited to the objectives of society. Adaptation of regulation could benefit from a framework for a conceptual map of laws, to help policy makers visualise legal interconnections and consequences, and machine-readable traffic laws, which AVs can interpret clearly and unambiguously across jurisdictions. Governments should anticipate mixed traffic of conventional vehicles and AVs and promote safe human-machine interaction during integration of AVs in the transport system.

There needs to be clear and coherent responsibility for ensuring automated vehicles work within a Safe System

Current responsibilities for road safety may not adequately cover all elements that contribute to the safe operation of automated vehicles as a new, integrated system. While developers and operators will maintain legal liability for their actions, each country needs a body that is responsible at a strategic level for understanding the safe operation of AVs on public roads, and for highlighting any problems that emerge. This organisation may be new or pre-existing, but needs to have the necessary skills and expertise to understand challenges and solutions that have no precedent, and to draw on international considerations.

Developers and policy makers should co-operate on a research programme focused on key issues related to automated vehicles

A co-operative research programme should be established, involving both infrastructure operators and industry/developers. Major priorities for this programme should include 1) agreeing a standard international approach to audits of the readiness of roads for AVs, 2) addressing key technical issues relating to the interaction between AVs and infrastructure and 3) agreeing longer-term visions for the future of transport and the role of infrastructure.

1. The link between infrastructure and automation

Chapter summary

- Automated vehicles (AVs) are already in use around the world, and can be expected to spread in the years ahead.
- Fully automated vehicles are still many years away. Until then, AVs will work in some places and not in others. Whether an AV works in a particular place will reflect the technology on board, but will also be determined by the situation in which it operates. This means that the ability of AVs to function will partly depend on the infrastructure present to support them.
- "Infrastructure" is more than the physical road. The digital and data components that support automation are just as important, and the legal and institutional frameworks governing and managing their use are also critical.
- This creates significant new challenges for policy makers and infrastructure operators. In order to deal with them, they will need new capabilities and skills, and will need to work with unfamiliar partners.

Since the mid-2000s, people have been looking forward to a world transformed by automated mobility. Today, automated vehicles (AVs) are driving on real-world streets; and in the future they are expected to play a growing role in transport worldwide (ITF, 2015). This may be the greatest change to the way roads work since the arrival of the motor car.

Transport automation will be an integral part of the transport system of the future, and it can shape a wider systemic change of the ways and means by which people move. In its best incarnation, transport automation can help achieve society-wide goals, such as more efficient and sustainable mobility in cities and better availability of services in sparsely populated areas. Deployed wisely, automation has the ability to transform the transport system by affecting what shape city centres will take in the future or greatly reducing the risks of crashes and casualties. It also has the potential for drawbacks, including new sources of congestion, new safety issues and a greater propensity towards urban sprawl (ITF, 2018a; 2018b).

Successfully deploying AVs as an integrated part of the public transport system and infrastructure can boost the attractiveness of shared modes of transport. This contributes to reduced congestion and vehicle-related emissions and frees up city space from past parking needs. Automation in transport also has great potential in enabling safe and independent mobility for people who currently have limitations in using the transport system.

This change has significant implications for how roads and related infrastructure are expected to operate. Over the 20th century, policy makers reinvented road infrastructure to safely manage the movement of millions of motorised vehicles (see e.g. Charlesworth, 1984). The century ahead promises a similar revolution, as the travelling public embrace vehicles that think and act differently to their human-driven counterparts; that require different kinds of support; and which can fundamentally change for the better the way in which people move.

However, the speed at which AVs are developing is significantly slower than was initially suggested (Burns, 2018). AVs that can drive on any road, anywhere, safely are still far away. Instead, the real-world deployments of AVs are constrained to defined areas, or roads of a high standard. There is no expectation of building a new, dedicated network of roads to allow AVs to operate in isolation, so the ability to use the existing road network safely and effectively alongside other human-operated traffic will determine the early history of AVs. The conventional physical infrastructure, together with the “invisible” infrastructures of data, connectivity and regulation, determine what is and is not possible with the technology that already exists. This presents both a barrier to overcome, and an opportunity to be seized.

Failing to prepare for the future has a cost. Infrastructure operators around the world are building and maintaining assets with a lifespan measured in tens or even hundreds of years, and a lack of preparation means that current projects risk becoming outdated before their design life expires. Conversely, unwise preparations may impose additional cost to no long-term benefit.

Learning to manage the relationship between infrastructure and automation unlocks a significant prize. Many benefits from AVs are expected; mastering the infrastructure challenge can unlock these benefits earlier. It helps those developing new technology to scale their technology up to a size where they become self-sustaining, and move from experiment into revolution.

Purpose and structure of this report

While the relationship between infrastructure and automation is crucial, relatively little has been done to date to explore its nature. Individual countries have made significant efforts to support the development of AVs, but primarily with the aim of allowing a new technology to prove its viability.

This report aims to explore the relationships between AVs and infrastructure, before developers release AVs onto the road network in large numbers, and before policy makers begin to change the way they work to accommodate and support this new kind of traffic. This includes helping governments take the best steps possible to accelerate that process, should that be their goal.

Specifically, the aims of this report are to:

- foster a better understanding of the respective viewpoints and priorities of industry and policy makers
- help policy makers identify the measures needed to support the introduction of automation – spotlighting emerging good practice and identifying measures that make the most difference at the current stage of development
- inform discussions about the extent to which the rise of automation affects the way policy makers and infrastructure operators ensure safe and effective transport
- help develop a shared understanding of the challenges of supporting AVs internationally, and to identify areas where international co-operation can help individual countries more effectively support the introduction of automated mobility.

Working group members agree that the decisions made between now and 2030 could have an outsize influence on the future of global travel. This report aims to provide the knowledge and the context to allow countries worldwide to craft informed strategies that best suit their objectives and policies, while striving to move the global community towards common understanding and, where appropriate, uniform practices.

This report examines three areas where policy makers can support progress towards automated mobility.

1. Physical infrastructure: understanding and managing physical roadways in a way that assists AVs.
2. Digital and data infrastructure: predicting concept of operations, opportunities and requirements for connectivity and data from AVs' role as data producers and consumers, and the potential changes in infrastructure capability required to provide them.
3. Institutional and legal infrastructure: the steps governments can take to develop regulatory and legal pathways relating to infrastructure that enable safe automated mobility, and the institutional capacity required to make this happen.

Each of these areas has been investigated through discussions among policy makers, infrastructure operators and developers from around the world (see Box 1). Working Group members have worked across four continents, at the height of the worldwide pandemic. They have shared best practices, identified gaps in collective knowledge, and examined how existing practice relates to the latest developments.

The report also considers cross-cutting issues that affect many different areas of technical activity. For those policy makers whose remit covers wider questions of regulation, strategy or funding, these challenges may be significant consequences of a slower, more place-based model of AV provision.

Some of the information in this report is derived from a survey of policy makers carried out by the ITF Secretariat in 2021. The objective of the survey was to gather input from ITF countries on issues policymakers are facing in regulating automated vehicles and on best practices they are using to deal with them. A total of 24 ITF member countries responded to the survey. Industry representatives were also surveyed through a combination of questionnaires and face-to-face meetings and interviews.

Box 1. Terminology used in this report

A variety of terms are used to describe vehicles capable of driving under their own control, including automated vehicles (AVs), autonomous vehicles, self-driving vehicles and automated driving systems. These terms embody differing views about the role of vehicle connectivity and the potential for driving without external assistance. Some have legal force or institutional meaning in specific countries. This report uses the word "automated" as a generic term and discusses relevant differences where necessary. It also makes a distinction between "automated vehicles" and "connected vehicles", as the latter only provide information and guidance to the driver, and the surrounding vehicles and infrastructure, without interfering with the driving task.

The report attempts to chart the interests of two key groups in the arrival of AVs. The first is organisations that are responsible for road networks, including those in national, regional and local government. This report uses the phrase "policy makers" to describe those making choices about how the road network is regulated or how funding is spent, and "infrastructure operators" to describe those who are directly responsible for managing roads. The second group is industry. A variety of companies in the automotive and technology sectors have an interest in building vehicles, developing artificial intelligence and sensors, providing parts or selling data. This report uses the word "developers" to describe all companies trying to create an AV. Where relevant, "AV operator" is used to refer to companies that offer services using AVs developed by others.

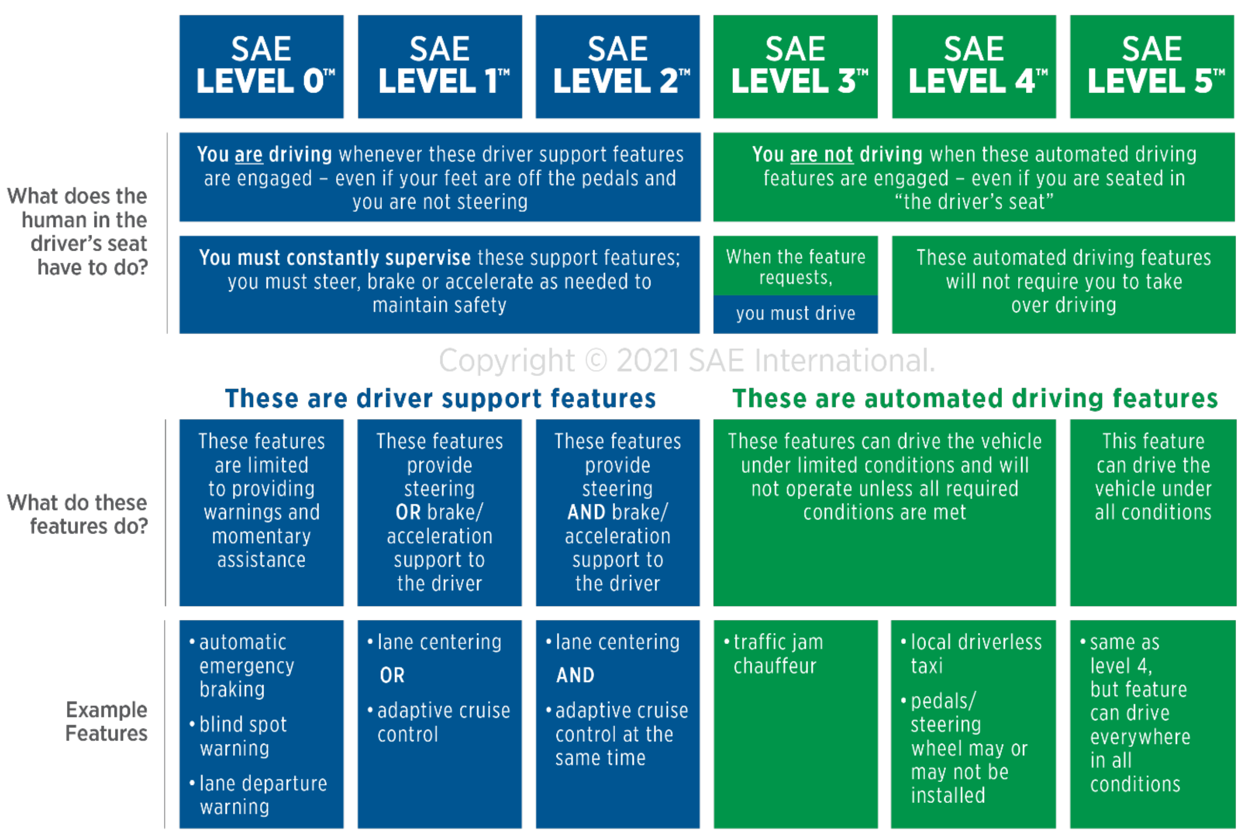
The rise of automated vehicles

Self-driving technology has been introduced to different parts of the transport system over the past century, but vehicle automation only became possible after significant advances in machine learning, machine vision and sensor technology. In 2005, four teams managed to complete the US Defense Advanced Research Projects Agency's Grand Challenge by driving a 100-mile (161-kilometre) route with no human control (DARPA, n.d.). This moment is generally recognised as showing that AVs were capable of driving on real-world roads.

The late 2000s and early 2010s saw substantial technical interest in the potential of the technology. Although tests still required the constant presence of a safety driver, a sizeable number of observers expected the technology would soon evolve to be able to operate on public roads without human oversight, disrupting the transport and automotive sectors (Burns, 2018: 278-80). Ambitious projections were made about how a transformation was imminent: to take one example, a large developer set out a plan in 2014 promising public roads testing by 2016 and 100 000 AVs in use by 2020 (Davies, 2021).

Also in 2014, the Society of Automotive Engineers (SAE) published an influential framework for understanding the levels of automation different vehicles were capable of delivering (SAE International, 2021). The framework's six levels are widely used today to describe the degree of functionality delivered by different technologies, and to clarify whether a human or a vehicle is taking responsibility for driving. Automated functionality increases at each level of the framework, from completely non-automated driving at Level 0, through to complete automation in all circumstances at Level 5 (see Figure 1).

Figure 1. The Society of Automotive Engineers' levels of driving automation



Source: SAE (2021).

While each increase in capability under the SAE framework is important, particular significance is ascribed to automation above Level 2. There, human driving is replaced by fully automated driving, with the human partially (Level 3) or completely (Level 4) relinquishing the whole of the driving task in certain situations. At these levels, infrastructure operators can no longer rely on road users being human or making judgements in familiar ways.

It is evident that automation in road transport has not developed at the pace predicted just a few years ago. However, the failure to deliver ambitious earlier goals obscures very real progress in delivering technical improvements. Today, AVs are not a possibility but a reality on the road network.

Testing of fully self-driving vehicles is underway in most developed countries around the world. The largest-scale trials are taking place in the United States, but almost all of the countries surveyed for this study had at least some form of testing underway, on test tracks, on local roads or (more rarely) on major highways. All of this testing remains at the stage of research and development, rather than large-scale commercial operation.

Self-driving “robotaxis” are achieving increasingly impressive performance. The successor to Google’s self-driving car project (now organised as Waymo) has delivered a real-world network in Phoenix, Arizona and in San Francisco, California, where members of the general public can hail and ride automated cars. As of 2021, the system had driven more than 65 000km without a human safety operator on board, within a defined test area (Schwall et al., 2020; Waymo, n.d.). Data provided as part of testing in California in 2020 shows six companies whose vehicles drove more than 10 000km between human interventions (Herger, 2021).

Automotive manufacturers are adding an increasing number of driver-assistance features to their fleets, using features seen on AVs to provide Advanced Driver Assistance Systems (ADAS). This began with optional extras, such as adaptive cruise control and automatic parking. More advanced ADAS systems, such as Tesla’s “autopilot” system, offer to carry out more elements of the driving task (Morris, 2021). Increasingly, vehicle standards regulators in key jurisdictions are requiring new vehicles to include systems as standard. In the European Union, from 2024 all new vehicles must include systems for emergency braking and keeping in-lane, effectively making it impossible to buy a new car without Level 1 automation (European Parliament and Council, 2019).

These systems are already evolving towards full Automated Driving Systems (ADS). In 2021, Honda released 100 vehicles with Level 3 automation (Myles, 2021); Mercedes Benz received approval for similar highway driving in the same year (Mercedes Benz Group Media, 2021). Other manufacturers are preparing to make their vehicles forward-compatible for autonomy, meaning that self-driving technology could be included at purchase or installed later. Volvo is preparing to introduce the hardware necessary for Level 3 automation as standard on its replacement for the XC90, which is expected to enter production in 2023 (Volvo Cars Global Newsroom, 2021).

Low-speed automated shuttles have been deployed at a variety of sites around the world. For example, the French firm Navya reported in 2020 that it had sold over 180 Autonom shuttles in 23 countries (Businesswire, 2021). While limited in speed, these systems have benefits that could make them an attractive proposition in the right circumstances. For example, the Japanese town of Sakai has invested JPY 520 million to subsidise an automated shuttle bus service as a response to a widespread shortage of qualified drivers and to prevent a reduction in public transport services (SoftBank News, 2022).

Automated technology has been used to develop new forms of public transport. CRRC’s Autonomous Rail Rapid Transport (a rail-less tram system) has been in operation in the People’s Republic of China since 2017, and is in the process of being exported to other Asian countries (Xinhua, 2017).

Significant effort is being made to enable goods vehicles to drive without a human on board. The freight market is experiencing a growing shortage of drivers and a large number of journeys on high-quality roads, making it a high-potential market for developers. In 2019, an unmanned heavy goods vehicle was tested on a Florida highway (Ohnsman, 2019). Shanghai's highly-automated Yangshan port has been used as a testbed for automated freight in China, with deliveries made across the 32km Donghai bridge (Pan, 2021). Swedish company Einride has announced that it will shortly offer fully automated freight pods, capable of speeds of 45km/h on pre-mapped routes (Einride, n.d.).

Away from public roads, AVs are becoming increasingly common in the port, mining, farming and construction sectors. Australia is world leader in the use of AVs in mining, with nearly 80% of the world's approximately 500 self-driving trucks present there (Global Data PLC, 2020). In the United Kingdom, automated trucks have been deployed to help with earth-moving on upgrades to the A14 near Cambridge (Sholli, 2019). China has launched a series of policies to promote the development of smart mining with automated technology, aiming for unmanned transportation in open-pit coal mines by 2025 (GlobalNewswire, 2021).

Setbacks have accompanied this progress. The first fatal collision between a human and an automated vehicle (with a human safety driver on board) took place in Tempe, Arizona in 2018 (Wakabayashi, 2018). Vehicles relying on automation have been involved in collisions where failures of onboard sensors are considered to have played a part (Krisher, 2022). The players in the market have also evolved and changed, most as part of a wider consolidation prompted by the global pandemic (Templeton, 2022a).

There is a consensus, both across the participants in this study and the sector more widely, that full Level 5 automation is unlikely to be achieved this decade (see also Templeton, 2022b). There is an equally strong agreement that the technology available before this point is still extremely valuable: a Level 4 robotaxi or ADS-equipped vehicle operating within a constrained or geofenced Operational Design Domain (ODD) will be largely indistinguishable from the "go-anywhere" Level 5 equivalent. This means that the promise of AVs will start to be fulfilled over the 2020s.

Key organisations linking automation and infrastructure

While the major organisations responsible for conventional vehicles and the roads they run on are well-established, the development of AVs represents a significant change in both the stakeholder landscape and the incentives operating on the different participants.

The technical development of AVs is driven by two main groups. The first consists of traditional automobile makers, for whom the technology represents a natural evolution of existing systems such as cruise control and lane-keep assist. The second group is drawn from the technology sector, either in the form of established players, or smaller start-ups focused either on self-driving technology or on the development of key pieces of hardware.

These two groups often overlap, particularly through mergers and acquisitions of different operators, and are also supported by a wide range of more traditional hardware suppliers and software developers. This process exists squarely within a private-sector context, aimed at creating and selling commercially viable products or services. This creates pressures both to move quickly (to be the first to serve a potentially lucrative market and generate outsize returns) and to act cautiously (to avoid the reputational risk from early accidents). Accountability is to corporate boards and investors.

In contrast, road infrastructure is predominantly operated by branches of local, regional and national governments. In some cases, this is as part of a dedicated agency with sole responsibility for managing highway assets; in others (especially for local roads) it is part of a wider portfolio of services provided by local government. Highway-management bodies are usually accountable to elected politicians. Given the central role of road-based mobility in daily life, the overwhelming priority of most highway operators is to keep the existing network functioning effectively.

Other kinds of infrastructure also play an important role, and are controlled by many entities (see Chapter 3). The telecommunications network, essential to digital connectivity, is predominantly in the hands of private companies serving the wider telecoms market. Data is provided by a range of different public and private organisations – for example, mapping companies, tech companies, vehicle manufacturers and public sector bodies. Geospatial positioning data is provided through satellite networks organised by governments or supranational entities. Legal and institutional infrastructures are the responsibilities of governments, with an important role for recognised certification bodies. Each of these different groups has its own priorities and incentives.

Highway operators have historically had little reason to engage with the kinds of organisations developing AVs, or providing many of the services that support them. Given the relatively unchanging nature of managing the physical road, and the variety of competing priorities, there has been relatively little opportunity for these groups to exchange perspectives. There has also been little investment in the skills and knowledge required to engage critically with the latest technical issues. However, as this report demonstrates, many of an infrastructure operator's traditional responsibilities will now draw them into the orbit of developers, data providers and the operators of other infrastructure networks.

Policy insight: Policy makers will need new skills and partners to optimise the function and benefits of automated vehicles on their roads

The deployment of AVs at scale has the potential to bring massive societal benefits, but also carries with it a degree of disruption and risk. The increasing assimilation of automation into both vehicles and infrastructure could fundamentally shift the relationship between the two. Increasing automation in infrastructure and associated systems makes new demands, and may work in ways that are unfamiliar.

Policy makers and infrastructure operators must engage with new stakeholders to understand the state of development of AVs and the critical issues relating to their widespread adoption; and they must invest in unfamiliar skills and expertise to be intelligent partners. This requires significant new institutional capacity among policy makers. Engagement must be structured and sustained, and in most countries will require the development of new forums and processes.

How infrastructure affects automated vehicles

AVs are often described by their SAE automation levels (see Figure 1), which describe the capabilities of the vehicle in terms of its ability to carry out some or all of the functions of driving without human intervention. However, a second equally important concept is the Operational Design Domain (ODD).

The SAE defines an ODD as "the operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics" (SAE 2021). In practice, this means an AV's ODD is crucial in determining where its automated features can function effectively. Road conditions, surrounding road users, traffic regulations and weather can all affect the ability of an AV to accurately perceive or understand its surroundings – and therefore whether it can operate safely.

AVs with Level 5 automation implicitly promised to solve ODD limitations by being able to operate everywhere. However, at Level 4 and below, AVs will only work in some places or under certain conditions. At Level 3, AVs must give control back to human drivers when the vehicle exceeds its ODD or other performance limits. If Level 5 automation remains a decade or more away, distinguishing between locations and environments in which AVs will and will not operate safely will continue to be critical to the real-world utility of automation. It will also be dynamic, as capability and requirements will shift as technology improves and AV market penetration grows.

At the most basic level, an AV must remain within the confines of the physical road. Closely related to this is the need to interpret and act on the markings and signs along a road. It would be of little comfort to know that an automated vehicle could accurately locate the edges of a road without being equally confident that it would stay within the marked lanes or respect a traffic light set to red.

This means that an AV must be capable of measuring the surrounding physical geometry and interpreting roadside features such as traffic signs and signals, and involves both passive (e.g. lane markings) and active (e.g. variable speed-limit signs) elements of the road environment. Some further elements of the physical roadway play a role in enhancing the usefulness of sensors on board a vehicle. For example, street lighting is not essential for an automated vehicle (or a human driver), but can influence the usefulness of on-board cameras. This tends to reflect the choices made by individual developers.

In addition to these physical elements, AVs may also make significant use of a parallel "invisible infrastructure" in order to operate. First among these is connectivity to a range of digital networks. While there is a widespread view that no automated vehicle should depend on connectivity for safe driving, almost every modern vehicle uses digital connectivity to enhance its effectiveness. This may include both general connectivity for data exchange (V2X) with other vehicles (V2V), infrastructure (V2I) and the wider Internet (V2N). It also includes the specific connectivity provided through global navigation satellite systems (GNSS), including the Global Positioning System (GPS). These systems act both to provide positional data and to allow the exchange of wider information between the vehicle and the outside world.

The second major piece of invisible infrastructure is wider data, used by the vehicle to understand its environment. Foremost among these elements are digital maps. High-level maps are essential for all routing decisions taken by the automation system, while detailed maps (ideally with centimetre-level accuracy) are currently an important piece of contextual information to support vehicles in orientating themselves (localisation) within their environment. Other forms of geographically specific information, such as traffic levels or speed limits, also provide context for the vehicle that is useful or even safety-critical (see Chapter 3).

The traffic codes and laws of a country can also be argued to represent a kind of infrastructure: by defining the correct behaviour for vehicles and other road users, they implicitly give predictability and order to the road environment. In many ways, the laws are the system through which physical road markings and traffic-control measures are given meaning and put to use (ITF, 2017a; ITF, 2017b).

Policy makers are also responsible for a wider set of institutional arrangements that represent a final invisible infrastructure. Meeting the standards of testing and safety regimes is essential to a vehicle being cleared for use on the road. The availability of certain essential private-sector services, notably insurance, is also closely tied to this infrastructure. Without these supporting services, AVs simply cannot operate.

All of this, taken together, presents a wide range of places where infrastructure and automated vehicle technology interact with one another. Making AVs safe and successful does not centre on a single, simple solution, but the successful management of many different challenges at once (see Box 2). The future of AVs will depend on how well that interaction can be managed.

Box 2. The path to real-world use of automated vehicles

With much of the publicity for automated vehicles (AVs) focused on full Level 5 mobility, relatively little attention has been paid to the ways in which developers prepare their vehicles to work on real-world roads using current technology. This represents one of the biggest logistical challenges to getting AVs into everyday use, whose importance is frequently underestimated.

Once an automated vehicle is ready to leave the test track, its developers pick a set of roads or a geographical area to further research and test the vehicle in real-world conditions. Exact methods vary between developers, but most of the companies consulted during the preparation of this report begin a process of localisation. This involves developing a series of highly detailed maps of an area (see Chapter 3), driving vehicles in the area under the control of an experienced human driver, and using machine-learning techniques to “teach” the vehicle’s automation system to drive in a similar manner.

This “experimental” on-road testing by developers differs from the “validation” testing carried out by governments for type-certification or developers for self-certification (see Chapter 4). A rigorous and disciplined test and validation programme that includes modelling and simulation, track testing, and on-road testing is imperative to ensure AVs will be deployed when they are safe for use, and the developers and their partners are prepared to handle the consequences of offering the vehicle to market. The industry is sensitive to questions of safety, legal risk and brand image, all of which make experimental testing a major step in the development process. Governments and industry also share a wider interest in the eventual successful and responsible mass deployment of AVs and a modern road infrastructure within the transportation system.

The amount of testing required is a matter of extensive policy debate. A human driver is considered safe to drive having passed an on-road test that is less than an hour in length. AV specialists recognise that the challenge to AVs rarely comes from failing to drive safely under normal conditions, but from failing to respond effectively to unlikely or unforeseen combinations of circumstances (“edge cases”). In some circumstances, these edge cases are best discovered during on-road testing, which provides the most operationally realistic environment for a test regiment.

As a result, the process of scaling up AV services into new areas is expensive and time-consuming, constrained by barriers that are financial, legal and logistical as much as technological. The same issues are likely to delay the spread of existing technologies to new jurisdictions.

Sources: Interviews with industry representatives and US Department of Transportation officials.

How policy makers and infrastructure operators can use automated vehicles

Just as AVs use infrastructure to provide mobility, policy makers can use AVs to help provide services, or to deliver wider policy goals. These uses are mostly theoretical at present, but play a significant role in shaping how policy makers think about the future of their infrastructure. They can be split into three broad areas, of increasing ambition:

1. Gathering data: Use of data gathered by AVs to help inform the operation and maintenance of the road network includes information on the condition of road surfaces, road signs, markings, traffic speeds and road performance (both in real-time and in the near future).
2. Delivering wider policy goals: Surveys of policy makers carried out for this report suggests that there is particularly strong interest in the potential to use automation to improve road safety; and in the potential to use new technology to improve the environmental performance and accessibility of transport services.
3. Transforming mobility: Most ambitiously, policy makers see AVs as having the potential to change the way in which people use the transport network, enabling new models of mobility for passengers and freight, as well as new levels of control over the ways in which the road network is used (see e.g. UK Government, 2022).

AVs are currently only able to perform the first of these three tasks, but the potential to shape the early development of the technology to better enable longer-term goals is an important consideration, which provides clear incentives for policy makers to engage more fully and systematically with AV developers.

2. Physical infrastructure and automated vehicles

Chapter summary

- From the perspective of road infrastructure, automated vehicles (AVs) interact with the road network in a way that is broadly similar to human drivers. Developers are currently designing for their AVs to work on existing roads, and do not request the construction of dedicated roadways for AVs.
- The intention to make AVs work on all roads, the rate of technological progress and the shortage of real-world experience mean that it is not currently possible to recommend a physical standard for "AV-ready roads". However, opportunities exist to move towards consistency and uniformity of roadway features.
- Nonetheless, industry consistently draws attention to the importance of well-maintained road surfaces and clearly visible signs and road markings. This need does not yet amount to a clear standard, but is likely to become a rising priority as AVs become more widespread.
- Collaboration between policy makers and industry is essential to develop standards as the technology becomes more familiar, further research is conducted and appropriate data is shared.

AVs cannot move anywhere without roads on which to drive. Regardless of how advanced AV technology becomes, it will always need to make use of a physical network, which itself has been created over many generations. The fact that this road network already exists means that it is defined by a set of pre-existing standards and practices, and cannot be adjusted without considerable effort.

While AVs do not change the nature of existing roads, they do pose a new challenge. Great efforts have been made to build roads that serve their users well – by encouraging safer journeys, providing more capacity or reducing environmental impacts. The arrival of a new kind of user has the potential to challenge these assumptions, creating the potential to improve outcomes or create new types of risk.

If AVs change the demands on physical infrastructure, there is the potential for significant changes to the ways in which roads operate. Early evidence of how far this will be the case is important to future strategic planning – both to enable futureproofing where appropriate, and to prompt research where uncertainty is high. This chapter describes some of the challenges for transport authorities in providing and maintaining infrastructure that will support automated driving and highlight areas of collaboration between transport authorities and developers and manufacturers.

The existing road network

Roads may be the largest system of physical infrastructure in the world, and are certainly the most visible. This network has been designed to meet or manage the needs of existing users, without consideration of automated traffic. AV developers interviewed for this report have been consistently clear that they expect their vehicles to need to work on existing roads, and currently have no expectation of reserved space or purpose-built roads solely for AV use. Furthermore, a network of this size cannot be adjusted to meet new requirements without many decades of effort. It is, therefore, helpful to outline the ways in which the network is organised and operated. This forms the starting point for everyone involved in AV development.

The physical infrastructure of a road network can be represented by several functional layers (see Table 1). The first layer of physical infrastructure includes the road design, road surface materials, geometric configurations, and facility separation. The second layer of physical infrastructure includes traffic control devices that provide safe movement and mobility management. The third layer includes the traffic operational components and systems the road operators need to manage the vehicle-road system performance and the components and systems needed to provide connectivity between vehicles and infrastructure. A fourth and equally important layer consists of the resources needed for physical infrastructure maintenance and operation activities.

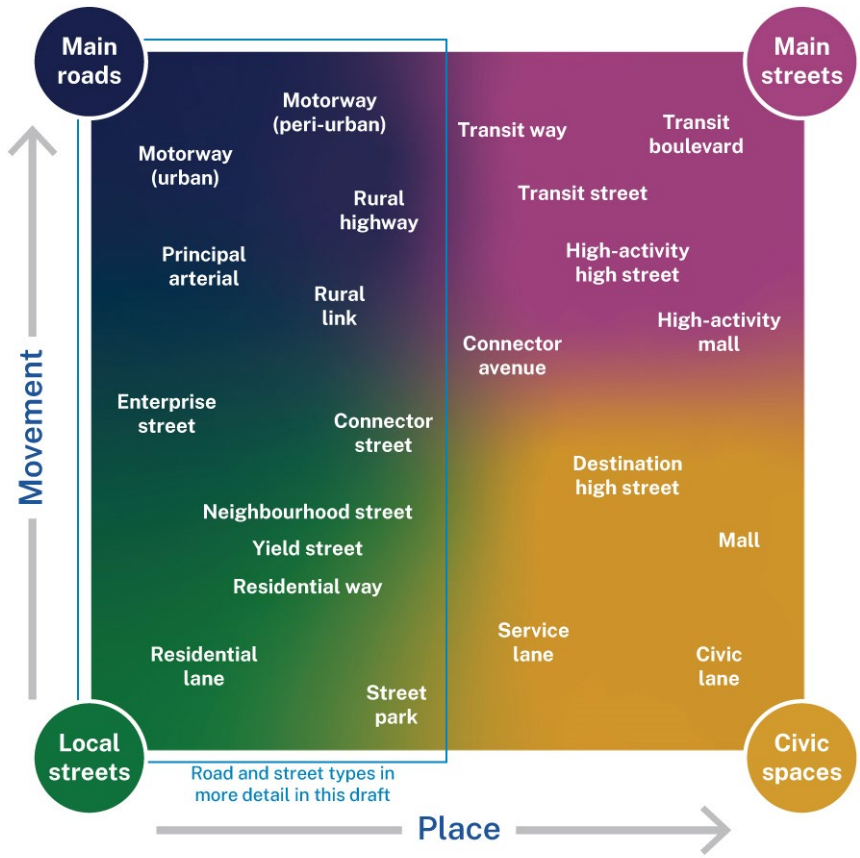
Table 1. The functional layers of physical road infrastructure

Layer	Description
1. The physical road	Each road consists of the roadway vehicles use, as well as features such as overpasses, bridges and tunnels, and roadside components such as medians, barriers, guiderails, pylons, kerbs and footpaths. The physical road may vary considerably based on circumstances, with substantial variations in materials and geometry, and in intersections with other roads.
2. Traffic control infrastructure	Traffic control devices are used to manage/regulate the flow and interactions of vehicles at road intersections, merges, and intersections with other transportation modes. Common examples include traffic signs, signals, pavement markings, message signs, work-zone traffic controls and other intelligent transportation system (ITS) devices. Controls can be static (e.g. traffic signs), dynamic (e.g. traffic signals, managed lanes) or a mix of both.
3. Traffic operation infrastructure	Traffic operation can take place at various road facility levels, jurisdictions or regions. Traffic operation usually incorporates a traffic operation centre that can operate traffic control devices, provide real-time information, and implement traffic and travel operational strategies across a route or area. Traffic operation centres deploy sensors and cameras to collect the data and information needed to monitor and manage the performance of the road system under the centre's jurisdiction. The centre influences traffic flow and manages issues, by changing signal timing, managing lane operations, changing speed limits, or providing travel information.
4. Maintenance and operations	Resources are needed to manage and maintain physical infrastructure and to make sure that the road infrastructure and traffic control infrastructure perform in a specified manner.

Source: ITF Working Group participants.

The various types of roads across different countries or global regions may have different names, but all follow a similar pattern. At one extreme are high-speed roads (e.g. motorways and expressways) with multiple lanes and limited points of access, designed to move large volumes of traffic. At the other are small roads serving few vehicles that travel at low speeds, designed primarily to provide access to adjacent properties and create a sense of place. Between the two are a series of roads designed to help manage the flow of traffic between these different environments while also forming part of the urban fabric or countryside.

Figure 2. Transport for New South Wales road hierarchy system



Source: Transport for New South Wales (2023).

Seen from one perspective, roads form a hierarchy: with high-capacity, high-speed motorways and expressways at the top and with a large number of smaller roads at the bottom. Other perspectives emphasise a balance between movement and a wider sense of place or environment (see Figure 2). Regardless of approach, there are relatively few roads built exclusively for the convenience of vehicular traffic, and most roads accommodate a range of users – meaning that AVs need to consider a variety of factors in their surrounding environment in addition to navigation and driving strategy if they are to expand beyond niche uses.

Many countries develop and maintain different types of roads according to a set of design standards, which specify how the road should be laid out (see e.g. Austroads, 2021; National Highways UK et al., 2023; USDOT FHWA 2021). These are technical documents, specifying design parameters at a level of precision at which an engineer can implement them in a consistent and reliable way. Some standards are very visible: for example bridge clearance heights are usually defined consistently across a single jurisdiction.

Others are less obvious, but still specified with precision, such as the expected layout of signs around a particular type of junction. There are also standards for many of the features that sit on or alongside the road – so a traffic signal in Paris will be the same as one in Lyon – and for non-physical items such as Intelligent Transport System (ITS) architectures (see e.g. FRAME NEXT, n.d.) and processes such as safety audits. This means that there is a substantial degree of standardisation within countries about how roads look, feel and function, based on written technical sources.

However, the existence of standards does not preclude substantial variation between roads in practice. Roads can be in urban, suburban or rural settings. Different environments demand adjustments in standards. The setting and types of users affect the way roads are designed and operated. The roads may or may not be congested for parts of the day. Road surfaces vary from multiple lanes of concrete to a single lane of gravel. Carriageways may be separated by a central reservation, other structures or not at all. There may be clear lane markings and signs or equally there may be no traffic control devices at all.

Roads in urban or suburban areas may have lighting while rural roads generally will not. Roads also degrade over time and require regular maintenance, and the extent to which this has taken place will vary from location to location. Differences can relate to weather conditions, foundational conditions, topography, land use, rules of the road and environment. Standards can exist at a national or regional level, meaning there is variation between jurisdictions; and standards are changed periodically to incorporate advances in practice and technology.

As such, roads around the world can be classified and organised to some extent, but cannot be treated like interchangeable parts. Given the extent of the road network and the variety of locations where roads exist, such a level of uniformity is almost impossible to achieve. The challenge posed by the inconsistency of the road network was raised by developers interviewed for this study more often than the value of any underlying standards. However new or emerging areas such as digital twins (PwC, 2022), high-definition maps (Milford, Garg and Mount, 2020), traffic regulation data (Tennant et al, 2021), work-zone information (US DOT, n.d.), and other infrastructure-related information may provide opportunities for greater uniformity.

How do automated vehicles use physical infrastructure?

One question considered in this study was the extent to which a fully separate network for AVs would support faster adoption of the new technology. Historically, automated transport systems such as metro trains have solved technical problems by creating a highly controlled environment where no other vehicle is allowed. Such a physical separation would solve various problems, but was not something that the AV developers or commentators interviewed for this report wished to see. There was a sense that full parallel networks of AV-only roads are not feasible because of limited space (particularly in urban areas), and more broadly that creating designated spaces for AVs would discourage their use on the wider road network – which was where developers were confident the greatest value could be realised.

Therefore, it seems certain that AVs will run on the existing road network, navigating around its existing limitations. The technology on board AVs is designed to meet this challenge: vehicles use a combination of sensors and software to perceive the surrounding environment and use the information gathered to drive, rather than relying on other technological solutions such as guidance cables. AVs use various road features to understand and navigate their environment, including lane markings, kerbs, signs, traffic signals, pavement edges, and other natural features such as landmarks. This information can be supported by digital information such as high-definition (HD) maps or data signals from roadside infrastructure (see Chapter 3), but all AVs try to understand the physical roads on which they drive in real-time, using their own sensors and processors (Udacity, 2021).

Much of the information that an AV uses to understand the surrounding road environment is gathered in a manner analogous to a human driver. AVs use on-board cameras to “see” traffic signs, signals, road markings and other features, and use this information to understand their surroundings. There are differences between human and machine vision – for example, AVs can use infrared cameras or radar to help see in the dark. Yet, overall, AVs are designed to read the roads that already exist, rather than navigate without reference to their surroundings.

These road features are frequently subject to design standards, but these standards were defined and implemented without AVs in mind. This means there is potential for some parts of the physical infrastructure to be laid out in a way that do not suit the needs of AVs or could be difficult to interpret. On-road experience is not yet widespread enough to indicate how widespread any such problems may be, but anecdotal evidence is beginning to emerge (see e.g. Datagen, 2022; Siddiqui and Merrill, 2022).

One interviewee recounted experience from a local trial, where an AV was confused by bus stop next to a roundabout. The AV could not successfully interpret the combined road markings from the two features, preventing the shuttle bus from stopping in this location until the markings were improved. The variation of standards between jurisdictions also presents a potential risk, as a vehicle developed in one country seeks to interpret different traffic signs or plan for unfamiliar road layouts.

Assessing the scale of the challenge

As part of the international policy survey, respondents from industry and policy-making contexts were asked about the extent to which they saw the physical design of the road infrastructure and the deployment of traffic control devices as a barrier to the uptake of AVs.

While industry representatives and policy makers rated both factors as “medium-to-high” barriers, they were most concerned about traffic control devices. This means that the physical road design is seen as less of a barrier compared to the availability of ITS equipment and devices for regulating traffic or facilitating communication. At the same time, there was significant variation between the answers of different stakeholders, suggesting that perspectives and perceived barriers differ between countries, and that there is little consensus yet.

The physical design of the road, including the geometric configuration, structures and surface materials, was rarely mentioned by stakeholders as a barrier, and was treated by most as an unavoidable reality. The only aspect that was mentioned frequently as a barrier and an opportunity at the same time, particularly by stakeholders from industry, is the physical separation of facilities to be used by AVs from other users and usages on the same road, which was generally seen as a low priority or actively undesirable.

Both stakeholder groups mentioned high standards in road management – such as ensuring clean and fully functional pavement, facility separation structures and particularly high-quality, readable and standardised road markings –as core prerequisites for introducing AVs. However, these standards were not seen as a fundamental barrier: stakeholders thought these problems can be resolved by applying existing knowledge and techniques, without the need to develop new practice. Other stakeholders from both groups argued that physical infrastructure design and road marking should not be barriers because AVs need to be able in any case to deal with a wide variety of infrastructure that has developed over hundreds of years. AVs must be able to drive on every road as it is, all year long, in a variety of conditions.

Some policy makers drew more pessimistic conclusions from this evidence, seeing the scale of the challenge in upgrading the whole road network and the likely limits on public funds as having the potential to be a significant a barrier to the roll-out of AVs. If it were the case that investment was necessary to raise infrastructure to a particular standard, they felt it was unlikely there would be scope for investing heavily on local roads; and if investment in upgrades was to be a precondition for AV operation, significant barriers would remain.

Box 3. Measuring the readiness of physical infrastructure

To date, there has been insufficient data to definitively prescribe roadway physical infrastructure requirements for automated vehicles (AVs). At the same time, evidence from these three case studies indicates that motorways in normal conditions are usually fit for AV operation. However, roads beneath this standard in some jurisdictions (including important roads that were not built as major highways) can lack edge lines, consistent lane lines and other features that AVs may require for safe operations. Signs may not be reliably machine-readable, and this may require investigation. This suggests that some countries wishing to encourage AV operations may have to invest in additional maintenance, and potentially new lane-lining or signage.

Australia

Austroads, the peak body for Australian and New Zealand road transport agencies, developed and published an audit specification for assessing the readiness of physical infrastructure to support automated driving (Austroads 2019a). These specifications cover line markings, traffic signs, route and lane discontinuities, temporary conditions due to roadworks and incidents, cellular data coverage and availability of map data. Austroads then undertook an extensive field audit of Australian and New Zealand freeways and highways to assess their readiness for active safety systems and automated driving (Austroads 2019b).

The road audit included more than 8 million individual line segments and 8 000 signs, on a 25 000 km sample of the road network which, although extensive, still represents less than 2% of the Australian and New Zealand total network. The audit used a combination of human observations, edge processing and machine learning algorithms to determine the readiness of the network to supported AVs.

The audit found that most freeways and highways in Australia and New Zealand can for the most part currently support Advanced Driver Assistance Systems (ADAS) operation and connected vehicles (CV) and AV lane positioning, with good quality markings and cellular availability. The presence of left and right lane-line markings is critical for lane positioning and there are significant proportions of the road network without edge lines. Increasing the use of edge lines and dividing lines (lane lines and centre lines) will provide a clear immediate benefit for both automated driving and human drivers.

Croatia, Greece, Italy and Spain

The European Road Assessment Programme (EuroRAP) has developed a physical infrastructure road safety rating and audit system for roads across Europe. In April 2019, EuroRAP commenced the Saving Lives Assessing and Improving TEN-T Road Network Safety (SLAIN) project, aiming to map and audit 10 000 km of roads that make up the TEN-T core road network across four European countries: Croatia, Greece, Italy and Spain. The audit incorporated aspects of the Austroads specification.

The SLAIN project final report (EuroRAP, 2021) determined the key physical parameters (lines and signs) required to assess if a road is CV- and AV-ready and then used these parameters to assess the CV- and AV-readiness of 2, 000 km of road across the same four countries. Analysis undertaken for the current report indicates that of the key five signs assessed across Croatia and Greece the most commonly undetected signs were speed signs (63% of all undetected signs) followed by stop signs (17%), overtaking restriction (14%), yield signs (6%) and pedestrian-crossing signs (0%).

Results for line detection using 360-degree imagery and computer vision techniques indicate that markings across the majority (88.5%) of the Core Ten-T network were AV-readable, with the remaining 11.5% comprising 7.3% tunnels, 3.2% undivided roads and 1% divided roads. Recorded dropout lengths (i.e. where the line was not detectable for greater than approximately 16 metres) ranged from 0 km (0%) on divided roads in Croatia to 62.3 km (82.1%) on undivided roads in Greece.

Finland

In 2021, the Finnish Transport Infrastructure Agency commissioned a study (Innamaa et al, 2021) on infrastructure support and classification for automated driving on Finnish motorways in 2021.The project assessed the feasibility of a motorway section for the operation of Society of Automotive Engineers (SAE) Level 3 and Level 4 AVs. Looking at the physical features of the selected section, the study concluded existing standards are likely to be sufficient for SAE Level 3 and Level 4 vehicle automation. The provision of sufficient space for minimal risk manoeuvres (MRM) is important (not least because of occasional poor weather conditions). On the right shoulder, the continuous width of 3 metres or more is sufficient space for automated trucks as well as passenger vehicles.

No major concerns were found regarding rut depths exceeding the set limit of 20 mm, suggesting the current road surface maintenance service level for the highway was sufficient for AVs. Lane markings were sufficient for existing lane keeping systems even in early spring conditions, again suggesting it was ready to support AVs. However, due to winter conditions and snowfall, there will be recurrent periods when lane markings are totally covered with snow, so additional positioning support will be required, especially in challenging locations. AVs, and their users, could be provided with accurate and predictive weather information to enable them to prepare for timely take-overs or MRMs (see Chapter 3).

The expected barriers were lower on highways and motorways compared to local roads, while urban areas were perceived as the main challenge. The hardest issues to solve regarding AVs were expected to be navigation and interaction with other road users. Difficulties were expected on narrow roads where hardly any separation of the different user groups is possible; roads that support community activities (e.g. people using the street as destination rather than a conduit for movement); around vulnerable road users (e.g. walking and cycling along the road and crossing the road); on roads with public transport, particularly rail-based vehicles and bus rapid transit (BRT) systems; and on roads with high levels of kerbside activities.

Some respondents mentioned stopping, waiting, loading and unloading as critical activities that are currently often under-designed and under-managed but which need more systematic management to facilitate AVs. Others mentioned the need for recognisable and set-out working zones/roadworks to ensure AVs could drive safely nearby and plan journeys that avoid congestion.

A number of respondents raised the fact that the deployment of traffic control devices and certain operational choices were held back by the lack of agreed standards (see Chapter 3) and limited funding. High uncertainty about future technology, coupled with financial limits, made it extremely difficult for policy makers to justify investment.

Others broached the possibility of adapting types and design of message signs and other ITS devices to be compatible with what AVs need (although this should only be done based on stable and internationally unified standards). The consistency between analogue and digital signs was mentioned as an important aspect to be considered.

Respondents also noted synergies between much of the traffic control equipment that could support AVs and that which could help with the management of conventional traffic. Traffic management is a well-established responsibility of road operators, and developments that benefit AVs can benefit all types of vehicles. Many transport authorities are implementing and enhancing ITS systems for existing traffic, at the same time as building potential capacity to prepare for AV integration (see Box 3).

Road elements inventory

Drawing on the evidence outlined in Box 3, the Working Group sub-group on physical infrastructure conducted an exercise to identify the physical infrastructure elements considered important to the early deployment of AVs. This cannot be predicted with complete accuracy – as more comprehensive digital information becomes available, positioning accuracy is improved, and the connectivity of vehicles can be used to provide data. Some elements of the physical roadway may then become intertwined with digital communications or different types of supporting data. This symbiosis between physical infrastructure, invisible infrastructure, vehicles and users is likely to be at the heart of how the transport system of the future evolves. Therefore, a breakdown of what is and is not important to AVs helps plan for the future.

Table 2 assesses the physical infrastructure elements for motorways and local roads, including road markings, traffic signs, traffic control signals, intersections, and passive/active landmarks.

Table 2. Current physical infrastructure roadway guidance elements for automated vehicles

Element	Essential for automated vehicle operations on motorways		Essential for automated vehicle operations on local roads	
	With driver	Without driver	With driver	Without driver
Longitudinal and diagonal pavement markings	Yes	Yes	Yes	Yes
Latitudinal pavement markings	No	No	Yes	Yes
Pavement markings at pedestrian crossings	No	No	Yes	Yes
Vehicle restriction signs	Yes	Yes*	Yes	Yes*
Variable message signs	Yes	Yes*	Yes	No
Regulatory traffic signs	Yes	Yes*	Yes	Yes*
Warning traffic signs	Yes	No*	Yes	Yes
Informational/guide traffic signs	Yes	No	Yes	No
Temporary signs (e.g. roadworks, temporary speed limits)	Yes	Yes*	Yes	Yes
Parking control	No	No	Yes	Yes*
Traffic signals	No	No	Yes	Yes
Tunnel closure/lane control signals	Yes	Yes*	Yes	Yes*
Guideposts and other landmarks	Yes	Yes	Yes	Yes
Roundabouts	No	No	Yes	Yes

Note: Elements marked with an asterisk (*) could also be provided through digital measures. Japan indicated the need for electromagnetic induction lines and magnetic markers. While these are not current elements, it is expected that they will be used in low-speed driving spaces and Global Positioning System (GPS) dead zones in the future.

Improving and maintaining physical infrastructure that supports automated vehicles

An important question facing policy makers and infrastructure operators is whether they need to change existing practices and standards to help AVs to travel safely and efficiently on roads. This conversation is still at an early stage, but decisions taken now will affect assets that can have lifespans of 100 years or more. At this point, any clarity on the shape of potential developments has value.

AVs are now running on some real-world roads without human drivers, providing insights into how AVs are likely to interact with infrastructure. However, much of what is currently known comes from the behaviour of early prototypes. Developers are improving their designs and answering shortcomings, and will continue to do so far faster than any improvements can be made to physical infrastructure itself – so, all insights are built on uncertain foundations.

New roads for a new vehicle?

The central finding emerging from discussions with developers and industry is that current AVs are designed to operate on the existing road network, without modification. There is no need for specialist apparatus to be laid in or alongside the roads in order to make current AVs function. Developers also design their vehicles in such a way as not to require a major improvement in the physical road in order to function safely. As such, it is difficult to say with confidence that any specific improvements are essential to AV operations, or should form the basis for an immediate programme of investment in physical roads.

However, it is notable that a significant amount of current ADAS technology is restricted by manufacturers to particular types of road –particularly motorways, expressways and other purpose-built highways. In principle, this could suggest that there is the potential to justify road upgrades on their ability to enable AVs to drive. This is misleading for a number of reasons.

First, much of the technology limited to particular types of road is a relatively low level of automation – ADAS systems equivalent to SAE Level 2 – and are mostly designed as driver assistance for private vehicles. Developers of more advanced systems have been aware from the outset of the need to drive in more complex environments, and are building AVs with substantially more capability.

Second, developers are also firmly committed to the idea of being able to use their technology to deliver end-to-end journeys, which necessarily relies on being able to handle a wide variety of types of road. Limitations on areas of operation represent a practical compromise for the short term, not a steady state to which infrastructure operators will need to adapt.

Third, the preference to limit the activity of ADAS systems to motorways and expressways is not always driven by technological requirements of the underlying system. It can also reflect a wish on the part of developers to limit their activities to low-risk environments or to provide simple guidance on where a system is safe to operate. There is scope for limits based on the physical roadway to be eased through greater confidence in the technology and relaxed regulations.

Upgrades to physical roads to match an “ideal” standard are a long-term process, which takes 5-10 years in most jurisdictions. In this timeframe, technology is likely to advance and confidence in the ability of AVs to work safely in a given environment is likely to improve, meaning that any upgrade designed to enable AVs would be at a significant risk of being obsolete before it was opened. Nor is it realistic to expect the widespread reconstruction of hundreds or thousands of kilometres of roadway within a short space of time.

Policy insight: Automated vehicles will use existing roads in the near term, and are supported by good maintenance to a defined standard

There are currently no calls from industry or developers to create special-purpose infrastructure solely for the use of AVs. Their intention is to create vehicles capable of working on the existing physical road network. Nor is there a standard for designing or refitting roads for the benefit of AVs.

Finally, there is also little idea of what steps might be taken to add to the capability of AVs on a given stretch of road. There may be effective measures far short of physical reconstruction. As such, there seems to be no sound case at present for building a special network of roads for AVs, or to begin rebuilding large sections of the road network to a new, higher standard. However, this should not preclude research and collaboration on reimagining a transportation system of the future that is not as bounded by today's constraints and assumptions.

Known challenges related to existing roads

Notwithstanding the impracticality of building new roads to accommodate AVs, some elements of existing roads may potentially be used by AVs in subtly different ways to human-driven vehicles. These elements are subject to many of the same uncertainties listed above, but they are nonetheless highlighted by discussions with industry as areas where developers think the quality of infrastructure can affect their work.

Road markings

Road markings are used by every AV studied in preparation for this report as one of the primary features that ensure the vehicle can position itself safely on the road. Indeed, AVs are arguably more dependent on these markers than human drivers – working out where a worn-out lane line "should" run is a task that is currently more intuitive to a human driver than an AV.

The markings that primarily interested developers interviewed for this report were lane lines, which perform a safety critical role in preventing head-on collisions and maintaining lane positioning. These are standard on roads across the world, but degrade over time and can be a low priority for maintenance. The location of lane lines is harder to supplement through digital sources, given that it must be accurate at the centimetre level.

However, there is no international consensus on whether standards of road marking should be changed from current practice. Ideas such as wider lines and brighter markings have been tested, but different countries have drawn different conclusions about how to proceed. Studies by USDOT have suggested that no firm technical standard can yet be set (see e.g. US DOT, 2021); while Austroads recommended that Australian and New Zealand road agencies improve the maintenance standards for road markings, and consider changing practices to prepare for AVs (Austroads 2020; see also Box 4).

Road markings include more than just the lines that define the edges of traffic lanes. Markings that can be driven over at exits and entrances must also be taken into account, as they frequently determine how it is safe for a vehicle to join traffic. Temporary markings in road works are often present with normal markings painted over (and visible to some sensors) or besides regular markings, making them a potential source of confusion. Markings on the kerbside are particularly important for vehicles that are collecting or dropping off passengers, and can prevent a user from reaching their destination.

Box 4. Maintaining road markings in Australia

Austroads, in its 2020 report on pavement markings for machine vision, recommended road agencies consider changing maintenance practice for road markings by

- halting the practice of mixing yellow and white pavement markings on construction sites
- improving the brightness and/or quality of dashed lines compared to solid lines
- improving minimum standards for removing redundant markings to avoid confusing lane keep assist systems
- measuring and modelling pavement-marking asset conditions, as well as improving monitoring regimes, in order to attract road safety funding.

Source: Austroads (2020).

Generally, most infrastructure operators do not gather comprehensive information about the state of road markings, making it difficult to assess how widespread a problem this is likely to be. A first step in addressing this issue in many jurisdictions is likely to be data gathering. If so, many of the technological improvements that underpin the rise of AVs create new ways of gathering such information quickly using the existing vehicle fleet. This both increases the speed with which action can be taken, and holds out the possibility of understanding where problems exist on the network in close-to-real-time if industry and infrastructure operators share information.

However, a lack of certainty about the precise technical needs of AVs in relation to road markings and the risks of misidentification mean that there is not yet an example of best practice that other countries can look to emulate. Further research is needed before it is possible to have confidence that any plan of action addresses all relevant risks without over-engineering the solution.

Overall, research carried out for the present report suggests that the maintenance of lane markings could become significantly more important to safety as AVs enter use, and if so would need to be considered more as part of maintenance planning. This is on top of their value for existing users.

Traffic signs

As with road markings, AVs use traffic signs to confirm how to behave safely. This information is often supplemented with mapping data, but many developers expect their vehicles to be able to act safely without having to rely on externally held data. This means that traffic signs have an enduring role, and the idea of the “naked road” – a road where connectivity removes the need for traffic signs – does not reflect how AV technology is developing. A mixed traffic environment means static and dynamic traffic control devices will need to continue to support both human drivers and AVs, and present consistent information to all.

As with road markings, signs need to be visible in order to support an AV. Unlike road markings, this may not need to be achieved entirely through physical maintenance or vegetation clearance – signs can exist both in the physical world and a parallel digital world, and can be presented to connected vehicles through maps and other sources of data. Reliance on non-physical signage raises questions about how maps can be kept at a sufficiently high level of accuracy in real time, especially where mapping information is not held by the infrastructure operator.

In addition to the more familiar static signs, dynamic displays (e.g. variable message signs, variable speed limits or lane control indicators) must be considered. Unlike static signs, dynamic signs can be programmed with a wide range of messages which may be instructions, advice, or simply useful information depending on circumstances. A vehicle may need to take very different kinds of action in response, but the way in which these signs are operated seldom considers the possibility of a non-human reader. The fact that these signs rely on light-emitting diodes (LEDs) also makes them less readable to machines than static signs, which can have further implications for safety.

The visibility of road signs is also raised more broadly as an issue for existing road users, and highlighted by representative bodies as an enduring priority. For example, the United Kingdom's road user representative body, Transport Focus, has actively campaigned on sign visibility since its creation in 2015 (Transport Focus, n.d.). This suggests that a more active maintenance strategy for visible and accurate signs may have value beyond AVs.

As with road markings, the maintenance of signs may need to be considered as more important to safety as AVs enter use. However, infrastructure operators who are able to prepare far enough in advance have options to substitute physical maintenance with other approaches.

Road surfaces

Many AVs are designed to behave cautiously in the face of the unknown, and to return control to the driver when uncertainty becomes too great. Potholes and surface defects can be difficult for vehicles to interpret, and have been known to lead to the AV returning control to the driver. This creates problems in terms of convenience to the user, and potentially in terms of safety (as the return of control may be unexpected, or there may be no human driver).

Road surfaces also play a relevant role in the visibility of other items on the road, including both road markings and other things that can be confused for road markings (such as repair lines). Questions such as the contrast between surface and markings may take on a greater significance in the future.

Road maintenance is a large expense for all infrastructure operators, and must take account of a wide variety of factors in making investment decisions. In general terms, the advent of AVs strengthens the case for maintenance over construction, especially on routes where AV traffic is most likely to be found.

Roadwork zones

Roadworks represent a disruption to the ordinary operation of the road, with existing markings and signs superseded by special instruction. It is also a situation where human workers are exposed on the highway, worsening the potential impact of any malfunction. AVs must adjust their behaviour at roadworks in order to be safe; and developers recognised this as an important test of their technology.

Survey respondents also made multiple calls for more streamlined communication around roadworks, and around changes to the highway more generally. While channels for infrastructure managers sharing this information do exist, they do not normally work in real time. Nor is data shared in a format that is instantly useable by a machine, requiring human data entry before important updates can be issued.

The development of real-time methods for communicating the status of roadwork zones to AVs in real time would appear to have clear safety benefits, and may make a useful contribution to workforce safety planning by infrastructure operators. There are initiatives underway to develop standard work-zone data messages that could be shared with AVs using existing communications channels (V2X).

Traffic control signals

AVs are expected to see and obey traffic control signals, using their cameras to assess the situation. Traffic control signals have been a focus of communications research, and are discussed in more detail in Chapter 3.

Other physical elements

A variety of roadside features can be used as passive or active aids to support vehicle navigation, including guideposts, road widths, alignments and structures. The main challenges in exploiting these elements are their placement, interpretability, and usability by AV as well as maintenance needs especially when these elements are covered with snow or ice. Also, some liability issues could arise if active landmarks (beacons) are not operational or malfunction. Intersection areas and roundabouts could be also challenging for AV systems in the way signs, markings and intersection configurations are interpreted and operational rules are understood, especially in mixed traffic situations.

There is little understanding of how AVs can be expected to behave when they need to end an automated journey because of safety concerns. In particular, AVs with no human operator or tele-assistance will require a way to safely pause their journey when they cannot continue, and there is not yet a consensus on how this will work. Infrastructure may need to take account of this need in some way in the future.

Managing weather

To date, AVs have mainly been operated in places where weather causes few operational problems. However, a substantial number of jurisdictions experience extreme weather. Heavy snow, ice and slippery conditions pose challenges in colder climates; while heavy rainfall is likely to be a significant issue in tropical areas. Safe operation of AVs in such contexts implies resolving these problems, and this has been a priority for AV research in some countries, notably in Scandinavia (see Box 5). Singapore has also invested in equipment to replicate monsoon conditions and heavy flooding. These are significant technical challenges, but trial work is giving some indications about how they can be addressed, with early indications suggesting an important role for digital information to support the vehicle's decision making.

Box 5. Vehicle positioning in extreme weather conditions in Finland

Extreme weather conditions such as snow, ice, heavy rain or sandstorms challenge the automated vehicle (AV) positioning in a road. To tackle AV positioning issues in snowy and icy conditions, Finnish researchers studied automated and connected driving at arctic latitudes. They tested accurate vehicle positioning using posts and poles embedded in roadside infrastructure that could support automated driving. In addition, they tested AV positioning modules using inertia, the Global Navigation Satellite System (GNSS) combined with real-time kinematic (RTK) positioning, simultaneous localisation and mapping (SLAM) and high-definition maps.

Early trials suggest that the challenges of operation in extreme cold can be solved. In 2022, a commercial AV developer undertaking a trial in the city of Tampere contended with temperatures of -20° Celsius, heavy snow and freezing rain. Snowfall obscured road markings, while snowploughs created an unfamiliar landscape to navigate on a daily basis. Nevertheless, the trial was able to operate on a defined route for two months as planned.

Sources: Kotilainen et al. (2019); Sensible4 (2022).

Policy insight: Automated vehicles will use existing roads in the near term, and are supported by good maintenance to a defined standard.

AVs may benefit from regular maintenance of existing roads, particularly the provision of clear road markings and signs, and reliable surface quality, although standards for such maintenance are not yet available. Live updates on changes as they occur are a key industry request, but are currently limited by the lack of global standards for sharing or communicating such information.

Updating data

Maintenance and improvements to the physical road have consequences for any digital representation of the road network. AVs may build their understanding by combining what they sense about the road around them with what they know from digital sources. Where maintenance and improvement mean that the real world no longer matches the digital network, this potentially creates a challenge for AVs.

It seems likely that management of the physical road will increasingly need to consider updates to associated digital representations, and doing so in a way that can automatically be shared with vehicles. Many road authorities still manage their highways through processes developed in the last century, relying on paper reporting or periodic updates. This will likely have to give way to automatic, machine-readable updates, ideally provided as part of the work of those physically working on the road (see Chapter 3).

Opportunities for collaboration

The arrival of AVs creates a high degree of uncertainty around the capabilities of new vehicles and the situations that expose them to the greatest difficulty. This will only become known as real-world experience expands, giving insight into where issues can be expected to emerge, or where there are opportunities to remove barriers to AV use. However, this process can be accelerated through collaboration between industry and policy makers, helping to craft collective strategies to advance the responsible integration of automation into the transportation system to meet the respective objectives of all stakeholders.

The traditional stakeholders for physical infrastructure are infrastructure operators, either within government or privately organised. These stakeholders must collaborate with AV industry stakeholders to better understand the characteristics of AVs, how AVs perceive the road environment, the data AVs could use to navigate, and their relationships to transport authorities' functions, activities and physical infrastructure investment. Reciprocally, the AV industry needs to better understand the realities, operational and business models, and possibilities, made available through investments in transportation infrastructure.

The inventory and development of physical road elements not only serves Automatic Driving Systems, but human drivers as well. The process of supporting AVs may also lead to a higher quality of infrastructure for human drivers or a road system that has less scope for confusion (e.g. through the harmonisation of information included in traffic signs). A digital model of the essential road elements that aid AV navigation, combined with accurate positioning, can reduce the impact of any deficiencies in physical infrastructure quality for all users who are sufficiently connected.

Collaborating over standards

Standards provide a degree of consistency across different roads within a jurisdiction; but they often highlight differences between one jurisdiction and another. Many standards also have variations at different jurisdictional levels to address national, regional or local conditions. A standard in one country may be designed to manage the effects of harsh winter weather conditions while another may serve areas that experience excessive heat. In addition, there are limitations regarding the ability of various authorities to co-ordinate their standards with those established and maintained by international standard development organisations.

The existing system is designed to create roads that are suitable for human drivers. However, some members of the AV industry have indicated that a greater level of consistency and uniformity would increase the effectiveness of AVs at perceiving and navigating the road environment. There is no realistic chance of a single engineering standard being applied to all of the world's roads in the foreseeable future, or of implementing new standards at a speed that can match the rapid pace of technological development. However, there is still scope to use the existing system of standards to drive a more consistent and uniform experience on the road, which can be more suited to the needs of AVs. It would also be beneficial to further understand the landscape of standards and investigate if there are opportunities for existing standards to evolve or areas where new standards could support uniformity and consistency.

At a minimum, transport authorities and developers face a similar challenge of trying to comprehend a network of roads and the extent to which they provide road users with a consistent experience. Taken together, road types, layouts, and static and dynamic traffic control devices define the road environment and play a role in constituting the ODD that define an AV's operational boundaries. Developing a more structured framework for this knowledge, aiming to describe the infrastructure on different roads in a standardised way will assist both groups. Further research could allow infrastructure operators to standardize ODD definition elements and identify physical infrastructure attributes that aid AV operation, meaning transport authorities could conceivably identify where their roads serve AVs well (and where investment could be beneficial), while developers could use this information to understand where their vehicles should be able to operate reliably.

In order to explore this potential, policy makers and infrastructure operators need to share more knowledge with industry regarding the standards landscape, and collectively identify possible opportunities that would support AV integration. In return, industry will need to share data with policy makers to more fully accumulate the knowledge required to prepare the transportation system-of-systems for an intelligent and connected future. Working together, they could then work to update standards and analyse the feasibility of increasing consistency and uniformity, potentially in a way that could cover multiple jurisdictions.

In addition to existing standards, there may be opportunities to set standards in emerging areas that support AV integration – whether affecting physical infrastructure directly or by setting out how invisible infrastructure relates to physical assets. As part of this report, policy makers have identified HD maps and digital twining as areas where there is potential for useful new standards. In the near-term, transport authorities and industry should capitalise on collaborating on these emerging standards to initiate a joint foundation that both transport authorities and AV industry can support.

Collaboration between developers and policy makers will enable each to understand and develop protocols for AVs that need assistance similar to those for human drivers. Collectively developing such arrangements will ensure the safety of AV users as well as the other users of the road environment.

Common research

Policy makers are aware of the gaps in their current knowledge, and in many cases are already carrying out research to identify the appropriate investments needed to ready physical infrastructure to support AV integration, including by developing network audits and inventory frameworks (see Box 2.1).

This work usually identifies road features that support AV navigation, inventories these features, develops criteria to assign readiness states, develops methodologies that analyse the current features state and the targeted state needed to support AV navigation, and sets improvement strategies that can be undertaken to improve readiness to support different stages of AV integration.

Such inventories and audits are currently being carried out independently by transport authorities in the absence of a standard approach to assessing readiness. There is a danger that independent developments could lead to action that lacks co-ordination, or to non-interoperable solutions or investments that do not ultimately support the operation of AVs. To ensure a co-ordinated effort, industry needs to work with policy makers internationally to help steer the development of audits that closely match the growing sense of technical needs.

This work also has the potential to link with another promising area of technical development: the growing availability of road condition data from connected vehicles. Infrastructure managers have already recognised the considerable potential from the increasingly sophisticated array of sensors in private vehicles, which provide a far more detailed picture of the state of the road network than the current generation of inspection vehicles. AVs have the potential to take this further, linking an understanding of asset condition to the way in which a vehicle attempts to drive upon it.

At present, a major barrier to using this data has been the lack of commonly agreed standards for sharing it. By considering any emerging data standards in design of AVs, developers would be able to produce the highest-quality dataset in this area, which many highway authorities would be keen to make use of.

Other types of research and development include:

- investigating road configurations that include AV challenges associated with roundabouts
- traffic control devices, including lane markings; communications and connectivity
- data requirements, including work zone data and traffic regulations data
- digital infrastructure
- testing, evaluation, and pilot demonstrations
- policy development, including eligibility of various improvements
- operational consideration to appropriately manage AV on the road network.

Where this research is being carried out by policy makers, it is often without the participation of industry, and without co-operation between jurisdictions. There is a danger that independent developments could decrease co-ordinated activity across various countries that do not support uniformity for AV operation. To ensure a co-ordinated effort, industry and policy makers must work together to understand the nature of these activities and provide a level of information that support a collaborative and co-ordinated effort; and policy makers should work together to tackle the common questions that face them all.

Policy makers and industry leaders need to discuss the usefulness of the portfolio of research and development activities, and share information to facilitate meaningful research that identify how they can take account of one another's approaches to make AVs work better. Once a research plan for AV-related physical infrastructure is identified, policy makers and industry need to discuss and identify how the research can be conducted collaboratively, so both transport authorities and industry will actively participate and improve understanding between sectors.

One area of collaborative research that is discussed by both policy makers and industry is measures, metrics, tests, evaluation, and pilots. Policy makers want to understand and improve how the road environment is perceived and understood by human drivers and AVs. Policy makers are constantly looking at opportunities to increase safety and effectiveness, while developers want to deliver a safe service to as many customers as possible. Both groups need to discuss their mutual needs and find connections between safety, effectiveness, and environmental outcomes.

Part of this discussion will address the need for targeted priorities, such as motorway truck AV operations, or ridesharing companies transition to AV operation, or for parallel focuses that work on specific areas that support later integration of AV across different road types and environments. Identifying a focus will facilitate defining the near-term and long-term tests, evaluations, and pilots needed. Both policy makers and industry have limited resources, so it is essential that testing, evaluation and pilot activities are focused on areas that deliver practical value in a short timeframe.

The research undertaken for this report has shown there is a particular interest from experts in countries that experience harsh winter conditions about industry expectations regarding seasonal driving conditions. There are questions regarding how AVs will navigate if rain, snow, or ice cover lane lines or other traffic control devices, or if heavy rain interferes with sensors. Will transport authorities need to change their infrastructure standards or seasonal maintenance protocols and to what degree?

Industry has provided little insight, saying that AV performance capabilities with advanced sensor technology will increase over time enabling AVs to navigate challenging road conditions. If transport authorities do not need to change seasonal maintenance protocols for AV integration, their resources can be targeted to other areas of AV integrations. However, it would be beneficial for transport authorities and industry to have a conversation to confirm industry needs and expectations regarding roads, weather and AVs.

A cross-cutting theme across all the road environment is establishing mechanisms for collaboration between policy makers and industry. This need for collaboration is important to physical infrastructure, data and digital infrastructure, and the institutional framework and discussed in more detail in Chapter 5.

3. Data, digital infrastructure and automated vehicles

Chapter summary

- "Invisible infrastructure" plays a key role and offers greater near-term investment opportunities than physical roadspace in supporting the introduction of AVs.
- Mobile connectivity to the Internet is expected to be important to AVs, helping them to be aware of the wider traffic environment and enabling functions that are safety critical on some designs, such as teleoperation during a fallback instance. As road networks have been built and operated without consideration of connectivity, there may be gaps in the communications infrastructure needed to support AVs. Strategies to address gaps, work within existing ownership and liability models and in co-operation with other types of user and degrees of spectrum availability are required.
- Geolocation services (such as GPS) are well-developed, and solutions already exist to improve their accuracy where needed. However, cybersecurity of geolocation services will become increasingly critical as AVs and intelligent infrastructure become dependent on such services.
- High-definition maps are used by almost all developers of AVs, and are the one form of "infrastructure" in which they invest regularly. As a result, maps will play an important role in enabling the safe operation of AVs. This means that the availability of maps, and the ability to keep them accurate and up to date, is an important new challenge. Maps may be provided by developers in-house, by third-party mapping companies, or by direct government procurement – but policy makers need an overarching strategy.
- Traffic management of AVs will be substantially different to existing practice. Rather than inventing new practice with every deployment, there is clear benefit in developing a shared "blueprint" to help manage AV operations worldwide – both for initial deployments and to adapt to new use cases as they evolve.

Traditionally, the interaction between vehicles and infrastructure has been a matter of physical vehicles on physical roads. For several decades, this has been changing, with the growing importance of data and digital connectivity. The rise of AVs marks the point at which the management of digital data becomes as important to safe travel as the physical surface on which the vehicle travels. This report has looked in detail at the interconnected themes of digital connectivity and data.

This is an area where thinking has continued to evolve as the report has been written, reflecting a growing recognition of its importance. Recently, significant work has begun in the United States, centred on the concept of "digital infrastructure" – a term generally referring to the communications technologies and data transport required to support the transportation system and related mobility applications. Digital infrastructure can support information exchange among public and private users and infrastructure operators/owners. It could consist of information sensing, communications, processing and storage used and located within public roads and at associated centres and elsewhere (e.g., cloud centres). It could also reflect the business models, agreements, organisational and institutional processes that support operation of those systems. Overall, the digital infrastructure for roadway transportation enables the management of the transportation system, including the pursuit of safety, efficiency, mobility, equity and other objectives of system operators and users.

Regardless of language and structure, this series of powerful, novel and interconnected systems is increasingly seen as critical to future developments.

Digital infrastructure as defined in this report includes the systems and networks that provide for connecting users to other communication systems and data, including:

- wired and wireless communications networks
- devices and systems needed to manage communications and data
- collection, processing, exchange, access, and storage of data in relation to identified data protocols, and specifications
- interactions among data providers and data users
- access to information services such as the global navigation satellite system (GNSS) for positioning, navigation, and timing
- security of the system that supports maintaining a level of system trust, and protection and recovery from cyberattacks.

Data infrastructure includes the information provided to and from a vehicle as it travels about the road network. This includes:

- mapping information of a variety of standards, including updates on how that world may have changed or altered
- information from roadside infrastructure, such as traffic signals
- information to or from the operators of an automated vehicle or from other vehicles nearby
- information provided by public road authorities, such as information on construction works or traffic regulations, including those issued in real time
- strategic information used to address safety or plan network performance.

Vehicle and infrastructure communication technologies

Vehicle communication is enabled with wireless communication and information exchange between vehicle and infrastructure (V2I), between different vehicles (V2V) and between vehicles and the wider internet (V2N) to enhance traffic safety and flow, reduce carbon dioxide (CO_2) emissions and provide better services for road users.

Traffic safety, for example, can be enhanced by exchanging safety-related traffic information to protect vulnerable road users, supporting emergency services or to warn drivers in advance of weather conditions or hazardous locations ahead. Congestion could be reduced with traffic control and fleet management services, for example with information exchange on end-of-queues or rerouting all or some of the rides. CO_2 reductions and fuel savings can be achieved for example by services using traffic signals for vehicle priority, such as buses, or green light optimal speed advisory. End-user services can range from information on fuelling and charging stations to finding a free parking place with enhanced accessibility.

A number of AV providers expect to make use of vehicle connectivity to intervene in situations where unmanned AVs run into difficulties. Rather than having a human backup driver on board, they would connect an AV in difficulty to a remote operator, who would approve a manoeuvre or take over operation from a control centre. This creates a much more specific, safety critical need to ensure that communications links are constant and reliable, and more complex questions around responsibility for safety. When faced with difficulty, if unable to connect, these vehicles will come to a halt, potentially creating inconvenience or risk to other road users. Prototypes of these vehicles are already on the road, so this need is no longer speculative.

AVs are only one of many users of communications networks, even among road traffic. Significant advances are being made in parallel to improve the performance and utility of public transport; create new transport services such as ridesharing; or to enable users to gather information on the go in a way that is totally independent of their choice of mode. All changes for AVs must be considered in this wider context.

C-ITS short-range communications

Historically, efforts to connect road infrastructure to the people and vehicles on the road network have centred on Cooperative Intelligent Transport Systems (C-ITS). The term C-ITS covers a range of intelligent transport systems that are capable of communication and co-operation, in line with a set of globally agreed standards, using a commonly agreed frequency band.

Specific C-ITS systems that are sometimes referred to individually include cellular vehicle-to-everything (C- V2X) direct and Dedicated Short-Range Communications ITS Generation 5 (DSRC/ITS-G5). Both technologies enable direct communication between vehicles, to the appropriate connected infrastructure, and to the other road users equipped with proper devices. Both the standardisation of ITS-G5 technology and the availability of ITS-G5 devices have been stable for years (ITS Standards EU, n.d.; ETSI, n.d.). The 4G/5G standardisation for Long-Term Evolution (LTE) V2X and 5G-V2X has emerged in recent years to provide short range direct communication possibilities in a variety of different devices (EC, 2023).

C-ITS enables communication between pedestrians, vehicles and infrastructure, as well as between road users and traffic managers. Examples include a traffic signal that informs vehicles when it is about to change, or an emergency service vehicle that warns other vehicles of its approach. While most of this system is based around centralised communication between road users and a C-ITS “station” or between one station and another, service levels can be further increased through direct interaction between road users.

C-ITS has been developed over many years, through a well-organised programme of international collaboration (European ITS Platform, 2022). Clear technical standards exist, as do the organisational structures to develop systems further. This makes C-ITS one of the most technically developed “invisible infrastructures” around AVs, and developers wanting to work with this standard should face few technical barriers where it is available.

C-ITS has been deployed by infrastructure operators, focusing on delivering specific functionality on parts of the road network (as opposed to more general data connectivity). This means that it has tended to be implemented in specific locations rather than across the whole network, and also that AVs are typically developed to operate safely without C-ITS being available. Nevertheless, the existence of clear standards (and the absence of widely recognised alternatives) means that C-ITS is particularly useful for immediate interventions in support of automation. As vehicle connectivity increases, the usefulness of C-ITS for specific on-road situations is also likely to rise (see Box 6). The greatest need for C-ITS is likely to be around dense areas with high communication network capacity requirements such as intersections, areas without mobile network coverage or areas with high network resilience requirements.

Box 6. Rolling out Cooperative Intelligent Transport Systems in Korea

Korea is actively expanding its use of Cooperative Intelligent Transport Systems (C-ITS) to improve road safety. Since the 1990s, the country has built ITS infrastructure including detectors, closed-circuit television (CCTV), variable-message signs (VMS) and dedicated high-speed optical network for its motorways. The *National Transportation System Efficiency Act* (1999) mandates the government to develop a national ITS masterplan every 10 years, with the first published in 2000 (Lim, 2012). ITS now covers all motorway networks and 30% of national highways, and has improved integration between road authorities. The National Traffic Information Center (NTIC) collects, integrates and disseminates traffic information from motorways, national highways, 48 city-level roads (including roads in Seoul) and private entities such as navigation companies and telecommunication companies (ITS Korea, 2016).

This existing ITS capability formed the basis of C-ITS development in Korea, with the first official C-ITS pilot programme beginning in 2014. The Korea Expressway Corporation (KEC) installed roadside units (RSU) for vehicle-to-infrastructure (V2I) communication in the new city of Sejong, followed by four regional pilots focusing on different use cases. The most notable case was Jeju, where 3 000 rental cars were equipped with C-ITS on-board units, providing tourists with information on signal phases and other safety information. The Jeju ITS centre was able to use data from the vehicles to identify black spots prone to crashes. Several AV pilots followed as C-ITS infrastructure became ready in Jeju and Seoul.

In 2015, the Korean government released its Plan to Support Commercialization of Autonomous Vehicles (MOLIT, 2015). The plan highlighted high-definition (HD) maps, the global navigation satellite system (GNSS) and C-ITS as supporting infrastructures for AVs. A 2019 act allowed paid AV mobility service pilots in designated AV pilot zones. It also allowed the Ministry of Land, Infrastructure and Transport (MOLIT) to install C-ITS infrastructure in these zones. Furthermore, the law introduced the concept of an “automated driving safety zone” in which AVs can drive safely. This does not mean AVs are not safe in other areas, but it was intended to give MOLIT the authority to ensure and maintain the quality of physical infrastructure and prioritise the installation of C-ITS infrastructure.

Between 2019 and 2020, multiple strategies (MOTIE, 2019; MSIT, 2019; MOTIE 2020) were announced to build communication infrastructure across the entire network of motorways and key major roads by 2025 and establish a vehicle-to-anything (V2X) certification system based on public key infrastructure by 2022. Based on these plans and goals, a legally binding ten-year ITS masterplan (MOLIT, 2021) was prepared, along with a more ambitious budget for C-ITS.

Korea is initially focusing on the use of Dedicated Short-Range Communications (DSRC) technology for C-ITS, while validating LTE-V2X technology by 2022. The intention is to pursue an adaptive strategy, adopting a single standard by 2024, but not to let uncertainty limit deployment in the short term. With existing cables in place, no substantial investment in network construction is needed other than installing roadside stations. These are expected to cost less than USD 10 000 per kilometre, and can be upgraded to include new technology as it becomes available.

Mobile networks and 5G

Significant debate has taken place in recent years about the roles to be played by different communications systems in supporting connected AVs. While different systems are not mutually exclusive, there is a growing consensus that many AVs will use and need the capabilities of mobile networks. These networks consist of fixed base stations that allow two-way communication between the network and nearby users, together with a supporting system of fibre-optic cables or radio links to connect individual base stations to the wider network.

The fifth and latest generation of mobile connectivity (5G) began to be introduced in the latter half of the 2010s (European 5G Observatory, n.d.). Telecom operators have started their 5G network rollouts in cities and larger suburban areas where demand is highest. As AVs are being introduced, 5G will be the most sophisticated communications standard in widespread use.

5G is an umbrella term that covers a number of different communications systems, deployed together in order to provide data connectivity. Systems using low frequencies with narrower bandwidths are able to provide a modest amount of capacity across a large area using a single cell. Systems using a high frequency can provide more than a hundred times the capacity, allowing them to cater to a much greater demand for data, but cover a much smaller area. Making 5G capacity as a whole sufficient requires a mix of these systems, catering to the expected level of use (see Table 3 for an example from Finland).

Table 3. 5G frequency bands and bandwidths in Finland

5G frequency band	Bandwidth per operator	Typical data rates in good coverage	Typical cell coverage
700 megahertz (MHz)	10 + 10 MHz	tens of mbit/s	several kilometres (≤≈10 km)
3.5 gigahertz (GHz)	100 MHz (+30 MHz)	hundreds of mbit/s	a few kilometres
26 GHz	800 MHz	a few Gbit/s	tens-/hundreds of metres

Source: Finnish Transport and Communications Agency (Traficom, 2021).

Automated transport and various new mobility services will create new requirements for mobile communication networks along main roads around the world. The requirements for data transmission will likely vary on different roads and parts of the road network. As an example, use cases for automation will be quite different for orderly highways than those for busy urban centres.

A commonly shared opinion is that current 4G/LTE mobile networks respond to most of the requirements of digitalisation today, prior to the introduction of AVs. 4G technology will also mature and gain in performance, and the transfer of load from 4G to 5G networks also helps to improve the performance of the 4G network, meaning that 4G remains sufficient for now.

However, the growth of future traffic means that 5G's faster transfer speed, greater capacity and smaller delays will become increasingly important. For examples of trials utilising different communication technologies and capabilities see Box 7.

Box 7. Hybrid communications trials in the European Union

In Europe, the C-Roads initiative brings together 18 countries to start deployments of safety critical Cooperative Intelligent Transport Systems (C- ITS) services, by using a hybrid communication mix. Existing communication systems are used for transmitting safety-relevant information into vehicles, first as an information service and potentially as a mandatory service if this becomes necessary.

This is built around a hybrid communication mix using currently existing and deployed communication technologies – 3G and 4G for long range cellular communication and ITS-G5 (802.11p) for short range communication. Future communications standards can be incorporated into the system as they develop. Overall, some form of C-ITS communications covers around 20 000km of European roads, and long-range services cover around 100 000km.

To ensure sustainability of service delivery, several key principles have been established:

1. Interoperability of the delivered services is essential, even when they are delivered via different communication channels.
2. Backwards compatibility is highly important. New C-ITS equipment needs to integrate with existing C-ITS services to ensure constant safety.
3. The evolution of cellular communication standards towards 5G is expected to bring further improvements to long range cellular communication (e.g. coverage improvements and signalling efficiency), providing benefits to the hybrid communication approach and complementing short range connectivity.
4. Road authorities need to have the option of providing connectivity via a hybrid communication approach, also including all suitable communication networks to vehicles in the future.

Source: C-Roads (n.d.).

A 2020 Finnish study on the costs of mobile networks assessed the future needs of automated transport (Sitowise Oy, 2020). The study found that individual vehicles are likely to have relatively modest needs for download capacity, and periodic needs to upload information at particular locations (e.g. at intersections) or in response to events (e.g. a remote assistance request from the vehicle to a remote control centre). The most data-intensive uses are updating HD maps and vehicle software updates, which are typically one-time occurrences during a longer period of time and do not need constant capacity.

Although the study found that the requirements for an individual vehicle are relatively low, this rapidly becomes a large need overall as traffic volumes increase. There is also one specific use case that requires much more bandwidth: remote assistance to an AV from a control centre, when multiple video streams would be transmitted from the vehicle over the network. If multiple vehicles required this type of assistance at the same time (which is a realistic scenario in case of a major traffic disturbance), there would be very high demand for capacity on the mobile networks in the area. This may mean that the demand for connectivity will be disproportionately high in the early stages of AV traffic.

Many early applications of automation can work with existing 4G networks. However, as the number of better equipped vehicles and range of services requiring mobile connectivity increases, the need for 5G technology and its capabilities quickly becomes overwhelming.

Policy insight: Developing "invisible infrastructures" offers greater opportunities for near-term benefits than upgrades to physical infrastructure

At present, there is limited evidence on what makes a road "good" for AVs, and technology is still developing. This means that there is limited scope to invest in physical upgrades to the road network until requirements are clearer. There is a better case for developing the "invisible infrastructures" of digital connectivity, data and institutional capacity, on which AVs will rely.

The clearest cases for action are for producing strategies to ensure adequate connectivity to communications networks and infrastructure on key roads; ensure availability and reliability of HD maps for key sections of the road network; ensure the availability of live data on road infrastructure, including all traffic regulations; and establish data standards, Concepts of Operations, and architectures for applicable digital infrastructures.

As these invisible infrastructures are often privately operated, these strategies are more about providing leadership than spending money. These measures are valuable regardless of the future of AVs, but each materially improves the ability of AVs to operate on the road network.

In locations with high traffic volumes, high-capacity 5G networks will be needed to meet increasing capacity needs. Automation use cases where latency is safety critical create a particular need for 5G or DSRC capabilities. Data-intensive application use cases also need 5G networks especially when these applications are used by many within a restricted area and cell coverage. The quality of service for transport automation should not be degraded due to sharing the network capacity with large numbers of other users. 5G includes isolation mechanisms to reserve a certain part of the network for specific users.

With growing clarity on the importance of mobile networks, policy makers and infrastructure operators will soon need to consider mobile connectivity a necessary part of a safe road. On heavily used highways this is likely to require consistent 5G connectivity. Historically, most countries have not planned how to ensure consistent mobile network coverage of transport networks, and providing a reliable connection along the length of the busiest highways will require organised action. Whether this is accomplished through state action or private investment is likely to reflect local circumstances, but the end result needs to provide sufficient coverage to ensure user safety. A complex range of related issues, including interoperability, cybersecurity, resilience, reliability, privacy, and data governance and ownership, also need to be considered.

Satellite-based location

AVs use positioning information for different purposes, including route navigation, lane control and collision avoidance. The need for positioning remains in all weather and operational environments from cities to highways to mountain tracks. Real-time positioning is one of the most crucial information needs for AVs: not only does it help a vehicle to function, but if a vehicle is not confident that it knows where it is, it will implement fall-back safety measures, decreasing operating performance or stopping automated operations totally. The safety-critical nature of this information need means that position should not be determined by relying on a single technology but must combine several complementary approaches.

Each AV is equipped with its own array of sensors, many of which are used to determine a vehicle's position through a range of approaches. However, external information also plays an important part, and the one most familiar to drivers today is GNSS-based positioning. Currently four different GNSS systems (Galileo, GLONASS, BeiDou and GPS) provide globally open positioning services, with a positioning accuracy of 1.5- 10 metres (EUSPA, n.d.). For an AV driving in a three-metre traffic lane, this accuracy is not sufficient to allow for safe driving in isolation, and can be worsened by unhelpful environmental conditions such as limited sky/satellite visibility (in forests or "urban canyons") or electrical disturbance (e.g. power lines, broken gadgets). GNSS positioning on its own also does not work properly indoors or in tunnels.

Maps and onboard sensors can complement GNSS-operated systems to provide a level of accuracy that allows for safe driving. However, complementary technologies can boost GNSS positioning accuracy and reliability. Each of these systems substantially raises accuracy in the places where they are available. Satellite-based Augmentation Systems (SBAS) are more accurate satellite systems, whose coverage is regional rather than global. These systems improve the accuracy of the GNSS positioning to 1-2 metres – enough to tell an AV which traffic lane it is driving in. In most ITF member countries, SBAS are usually built into conventionally sold GNSS systems. Like GNSS, SBAS are owned and operated by governments.

Differential GNSS (DGNSS) or real-time kinematic (RTK) positioning services are based on locally placed reference stations. They can improve the GNSS accuracy to the centimetre level but the efficient operating range from the reference station is tens of kilometres. Therefore, while SBAS are capable of providing coverage across entire continents, DGNSS and RTK systems are better scaled for cities. DGNSS and RTK service operators can be either governmental or commercial.

Taken together with other available positioning systems, these technologies allow AVs to understand where they are, and can be boosted to allow greater accuracy where needed. Significant investment has already been made to deliver high-quality positioning information, and in most countries there is limited need for new investment to provide a better service.

Satellite-based navigation is notable for the types of stakeholders involved. Relatively few countries have access to a nationally organised system, and may need to make contacts in other jurisdictions if they wish to influence the development and use of this infrastructure. As intelligent vehicles and infrastructure become increasingly dependent on GNSS for localisation information, there is a correspondingly greater degree of vulnerability and cybersecurity risk that needs to be addressed at the system and system-of-systems levels. Whenever possible, cybersecurity should be "baked in" to the architecture, design and procurement of associated policies and initiatives.

High-definition mapping

Mapping plays a crucial role in the operation of AVs. An accurate map converts a set of co-ordinates into a real location, facilitating the localisation, perception, world view and (for higher levels of automation) navigation. Most of the developers and organisations consulted with during the preparation of this report acted on the basis that high-quality maps were an essential requirement for the safe operation of their vehicles. Traditional maps, together with a basic level geospatial positioning, already help human drivers to plan their route; but for AVs a much greater level of accuracy is required.

AVs frequently make use of HD maps, which are substantially more detailed than their traditional equivalents (see Box 8). Rather than just a high-level chart of an area, an HD map has a level of detail closer to a photograph or a three-dimensional model. This allows AVs to locate themselves with much greater precision, decode their surroundings and make better driving decisions. Rather than trying to understand its surroundings from first principles, a vehicle using an HD map is more likely to be confirming a picture that it already understands.

Box 8. What is a high-definition map?

High-definition (HD) maps are created through the detailed surveying of the road network using vehicles equipped with sensors similar to those used by AVs. By using high-definition cameras, light detection and ranging (LIDAR) and other sensors, survey vehicles build up a finely-detailed picture of their surroundings. This data is then joined together, analysed and structured to provide a high-precision picture of the road and surrounding environment. The map also places much of this information in context – for example, identifying which traffic signals relate to a particular junction.

This information is separated into a series of "layers" with their own meaning. Some are functional descriptions of elements of the roadway, such as the precise locations of traffic lanes. Other layers can cover more conceptual information: for example, in 2020 TomTom introduced a product called RoadCheck, which explicitly helps AV developers decide whether roads are suitable for the operation of their vehicles.

Traditional maps rarely need to be completely accurate at all times. The intended uses of HD maps mean that they need to be precise, potentially even in real time. For this reason, the creators of HD maps also need to invest in keeping them up to date. Whereas a traditional map might be re-surveyed once every 10-20 years, an HD map requires regular updating. This can involve further visits by survey vehicles, updates from infrastructure operators and reports from road users. AVs themselves will be major data providers in the future, as they constantly compare the previously built map with the current situation on a road and flag discrepancies. There is also a parallel challenge for infrastructure operators, who will have a much more immediate need to ensure that maps are updated to take account of any recent changes and any events taking place.

Updated maps are then communicated to users through the Internet. The very large size of detailed HD maps means that the necessary data for a full HD map must be carried on the vehicle itself, but updates can be delivered remotely. More streamlined mapping layers can be communicated more efficiently.

HD maps do already exist for a small number of roads, but coverage is still limited. One mapping provider who helped inform the current report had completed around 5 000km of HD mapping for Europe – around 0.1% of the total road network in the European Union. This lack of coverage partly reflects the lack of a strong commercial market for such information at present. While coverage could be increased significantly within existing structures, at present the private sector does not provide widespread HD-map coverage.

It is notable that developers rarely invest in roadside infrastructure, or in installing mobile communications masts; but a substantial majority invest in building maps or buying them in from a third party. This is true despite the relatively high cost of HD mapping, at least by the standards of traditional mapping companies. HD maps have historically been expensive to produce, complex to keep up-to-date and are several terabytes in size. Different strategies have been adopted across the industry to address this, from reducing reliance on mapping to streamlining data layers. Some developers (notably Telsa) hope to develop AVs that do not require any HD maps at all. Yet the majority of developers continue to rely on some form of HD map, with most of the information carried on board the vehicle rather than accessed from the cloud.

Some developers source their maps from third-party providers, and the largest mapping companies are well-aware that there is a large market to share. However, many others, including the providers of the most advanced AVs, have their own proprietary mapping that only works with their own systems. The closest steps towards single, common formats come in Japan and Korea, where there are government-led efforts to provide HD mapping on key routes as a public service. Elsewhere, the of compatibility has implications for a range of areas, including market competition and the ability of different developers to make use of the same areas for on-road testing.

Once an AV is able to use an HD map (or any alternative), developers are usually careful to test that the vehicle links together the evidence of its sensors and its understanding of the wider map in a way that leads to safe driving. This includes extensive test-driving, slowly working towards the point at which a human driver can be removed from the equation. Provision of HD maps by itself does not allow AVs to operate on the road network, but they are on the critical path to safe, driverless operations for many AV designs.

Taking action on mapping for automated vehicles

Maps, potentially more than any other kind of data, represent a key new "infrastructure" for AVs, with many developers considering them to be critical to safe operation. If mapping is central to the near-future of automated mobility, it has significant implications, both for the people who build and operate AVs and the policy makers who oversee the system as a whole. Policy makers need to actively consider the following four significant policy challenges, alongside more practical challenges.

1. Maps play a growing role in safety. If maps cease to be effective, automated driving capability may be suspended. In a worst case scenario, the vehicle may not be aware of this failure before its passengers or other road users are placed in danger.
2. Maps are not being made to a single standard. There is no recognised standard for HD mapping. Given that many leading developers have their own in-house mapping solutions, there may never be a common approach. This creates risks for those creating maps and those using them.
3. Maps are unlikely to cover the whole road network. While mapping high-traffic roads is relatively inexpensive, mapping an entire country's road network would be extremely expensive by private sector standards. Extrapolating from experience in Korea it would cost around ten million dollars to map the motorway network of a mid-sized country in full, but several hundred million dollars to map the entire road network. This is before considering the costs of keeping this information up to date. If HD maps are expensive, developers are likely to focus on covering densely populated areas and heavily used highways, while neglecting poorer or more rural areas. Countries that wish to see universal access to AVs will need to consider how adequate maps can be provided.
4. *Maps may discourage competition* – If mapping is costly and expensive, it means that incumbent providers in an area will be at a substantial advantage compared to new entrants. This may not be an issue where third parties are selling maps, but if in-house mapping by individual developers becomes the dominant approach, it may create a tendency towards monopoly provision.

Once created, HD maps must be kept up to date. The existence of temporary changes to road layout, such as roadworks, needs to be added to the map and taken off at the same time as the road itself changes. Permanent changes to the highway, such as the introduction of new traffic signals, also need to be incorporated in maps once they are in place. This is ultimately a shared enterprise, with infrastructure operators having information about planned activities or changes, map-owners incorporating that information into their maps; and communications providers distributing that information to vehicles and users.

Policy insight: Developing “invisible infrastructures” – such as mapping – offers greater opportunities for near-term benefits than upgrades to physical infrastructure

At present, there is still limited evidence on what makes a road “good” for AVs, and technology is still developing. This means that there is limited scope to invest in physical upgrades to the road network until requirements are clearer. There is a better case for developing the “invisible infrastructures” of digital connectivity, data and institutional capacity, on which AVs will rely.

One of the clearest cases for action is for producing a strategy to address availability of HD maps for key sections of the road network. As maps are often privately provided, this strategy can be as much about setting direction as it is about spending money. The desired outcome could be delivered through a number of channels, for example by:

- birectly tasking a government department, government mapping agency or infrastructure operator with surveying the road network
- ensuring that private sector mapping providers are able to provide adequate coverage
- consciously empowering developers and industry to provide the level of coverage that best meets their needs.

As part of this assessment, policy makers will need to consider how widely they wish to see mapping coverage provided, by when, and to what extent they are willing to invest public funds in order to achieve it. They will need to assess both initial coverage and the ongoing need for updates. Consideration must also be given to the interoperability of data and the application of emerging global standards.

Policy makers must then continue to support and monitor the developing availability of maps, to ensure that the quality and flow of data is sufficient to ensure the safety of the public.

Seen from the perspective of an infrastructure operator, providing accurate information in real time is not only important to those driving AVs, but will also make an important contribution to the safety of staff working on the road. Commentators interviewed for this report highlighted the importance of having an update system that can be used in real time by operational staff.

Mapping companies interviewed for this report are clear that the flow of data between infrastructure operators and the maps used by the travelling public is slow and inefficient, and a major improvement in data exchange will be needed. Some infrastructure operators are already looking to improve their provision of data, particularly around roadworks and dynamic traffic control, but this is still work in progress and no global standard exists for exchanging this information.

However, those infrastructure operators that have decided to survey their networks and provide publicly accessible HD maps (see Box 9 for the case of Korea) have already begun to implement measures at a national level to ensure immediate and comprehensive updates. This includes:

- ensuring that all construction projects include detailed re-surveying of the highway and updating of public maps once complete
- requiring all maintenance work making changes to the highway, signs or other physical infrastructure to also update maps as appropriate.

Box 9. High-definition mapping the network in Korea

In 2015 the Korean government began producing high-definition (HD) maps of its national road network. Korea's National Geographic Information Institute (NGII) began with surveys of 471km of major highways and priority test areas (NGII, 2019). By 2019, a total 6 700km of roads, including all motorways, had been mapped (MOLIT, 2020).

The following year, the Korean Ministry of Land, Infrastructure and Transport (MOLIT) announced that it expected all national highways to be mapped by the end of 2022 (MOLIT, 2020). In order to do this, NGII commissioned private companies to produce HD maps of the network.

Recognising that surveying the road network with high definition was set to be an ongoing source of business, private survey companies purchased a fleet of survey vehicles with mobile mapping systems, each costing around USD 1 million. One expert interviewed for this report estimated the operational cost of mapping averaged USD1 600 per kilometre across the whole network, allowing for the rapid expansion of HD maps.

While expanding the HD-map coverage, NGII worked together with MOLIT to change road construction and maintenance procedures to include HD-map production as a part of standard procedures. This meant that changes and additions to the network were automatically added to NGII's maps (MOLIT, 2020). This mapping information is publicly available free of charge, and is used by a wide range of public and private sector bodies, including large corporations and smaller developers.

Managing data and infrastructure

AVs are an exciting opportunity to policy makers as a way of opening up new types of mobility, or enabling a more dynamic or data-rich management of existing journeys in a way that delivers policy goals. In order to realise many of these aims, traffic management measures will be key to integrating AVs and new mobility services in the transport system.

Integrating automated vehicles in the transport system

Traffic managers around the world have many interests in new types of vehicle. Communication infrastructure enables direct interaction with single vehicles or fleets, enabling new ways of managing traffic by influencing single vehicles, interaction with AV operators, and possibly even introducing service-level agreements with major players. AVs follow digital directions more closely and comply with regulations. There are new opportunities to use new AV services to support existing systems of public transport, creating opportunities for intermodal connection. Less helpfully, the arrival of mixed traffic situations with automated and non-automated vehicles sharing the roads will create new challenges, which traffic managers will be expected to address.

These desires are likely to be very similar across the world. However, the ways in which traffic managers approach this problem are not guaranteed to be the same. The spread of ridesharing and micromobility across the world shows the potential for new technologies to spur the disconnected development of different models for management, ultimately making it harder for innovation to spread. There is a real benefit to establishing a standard method for how traffic managers and AV operators interact, which can be used around the world without the need for extensive localisation. To be most effective, the outline of a common approach should be in place before AV use becomes widespread.

Policy insight: A blueprint for co-operation can help traffic managers maximise the benefit of the introduction of automated vehicles as part of a wider transport network

AVs, particularly those designed to co-operate with other vehicles and talk to infrastructure, will offer traffic managers an unprecedented opportunity to understand and manage traffic flows in their cities. Achieving such capabilities and benefits will require co-operation, which can be facilitated through a global "blueprint" setting out how different parties can work together and support the arrival of new mobility services, and then customised to local circumstances. Drafting this blueprint requires co-operation between industry and policy makers worldwide.

Such a "blueprint" does not remove the ability of different jurisdictions to make their own choices about how to manage AVs or operate their transport network, but it can be a helpful device to help start effective co-operation between unfamiliar players. By providing a workable set of options to customise, it can avoid the need to invent new arrangements in every city; and by structuring interactions, it can help to give shape to a wide-ranging and complex process.

In particular, it can help consider how arrangements evolve over time. Initially, AV operators need access to large amounts of information about the areas in which they operate. At a minimum, this needs to include the rapid sharing of information in machine-readable formats, and ideally it would include communication with live traffic management systems. Traffic managers need to take steps to ensure that people can use AVs safely and understand risk on their highways.

In the medium term, structures need to exist to allow for the intelligent management of AV traffic, and to allow the operators of AV fleets to have effective control over their vehicles. This includes the integration of traffic management centres and services towards a traffic management ecosystem, and facilitating traffic management across different modes, integrating highway, cities and corridors, as well as public private collaboration. This approach needs to understand the requirements and interests of AV operators and providers of services based on AVs, as well as those of traffic managers.

In the longer term, new mobility services based on AVs and evolving expectations about the state of the transport system could lead to a significant evolution of how the transport system functions or what it delivers. Any system must be able to develop and improve, using research, developing more sophisticated tools to predict or deliver outcomes, and defining concepts such as appropriate performance in a way that matches new needs. Where appropriate, this could include expanding the range of interested parties if, for example, new mobility services complement the existing public transport system create a need for new types of intermodal hubs.

Data management and analytics

Data is an essential component of automated transport. The process through which an AV comprehends the world centres on converting information on its surroundings into a digital format, and taking decisions on how to drive safely. Some of this data comes from within the vehicle; some can potentially come from external sources. In all events, the process by which the vehicle drives is a rich source of data in its own right.

This volume of data is both a valuable asset and a systemic problem. Traffic authorities can make use of new forms of data to greatly improve the operation of the road network, and to manage traffic in ways that are currently impossible. However, the volume of data being processed by a single AV can be several terabytes an hour and is growing over time as sensors and on-board processing and storage improve, meaning most cannot be shared in an unprocessed form. Streamlined, wide and fluent sharing of data between different actors is needed to realise the full potential of this technology.

One crucial requirement is to fully decentralise data collection, storing and sharing where applicable. Other tasks should or could be handled by a number of distinctive entities in a co-ordinated manner. Many roles in the data sharing ecosystems are well established, such as the end users and service providers. However, new intermediary roles with co-ordination tasks have started to emerge, and it is important to recognise these roles and define the rights and responsibilities attached to them. All roles within such a system need to be defined, with responsibilities and rights. Data ownership, privacy, business models, liability over veracity, security, credentialling, and performance for discrete applications will need to be addressed.

Data should be digital in machine-readable format where applicable, and available as real-time data where feasible. Data should be stored only once and collected from the original source by using, where possible, application programming interfaces (APIs) accompanied by machine-readable access and licensing terms as well as information related to intellectual property rights.

Data holders, or controllers working on their behalf as defined in the European General Data Protection Regulation (European Parliament and Council, 2016), are able to control the authorisations for data sharing via APIs; but the restrictions on data sharing should be based on well-defined reasoning at the corporate (industry or government) policy level and should enable third-party access to data to generate wider value. The functioning of ecosystems is based on the principle of decentralised data management.

As with all decentralised information management, the curation, discoverability, accessibility and interoperability of data is essential, as is the interoperability of systems. Interoperability is also needed in areas of regulation, organisation, semantics and ontologies. Only by making the combination of data from different providers and sources as easy as possible will it be possible to maximise the potential of the system as a whole.

Proven means of improving interoperability in the long run include standardisation, common data formats and protocols. Some sectors already apply systematic approaches that aim at interoperability, but AVs lack this more holistic approach at present.

This is not to say that developers should be forced to adopt complex and inefficient standards; but the standards and architecture for managing AVs collectively are best established now, before vehicles begin operating on-road in large numbers. This will allow developers to find their own ways to co-operate with the evolving data strategies for the wider transport system.

Data to and from infrastructure

The data required from infrastructure to support automation is likely to include both static and dynamic data. Static data is data that does not change or changes very rarely, usually relating to the physical road infrastructure or digital infrastructure alongside the roads. In order to promote transport automation, it is necessary to transform this data into digital machine readable format, primarily for mapping purposes and to support the vehicle’s attempts to understand its own surroundings. Such static data is typically produced or controlled by road authorities. Categories of static data required for road transport automation include:

- type of pavement, lane widths
- height and weight restrictions of bridges
- lane and carriageway/roadway markings

- mandatory traffic control devices and signs (traffic lights and traffic signs).

Dynamic data is data that changes constantly, and in practice covers a diverse range of items on and around the road that are either in motion, or which change from moment to moment. It not only covers information necessary to automation, but also data that can be used to understand the operation of the road network at an operational or strategic level. Dynamic data that is either provided by infrastructure or is necessary to make sense of it includes:

- data collected by the vehicle's onboard systems (including acceleration, speed, braking, traction control and functioning of equipment)
- vehicle positioning
- road infrastructure maintenance
- traffic data (including on faults and disturbances) and vehicle travel time
- weather-related data (information on weather conditions and slipperiness, forecasts).

Dynamic data can be collected in a number of ways, including existing traffic detection systems, on-road cameras and parallel sources such as mobile phone data. However, the advent of AVs, as well as other vehicles equipped with more limited forms of automation, means that there is great potential for it to be collected by vehicles. This data currently typically resides in the vehicle manufacturer's systems, and cannot be controlled by the driver or by public authorities without some form of agreement.

Most current transport information services involve traffic fluency and incident data as well as road-condition data. These services work well on current mobile networks (2G-4G). Safety-related traffic information services are being developed and launched, and in the near future C-ITS will become more common. Europe is one region that invests in accelerating the deployment of these services.

Table 4. Cooperative Intelligent Transport Systems (C-ITS)

Initial ("Day 1") C-ITS services	Early ("Day 1.5") C-ITS services
Slow or stationary vehicles and traffic ahead warning Road works warning Weather conditions Emergency brake light Emergency vehicle approaching Other hazardous notifications In-vehicle signage In-vehicle speed limits Signal violation / Intersection Safety Traffic signal priority request by designated vehicles Green Light Optimal Speed Advisory - GLOSA Probe vehicle data Shockwave Damping	Information on fuelling and charging stations for alternative fuel vehicles Vulnerable Road user protection On-street parking management and information Off-street parking information Park & Ride information Connected and co-operative navigation into and out of the city (first and last mile, parking, route advice, co-ordinated traffic lights) Traffic information and smart routing

Source: European ITS Platform (2021).

As shown in Table 4, many C-ITS services are also relevant for automation purposes. It is important to note that activities to enhance co-operation in exchanging this information are underway around the world.

Data privacy will be a significant issue influencing how much in-vehicle data is handled. The European Data Protection Board has issued guidelines on processing personal data in the context of connected vehicles and mobility related applications (EDPB, 2020). They note that connected vehicles are generating increasing amounts of data, most of which can be considered personal data. The Board's proposed starting point to deal with this would be the aim for "privacy by design". This adds a further level of complexity to the data-sharing environment, creating issues both of trust, and also around balancing privacy with safety.

Access to data is a question which is likely to be resolved in different ways between jurisdictions, reflecting local attitudes towards privacy, policy makers' ability to gain access to information (whether by voluntary agreement or regulation) and the range of sources available. What will be universally true is that the range and richness of data becoming available has the potential to greatly enhance the capability of governments and infrastructure operators to make roads run more safely and with greater efficiency. Translating this potential into benefit will require the co-operation and investment discussed earlier in this chapter.

In particular, the survey of policy makers undertaken for this report highlighted an interest in getting data about the state of roads and the timing, routes and distance of journeys. This is mostly aimed at managing congestion and targeting maintenance. Some countries are also interested in data that reports unlawful actions, although the extent to which AVs break laws is likely to be low. The majority of countries report that data captured from AVs can also be very useful for infrastructure planning and management, reducing the risk of collisions, tracking the state of infrastructure, understanding patterns of demand for mobility services, managing traffic flow and carrying out winter maintenance. Some countries are working with industry to facilitate exchange of data between AV, service providers and infrastructure operators, and the EU is currently working on defining data that would be mandatorily provided to government within its jurisdiction.

Similarly, there will be a universal need to get data out of infrastructure operators, and shared with those that would benefit from such situational awareness of road and traffic conditions (see Box 10 for an example from the Netherlands). In addition to traffic authorities, those operating fleets of AVs will need to be able to assess the safety of their vehicles as they operate; and users of AVs will want to be reassured that the vehicles they travel in have the latest information about potential hazards. All of this means that highway authorities around the world will need to get far better at sharing and exporting information.

Box 10. The Talking Traffic partnership in the Netherlands

In the Netherlands, the Talking Traffic partnership has been created to join together data from a wide range of national, regional and local infrastructure providers, as well as the companies making use of that data. Focusing in particular on the information provided by traffic lights and smart cities infrastructure, it creates a forum where datasets can be created, improved and put to use, delivering a better transport network.

The partnership is arguably most notable for its ability to connect a variety of different organisations. Although the Dutch Ministry of Infrastructure and Water Management is a key participant, more than 60 regional and local authorities are also involved, together with a wide range of private companies. This range of different perspectives allows for a much broader understanding of what is feasible and useful, and what requires longer-term strategic action.

Source: Talking Traffic (2018).

Policy insight: Developing "invisible infrastructures" offers greater opportunities for near-term benefits than upgrades to physical infrastructure

At present, there is limited evidence on what makes a road "good" for AVs, and technology is still developing. This means that there is limited scope to invest in physical upgrades to the road network until requirements are clearer. There is a better case for developing the "invisible infrastructures" of digital connectivity, data and institutional capacity, on which AVs will rely.

This includes action to 1) ensure the availability of live data on road infrastructure, including all traffic regulations, and 2) establish data standards, Concepts of Operations, and architectures for applicable digital infrastructures. As with other aspects of invisible infrastructure, much of this activity is about leadership and management of existing assets and services, rather than large-scale new investment.

Achieving this change requires innovation, which has the potential to be challenging in a sector which has been building and maintaining roads in much the same way for a hundred years. It also requires extensive collaboration between policy makers and industry, working to overcome barriers in a way that generates value for both sides. Feedback from industry has been clear that there is much potential to improve services. Change cannot be achieved without investing in staff with new and unfamiliar skills, systems for sharing data in an efficient, machine-readable way, and the managerial structures that will allow for the reinvention of existing practices.

Automated vehicles and cybersecurity

The introduction of automated driving, connectivity and broader digital infrastructure have raised concerns of cybersecurity. Although the increasing complexity of AV software and hardware increases the attack surface of a vehicle, these concerns also relate to the security of the digital infrastructure and related digital systems. The EU Agency for Cybersecurity has outlined how connected vehicles rely, among other technologies, on infrastructure surrounding it (ENISA, 2020). Infrastructure owners and operators providing ITS, with legacy systems and continuous integration projects, face challenges of better understanding future threats, how to manage the risk from these threats and mitigate risk as well as achieve situational cyber awareness and cyber resilience (ENISA, 2021).

Cybersecurity includes actions that can be used to control and mitigate different cyber threats and their impacts. Information security, protecting the availability, integrity and confidentiality of data, is the crucial component of cybersecurity (see Box 11 for a case study from Korea).

Box 11. Cybersecurity and Cooperative Intelligent Transport Systems in Korea

With a relatively widespread network of Cooperative Intelligent Transport Systems (C-ITS) infrastructure, Korea has needed to engage with questions of cybersecurity as an urgent and important issue. Legislation supporting automated vehicles (AVs) was revised in 2021 to establish new institutions that will manage C- ITS certificates and allocate public key infrastructure (PKI) certificates to both roadside and on-board units so that only certified modules are allowed to communicate with each other. The Korea Transportation Safety Authority (KOTSA), which manage Korea's vehicle registration system, will serve as the top-level authority overseeing the whole certification system.

Box 12. The US National Institute for Standards and Technology's cybersecurity framework

The National Institute for Standards and Technology (NIST) cybersecurity framework provides voluntary guidance, based on existing standards and practices for organisations to better manage and reduce their cybersecurity risk. It also helps to encourage risk and cybersecurity management communications between different stakeholders within and outside of an organisation.

The components of the framework provide a group of cybersecurity activities and desired outcomes using simple, common language. They also assist organisations by providing context on how an organization views cybersecurity risk management. The NIST cybersecurity framework supports entities assessing and updating their system such that their systems can identify, protect, detect, respond, and recover to increase the cyber resilient level of their systems.

Source: NIST (2018).

The criticality of data will grow as data is used more and more in different automation applications. The interconnections between communication networks, the transport system and vehicles will also increase. The cybersecurity risks in transport will inevitably seem closer to the everyday life of people and could, when realised, even lead to safety failures. Managing cybersecurity risks in transport becomes vitally important, and more attention needs to be paid to protecting information and communication systems against threats (see Box 12 for a case study from the United States).

Developing transport system cybersecurity based on active risk management is called for in the future. Ensuring the safe development of information systems in all areas of transport – including infrastructure, vehicles and services – is likewise crucial. Cybersecurity must be maintained during the life cycle of the systems taking advantage of existing standards and good practices. Automated transport pilots and testing should address cybersecurity at the earliest planning stage, and the security-by-design principle should be applied at all times (see Box 13 for a case study from the EU).

Box 13. Cybersecurity and Cooperative Intelligent Transport Systems in the European Union

Following the European Union's Cooperative Intelligent Transport Systems (C-ITS) strategy and the EU Sustainable and Smart Mobility Strategy, the European Commission has worked together with all relevant stakeholders in the C-ITS domain and developed the EU C-ITS Security Credential Management System (EU CCMS) to support the deployment of C-ITS services.

The EU CCMS is the EU C-ITS framework for the provision of trusted and secure communication using a public key infrastructure. It is required to support different communication technologies including:

- short range communication Cellular-V2X (C-V2X) direct and DSRC/ITS-G5
- long range cellular communication in dedicated, commercial and private networks
- wired communication networks.

Source: EC (2021, 2019).

4. The institutional framework for automated vehicles

Chapter summary

- AVs create new challenges for policy makers. Being a pioneer in the uptake of AVs requires an agile approach and a readiness to handle risk that are unfamiliar in most areas of infrastructure management; and demands co-operation with unfamiliar partners. Institutions will need new skills and appropriate capacity.
- Testing of the safety of AVs is fundamentally different from current testing for other road vehicles, and depends on large amounts of modelling and simulation, track testing, and eventually on-road experience. This means that recognising international evidence on testing and working closely with industry can greatly speed up the adoption of AVs in some jurisdictions. Practice can be improved through simple application processes, close co-operation with industry, and testing rules that are fit for purpose.
- Laws condition the use of infrastructure and the behaviour of vehicles, and AVs may require existing laws to be interpreted or updated. Modernisation of the legal framework (ideally in a harmonised manner and an internationally recognisable, machine-readable format) will speed up the introduction of AVs in new areas. A conceptual map of current driving laws is a crucial step in delivering this.
- AVs and conventional vehicles will co-exist for the foreseeable future. It will be necessary to help human drivers understand how AVs behave, and to raise awareness generally. Over time, regulation and practice will need to evolve to consider this interaction as well as the needs of AVs in their own right.

This chapter addresses the institutional framework that surrounds AVs and recommends concrete actions to facilitate the introduction of AVs in transport systems. In addition to requiring physical infrastructure and supporting systems of data and connectivity, AVs also require significant support from state institutions and laws. Many jurisdictions will require AV developers to prove their vehicles are safe to operate. Developers wishing to operate in a country must also take account of varied laws and practices. These institutional and legal elements represent a further type of "invisible infrastructure".

The institutional framework includes two main aspects:

1. **Organisational aspects**. These include co-ordination within the organisation and across other relevant agents and institutions; communication and transparency; capacity building; and database development.

2. **Legal and public policy aspects**. For example, testing and operation regulations, or planning for the future.

Both aspects need to be considered carefully by governments when they are planning to introduce AV technology. Adapting structures, regulations, and public policies appropriately could maximise the benefits of AVs within society, while minimising their risks.

Current uncertainties regarding AV capabilities and their integration into an initial mixed traffic environment have made it challenging for transport authorities to develop and implement strategies to support AV integration. From the organisational perspective, it is essential to identify the main national and regional actors and establish a co-ordination strategy, and begin co-ordination with industry stakeholders as early as possible in the process. In addition, governments would benefit from building knowledge on AVs within their organisation to enable them to develop effective public policies to facilitate the introduction of the vehicles and future infrastructure planning. Communication and transparency are equally important to support the introduction and acceptance of AVs within society.

From a legal and public policy perspective, governments and industry could also work on advancing and collaborating across their research and testing procedures to facilitate common expectations and approaches on testing, validation and safety assurance methods. In addition to testing, governments should consider uniform practices for adapting or creating the necessary norms for operation of AVs on public roads. Long-term considerations for governments include considering the impact of AVs on future infrastructure planning.

Changing the fundamentals of legal frameworks

All of today's legal and organisational systems for managing the road are based on the assumption of a human driver. Drivers must demonstrate that they are competent to drive before they have the right to control a vehicle. Large amounts of law are dedicated to ensuring that human drivers exercise their responsibilities safely and responsibly. The vehicle itself is treated as an inert device, and provided it is in good working order takes no responsibility for the dynamic driving task.

This paradigm does not reflect the world of AVs, where many of the driving responsibilities currently belonging to humans pass to complex digital systems, and may also pass back to the human at lower levels of automation in circumstances where the vehicle is unable to operate safely.

Seen from a regulator's perspective, this is a fundamental challenge to how access to the road is managed. For example, in the EU – and in the United Nations Economic Commission for Europe (UNECE) general vehicle testing and approval framework – the emphasis of regulation has traditionally been on vehicle technical issues. The growing reliance on connections to communication networks, together with the use of automation, compels regulators to look at a wide variety of interlinked sectors. It is no longer possible to develop regulatory issues in silos; instead, there is a need for a more complete, cross-sectoral view of regulatory matters.

In order to be future-proof, regulation needs to be at all times fit for purpose, enabling, technology-neutral, and focused on risk, goals and performance rather than narrow technical requirements. Industry partners must be able to choose technologies according to their varying needs, while regulation must also evolve to enable and govern new concepts and procedures, testing and pilots.

There is also an important change in how industry and developers engage with regulatory requirements. At present, manufacturers have had to meet the requirements set by a national authority in order to access a particular market. Now, developers are more able to pick and choose where they deploy their early AV technologies. Their decisions will partly reflect the environment and the nature of the road network, but other factors are partly within the control of policy makers. National authorities may be competing to be early-stage recipients of new technology. If so, those who wish to encourage foreign AV developers to adapt their technology for local use will need to consider how to make it easy to bring existing technology to a particular jurisdiction, and how to make their country an attractive environment for developers.

Drawing these perspectives together, this suggests that the institutional and legal arrangements for transport will need to evolve.

AVs will drive amendments to a range of driver-orientated legislation to remove barriers and address new risks, including road rules, vehicle regulations, passenger transport legislation and regulation of freight vehicles. Not all of these areas can be changed at once; an important question is where to start.

Governments will need either to adapt existing regulations or develop new ones to meet the challenges raised by AVs. Changes must consider all aspects of commercial operation, including ensuring that AV companies can charge for services and practical operational challenges such as access to kerb space. These and associated considerations should be aligned with wider changes, including those concerning freight deliveries and other transport modes.

Governments will need to work closely with industry and international stakeholders and seek to harmonise approaches nationally and internationally to target practical outcomes . Many jurisdictions have developed preliminary testing regimes for lower levels of AVs. Common methodologies setting standard approaches for measurements, metrics, scenario frameworks, modelling and simulation approaches, test, evaluation, analytics, and validation of AVs could reduce development costs and risks, advance the state of the art, and shorten the time to market.

Collaborative testing can accelerate the pathway to commercial AV operation. Many jurisdictions will be importing AV technology from other areas. Both industry and policy makers benefit from finding ways of using testing evidence from other jurisdictions to provide the assurance they desire.

This chapter introduces the organisational, legal and public policy challenges involved in facilitating the introduction of AVs in transport systems, and suggests concrete actions.

Building institutional capacity

The requirements of managing traffic and highways have been broadly similar for more than a hundred years; and most of the tools and techniques used to manage them today would be familiar to policy makers working 50 years ago. AVs challenge these assumptions, and force policy makers to consider new approaches. The skills needed to do this are not the same as those needed to manage the highways of today.

Chapter one outlined the wide range of organisations and technical disciplines that play a role in the safe and effective management of AV traffic. This includes companies on the cutting edge of artificial intelligence (AI) and hardware research, and providers of different kinds of road data. As outlined in this chapter, it also means dealing with areas where there is no precedent for how to act, and where a significant degree of uncertainty cannot be avoided.

In order to manage this situation effectively, a generation of policy makers will need to understand both the certainties of existing highways management and the new ways in which vehicles operate on the road network. They will need the skills and attitude not only to enforce compliance with the established regime, but to build a new system in a way that unlocks benefits and pre-empts risks – and this will not happen without change.

In particular, policy makers as a group will require:

- an understanding of concepts and terminology in each other's areas in order to effectively collaborate
- an awareness of how elements of physical infrastructure relate to the operation of AVs
- an understanding of the "invisible infrastructure" of data and institutional arrangements (see Chapter 3)
- knowledge of the broader impacts of AVs (e.g. on employment, the environment and ethics) within society and potential barriers to acceptance
- an ability to make intelligent risk-based decisions while the safety of AV technology remains uncertain, and may be politically contentious
- the capacity to take action quickly, addressing gaps, shortcomings or obsolete requirements in the current legal system.

In the survey of policy makers undertaken in preparation for this report, governments signalled that they are investing significant efforts to build capacity within their organisations by connecting with industry, engaging with regulators in other countries, published research, and formal training. Some countries, such as the United Kingdom, are recruiting experts from industry; others, such as Canada and Singapore, are developing specific training for AV-related policy making.

Discussions with industry also highlighted how ready industry has been to help policy makers understand how AVs function; and professional bodies are also keen to help their members to remain up to date. Although commercially valuable information and proprietary technologies will remain sensitive, there is clearly scope for greater collaboration.

This is not only a responsibility at an institutional level. Individual policy makers who aspire to shape the future of road transport will need to challenge themselves to remain alert to developments and curious about their implications. The leaders of the future will have different skills and backgrounds to the leaders of the current highway system.

Policy insight: Policy makers need new skills and new partners to optimise the function and benefits of automated vehicles on their roads

The deployment of AVs at scale has the potential to bring massive societal benefits, but also carries with it a degree of disruption and risk. The increasing assimilation of automation into both vehicles and infrastructure could fundamentally shift the relationship between the two. Increasing automation in infrastructure and associated systems makes new demands, and may work in ways that are unfamiliar. Policy makers and infrastructure operators must engage with new stakeholders to understand the state of development of AVs and the critical issues in relation to their widespread adoption; and they must invest in unfamiliar skills and expertise to be intelligent partners. This requires significant new institutional capacity among policy makers. Engagement must be structured and sustained, and in most countries will require the development of new forums and processes.

Institutional and stakeholder co-ordination

Various government departments have a stake in the development of AVs, from the national level down to the local level. These may include government services dealing with transport, the economy, energy, digitalisation, traffic and justice. While AV developments are usually led by the national transport department, the existence of numerous ministries, departments and agencies requires co-ordination at different levels. There is also a need for co-ordination at the intra-national and inter-authority levels, and with stakeholders more generally, to facilitate the most uniform policy and regulation for industry.

Interdepartmental co-ordination

Responses to the policy survey indicate that a variety of strategies have been adopted by different countries to ensure co-ordination across national government departments. In most cases, this co-ordination occurs through periodic and informal meetings. In some cases, AV policy is created in the context of other strategic configurations, as has been the case with Spain's Strategy for Safe, Sustainable and Connected Mobility 2030. Such arrangements are formalised in some cases. For example, in Denmark, a multi-agency task force has decision-making responsibility for AV-testing applications, based on the parliament-approved legislative framework.

A smaller number of countries – including Australia, Greece, Italy (using an existing "Observatory"), Mexico, Russia, Sweden, and the United Kingdom – have set up formal structures responsible for co-ordinating AV policy between ministries. Both Austria and Switzerland confirmed the existence of a central agency with responsibility for co-ordinating policy and also for authorising AV validation testing.

There is no obvious correlation between centralisation of policy making and the speed of AV uptake – indeed, research proceeds fastest in the United States, where responsibility is notably spread between the state and federal levels. The choice of institutional structure appears to reflect national governing styles more than an optimum organisational approach.

Co-ordination between regional and national governments

In many decentralised countries, regional authorities hold responsibility for functions such as vehicle and driver testing or traffic regulation, all of which apply to the development of AVs. So far, there have been no moves to change the boundaries of responsibility to centralise responsibility for AV-related functions, and national governments have focused on developing guidelines to co-ordinate and clarify national policy.

Given that AVs are likely to be a global technology, the need for co-ordination between regions is as clear as between countries. There will be a stronger commercial case for developers to adapt their technology to work in a large country, rather than a single region within that country. Governments should increase efforts to unify procedures by collaborating with other relevant authorities, developing guidelines, or agreeing on a common approach to testing, so that high levels of interoperability can be achieved.

It is also likely that decentralised countries will see a small number of regions taking the role of national pioneers. One example is California, which is a global centre of on-road AV testing and where rules for on-road regulation of AVs have been tested by real-world experience. AVs in California are still required to comply with the National Highway Traffic Safety Administration's Federal Motor Vehicle Safety Standards, and must formally apply to the US Department of Transportation (USDOT) for any exemptions. Nonetheless, arrangements made in these pioneer areas (and in smaller test areas in more centralised countries) will likely be influential in shaping national norms, and need to be considered for their ability to be scaled up to nationwide operation.

Box 14. Co-ordinating efforts in Australia

Three main structures advance automated vehicle (AV) developments in Australia, two of which are focused on policy and the third on technology. National-level AV policy is adopted by the bi-annual Infrastructure and Transport Ministers' Meeting. Actual policy is developed by the National Transport Commission (NTC) with input from each state and territory. The NTC has been tasked by transport ministers with developing an end-to-end regulatory system and is responsible for co-ordinating AV policy among different levels of authorities across federal and state governments.

The third structure is the Transport and Infrastructure Council, led by the Office of Future Transport Technology (created in 2018), which works closely with state and territory transport and road agencies to support technological development, awareness raising and outreach (DITRDC, n.d.).

Collaboration with local authorities

AV testing occurs in cities, towns and in rural areas, where local authorities normally have responsibility for managing traffic and undoubtedly have better knowledge of the terrain. There is consequently a need for inter-authority co-ordination, between the national level and the regional and/or local level (where the tests actually happen), to simplify procedures for industry partners and the regional/local authorities hosting the pilot.

Collaborative arrangements range from the informal (no co-ordination) for specific projects (e.g. in Norway) to formal structures (e.g. in Canada). The type of collaboration depends partly on the country's competences, structure, and size. Whatever the arrangement, the important point is to co-ordinate.

According to the survey of policy makers carried out as preparation for this report, few countries appear to be working in a structured manner with local government, potentially reflecting the limited number of local authorities currently dealing with on-road tests. Co-operation tends to happen through AV test beds (where the respective local authority has to be involved) and other AV research and development activities. Some ministries formally co-operate with state-level counterparts. Examples include Australia's Transport and Infrastructure Council (see Box 14) and Austria's national dialogue with states.

Co-ordination with industry

Co-ordination with industry is key to ensure the timely, successful, and responsible mass deployment of AVs into transportation infrastructure. While co-operation between government and industry is essential for the development and deployment of AVs, relatively few formal structures have been created that serve as the basis for a long-term relationship.

The countries with formal government-industry programmes or other co-ordination mechanisms tend to have established inter-ministry and/or cross-government level co-ordination on AVs. There is a range of national-level initiatives to co-ordinate industry and government activity. For example, the United Kingdom has created the Zenzic programme (see Box 15).

Elsewhere, Australia engages with industry through the National Transport Council. Sweden pursues co-ordination through Drive Sweden. Russia brings together government, scientific and business communities through its interdepartmental Working Group. Informal government-industry co-operation also occurs in other countries through close collaboration with industry associations (as is the case in Austria and Germany) and public-private partnerships (as is the case in Finland).

Box 15. The UK Centre for Connected and Autonomous Vehicles

The United Kingdom has established several structures and programmes to co-ordinate and promote policy development and to accelerate research and testing. The Centre for Connected and Autonomous Vehicles (CCAV), which is the joint policy unit of the departments for Transport and Business, Energy and Industrial Strategy, has been the initiator and driving force of many of these activities.

CCAV has overseen joint government-industry investments, the delivery of a code of practice for testing and new primary legislation. It has succeeded in mobilising GBP 450 million of public and private investment through the Zenzic programme. It has been instrumental in securing the engagement of local and regional authorities in national projects.

CCAV has also tasked the UK law commissions to carry out a far-reaching review of the legal framework for automated vehicle – an exercise that has lasted close to three years and will shortly come to an end.

Source: UK DfT/BEIS (n.d.).

Testing automated vehicles

The first step to getting an automated vehicle into real-world use is testing. In many jurisdictions, this is a regulatory requirement; in any event a large majority of AV developers carry out their own testing to confirm that their vehicle is safe to drive as part of their research and development efforts. This system is designed primarily to ensure public safety, but it can also help create new business models and innovative mobility services.

It is helpful to separate experimental and development testing (the testing done by developers and their partners to assess technical capability) from validation testing (the testing prescribed by regulatory authorities to formally approve a vehicle for sale or use, or confirm that a driver is competent, against defined standards).

Not all countries approach validation testing in the same way: in some jurisdictions (notably the United States, where most AV testing is taking place) the current system of vehicle regulation is centred on self-certification. In other jurisdictions, a more explicit model of type approval applies, which would suggest a more proactive process of setting requirements and testing can be expected before full public operation.

Nevertheless, even the most permissive jurisdictions expect vehicles and drivers to behave safely, and ascribe legal liability on the basis that a developer or manufacturer will confirm that their vehicle is safe to use. The development of safe and fit-for-purpose automation requires the facilitation of experimental and validation testing. For experimental testing, governments can use different tools to facilitate industry access to testing: from providing information, to offer personalized engagement, revising and simplifying procedures, and funding support (see Box 16 for a case study from Finland).

Box 16. Finland's experience of facilitating automated vehicle testing

Finland's Transport and Communications Agency (Traficom) lowered the threshold for the testing of automated vehicles (AVs) via a series of discrete steps. First, it established a single point of contact at the approval authority (for the purposes of obtaining a testing permit or exemption). It then evaluated AV testing plans through interactive discussions, requiring information across six main areas:

1. General information (what, where, when)
2. Vehicle technical information (type, steering)
3. Test area information (routes, precautions)
4. Research plan (purpose)
5. Ensuring safety and security (risk evaluation and mitigation)
6. Follow up and reporting (results, deviations from plan)

Challenges to testing methods

Existing methods for validation testing of traditional vehicles are predominantly physics-based and most mechanisms are designed to confirm to mechanical compliance standards. Autonomy alters the fundamental driving functions of the traditional vehicle by replacing the human functions of sensing and cognition with that of machine sensing and intelligence, thereby transforming a number of the foundational principles and tenets of classical test and evaluation.

In addition, advanced driving systems will incorporate a degree of AI and machine learning within their software stack. This results in a complex software-intensive system, with an internal network connecting numerous processors, that produces non-deterministic behaviour and performs in an unbounded state space. Plus, due to its machine learning capabilities, the system will often not behave in a repeatable manner when faced with the same stimuli in the same environment and tasked with the same objective.

This creates a need to apply new test methods. When the effort scales from testing a single system to testing a system-of-intelligent-systems in an ecosystem environment, the challenge becomes exponentially more complex. It is therefore necessary to create goal-based, risk-based and performance-based criteria for validation testing that reflects the early stages of AV development.

From the perspective of the infrastructure community, it is imperative that AV testing includes operationally representative scenarios and environments that encompass all relevant elements of the transportation infrastructure (physical and invisible) in order to test the complete system-of-systems.

Development of transport automation must contend with a wide range of uncertainties. It is widely agreed that it is not possible to assess the capability of an AV based on a one-off test, but that safety can only be judged through analysing large quantities of quality test data. This means that validation testing can no longer be confined to the workshop and must consider an ongoing assessment that includes simulation, testing in closed areas and testing on general roads among the traffic flow. These changes are already beginning to influence the latest testing arrangements (see Box 17).

Box 17. The United Nations Economic Commission for Europe's approach to validation testing

The United Nations Economic Commission for Europe (UNECE) administers the World Forum for the harmonization of vehicle regulations (WP.29). The WP.29 Working Party on Automated/Autonomous and Connected Vehicles (GRVA) contains an unofficial Working Group on Validation Methods for Automated Driving (VMAD). The Working Group is currently developing a New Assessment/Test Method (NATM) for Automated Driving, which will apply to automated vehicles (AVs).

As a starting point, NATM is based on a "multi-pillar approach" that includes auditing, simulations/virtual testing, testing on closed tracks, and testing in real-world situations among normal traffic. To support these testing methods, the method proposes to identify a list of scenarios that represent real traffic situations. The intention is for NATM to be reproducible, objective and evidence-based, while also flexible enough to leave room for technical developments and innovations.

The considerations for evolving testing have also shaped the recent UNECE regulations on automated lane-keeping systems. These set new provisions for a range of test cases, as well as tests in real-world conditions (UNECE, 2021).

An added level of complication can be found in decentralised countries, where testing procedures may vary between subnational jurisdictions (as for example, in Australia, Canada and Germany), but national governments can develop testing guidelines to give clarity on the general authorisation steps to follow.

For example, Canada's federal government has developed a checklist that provinces can use. In the United States, USDOT has released an AV policy clarifying the roles of state governments and outlining safety recommendations for testing, while also maintaining a wider suite of policy documents and advice (US DOT, n.d.).

In decentralised countries, governments should consider increasing efforts to unify testing procedures by collaborating with other relevant authorities, developing guidelines, or agreeing on a common approach to testing.

Testing together with industry

Testing in partnership helps both governments and industry. On the one hand, industry actors may be testing their technologies for the first time and may therefore benefit from open discussions with governments about possible challenges and problems. On the other hand, industry actors' research and development on AVs provides them with the clearest understanding of what AV technology can and cannot do. This helps governments evolve their validation testing requirements to ensure they reflect practical and feasible test methods that suitably validate safety assurance.

However, the traditional culture and methods of validation testing can be a poor fit with the challenges of developing a fundamentally new technology. This is particularly the case when assessing the safety of automated or autonomous systems operating in a highly dense, dynamic, multi-agent, and complex environment such as the surface transportation system.

There is a significant difference between assessing the safety of deterministic systems with static configurations and assessing systems that learn as part of their operation, which will be updated constantly by their developers, and which form part of other complex, interconnected systems. Regulatory regimes designed for the current paradigm may struggle to adapt to this new challenge (see Box 18 for an example).

Box 18. Waymo's Arizona experience

The US automated vehicle (AV) developer Waymo started out in 2009 as Google's self-driving car project but became a separate company in 2016. In 2017, Waymo conducted the first public trial of AVs, in Phoenix, Arizona. As part of the process of setting up its operations, Waymo representatives met with local and regional authorities and the regional police department. Together, they clarified how they were going to overcome a number of problems derived from not having a human present in the vehicle (e.g. police enforcement, ticketing). This kind of government-to-industry interaction facilitated a long-term relationship that allowed the company to invest in the state and promote AV services within it.

Source: Industry interviews.

Testing represents a significant percentage of the development cost, particularly for new technologies being applied in a new domain. In the case of highly AVs developers cannot provide the safety assurance evidence to give the level of absolute certainty for all possible operational conditions and all plausible use cases currently expected in validation testing of non-automated vehicles.

However, through research and collaboration, the global community is beginning to coalesce around safety assurance methodologies that include a combination of simulation, track testing and on-road testing designed to advance the responsible deployment of AVs in the transportation system in a manner that respects the perspectives of all stakeholders.

The fitness of the testing framework

The technology enabling transport automation is advancing quickly. By contrast, today's regulatory environment is purposely designed to move deliberatively through thoughtful and calculated processes. The pace of exponential technology and government regulation can seem at times to be diametrically opposed.

To keep AV testing and deployments progressing and expanding at an appropriate level, governments should regularly assess the fitness of their regulatory framework in collaboration with the stakeholder community. By doing so, they can make sure AV policy is effective, efficient and relevant given the current state of automation. Governments can also ensure coherence both internally and with other interventions, and achieve their own missions and national objectives.

From testing to investigation

At present, there is a clear distinction between testing a vehicle before it enters use and any process of investigation that occurs after a collision or mechanical failure. Once AVs are in use, these activities will begin to overlap.

The software in AVs will continue to be upgraded and improved throughout the vehicle's life. Over-the-air upgrades are likely to be an essential part of ensuring ongoing safety. Assessing the performance of these upgrades cannot be separated from day-to-day on-road use.

Both testing and crash investigation will be searching for similar kinds of situations – the "edge cases" where multiple circumstances combine in unanticipated ways to create unexpected danger. Both elements of the road safety system are seeking to understand very similar events.

Policy insight: Standardised testing procedures across jurisdictions can accelerate the spread of automated vehicles

Assessing AV safety requires far more data than current laboratory-based and test track approaches. While different countries and jurisdictions carry out research, setting policy and developing validation testing procedures for safe operation of AVs on their roads, integrating international experience in standardised testing procedures can help introduce AVs across jurisdictions faster. In collaboration with industry, governments should work together to pursue complementary strategies to design, implement, and revise their measures, metrics, analytics, testing procedures, and test data and reporting methods. Similar arguments can be made for co-ordinating crash investigations internationally.

As with validation testing, there is a strong benefit to international co-operation in crash investigation. In the early years of AV operation, the number of crashes is likely to be modest, making it difficult to draw wider conclusions from the available evidence. System failures are also likely to play a disproportionate role in determining levels of public trust, meaning there is likely to be a wish in many countries to respond intelligently to developments worldwide.

The ability to share findings and information between safety agencies is not something that will occur automatically, especially when it relates to proprietary software and sensitive intellectual property. A growing internationalisation of testing would be a chance to build these new links, ideally in circumstances that would maintain confidence while maximising a common understanding of safety. Similar opportunities exist to standardise the ways in which information on crashes (e.g. event data recorders) is collected and shared. As part of a wider package to join up testing and accelerate the global uptake of AVs, it may be possible to enable the sharing of detailed crash analysis internationally.

Updating laws and norms

The laws and regulations governing the use of the highway were devised well before the invention of AVs. Some elements of existing law are designed around the assumption of a human driver; and almost all laws are written on the assumption that they will be interpreted and applied by a human being. In a world of AVs, this is no longer the case. Governments will need to update laws to this new technology.

In addition, AVs are affected by regulations (including privacy regulations) that do not affect conventional vehicles in the same way, and which may create new legal needs. Governments will need to work from a holistic view, considering not only traffic laws, but also the wider range of laws that may affect AVs. Some of these questions relate to the way in which laws are structured and expressed. Parts of existing road traffic laws can be articulated in a machine-friendly format relatively easily. For example, there is already good information available about what speed limits apply on specific roads, and about how a vehicle should behave in order to comply.

However, a much wider range of laws describe less structured circumstances (e.g. how much space to give when passing a bicycle or horse) or situations where custom and practice play an important role in shaping what road users consider "safe" (e.g. how it is appropriate to pass an illegally parked vehicle blocking traffic). AVs cannot be expected to be able to make the same contextual judgments as humans without some degree of guidance or clarification. While it is impossible to rewrite traffic laws to remove all ambiguity, much existing traffic law is expressed in ways an AV cannot easily engage with (UK Law Commissions, 2022; see also Box 19).

Box 19. The UK Law Commissions' review of automated vehicles

In 2018 the Law Commission of England and Wales and the Scottish Law Commission (the UK Law Commissions) working with the UK government's Centre for Connected and Autonomous Vehicles, began a four-year review assessing how the country's existing laws would need to be adapted to successfully absorb new automated vehicles (AVs). The review covered initial approval and authorisation of self-driving vehicles, ongoing monitoring of their performance while they are on the road, misleading marketing, and both criminal and civil liability.

Key recommendations included:

- creating a clear legal sense of what is self-driving technology, as opposed to driver support features, together with a transparent process for setting a safety standard and new offences to prevent misleading marketing
- a two-stage approval and authorisation process involving building on international and domestic technical vehicle approval schemes and adding a new second stage to authorise vehicles for use as self-driving
- a new safety assurance scheme to provide regulatory oversight of AVs throughout their lifetimes to ensure they continue to be safe and comply with road rules
- new legal roles for users, manufacturers and service operators, with removal of criminal responsibility for the person in the passenger seat
- holding manufacturers and service operators criminally responsible for misrepresentation or non-disclosure of safety-relevant information.

Source: UK Law Commissions (2022).

Any revision of law on this scale affects multiple jurisdictions, with the potential for mismatched policy. Governments may need to strive for consistency of procedures and regulations at the local, regional and international level. This harmony not only avoids confusion, but plays an important role in accelerating the rollout of AV technology in new areas.

Harmonising regulations and core principles

A crucial question to consider when adapting laws for AVs is where to start. In general, traffic laws and other relevant systems have developed organically over time, without an attempt at creating a simple-to-understand regime or even to remove outdated provisions. It is important to identify the wide range of laws that are related to AVs and their interrelations before starting the adaption of norms.

A number of countries have begun the process of establishing an overall framework for the legislative changes required to support AVs by setting out principles or goals. This can be particularly important in guiding regulation in countries with federal or decentralised powers structures, to ensure that all levels of government are moving in a common direction.

Governments may benefit from setting out principles to guide the substantial detailed work that needs to be carried out. These may reflect the wider objectives government hopes AVs will help to achieve. For example: safety, industry development and investment, mobility, privacy and equality were all cited by policy makers surveyed for this report. Governments will likely seek to achieve a combination of these objectives but setting them out in advance will help to guide more detailed work.

Overall objectives can help guide the development of more detailed policy principles to guide regulation. These could be framed as a set of criteria that any new policy framework will need to meet. Such principles could stipulate that the final policy framework should:

- be nationally/ regionally consistent – support a single market for vehicles
- be internationally aligned – maintain alignment with evolving international standards where possible
- support and enable deployment through removing barriers to ensure citizens can gain the benefits of this technology.
- be effective – ensure safety as the key outcome
- provide flexibility – be technology, application and business model neutral
- be adaptable – allow technology and solutions to evolve over time
- provide clarity for infrastructure operators, industry and consumers on their responsibilities and liabilities
- be efficient – the end state should be scalable to size of the deployment and use existing systems/ processes/ legislation where possible
- ensure that risks sit with those parties best able to manage the risks
- consider the implications of other potential changes to transport, such as the emergence of new modes.

An example of these principles is the guidelines developed by the Asia-Pacific Economic Cooperation's Automotive Dialogue (APEC, n.d.). Outlining such principles can help to provide a checklist to ensure that regulation is designed to meet its overall objectives.

Conceptual map of laws affected by automated vehicles

One tool likely to be particularly helpful in achieving the outcomes above is the development of a conceptual map of the existing laws that affect AV operation. In addition to traffic laws, AVs are affected by a wider variety of legal concepts, such as privacy: concepts that have not been relevant to conventional vehicles. A map of laws would help to identify how vehicles and infrastructure in a jurisdiction interact with one another, and with the wider legal system. By understanding these issues, it becomes easier, to facilitate their adaptation to AVs and to help guarantee consistency within the legal framework.

In addition, laws are currently expressed through a series of statutes or precedents, each with their own independent existence. Connecting them together as a single source of requirements (with appropriate links to local or regional requirements), makes it far easier to ensure AVs abide by the law. By articulating these laws in a format that is more suitable for digital interpretation, it should be possible to improve compliance.

This will require recognition of different aspects of the regulation of AVs across government departments and agencies, including agencies responsible for insurance, justice, police, road safety and commercial transport. It may also require mapping laws and regulations across multiple levels of government (national, state, local) and consideration of international standards development such as through the UNECE.

Interdepartmental co-ordination, stakeholder dialogues, international co-ordination and lessons from testing may all play an important role in the process.

A conceptual map of laws not only helps navigate legal practice in one jurisdiction, but it could also help adapt vehicles to run in other jurisdictions. In other words, such a map could help an AV to understand the different road systems in comparable terms, which the existing law does not facilitate. The existence of a global standard for articulating traffic law would advance this process further. The maps will vary by jurisdiction but may benefit from recognising areas of regulation beyond traffic laws, such as:

- vehicle safety at first sale
- in-service (or on-road) vehicle safety
- heavy or commercial vehicles
- public transport
- taxi/ rideshare
- transport of dangerous goods
- road rules
- criminal laws
- police powers
- infrastructure and road managers
- privacy.

Using this information, governments can consider both how existing provisions apply, and how they will need to change to accommodate AVs, and can have greater certainty that the overall regime responds comprehensively to new challenges.

While an initial survey will set out which areas are likely to affect the uptake of AVs, a full legislative audit will likely be required to create a document useful for a technical audience. Also, converting existing law into a more standardised format, which can be compared between countries, will make it substantially easier to ensure that AVs being adapted for local use will be able to properly respect the rules of the roads on which they drive.

The initial survey and detailed audit should also set out how ready the existing law is to answer questions posed by developing technology. Are there provisions that would be impractical for an AV to comply with or that could be achieved in another way? Are there requirements that will impede commercial services using the new technology? If there are potential gaps in existing legislation, this should become clear as part of defining the map. Examples found in previous work have included:

- who is in control of, and legally liable for, an automated vehicle when it is operating in automated mode?
- how to ensure AVs operate safely throughout their life on the road?
- what are the insurance requirements for AVs? What happens in the event of a crash involving an automated vehicle?
- are there risks created by AVs that are not currently addressed in legislation and may not be addressed by the market?

Some of these questions go beyond the resolution of simple technical points, and begin to raise issues that present fundamental policy choices with widespread ramifications. As part of defining a conceptual map or regulation and conducted an audit to identify the detailed issues, governments may need to consider the outcomes that they are seeking in each key area of regulation (see Table 5). This is a further layer of detail to the high-level objectives and principles and can help set the direction of detailed amendments.

Table 5. Potential outcomes of government regulation of automated vehicles

Element being regulated	Potential desired outcome
Import/first supply of automated vehicles (AVs)	Vehicles with safe automated driving systems (ADS) can enter the market Ability to identify the responsible entity for the ADS and set minimum requirements for that entity The regulator has appropriate powers to address non-compliance with first supply requirements
Registration and road access for AVs	Registration systems record key information about AVs and the responsible entity to support registration and enforcement functions AVs can access public and private roads within their operational design domain, with authorisation where required
On-road safety for AVs	AVs operate safely throughout their on-road life Safe disposal/disengagement at end-of-life of the AV Obligations on on-road parties are clear, support safety and support compliance and enforcement functions Regulators have appropriate powers to address safety issues
Road rules for AVs	AVs operate predictably, safely and consistently with other road users Use of AVs does not impose unreasonable costs on others
Civil and statutory liability	Efficient legal pathways to establish liability for damage, injury and loss
Other transport laws and AVs	All relevant laws regulating driving (including those for freight and passenger transport) support safe operation of AVs across all vehicle types
Equity and accessibility	AVs improve mobility across demographics AVs do not increase congestion AVs complement, rather than replace, active transport and public transport

Machine-readable traffic laws

Ultimately, a review of the legal system of the kind suggested above will create an inventory of traffic laws in a format that is conceptually clear and readily usable for someone adapting an AV to local circumstances. From here, the next step would be defining traffic laws in a truly machine-readable format. Some traffic laws are already machine-readable – for example, speed-limit information is widely available and comprehensively mapped in many jurisdictions. By making this consistently true for the entire body of relevant traffic laws, it becomes significantly easier to confirm that AVs will drive within the law.

Policy insight: Traffic laws must be ready for automated vehicles

As AV technology and operating conditions evolve, governments should continuously review and update their regulatory frameworks to remain consistent, accessible, and suited to the objectives of society. Adaptation of regulation could benefit from a framework for a conceptual map of laws, to help policy makers visualise legal interconnections and consequences, and machine-readable traffic laws, which AVs can interpret clearly and unambiguously across jurisdictions.

Unlike a human driver, an AV does not choose whether or not to comply with the law – it follows without question all instructions that it can understand and implement. A law that can be explained digitally can be incorporated into the behaviour of an AV at a fundamental level; and tools such as computer simulations can be used to confirm absolute compliance.

Traffic laws around the world mostly describe a range of very similar regulations, which in theory can be expressed in a common technical language. Early work to do this is underway through an international project called Management of Electronic Transport Regulations (METR); but until a standard for communicating traffic laws to vehicles exists, individual governments will need to take care to express their laws in terms that machines cannot misinterpret. This will require policy makers to work with technical experts, to ensure that traditional law-making is fit for future needs.

Deploying automated vehicles

Governments will have to deal with traffic that combines conventional vehicles with automated ones, in a mixed traffic situation that could last for decades. Planning a transitional regime is therefore important. This regime could include a communication strategy to inform, educate and familiarise road users with AVs incrementally. In addition, governments should continually assess the efficacy of their legal systems, learning throughout the deployment of this technology.

Evolving traffic laws and norms

Traffic laws will continue to evolve after the arrival of AVs. Governments need to think of laws surrounding AV technology as a continuum, as a body of norms that need continuous adaptation to the evolution of AVs. Legal regulations will change frequently because automation levels and models of mobility might require different infrastructure functionalities and services. It is not possible to foresee all configurations that co-operative mobility will have in the future. To ensure the optimum balance of efficiency and societal benefit, governments should carry out regular fitness checks of AV laws, learning from the experience gathered so far with testing, pilots and full-scale vehicle operations.

Enforcement of existing traffic rules in the real world may also need to evolve. For example, existing rules on waiting, stopping and parking may not be relevant to AVs in the same way as other vehicles. City authorities may need to innovate to address kerbside management and parking policy in order to keep control over what is happening on their road networks. In much of this work, most road authorities will be able to draw on best practice elsewhere, and learn from what has and has not worked in other jurisdictions.

Communication and promotion of explicit human-machine communication

In mixed-traffic scenarios, governments should consider how to assist the interaction of human road users with AVs, as it will be critical to the successful deployment of AVs. This is an area where existing law expects much of drivers and other road users, and where machines will have to handle existing challenges in new ways.

Experts have debated the value of dedicated lanes for AVs, separated from conventional traffic, to manage human-machine interaction (HMI). Industry sources interviewed for this study were unanimous that this was more likely to hold progress back than move it forward. Instead, there was a strong focus on making sure that AVs could interact safely with all road users on the existing road network, although there might be value in separating AVs from pedestrians and cyclists where these represent a large share of road users (Tabone et al, 2021).

Governments will need to facilitate a clear understanding of what AVs can and cannot do, as well as what is required from humans when using vehicles equipped with an ADS. Governments should develop clear strategies on what they need to communicate to facilitate the interaction of road users with AVs on real-world roads. This is likely to be especially challenging in urban environments, where the mixed traffic includes many vulnerable road users.

Raise awareness among road users about AVs

One way for governments to facilitate the interaction between AVs and road users is to communicate with their population on rollout plans for AVs in their cities. This will require co-ordinated messaging between government and industry, with each covering associated areas to inform the public and discuss how AVs may impact transport. This will include the content of advertising for AVs. Whenever a city starts allowing AV operation in public roads, government and industry should use social media, official web pages, and other publicity means to communicate where, how and when road users can expect to start interacting with these vehicles.

In these communications, government and industry take a joint approach to informing the public about the AVs themselves. For example, they could inform users about what AVs are, what their main capabilities are, the rules and regulations under which AVs have to operate and their appearance or distinctive elements. This information should increase road users' understanding of the technology and their awareness of risks, and facilitate their interaction with AVs when it happens.

Reinforce informal rules and non-verbal communication

Another way to facilitate HMI and communication between AVs and pedestrians is by replicating the non-verbal communication that disappears when there is no human driving (Vissers et al., 2016). Informal, non-verbal human communication is important for safety and trust. To substitute for it, external human-machine interfaces (eHMI) can be employed, such as LED strips and screens, robotic attachments, light projections on the road, and auditory signals (Li et al., 2021). This non-verbal communication is especially important in shared spaces where there is no formal separation of traffic between vehicles, pedestrians and other road users, and more broadly where vulnerable road users are involved (Schieben et al., 2019).

Integrating automated vehicles in the transport system

Governments could facilitate HMI by introducing AV technology gradually into their transport systems. An incremental introduction of AVs could make traditional road users more familiar with the technology, increasing safety and acceptance. It would also allow governments to prioritize the introduction of AVs for mobility solutions of public interest. An incremental approach will also help governments adapt and prepare for future mass deployment of AVs.

The results from the survey of policy makers conducted for this report indicate that most countries seem to be thinking of integrating AVs incrementally into the existing transport system. Some could use ODDs or specifically defined areas to start introducing AVs, whereas others may focus on introducing AVs in specific types of transport (e.g. public transportation). Finally, some countries could approach the introduction of AVs by geographical extension of successful pilot projects.

Policy insight: Traffic laws and behavioural norms must be ready for automated vehicles

Governments should anticipate mixed traffic of conventional vehicles and AVs and promote safe human-machine interaction during integration of AVs in the transport system.

5. Strategic challenges for policy makers and developers

Chapter summary

- The locations in which AV work will depend on the kinds of infrastructure available – but the infrastructure that will have the greatest impact in advancing AVs is based around digital connectivity, the availability of key data and institutional and testing arrangements.
- The first steps in improving this infrastructure do not have to involve extensive government spending, but can involve organising different participants, creating market opportunities and setting strategies.
- Developing new skills and capabilities is essential to leading in the deployment of AVs. This is a technology that will operate across borders and shift many of the traditional ways in which transport policy operates. The ability to deal with new and uncertain developments, and to work with new partners, will be essential for a new generation of policy makers.
- Many of the uncertainties about how and where AVs can operate are best approached through a global collaboration between industry and policy makers, working together to explain uncertainties and develop a standard approach that can encourage innovation and protect the public.

Expectations of AVs have changed significantly since the optimistic early predictions of the mid-2000s. AVs are not only plausible, but already drive on roads around the world. Yet the creation of a Level 5 automated vehicle, capable of driving everywhere without difficulty, seems to be many decades away. As discussed in chapter one, this means that automated mobility will be a technology limited by policies, choices and infrastructure as well as by the capabilities of AI and sensors.

This is a significantly different vision of the future to that imagined a few years ago; and this report has examined what constraints this may pose and what can be done to manage them. There are also a range of implications that reach across physical, digital, data and institutional issues to present wider strategic challenges. If AVs are to become a significant part of global mobility, and their operation depends in part on their relationship with infrastructure, there are important consequences for policy and strategy development.

Regardless of what barriers stand in the way of automated mobility, it remains a technology with great social value, and it is important that the benefits of introducing it are realised as soon as the technology is ready and safe to use. For this to happen, all actors including public organisations, private companies, local authorities and national policy makers need to address this new range of challenges. This report has highlighted eight strategic challenges that policy makers and developers alike should be alert to.

Automated vehicles depend on infrastructure – but not only physical infrastructure

Developers of current AVs do not expect the road network to change substantially from today; their business model depends on working on the roads that already exist. When discussing physical infrastructure, the main requests from developers are not rebuilt highways or dedicated lanes, but far smaller things – a preference for clear signage and reliable markings that a vehicle's cameras can see.

However, these companies do depend heavily on other, "invisible" forms of infrastructure – geolocation services, mapping information and up-to-date information about the world around them. They also rely on the presence of a testing and authorisation regime that allows them to take paying customers.

While the management of conventional road vehicles is anchored in the physical world, AVs will unavoidably have a large digital footprint. This means that the definition of what "infrastructure" means will grow as AVs play a growing role in transport. If the highway expert of today pays attention to surfaces and drainage, tomorrow they will need to be familiar with issues such as data flows, satellite signals, mobile connectivity and mapping precision.

Automated vehicles will be an international technology, not a national one

The regulation of roads and the provision of infrastructure have historically been national concerns. Even at this early stage, it is clear that AVs are developed on a global scale, with development concentrated in a small number of sites. The challenges inherent in testing and scaling up also encourages developers to stick with areas that are familiar to them. This discourages all but the biggest jurisdictions choosing a truly unique local approach to regulating AVs.

Many of the immediate steps that could be taken to support the deployment of AVs are also international challenges. In areas such as communications technology, where no settled consensus has yet emerged about preferred methods of connectivity, the absence of agreement makes it harder to justify immediate investment. Global work towards technology-neutral agreed standards would increase ambitious policy makers' confidence that they are investing in the right equipment; and would equally help developers adopt generally applicable solutions that could cut development costs and improve the scalability of their technology.

Automated vehicles are part of a wider change across the transport system

Although the advent of AVs will be a major change to road transport, it is still one change among many, several of which may have important interactions with developments covered in this report. The conventional vehicle fleet is already becoming more connected, and more capable of using or providing some of the information expected to be relevant to AVs.

There are also ways in which parallel developments, such as the growing importance of data and connectivity for public transport, may be relevant to AVs. This increases the complexity of planning for the future, but is also an opportunity, particularly when building the case for investment or action.

Governments may not pay for new infrastructure, but their actions can speed up its provision

While AVs are a global technology, different countries have historically pursued a range of approaches to funding infrastructure. This is especially true when considering the invisible infrastructures that support AVs. Whereas most highways are funded by governments, the provision of communications infrastructure, high-quality mapping and operational data can be handled through a variety of channels.

Across much of the world, this infrastructure is provided by private companies. The funding to fill the gaps in provision can come from private sources, and can ultimately form a sustainable business model by harnessing a share of the value generated through enabling automated journeys. Provided AVs are a useful technology it is likely that much of the necessary infrastructure can be created without direct state funding.

However, a reliance on this market-led approach is proving slower than direct state action. The most state-led approaches are in East Asia, meaning that countries such as Japan and Korea have established a more developed infrastructure for AVs in recent years. Conversely, those countries relying on private provision of infrastructure are often finding that existing systems and networks are not set up to enable AVs, and that at present little work is being done to correct this.

A common example is the mobile network – a system of increasing importance to AVs, but whose network coverage often leaves significant gaps across the highway network. Convincing telecoms providers to cover the entire highway network does not require government to directly fund the work. However, it does mean that policy makers need to recognise that connecting the road network is a task that depends on co-ordinated action, and consider how to achieve it when, for example, tendering mobile network licences.

A market-creating approach, where governments take an active role in explaining the challenge of adapting to AVs and incorporating it into wider infrastructure management or regulation, has the potential to produce faster results than simply waiting for the market to provide the answers spontaneously.

Automation will affect vehicle taxation

More broadly, technological changes are challenging the way in which vehicles and fuels are taxed around the world. Most attention is focused on the shift away from oil-based fuels towards electric propulsion. However, AVs also undermine some established sources of revenue, particular for local governments. AVs may not need to park the way human drivers do, and should be incapable of incurring fines for breaking traffic laws. They may also promote different models of access to transport, through shared use.

These changes will leave some authorities with budgetary pressure. As AVs still make demands of infrastructure and cities, it could be appropriate to consider new taxes that focus on part or all of an automated journey. Examples could include:

- updated parking/stopping regulations or introduction of a paid entrance to the city centre
- introducing payment for distance travelled (especially for empty vehicles)
- charging for use of the kerb, particularly in convenient locations.

These taxes may be more acceptable to the public if they can be linked to specific improvements to supporting infrastructure.

Conversely, AVs also make some types of journeys easier to make. For example, overnight freight deliveries become significantly easier. Once the technology behind AVs is well-established, this may create an opportunity to incentivise better types of journeys, potentially generating new kinds of revenue. Over time, a shift away from parking towards automated journeys may also free up some urban land, allowing it to be profitably redeveloped. This represents a prize for jurisdictions that can make AVs work in their areas.

Developers will pick where automated vehicle technology works. Governments need to learn to influence their choices

The development of AVs is still proceeding in the shadow of bold promises made in the mid-2010s, which expected Level 5 automation to dominate. Under such conditions, there was little need to think about the steps needed to make AVs function – the technology would be able to go anywhere and therefore would face no barriers. Today's AV technology is more limited in its nature: many developers are unwilling to operate without a substantial degree of testing, which can involve intensive scrutiny of performance over a small number of roads. Proving an AV that works safely in one area or environment will work safely in another may entail further testing and development – activities that are in the gift of private sector developers rather than policy makers.

Many developers of AVs are animated by a wish to change transport for the better, just like their counterparts in government. However, they are subject to different incentives, and in particular are compelled to seek out market opportunities that will provide a return on investment. This means they will be inclined to focus on the locations that are likely to be most lucrative, or where existing technology can be adapted at the lowest cost.

There will be less incentive for established players to serve sparsely populated areas, adapt to jurisdictions with quirky rules, or provide more unusual types of service with an uncertain business case. This does not mean that policy makers have no role in the process of bringing AVs into service in the real world: but the policy makers that are most successful in shaping the development of AVs will do so by influencing the actions of developers, rather than creating wholly new visions of transport by themselves.

This report has highlighted the importance of creating an environment where AV developers and operators find it easy to localise their technology. This includes limiting the scale of regulation or making provisions similar to jurisdictions where AVs are already well-established, making testing requirements procedurally simple, and recognising evidence from one jurisdiction in another where appropriate. Other measures highlighted include making resources for AV localisation (e.g. maps, traffic codes) readily available in internationally-recognised formats; ensuring that supporting infrastructures are well-developed and reliable; and providing direct support for the development of services that meet policy needs.

This last point is worthy of detailed consideration. Many policy makers and thinkers have looked to AVs as a tool for disrupting the current model of mobility and encouraging people to lessen their dependence on private cars. Many AV developers share this vision on a personal level, but most start-ups must produce results within a relatively short timeframe before their initial funding runs out. As the first generation of passenger AVs accessible to the public is likely to be predominantly robo-taxis or private cars with driver-assistance systems, developers are likely to focus on these areas. If the early days of automation are spent reinforcing the existing paradigm, this may be a significant missed opportunity.

This is one area where governments' interests differ significantly from developers. Governments have a much longer timeframe and an ability to justify investment on the basis of social value. This means they can justify supporting development into more innovative uses of AV technology. Developers and commentators interviewed for this study highlighted the potential of a stable, long-term contract between a developer and a city to support the joint development of a model for public transport AVs. This work could help shift the development of AV technology back towards those widely-held policy goals; and also has the potential to be cheaper, faster to deliver and more effective than more conventional transport investments such as new light-rail systems.

Keeping the roads safe for automated vehicles means creating new partnerships

If AV operations are constrained by the surrounding infrastructure, much of that infrastructure is in different hands. The vehicle itself will be the responsibility of those who develop, manufacture, maintain and operate it. The physical highway belongs to a conventional infrastructure operator, while other critical infrastructure may be managed by telecoms firms, by private companies or (in the case of geolocation systems) even foreign governments. Wider testing, authorisation and legal regimes also set vital context. The individual choices of all these parties affect the ability of an AV to drive safely.

An AV operator defines the ODD the vehicle will operate within and then gains the associated certification or test approval by a local authority. They will then operate on a daily basis with the information at their disposal. If certain assumptions are untrue – for example, a particular stretch of road is poorly maintained, a map is out-of-date or a mobile communications mast is down for maintenance – a vehicle may either lose the ability to drive itself, or may be driving outside of the conditions judged to be safe.

Even handled well, this multiplicity of new relationships risks making automated travel less reliable and convenient than it would otherwise be. Drivers who expected their vehicles to drive for them will find themselves back in control; vehicles that are under fully automated control may be compelled to stop. Companies using AVs for logistics risk having their supply chains disrupted. Handover between automated and human drivers can be expected to cause congestion where it is required.

Implications for safety are more serious. A failure of many of the “infrastructures” discussed in this report could potentially lead to a fatal crashes, especially if a self-driving system was not aware of a problem until it was too late to act on it. Given that national governments do not have a real-time understanding of the state of multiple parallel infrastructures, it cannot realistically be expected that AV operators can do so either – so at present there is no entity capable of managing the safety of the system as a whole.

This is a situation which is to the disadvantage of all parties: developers and operators must bear risks of infrastructure failures, and in practice this means limiting where and when their vehicles can operate. Those running the transport network have to deal with more disruption over which they have no control. And those using AVs or near to them may be inconvenienced or put at risk.

Without some form of action, accountability for the safety and performance of the road network could worsen as AVs become more common. While it would be inappropriate for any single party to be held liable for the safety of every element of automated mobility, there is a critical need for there to be an entity in every jurisdiction that understands how the different technologies and choices behind automated mobility function together at a strategic level.

Individual challenges – such as which roads are ready for which kinds of AV, whether a vehicle is safe to carry passengers, or how best to share information on the road – may be handled by a range of different agents; but the travelling public has a right to expect someone to watch over the system as a whole and encourage action by the right person if problems emerge. This report recommends that each country identifies a body – existing or new – with responsibility for understanding technical challenges within AVs and co-ordinating their operation on real-world roads (see Box 20 for an example).

Box 20. The UK Road Safety Investigation Branch

In 2022, the United Kingdom announced the creation of a new Road Safety Investigation Branch (RSIB), responsible for analysing the causes and contributory factors in road collisions. While similar organisations have existed around the world for many years, the RSIB may be the first with an explicit remit to consider the safety of new and emerging technologies, such as AVs.

This is a significant policy departure for the United Kingdom. While the country’s road safety record is strong by international standards, and it has operated accident investigation branches for other modes since 1915, the UK government has historically declined to create an organisation responsible for investigating crashes on the road. The government’s announcement makes clear that the advent of AVs has been a crucial factor in changing its position.

Source: UK DfT (2022).

Policy insight: There needs to be clear and coherent responsibility for ensuring automated vehicles work within a Safe System

Current responsibilities for road safety may not adequately cover all elements that contribute to the safe operation of AVs as a new, integrated system. While developers and operators will still maintain legal liability for their actions, each country needs a body that is responsible at a strategic level for understanding the safe operation of AVs on public roads, and for highlighting any problems that emerge. This organisation may be new or pre-existing, but it needs to have the necessary skills and expertise to understand challenges and solutions that have no precedent, and to draw on international considerations.

Delivering the goals of policy makers will require acquiring new skills and engaging with unfamiliar areas and organisations

Historically, policy makers have seen their role as providing a road, making capacity available in a way that is safe and environmentally appropriate. This has involved a relatively narrow community of policy makers, engineers and construction companies. When AVs come into use on those roads, that role will expand, beginning to cover new types of infrastructure and new stakeholders with unfamiliar interests. It will involve private companies who are not expected to maintain service; who do not have government's ability to take risk; and who are much more sensitive to issues such as brand perception.

This is more than a philosophical observation: the interconnected judgements among different organisations ultimately determine whether or not AVs function on the road in question. While AVs provide many opportunities to deliver better transport, a policy maker who is not ready to work differently will miss opportunities to make that improvement happen. For example, making the roads safe today is about engineering and driver education; making AVs safe in the future relies on a cutting-edge knowledge of automation, as well as the ability to get access to data and take action with new evidence that becomes available. In return, policy makers and infrastructure operators can offer much knowledge about the infrastructure limiting AVs; and have more power than any other entity to fix problems and improve coverage.

This will not happen unless policy makers and infrastructure operators widen their range of skills, put them to use in new ways, challenge existing processes and engage in new dialogues.

Co-ordinated research will help all participants in a growing industry

Given that AVs are still at the research and development stage, and the operational characteristics of new systems are still emerging, there is clear value in establishing a sustainable and structured way for transport authorities and industry to work together. Although the development of AVs will be a commercially competitive process, it will take place on publicly funded highways that are open to all. This report recommends that policy makers and industry should work together to reach a better understanding of developing needs and expectations, and where useful to set up co-ordinated research that will help increase the consistency of action across the world.

This includes developing research and development plans and roadmaps to investigate the investments needed to support AV integration. For example, it will be important to determine if weather conditions will impact AV integration and how these impacts will change transport authorities weather maintenance activities and protocols. Tests, evaluations and pilot demonstration activities will also need to be conducted.

Policy insight: Developers and policy makers need to co-operate on a research programme on key AV-related issues

A co-operative research programme should be established, involving both infrastructure operators and industry/developers. Key priorities for this programme should include 1) agreeing a standard international approach to audits of the readiness of roads for AVs, 2) addressing key technical issues relating to the interaction between AVs and infrastructure; and 3) agreeing longer-term visions for the future of transport and the role of infrastructure in it.

In addition, international methodologies will be needed to inventory road elements that support AV operation and integrations. Analysis capabilities will be required to identify where investments may be needed to enhance physical infrastructure to support AV operation.

Given the challenges regarding the range and diversity of physical infrastructure standards, policy makers will also need to collaborate with industry to identify opportunities where standards can be made more consistent and uniform between jurisdictions. The certainty that this work delivers will significantly reduce the risk of public investment, and make it easier to direct public funds towards accelerating the uptake of AVs.

Ongoing dialogue between developers and policy makers is essential

All of the work carried out in preparation for this report has highlighted how important dialogue between developers and policy makers is, and the need to make more of it happen. It is easy to see why this is not currently a priority – developers are focused on proving the viability of their new vehicles, and policy makers and infrastructure operators have plenty of work to do catering to existing traffic. But over the coming decades the advent of automation will fundamentally change what is expected of the world's most-used transport network. Making a success of this requires dialogue ahead of that shift, and not after it has happened.

This is not dialogue for its own sake: developers and operators of AVs profit from having an infrastructure network that helps their product to work in more places and attract more business. Policy makers want to save lives, cut costs and serve the public better. Both sides are best served by the rapid responsible deployment of AVs. Good dialogue is not about points of policy or language, but about how to resolve the practical barriers standing in the way of AVs driving safely, in large numbers, on real-world roads.

No regular forum exists through which this dialogue can take place. However, the consultations conducted for this report have demonstrated the readiness of participants in all areas to share their insights and highlight the potential for greater co-operation. There is an opportunity for transport authorities and industry to develop their collective voices, and to approach shared problems from multiple angles at the same time. Resources are limited on both sides, and commercial pressures may constrain what some companies are able to discuss; but bringing together the insights of innovators and the institutional power of policy makers and infrastructure operators makes the world readier for the changes that lie ahead.

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Glossary

Advanced driver assistance system (ADAS)	Entity consisting of interdependent components that support human drivers by performing a part of the dynamic driving task or providing safety-relevant information (e.g. adaptive cruise control and automatic emergency braking).
Automated driving system (ADS)	The hardware and software collectively capable of performing the entire dynamic driving task on a sustained basis. It is a type of driving automation system used in vehicles with Society of Automotive Engineers International (SAE) Level 3, Level 4 or Level 5 automation.
Automated vehicle (AV)	A vehicle with SAE Level 3, 4 or 5 automation. It has an automated driving system, which makes it capable of performing the entire dynamic driving task on a sustained basis without human input. Distinct from vehicles with automated features to assist a driver (SAE Level 1 or 2), which still require a human driver to perform part of the dynamic driving task.
Cooperative Intelligent Transport Systems (C-ITS)	Technologies and applications that allow effective data exchange through wireless technologies among elements and actors of the transport system, very often between vehicles, or between vehicles and infrastructure, but also with vulnerable road users (e.g pedestrians, cyclists or motorcyclists).
Global navigation satellite system (GNSS)	A constellation of satellites providing signals from space that transmit positioning and timing data to GNSS receivers. The receivers then use this data to determine location. Currently four different GNSS systems (Galileo, GLONASS, BeiDou and GPS) provide globally open positioning services, with a positioning accuracy of 1.5- 10 metres.
High-definition map (HD map)	A highly accurate map used in automated driving, containing details not normally present on traditional maps. Such maps can be precise at a centimetre level. HD maps for automated vehicles usually include map elements such as road shape, road marking, traffic signs and barriers.
Operational Design Domain (ODD)	The operating conditions under which a driving automation system is specifically designed to function (these conditions can relate to locations, weather conditions, driving modes and other factors).
SAE levels	The levels of driving automation set out by the Society of Automotive Engineers, from no automation (Level 0) to full automation (Level 5).
Satellite-based Augmentation System (SBAS)	Systems that improve the accuracy and reliability of GNSS information by correcting signal measurement errors and providing information about the accuracy, integrity, continuity and availability of its signals. SBAS are owned and operated by governments.
Vehicle-to-everything communication (V2X)	Wireless communication between a vehicle and any entity that may affect, or may be affected by, the vehicle.
Vehicle-to-infrastructure communication (V2I)	Wireless exchange of data and information between vehicles and road infrastructure.
Vehicle-to-vehicle communication (V2V)	Wireless exchange of data between vehicles. These data include information on speed, location, direction of travel, and braking.

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Preparing Infrastructure for Automated Vehicles

Automated vehicles are becoming more prevalent and capable, but they have different requirements than cars wholly controlled by human drivers. This report examines what is needed now to support automated vehicles, focusing on three policy-making areas: physical infrastructure, data and digital infrastructure, and institutional frameworks. It draws on the deliberations of an ITF Working Group, as well as interviews with policy makers, developers and experts.

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