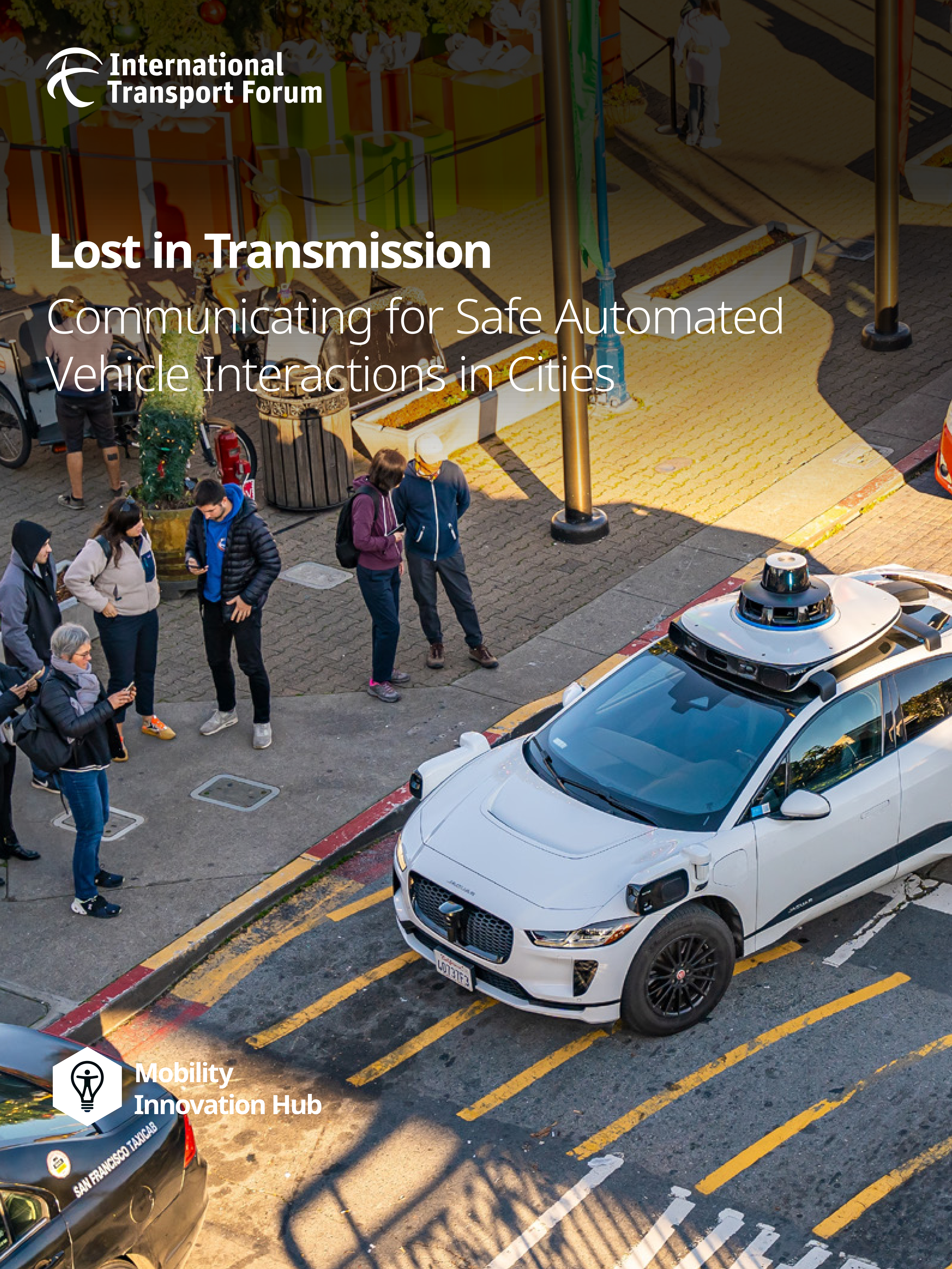
International Transport Forum

Lost in Transmission

Communicating for Safe Automated Vehicle Interactions in Cities



Mobility Innovation Hub

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The International Transport Forum

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About the ITF Mobility Innovation Hub

ITF's Mobility Innovation Hub helps governments to develop innovative policies for better transport in the face of uncertainty and rapid change. It scans for transport-relevant developments at the horizon of public authority foresight, assesses their potential impacts and highlights best practices for deploying effective policies.

Case-Specific Policy Analysis Reports

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Most interactions between public space users are silent and rely on implicit forms of communication

Automated vehicles must use universal and implicitly interpretable communication and cues for safe and efficient interactions in public spaces.

Main findings

The increasing deployment of automated vehicles (AVs) is set to create a paradigm shift in the transport sector. In cities – where human-to-human interactions prevail – automated vehicles will likely transform how other public space users interact with road vehicles. Misinterpretations on the part of AVs and other public space users can lead to conflictual interactions and accidents. AVs' ability to interpret the intentions of public space users and understand their surroundings will influence the interactions between automated road vehicles and other public space users, such as pedestrians, bicycle riders and other motorized vehicles.

In safety-critical situations, incorrect predictions or misinterpretations of another public space user's behaviour can cause harm. While misinterpretations cannot be completely avoided – with malicious behaviours towards AVs such as GPS- or sensor-based attacks still representing a threat – risks can be mitigated. For vehicles to interact safely with one another and with other public space users, it is necessary to build safe systems. The entire transport system will need to create this, from vehicles to the infrastructure network.

The absence of human drivers and the introduction of highly automated-driving modes will change road communication in cities. One important hurdle to effective communication is the fact that AVs and humans do not communicate their intent in the same ways. While most traditional urban interactions rely on silent or implicit forms of communication, AVs are expected to communicate via explicit "external Human-Machine Interfaces" (eHMI) which can take many forms (e.g. light, verbal or symbolical messaging regarding the AV's intent on a screen). AVs also tend to adopt non-human driving and braking patterns, which can make it difficult for other public space users to predict their movements and intentions. These discrepancies between AV behaviour and existing forms of communication in cities can result in misinterpretation and conflicts, especially during the early stages of AV deployment.

In cities, physical infrastructure is the shared reality for drivers of all vehicle types and for all other public space users. Street characteristics play a mediating role that promotes safe interactions between public space users and AVs. Street role and design (e.g. street space allocation), artefacts (e.g. traffic signs, road markings) and less tangible measures (e.g. speed management) are crucial components to consider in order to improve interactions between vehicles and public space users. Public authorities can play a central role in fostering safer interactions between public space users by applying best practices in terms of street design and speed management policies.

Reliable digital infrastructure is essential for the successful deployment of AVs. AV decisions rely heavily on data from digital maps, communications between AVs and their environment, and machine-readable regulations. This invisible infrastructure is prone to cyber threats and thus requires a robust cybersecurity framework for safe and trustworthy integration.

Top recommendations

Automated vehicles should adapt their communications to cities

Efficient communication is crucial for safe automated vehicle (AV) deployment in cities. AVs should mainly use predictable and interpretable implicit forms of communication with kinematics – lateral and longitudinal trajectories and speed – that mimic human behaviour while adhering to road regulations and safety procedures to reduce miscommunications. In conflicting situations (i.e. observable situations involving users that could result in a crash) or when implicit communication no longer works, AV manufacturers should prioritise explicit forms of communication. More importantly, external Human-Machine Interface (eHMI) messages should convey information regarding the vehicle's intended action (i.e. “I yield”) to all concerned public space users rather than expressing what public space users should do (i.e. “You can cross”).

Design street-friendly automated vehicles, not automated-vehicle-friendly streets

Policy makers should take a human-centric approach to automated vehicle (AV) deployment to ensure that AVs become a positive force that enables them to reach public policy objectives, especially regarding the use of public space. Safe interactions with AVs will require inclusive access and minimal conflict as the foundations of safe street design. Public authorities should reduce speed to 30 km/h in interaction-intense areas to prevent the occurrence and severity of crashes between different public space users and automated vehicles.

Use automated vehicle crash data to improve safety

Public authorities should consider automated vehicle (AV) crash data as a new form of essential infrastructure for safe and efficient AV operation. Crash data is critical for enabling safer interactions and improving overall system safety. An antifragile approach – where data from crashes and near-crashes is shared with stakeholders, similar to practices in the aviation sector – can lead to continuous improvements in safety policies and the AV design sector. To implement this approach effectively, mechanisms must be established to protect personal and commercially sensitive information while facilitating data sharing across the transport ecosystem.

Establish robust cybersecurity systems for safe and trustworthy automated vehicle interactions in cities

Trust is key to making automated vehicle (AV) deployment acceptable in cities. Ensuring AV robustness against cyber threats is crucial to make AVs’ actions trustworthy and ensure safe interactions. Public authorities should adopt a holistic approach and acknowledge that the different components that AVs rely on to operate can fail. Stakeholders such as digital maps providers, infrastructure managers and vehicle component manufacturers should validate that their cybersecurity processes are robust enough to avoid potential threats to human safety.

Translate regulations into machine-readable format

Rules governing the use of the public space constitute a form of invisible infrastructure which enables society to function. Humans and machines do not abide by rules in the same manner. Machine-readable regulations provide automated vehicles (AVs) with a reliable source of regulatory information and reduce the risk of regulatory ambiguity. Digital regulations also constitute an additional layer of information, thus creating redundancies between different sources of information for AVs. Machine-readable regulations should be consistent across jurisdictions. Standards used should allow for frequent updates and maintenance to avoid discrepancies between real-world disruptions (e.g. presence of a construction site) and machine-readable regulations.

Cities as complex, intense and unpredictable settings

In 2024, automated vehicles (AVs) began their commercial deployed in some cities. Human drivers are gradually transferring their functions to computer systems due to developments in artificial intelligence (AI), information and communication technologies (ICT) and sensing technologies. The complexity of traffic will likely increase with automated vehicle (AV) deployment. Some interactions between public space users and AV drivers might be impaired, while others might be improved. AVs will likely alter their users' perception of space and time and impact cities as physical and social objects (Larco et al., 2020).

AVs are vehicles with a different levels of automation for driving tasks. SAE International (2021) Levels of Driving Automation provide a taxonomy of the different AVs ranging from vehicles with no or minimal and restricted driver assistance features (i.e. lane centring, adaptive cruise control) to vehicles with automated driving features (i.e. where the system takes action on the vehicle). Replacing the driver with an automated driving system will likely introduce second-order changes in terms of use and activity (i.e., new travel behaviour, change in the urban form, etc.). AVs are also expected to have wider impacts on safety, the environment, public health, landscape, and vehicle ownership (ITF, 2023a).

Automated transport modes already affect urban interactions. Metros are among the most automated modes in cities (UITP, 2018). The conditions under which an automated metro is designed to safely operate (i.e. Operational Design Domain - or ODD) are more simplified and predictable than for vehicles operating on city streets: metros operate on dedicated tracks with very limited and controlled interactions with other users. In contrast, urban roads and streets are far more complex environments (Cheng et al., 2022). Factors such as the presence of open intersections, the mix of various users and transport modes, and dense traffic volumes increase the unpredictability of interactions.

Taking humans out of the driving seat does not guarantee the absence of errors (ITF, 2018a). The unanticipated operation of automated driving systems (ADS) coupled with a decrease in driver responsibility and concentration can lead to higher risks, particularly for other public space users (M. L. Cummings and Bauchwitz, 2024). Human mistakes in driving will be replaced by unanticipated operations and unwanted outcomes from automated driving systems. These can be caused by human errors in programming (M. Cummings, 2023; ITF, 2015a). Vehicles' lack of interaction capabilities does not ensure safe interactions with other public space users (Madigan et al., 2019). For example, low-level interaction capabilities of AVs has already been cited as dangerous for conventional vehicles (Sinha et al., 2021), pedestrians (The Guardian, 2024), and cyclists (Hawkins, 2024).

Navigating physical and social urban space

City space is composed of several components, such as the built environment and street networks (Salazar-Miranda et al., 2022). Street networks enable society to function efficiently, providing users with physical, economic and social access. Streets are both an amenity and a connector: they serve non-connective functions (e.g. activities, resilience, safety) while at the same time enabling people to gain access to spatially distant locations (ITF, 2023b; NSW, 2023). In this respect, street space is a partial embodiment of social space that AVs should be able to discern and navigate (Bourdieu, 1997).

Streets provide a wide array of often invisible functions beyond movement. Several factors shape streetscape and influence its characteristics (NSW, 2023). Social, environmental, or economic factors endow streets with different characteristics. For example, the conversion of parking spots into parklets or patios is associated with significant societal benefits for communities while having a limited impact on vehicular travel (Dai, 2012). Similarly, in the context of climate change, streets are expected to play a role in improving cities' resilience, reducing emissions and supporting greener and healthier cities (TfL, 2013).

Streets have different characteristics, designs, and functions, which determine their capacity to provide amenities and connect. Although the long-term impact of AVs on physical space is unknown (Stead and Vaddadi, 2019), the reallocation (i.e. a shift in the allocation of space of different uses) and repurposing (i.e. a shift in the way the space is used under the existing allocation of space) of public space towards AVs is expected to improve AVs' operation. Yet, as public space is a scarce resource in cities, its allocation should favour the streets' diverse uses and users (ITF, 2022b).

Public authorities should not provide more space or re-configure existing public space for AVs at the expense of other urban modes of transport. The often-proposed repurposing of public space aims to address AVs' interactions weaknesses in open environments. However, just as the radical monopoly of cars in cities degraded cities' ability to enable interactions between public space users, thus impeding their social functions (Illich, 1973) (Box 1), a monopolistic allocation of public space for AVs might reveal itself counterproductive or even destructive to urban interactions.

Box 1. Ivan Illich's perspective on the radical monopoly of cars on public space

Illich's Tools for Conviviality explored how people and societies interact with tools and machines at their disposal in modern societies. He highlighted how and why tools should be designed as convivial, i.e. they should serve individuals rather than manipulate them. According to Illich, tools should be responsibility-limited to ensure they do not go beyond natural limits and avoid creating a new kind of serfdom.

Illich notes that radical monopoly reduces personal autonomy and exerts a form of social control as it imposes a form of consumption over others. Machines and tools can exert a form of dominance over space when they are applied to facilitate people's interactions with the physical environment. The monopoly of these tools describes the often-exclusive dominance of one product over the satisfaction of users' needs.

Illich uses the example of motorised vehicles in cities to illustrate a radical monopoly over space. Cars shaped cities to their use and purpose. To be over-efficient, cars rely on an extensive use of space, enabling the increase of their speeds. This, in turn, creates distance between urban dwellers. Illich argues that the radical monopoly of cars further had impacts on other forms of transport, as vehicle traffic curtails the right to walk and cycle in cities and on the environment, as large infrastructure was often deployed to other natural ecosystems (i.e. highways covering rivers, etc.).

Source: Illich (1973).

Instead of adapting cities to AVs' design and operational characteristics, public authorities should seek to adapt AVs to how cities function and create value for people (i.e., enabling diverse and serendipitous interactions) (Illich, 1973). AV developers and authorities should ensure that AVs can communicate their intent, understand other public space users' intent, and navigate complex urban settings in cities', rather than curtail the use of public space for everyone else to AVs' terms.

Co-ordination, co-operation, and competition within the public space

Public space is a dynamic environment, home to constant interactions between diverse users. People share public space as a common and scarce resource (ITF, 2022b). The main characteristic of this space is that its use can change the conditions of use for other users (Juhlin, 1999): the decision of a vehicle not to stop at a crossing will alter the possibilities for other users to use the same street. Similarly, a user’s behaviour might instigate different impacts on other users, depending on the characteristics of the other user (e.g. age, gender, disabilities).

Interactions are about co-ordination, defined here as the capacity of different complex system elements to work together. However, co-ordination is not a synonym for co-operation (Angulo, 2014). While public space users share the same resources, they can behave in a collaborative or a competitive manner. Collaboration within public space emerges when parties to an interaction make decisions that bring them mutual benefits (Juhlin, 1999). These benefits are multidimensional: they can be related to comfort, safety, time, cost or other meaningful outcomes. Conversely, users can act in a competitive manner, where users disregard other users’ needs, desires and feelings to keep their own benefit in mind. Competition for access to and use of public space can lead to selfish and unfair behaviours. Nonetheless, even with competition for public space, users typically seek to avoid major risks such as crashes and major disruptions (Angulo, 2014) or otherwise constrain their behaviour under the threat of punitive enforcement.

Many interactions are enabled by silent co-ordination (Sørgaard, 1988) where public space users rely on available, shared and transparent information (Angulo, 2014). Urban streets are also an information space in that they are filled with information that facilitates more or less silent co-ordination (Angulo, 2014). Information can take various forms. For example, written (i.e. legal) and un-written (i.e. ethical and heuristic) rules, and the presence of physical artefacts and the affordance embodied in the built environment influence or condition interactions (e.g. traffic lights, road markings, street width, roadside parking, etc.) and facilitate co-ordination between users.

Decoded and collaborative communications for safer interactions

Information plays a crucial role in enabling collaborative, safe and efficient interactions between all public space users – including AVs. Users of public space continually seek information to increase the predictability of encounters with other users (Rettenmaier et al., 2021). Communication in road traffic has several functions: it enables public space users to understand how the actions of other users might affect their own actions and decisions; to make themselves understood to the other users; and finally, it can contribute to enhancing both traffic safety and efficiency (Chaloupka and Risser, 2019).

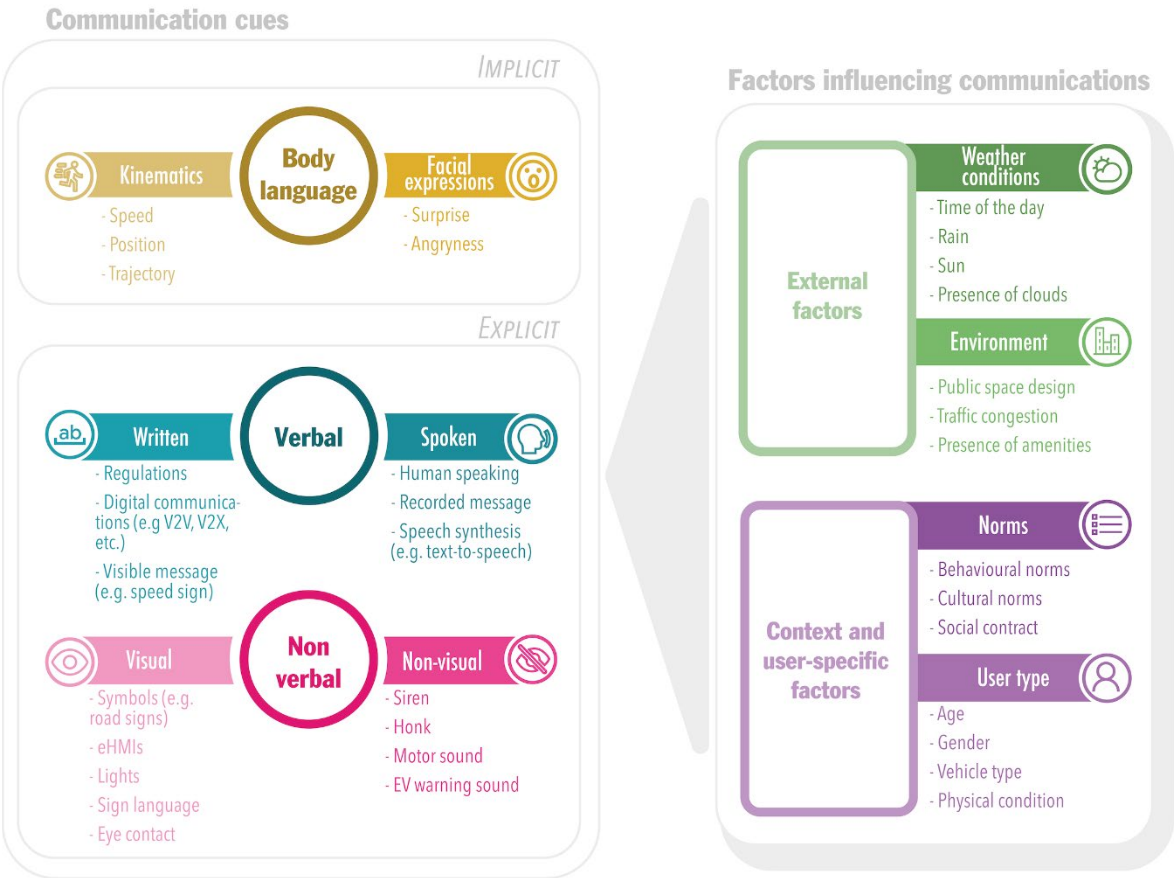
An effective approach to urban interactions between AVs and other public space users should account for communication-related factors that make urban interactions more challenging. This section explores these factors and proposes principles to ensure safe interactions between public space users and AVs.

AVs and humans sense and perceive their environment in different ways. Sensing and perceiving are not the same: the act of sensing detects and transcribes information (e.g. visual, aural, temperature, positional, etc.) about the environment in a way that guides awareness and action. Perception describes the process of selecting, interpreting and prioritising sensory inputs (e.g. via cognitive-brain processing or combined processor-algorithmic processing – including artificial intelligence (AI) compute). In this context, the interpretation of the same sensory information can vary from one person to another, as humans tend to react to stimuli based on their own experiences, emotions and expectations. Similarly, the interpretation of sensory information may vary from one cyber-physical platform to another depending on the type of sensors and processors involved and the range of algorithmic processing outcomes. AVs must take into account the unpredictable nature of human reactions just as humans may face variable behaviours on the part of AVs.

AVs and humans do not abide by rules in the same manner. Human interactions are governed by a range of legal and formal rules (e.g., traffic rules), as well as by informal and moral rules (e.g., priority given based on a user type). Cultural and social norms play a key role in interactions involving humans (Sheppard et al., 2023). AV system interactions are governed by algorithmic processing of various sensor inputs using machine learning and other forms of AI. AV AI code establishes various optimisation targets (e.g. reduces the compute cost of determining trajectories that minimise interactions with other cars) which the system itself may modify based on observing its own behaviour. Safe interactions within a specific context might require AVs to adapt to cultural norms to some extent but it may be that the AV AI, in carrying out its optimisation processes, may adopt technically sound but asocial behaviours.

Information encoding rules or users' intent takes many forms. Traffic signs, hand gestures, lane markings, or a user's behaviour all convey information about a situation (Lee et al., 2021). Interactions cannot be reduced to explicit interactions. Public space users convey information regarding their intent by relying on both explicit (i.e. hand gestures, honking, etc.) and implicit forms of communication (i.e. speed, behaviour). Implicit forms of communication are, to some extent, transparent: they are visible and accessible to other space users. They are also learned in a social rather than technological context. They form a shared material (Sørgaard, 1988), which supports the mediation of users' interactions in the public space. Figure 1 provides a taxonomy of some of the main forms of communication cues in urban settings, and the factors that can influence communication between public space users, including AVs.

Figure 1. Influencing factors for communication cues between public space users



Note: V2V = vehicle-to-vehicle, V2X = vehicle-to-everything, eHMIs = external Human-Machine Interfaces,

AVs will likely introduce new forms of communication (e.g. data-sharing, vehicle-to-vehicle (V2V), vehicle-to-everything (V2X), etc.). They will also accentuate the use of human-machine interfaces. In the longer term, public space users will increasingly have to interact with technical systems, which will potentially induce changes in how the information between public space users is communicated within the public space (Chaloupka and Risser, 2019). External Human-Machine Interfaces (eHMI) on vehicles will potentially share AVs' intent using different modalities (i.e. visual, auditory, vehicular body language, and others) (Dey et al., 2020). These different modalities convey information differently, thus enabling the eHMI message to adapt to the needs and impairments of the receptor.

Urban interactions between vehicles and other public space users relies on cumulative communication cues. The urban realm is saturated with information that people rely on to situate themselves in and navigate through public space. There is no single source of information for all public space users to draw upon. A communication cue will work with other information conveyed in a given situation and for a given user. Users will make decisions based on a combination of cues such as their own condition, the presence of another public space user and their behaviour, weather conditions, the time of the day, etc.

Inconsistencies between cues can blur situational understanding and thus hinder the perceived safety within any given situation (Rettenmaier et al., 2021). Communication cues should work in tandem (Dey et al., 2020, 2021). For example, when an automated vehicle conveys its intent using both implicit communications (e.g. by adapting its speed and steering to the situation) and explicit information (e.g. with the use of an eHMI), the ensuing vehicle behaviour should be consistent with the displayed or signalled intent (Harkin et al., 2023). Experiments led by Dey et al. (2021) show that pedestrians will not blindly trust eHMIs. When implicit and explicit messages contradict, pedestrians revert to movement-based cues to make their own decisions. However, Kaleefathullah et al. (2022) show that repeated exposure to eHMI can lead pedestrians to over-rely on eHMIs, and under-rely on vehicle's speed and steering, creating a danger of crashes.

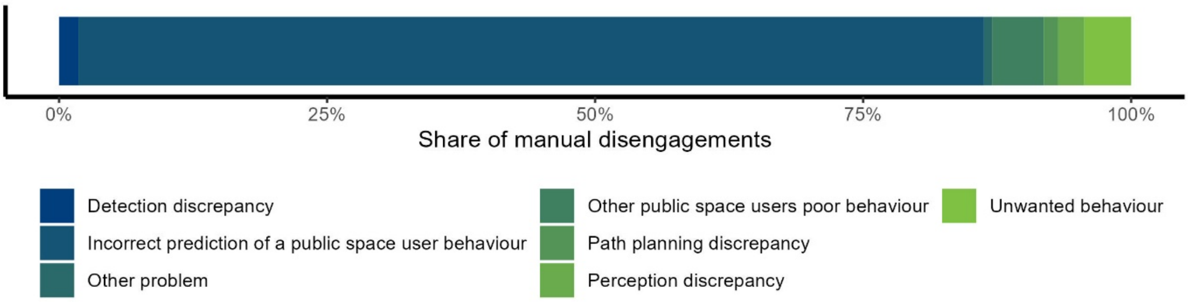
Interactions in cities are not one-to-one. Traffic can be defined as a network of interactions between different public space users (Chaloupka and Risser, 2019; Madigan et al., 2019). Several interviewed experts highlighted the fact that interactions between public space users were usually not one-to-one communications. In this context, AVs will need to simultaneously collect and make sense of information collected from several public space users. At the same time, AVs will have to avoid misinterpretation of their intent when sharing information with other public space users. Several experts emphasised the often siloed state of research in the field of urban interactions between public space users and AVs. Further research in one-to-X and X-to-one interactions is needed.

Safer interactions within the Safe System

Conflicting interactions between AVs and other public space users emerge when public space users fail to effectively signal their intent, especially in cases where signalled intent is overlooked or misunderstood. These situations can result from various factors: an incorrect perception of the user's intent (i.e. an AV or a public space user has not perceived the communication cue), or from an incorrect prediction of the public space user's behaviour (i.e. an AV or a public space user incorrectly assumed other users' behaviour). The current lack of AV interaction capability makes interaction more complex (Madigan et al., 2019).

The correct interpretation of public space users' intent will be crucial to enable safer interactions between public space users and AVs. Data from AV deployments in California shows that 22% of manual disengagements from the AV safety driver followed an interaction with other public space users (Sinha et al., 2021). Figure 2 shows that 85% of these manual disengagements involving other public space users were caused by an AV's incorrect prediction of public space user behaviour.

Figure 2. Causes of manual disengagement between automated vehicles and other public space users



Source: Based on Sinha et al. (2021).

Box 2. Automated vehicles within the Safe System approach

The Safe System approach relies on four main principles:

- It acknowledges human fallibility within the traffic system and seeks to ensure that mistakes do not result in deaths or serious injuries.
- The human body has a limited physical ability to absorb crashes without causing harm.
- Responsibility is shared between those who use the roads. But focusing only on drivers' mistakes fails to acknowledge that road design, construction and maintenance are also a contributor to crashes.
- A safer traffic system implies strengthening the different components of the system to increase their effectiveness on safety.

With the development of automated vehicles (AVs), the elimination of the driver is expected to improve the overall safety of the traffic system since it would help reduce the common misjudgements made by impaired, distracted, or fatigued drivers. Yet, as highlighted by ITF (2018), human error does not only imply driver responsibility. Vehicle computing and automation led to the emergence of a new class of errors. In the context of the Safe System, the approach shifts from driving errors to programming errors and unwanted outcomes that must be taken into account.

Human error can also result from non-driven-related errors made by other motorists, cyclists or pedestrians. Even in a fully automated traffic system, these errors will likely continue to occur.

Source: Cummings and Bauchwitz (2024); ITF (2018a).

AV deployment that follows the Safe System principles (Box 2) is crucial for the overall safety of traffic. The transport system should be adapted to accommodate potentially defective or degraded automated vehicles. In this context, enabling safe interactions will imply ensuring failsafe actions across the entire transport system, from the vehicle to the infrastructure network. While ensuring efficient communications of intent between public space users and AVs is important, infrastructure design might also play a key role in enabling safer interactions. Road characteristics (e.g. width, presence of zebra crossings) impact user trajectories and thus interactions between users.Madigan et al. (2019) asserts that the design of road infrastructure significantly conditions interactions between AV and other public space users.

Interaction domains and stakeholders

Interactions between public space users in cities happen within and across different domains (Figure 3). Two forms of infrastructure play a central role in supporting interactions.

- Physical infrastructure: composed of streets, urban equipment and the built environment, hosts the majority of the interactions between users. Pavement, traffic signs, and road markings provide physical rules and facilitate interactions between users.
- Digital infrastructure: composed of digital maps, data, and standards, has played an increasing role in supporting essential interactions between urban dwellers. It connects users with transport

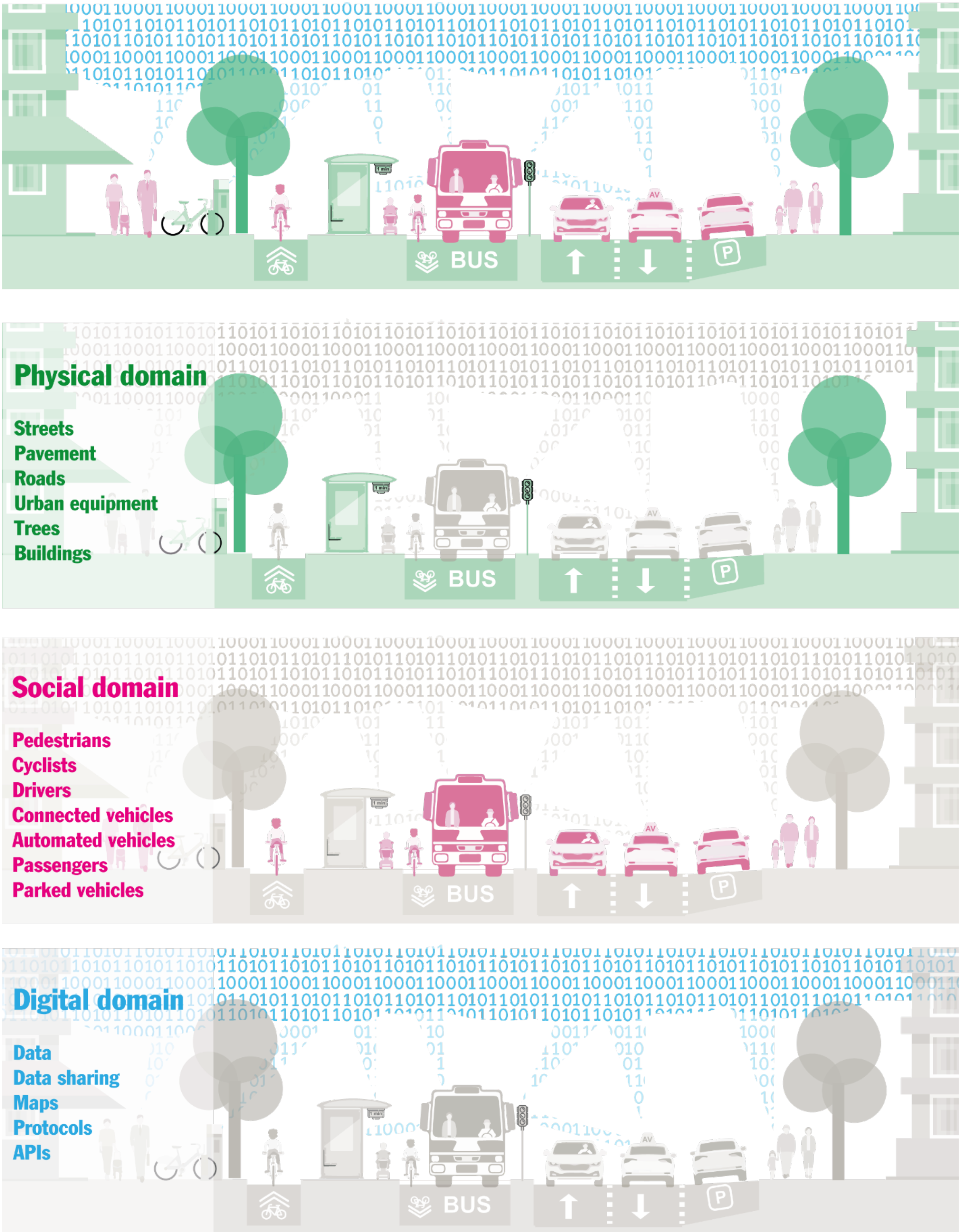
infrastructure and services. AVs rely heavily on this infrastructure to make decisions compared to other public space users.

However, infrastructure can mean different things depending on its users: it is relational by essence (Star, 1999). A step can constitute a connection for certain users and, at the same time, a barrier for people in wheelchairs. There is a need to broaden the definition of infrastructure – as a system of substrates supporting human activities – to consider infrastructure as an enabling resource (Bowker et al., 2009).

Several parameters influence interactions in the social realm. Culture, language, common understanding of a situation, or knowledge of users will act as enabling resources to facilitate interactions. Several authors suggested broadening the conceptual umbrella of what constitutes an infrastructure to include knowledge and users (Bowker et al., 2009; Star, 1999; Star and Ruhleder, 1996).

Urban interactions refers to public space users interacting amongst themselves (i.e. social realm), with elements and characteristics of the street and the built environment (i.e. physical realm) and also relying on digital tools and signals, and data (i.e. digital realm). In the context of AV deployment, interactions between public space users and AVs will increasingly comprise elements of digital infrastructure.

Figure 3: Urban interaction domains for public space users and automated vehicles



Understanding how the deployment of AVs will impact urban interactions requires looking specifically at the different forms of interactions between users and in which realm they happen.

The next sections will explore how meaningful information regarding public space and its use can be encoded and transmitted to AVs and how automated systems can acquire and use information to guide their actions safely and beneficially manage interactions. More specifically, it will look at 1. how public space users (including Avs) interact and how these interactions can be improved; 2. how the built environment influences and can facilitate safer interactions between public space users; and 3. how digital infrastructure, central to safe and predictable AV operation, can facilitate interactions amongst different public space users.

Safe co-operation between public space users and automated vehicles

Automated vehicle (AV) deployment will create crucial public space use and management challenges for policy makers. The absence of human drivers and the uptake of highly automated driving modes will change public space interaction and communications in cities. AVs will not be able to perform certain forms of explicit communication people are used to (e.g. hand gestures, eye contact), and their implicit communication may not be correctly perceived or understood by humans. AV deployment will also create mixed-traffic scenarios where communication will play a central role in enabling safe and efficient interactions. Their deployment, however, should not lead to inequitable outcomes. Many people, including children, older adults, and the cognitively impaired, already face difficulties navigating urban environments. AVs should not further complicate this task.

Sharing public space with automated vehicles when they are first deployed

Drivers of non-automated vehicles have a wide range of communication techniques at their disposal, which they use for successful and safe interaction with other users of public space. AV uptake affects the delicate balance between explicit and implicit communication on city streets and raises questions regarding future communications in cities.

Automated vehicle implications for explicit communication

Human-to-human explicit communication (i.e., verbal communication, hand gestures) will be significantly impacted by AVs as it requires direct interaction between the human driver and other users of public space. Hand gestures, eye contact and human verbal communication are among the several forms of explicit communication that AVs will not have access to nor will necessarily perceive or understand. Eye contact, for example, is considered essential not only to communicate intent but also to acknowledge the presence of other users of public space. Pedestrians often seek eye contact with drivers to confirm acknowledgement and feel more confident about crossing the street (Müller et al., 2016; Sucha, 2014). Guéguen et al. (2015) support this hypothesis and assert that eye contact significantly affects drivers yielding to pedestrians.

However, explicit communication cues are not always required to communicate intent. Al Adawy et al. (2019) attest that 90% of pedestrians cannot determine the driver's gaze at 15 m or see the driver through the windshield at 30 m. Dey and Terken (2017) explain that human-to-human communication rarely occurs between drivers and pedestrians in crossings. Pedestrians always look at the car without necessarily engaging in eye contact and indicate their will to cross by stepping onto the street (Dey and Terken, 2017). Similarly, Lee et al. (2021) found that only 27% of pedestrians reported using eye contact at crossings.

As with vehicle-to-pedestrian interactions, vehicle-to-vehicle interactions require limited explicit communication, and the driver is rarely the origin of the explicit communication. Instead, drivers use simple forms of explicit external Human-Machine Interfaces (eHMIs) like turn signals, braking, and parking lights to accompany implicit cues and ensure that intent is duly transmitted to all nearby users of public space. The development of AVs has been accompanied by many proposals for new eHMIs to fill the communication gaps that driverless vehicles create.

Dey et al. (2020) identified 70 different AV-based eHMI concepts and created a unified taxonomy across 18 dimensions. Some examples of these prototypes are virtual eyes (created by and experimented with by Jaguar and Land Rover) and LED screens which display text-based messages (created by and experimented with by Drive.ai). External interfaces can improve communication under certain conditions. Dey et al. (2020) found that displayed messages through eHMIs help pedestrians decide to cross the road when the vehicle's speed does not provide sufficient information. They also found that pedestrians do not blindly trust eHMIs and still rely on a mix of explicit and implicit cues.

However, there is not yet consensus on which eHMI, or combination of eHMIs, is the best for AV communication given the numerous prototypes and early stage of eHMI development. Additionally, there is no consensus on whether replacing these forms of explicit communication is necessary in the first place. As highlighted by experts interviewed as part of this project (Annex 1), using eHMIs to fill relatively small communication gaps may cause greater confusion and create new problems if used incorrectly.

The minimal but sufficient level of communication needed for conventional drivers incorporates only a small share of explicit communication. New eHMIs should be studied to ascertain how necessary they are to communicate vital information, and their implementation should focus on solving conflict situations requiring more than implicit communication. Implicit communications, in essence, require time to assess the vehicle speed (i.e. speed is calculated between point A and point B). However, when two public space users are close together, reaction times may be insufficient to avoid conflict (e.g. parties may not perceive in time that they are on a collision course at higher speeds). In these situations, AVs should rely on explicit and direct forms of communication (i.e., a message that can be interpreted immediately such as a light or noise). Messages indicating to other public space users what to do should be avoided since they can create confusion or misinform in complex scenarios. If introduced, external interfaces must convey messages to all concerned public space users regarding the vehicle's own actions and be standardised to avoid confusion between different vehicle models.

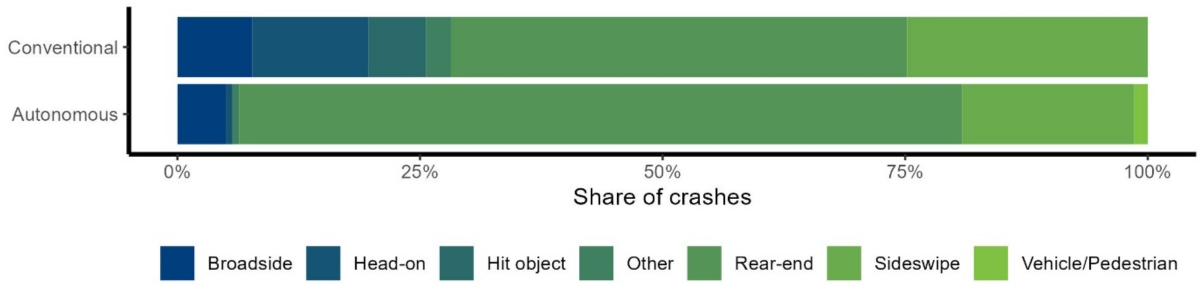
Automated vehicle implications for implicit communication

Contrary to some explicit forms of communication, implicit communication does not require direct human-to-human interaction. The driver's role is reduced to executing commands, and the vehicle transforms them into implicit cues. Implicit cues are more commonly used to communicate intent at crossings than explicit cues. Most of the time, pedestrians can make a correct crossing decision relying only on an approaching vehicle's kinematics (i.e. the behaviour, motion and speed of the vehicle) (Harkin et al., 2023; Lee et al., 2021; Wang et al., 2021). Wang et al. (2021) found that pedestrian crossing times were the same whether reacting to explicit eHMIs or a baseline scenario without any external interface from vehicles. Furthermore, the authors found in a post-experiment survey that pedestrians identified vehicle kinematics to be crucial whether there is an external interface or not.

The indirect involvement of drivers in implicit communication does not mean that AVs' implicit cues will mirror those of conventional vehicles. Autonomous driving modes do not drive like humans, and public space users may not be familiar with AV kinematics. These subtle behavioural differences stand out when executing routine tasks like steering, accelerating or braking, creating miscommunication and, possibly, crashes.

California Department of Motor Vehicle (CDMV) crash data show differences between types of collision when cars were driven autonomously or conventionally (Figure 4). Automated driving led to a higher and predominant share of collisions on the AV's rear end, followed by a sideswipe and broadside collision. Conventional driving shows more diversified types of collision. Human drivers tend to crash more frequently in the frontal and lateral sections of the vehicle. Head-on crashes, a type of collision that is practically non-existent for autonomous driving, surges as the third most frequent type of collision for conventional driving. Even though rear-end collisions are dominant with both driving modes, the lack of diversification of collision types when the autonomous driving mode is deployed may indicate a systematic deficiency in how AVs communicate with other vehicles.

Figure 4. Collision differences between automated and non-automated vehicles



Source: Based on Sinha et al. (2021).

Tester programmes, like the one managed by CDMV, are the best way to detect flaws and train AV-driving algorithms to operate in a more human-like manner. AV testing must be conducted in complex situations, like those human drivers face in urban environments, to improve the autonomous driving system's predictability and solve its systematic deficiencies. Tester programmes that oversimplify driving conditions will impede AVs from driving more like humans and will not provide insightful takeaways for improving AV design (Box 3). When deployed, AVs should be fully adapted to urban environments and human users of public space, and not the other way around.

Box 3. Automated vehicle training programmes

Autonomous driving systems capabilities are being tested through simulations and controlled real-world environments.

Virtual tests attempt to recreate real-life situations to test AV responsiveness in safe environments. These tests are crucial for conducting research on safety perception and road users' behaviours. One example is the Highly Immersive Kinematic Experimental Research (HIKER) pedestrian lab at the University of Leeds. Even though these tester programmes help to answer specific questions, their reach is limited as they are not suitably prepared to approach the complexity of urban interactions.

Tester programmes that place AVs in real-life situations are better adapted to study the overall performance of autonomous driving systems. For AVs to drive like regular drivers, they must train in complex situations like those human drivers face in urban environments. Policy makers must ensure that tester programmes consider the safety of all public space users while learning from these experiences to prepare regulations for larger AV deployments. Tester programmes must restrict AV's operational design domain (ODD) to ensure that they are tested in environments that ensure other users of the public space safety. It is equally important to restrict AV circulation when meteorological conditions do not ensure the correct functioning of all sensors and set stricter speed limits for AVs to reduce crashes.

People and AVs must be able to distinguish AVs from conventional vehicles. AVs and humans will continue to drive differently during the early stages of deployment, therefore, distinguishing AVs will allow other public space users to adapt how they walk or drive in their presence. Just as novice drivers are designated with specific license plates or other signifiers (Box 4), AVs should signal their automated status to others. Buses and taxis are other examples of how vehicles displaying specific behaviours (e.g. frequent stops to pick up and drop off passengers) are sign-posted to other public space users so that they may adapt their behaviour accordingly. Acoustic vehicle alerting systems, like those used for electric vehicles assigned by the Commission Delegated Regulation (EU) 2017/1576, can also be helpful for cyclists and pedestrians by making them aware of the presence of an AV in their surroundings (European Commission, 2017). Finally, driving lessons should include modules that explain how to identify and communicate with them.

Box 4. Making level of driving skill known to other users

Inevitably, novice drivers experience high collision rates. The "Young Driver Paradox", introduced by Warren and Simpson (1976), explains that new, inexperienced drivers need to practice as much as they can to reduce their collision rate; however, more driving exposes them to higher collision risk. Many countries have implemented graduated driver licensing (GDL) programmes to reduce novice drivers crashes during their first years of practice. Novice drivers must follow stricter driving rules and can lose their driving license if they do not comply. The Australian GDL programme introduced probatory periods, lower speed limits, restrictions on the number of peer passengers and the use of a learner and probatory plates (L-plate and P-plate), among other restrictions. Special plates to signal driving skills have proven to be one of the most important requirements for novice drivers. Not only do they help monitor novice drivers' behaviours on the road, making sure they comply with all requirements established in the GDL, but they also help other drivers exercise caution and reduce aggressive behaviours. Hirschberg and Lye (2020) studied the effect of different modifications to the Victorian (Australia) GDL programme. They found that increasing the number of years for novice drivers under 21 on their P-plate, among other restrictions, significantly reduced crashes and hospitalisations.

Sources: Hirschberg and Lye (2020); Warren (1976).

Automated vehicles and vulnerable public space users

Some users of public space are more exposed to danger than others. For example, pedestrians, cyclists, motorcyclists, and users of other forms of active mobility are most likely to be the victim of a road crash. These vulnerable road users represent a high share of fatalities in both urban and non-urban areas. According to the European Commission (2022), 69% of urban road fatalities correspond to vulnerable users of public space. This share drops to 48% when looking at all fatalities. On the other side of the spectrum, passengers in vehicles constitute smaller road fatalities in cities. Behind this disparity lies the main cause of crashes: passenger and goods vehicles. Figure 5 shows the collision matrix between fatalities by type of user of public space and what collided with them. Passenger cars stand out as the main cause of fatalities for all types of vulnerable users.

Figure 5. Road traffic collision fatalities in urban areas in the European Union

Fatalities ↓ / In a collision with… →	Pedestrian	Bicycle	Moped	Motorbike	Car	Lorry (<3.5T)	Heavy goods vehicle (>3.5T)	Bus or coach	Other/unknown	No other vehicle involved	Total
Pedestrians	0	21	17	96	1674	282	260	84	161	0	2595
Cyclists	6	35	9	13	491	84	130	25	36	316	1145
Moped riders	2	4	2	3	114	27	13	4	10	110	289
Motorcyclists	12	4	1	24	603	91	45	10	21	490	1301
Car occupants	6	6	1	8	551	119	126	41	87	1147	2092
Lorry (<3.5T) occupants	0	0	0	0	21	12	15	1	2	64	115
Heavy goods vehicle (>3.5T) occupants	0	0	0	0	3	2	3	1	3	25	37
Bus or coach occupants	0	1	0	0	10	3	2	0	2	11	29
Other/unknown	0	0	0	1	71	14	18	11	8	154	277
Total	26	71	30	145	3538	634	612	177	330	2317	7880

Number of fatalities: Less – More

Source: Adapted from European Commission (2023)

Within the category of vulnerable road users, there are those who are more exposed to risk than others. Sensory, cognitive, and motor abilities, together with previous experiences, are essential to navigating urban environments. Certain vulnerable public space users, such as older adults, children, and cognitively impaired people, face difficulty communicating with other users due to specific limitations. Children have developmental and physical limitations, and they lack experience, resulting in riskier behaviours. Cognitively impaired people have problems understanding specific implicit and explicit cues, hindering communication and comprehension. Ageing adults with hearing and vision loss are especially vulnerable as they can suffer from sensory, cognitive and motor limitations at once. They are also more prone to forms of neurodegenerative disease, like dementia, causing memory problems and confusion. In the European Union, adults older than 65 account for 28% of all fatalities and 38% in urban areas (European Commission, 2022). Automated vehicles must not further complicate communication and comprehension of urban environments for these people. On the contrary, automation should enable and support inclusive communication and improve road safety.

IRTAD datasets on road fatality show the amount of older people in total road fatalities increasing by 22 percentage points between 2002 and 2022. There are two main reasons for this increasing trend. First, older people are the fastest-growing segment in most developed countries with low natality rates. This increases the likelihood of car crashes involving older adults. In parallel, significant efforts have been made to reduce young people's fatalities on the road, reducing their fatal crash rate. Second, older people are more mobile than before. Health conditions have improved, and new modes of transport allow them to move more often and easily in urban environments.

The effects of AV deployment on older adults' safety in urban environments are still uncertain. Studies show that senior pedestrians are more hesitant to cross the road when they know that the approaching vehicle is driverless; however, not knowing the status of the vehicle may lead to risky behaviour that the AV may not be prepared for (Madigan et al., 2019; Razmi Rad et al., 2020). Research shows that older people have riskier road-crossing behaviours than younger people. Dommes et al. (2013) conducted a study in which they simulated a street-crossing situation with a diverse group of participants to test their perceptual, cognitive, and motor abilities. The researchers noted that seniors made risky decisions to cross the street when an approaching vehicle was driving fast, and they missed crossing opportunities when the car was approaching slowly. These findings align with previous studies (Holland and Hill, 2010; Lobjois and Cavallo, 2009), concluding that the crossing behaviour of older pedestrians could lead to collisions more often than for younger pedestrians. This research highlights the importance of signalling when a vehicle is driven in automated mode.

It is imperative to design AVs that acknowledge all public space users, especially older and more cognitively impaired people, and can communicate clearly with them. Many road traffic regulations, such as the German (Federal Office of Justice, 2013) or Spanish (Ministry of the Presidency, 2003) Road Traffic Regulations, stipulate that drivers are responsible for taking precautionary measures in the presence of older pedestrians or children. AVs must also be able to distinguish these users from the rest and reduce speed and operate safely to avoid collisions. AVs can also use a combination of explicit and implicit cues (i.e. multichannel communication) to ensure that a broader range of public space users will properly comprehend their intent. Adapted frontal light eHMIs can be a solution for users with certain visual impairments to provide explicit information on vehicle deceleration which is a crucial implicit cue influencing crossing behaviour (Hensch et al., 2019). These signals are consistently better evaluated by older compared to younger participants.

Visual communication is not the only way to generate implicit cues. Other channels, including auditory messages and wearable devices (Hasan & Hasan, 2022), can improve safety on top of current safety measures considered by drivers. AVs can use auditory messages to communicate what the vehicle's planned subsequent actions are and notify other public space users when the system malfunctions when the vehicle drives in autonomous mode. Wearable devices are already used by cognitively impaired people. Smartphones, for example, help blind people to navigate urban environments through orientation and mobility apps.

AVs can also communicate position and intent through wearable devices and smartphones (Hussein et al., 2016). Some of these applications are still in the early stages of development, presenting disadvantages like high latency and energy consumption. Improvement is required before they can be fully deployable. Additional explicit cues can also be embedded in public-space infrastructure. These solutions can reduce the impact of AVs and conventional vehicle damage on people's safety and mobility. AVs will be deployed in cities that are already challenging for many people to navigate – their uptake should contribute to making these spaces more, not less, inclusive.

AV technology must address inclusivity by design. Car manufacturers and the research community must make additional efforts to include a wide range of public space users in their studies. The participation of old and cognitively impaired users in product focus groups and research experiments is imperative, as accommodating these users helps to accommodate all users. Car manufacturers should also consider communication inside the vehicle. Inclusive communication between AVs and their riders will allow all types of users to leverage this technology, gaining mobility and independence.

Policy makers must ensure that AV deployment complies with the Safe System approach and accounts for the diversity of sensory, cognitive, and motor impairments. More vulnerable public space users cannot share the same level of responsibility as other people who do not face impairment. Human mistakes can happen, and AV design cannot assume that all public space users will strictly abide by rules. For this reason and based on the fourth Safe System principle (Box 2), all other components of the Safe System must assume a precautionary approach to protect all users. Controlling speed limits for all vehicles, including AVs, is extremely important when interacting with impaired users. This will minimise the number and severity of crashes by increasing decision-making time for all users and reducing impact forces. In addition, educational programmes are fundamental so that vulnerable population segments understand how AVs behave and how they communicate their intent with others.

Exposure to increased automation will redefine skills and behaviours

Prolonged exposure to automation may impact driving skills and awareness of users within a vehicle. Differing SAE levels of driving automation will most likely co-exist in urban environments; increasing the complexity of interactions between users. In a mixed-traffic scenario, human drivers will still play an active role in driving. Experts interviewed for this report (Annex 1) are highly sceptical that full AV SAE Level 5 deployment will be reached, meaning that human drivers will still be engaged in the driving task and must be able to take over when the automated driving function disengages. AV deployment will also impact human drivers' experience, and their skills to deal with AV functions will depend on how much they have been exposed to automated driving behaviours.

Cross-cultural road experiences shape differences in levels of driving and communication skills. How others drive, their risk profiles and the composition of the vehicle fleet significantly impact urban communication and driving skills (Lim et al., 2014; Sheppard et al., 2023). People in developed countries are less exposed to motorcycle behaviours and may not readily understand implicit motorcycle cues. Appraisal mistakes are common in the absence of explicit cues and more so when explicit and implicit cues are contradictory. In contrast, public space users in countries where motorcycles are more common better interpret their behaviours without explicit information and react faster to their cues. Sheppard et al. (2023) described how British drivers are more likely to make wrong decisions when interacting with motorcycles than Malaysian drivers, who are used to driving in the presence of many motorcycles.

How well public space users understand certain forms of communication and how long it takes them to react to these depends strongly on their training and environment. Another example of how cultural differences affect public space user interactions is the type of communication used in each country. In most developed countries, honking is reserved only for extreme cases, such as when a crash is about to happen. In some developing countries, however, honking is widely used to communicate all sorts of things: letting other drivers know that the traffic light has changed to green, notifying their crossing decision near intersections, thanking other drivers when they receive the right of way, and so on. Just like cultural differences affect drivers’ communication skills, AV deployment can also affect communication through training and experience.

Driving skills are most notably influenced by how frequently people drive. People who report driving regularly are more confident in their driving skills than those who stop or start driving again after not doing it for an extended period (Trösterer et al., 2016). Previous experience plays an important role, even though it does so to a lesser extent than driving regularly and uninterruptedly. These findings have a significant implication in the AV context. The large-scale deployment of AVs will reduce the number of hours many people actually drive, and this will likely have an even greater and disproportionate impact on novice drivers. In the case SAE level 4 automation, this overall reduction of driving time may be accompanied by a shift in the balance of driver tasks from actively driving to actively monitoring the vehicle and standing ready to take over control. In the long term, a lack of manual driving will affect perceptual and motor skills, creating dangerous situations when inexperienced drivers intervene.

De-skilling, or automation addiction[1], is a normal process that occurs when new technologies disrupt the acquisition and retention of skills, contributing to less qualified workers. In the AV context, lack of experience or imperfect situational awareness leads to reduced skills and delays by humans in carrying out driving functions (ITF, 2018a). Land transport was not the first mode in which automation was introduced. Aviation automation has enhanced safety in the last decades (Box 5). In parallel, pilots intervene less, and their tasks have been simplified, making them increasingly reliant on automation to operate planes. Many experts claim that pilots relying on automation means the aviation sector suffers from de-skilling. This experience in the aviation sector indicates the potential impacts of vehicle automation. However, there are significant differences between flying planes and driving cars in urban environments. Even if cars require less technical knowledge than planes, cars demand greater communication skills and adaptability due to constant and sometimes unexpected interactions with other public space users.

If future drivers do not have the experience that today's drivers have in communicating and safely navigating urban environments, automation can create new problems in cities. As active driving will not completely disappear, many AV users will still be required to take control of the vehicle when the automated driving system disengages. In these instances, the driver's skills must be sharp to react to a rapidly evolving and complex environment.

Box 5. De-skilling in aviation

One of the main motivations behind automating aviation was the high percentage of human-caused crashes or near-crashes and the increasing complexity of modern aviation systems. Technological advances in this field have reduced the total number of crashes, but the participation of human factors in crashes has increased compared to technical factors (Madeira et al., 2021). Stanton and Marsden (1996) studied the shortcomings of aviation automation, signalling training and skill maintenance as one of the main challenges of automation in this sector. The effects of automation on workers' knowledge and skills have been well studied. Automation seeks to simplify specific tasks, allowing less-skilled workers to perform better. Automation also influences high-skilled workers, reducing their competencies in the long run due to a lack of practice. Automation does not guarantee success, and it can change the nature of human errors. Billings (1997) highlights examples of how automation and de-skilled crews can cause crashes. The author argues that the malfunctioning of automated systems can lead to unsafe flying configurations, being especially dangerous when the crew fails to notice the problem. Risky situations can also arise when the crew does not understand the system's warnings or simply when the automation system is operating at its limits and does not warn the crew about it.

Source: Billings, C.E. (1997); Madeira et al. (2021); Stanton and Marsden (1996).

Vehicle automation presents a unique opportunity to improve safety. However, it can result in harmful outcomes that should be minimised before AV deployment. If developed correctly, vehicle automation will not necessarily imply driver de-skilling but rather a re-skilling. Bravo Orellana (2015) defines re-skilling as

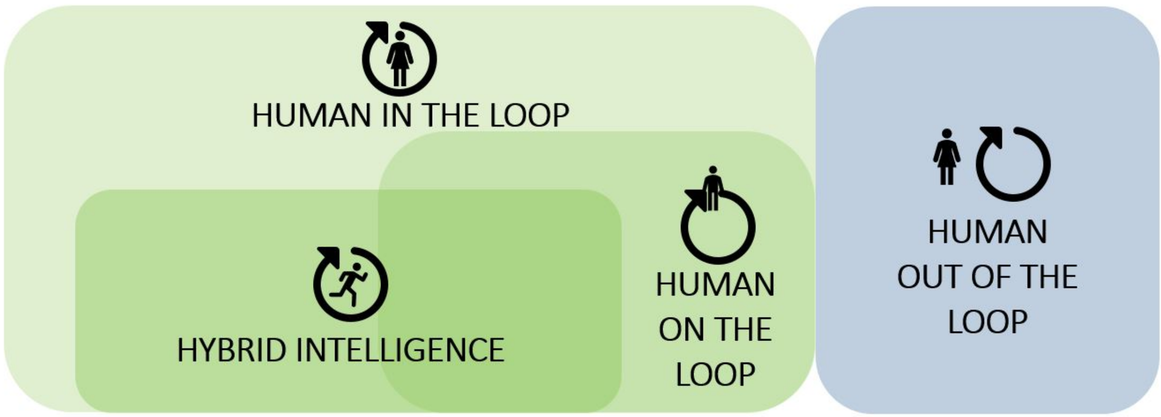
1 Term used by the US Federal Aviation Administration (FAA).

a simultaneous decrease in competency in performing a task and an increase in system knowledge. Perceptual and motor skills lost by drivers must be minimal and compensated with a better understanding of the technology, the way in which it should operate and how to manage unexpected performance of the AV. Interactions between humans and algorithms can be broken into three systems depending on the human's participation (Christiano, 2015):

- Human in the loop (HITL): the AI system helps plan, execute, or evaluate a data acquisition plan. In these systems, humans' involvement is necessary for the system to function.
- Human on the loop (HOTL): the AI decides, and the human is responsible for revising and approving it.
- Human out of the loop (HOOTL): the decision-making process was done entirely without the participation of the human.

Rafner et al. (2021) introduce a fourth relationship, named Hybrid Intelligence, which suggests that sociotechnical systems, such as automation, combine human knowledge and AI capabilities to perform tasks better than either of them separately. This relationship considers the direct impact of AI systems on humans and how AI is to be designed to the benefit of humans.

Figure 6. Relationships between human and machine intelligent systems



Source: Rafner et al. (2021).

Increased human de-skilling can bring safety problems in the foreseeable future and, thus, should be prevented. Driving lessons can achieve skill maintenance by reinforcing competencies that must not be lost, regardless of technological advancements. Lessons should also incorporate information on how the system works and what to do in case of an emergency. Reinforcement lessons after obtaining a driving license are valuable to mitigate rapid technological innovation and automation. AV technology should be designed so that technological advancements complement human skills instead of competing with them. Additionally, automation should target tasks that are more complicated for humans to do under certain circumstances (ITF, 2018a). According to experts interviewed (Annex 1), humans are not necessarily good at passively monitoring systems; this leads to boredom and disinterest in what the AV is doing. Instead, humans should be actively involved in the decision-making process and encouraged to take control of the vehicle to practice manual driving and direct interaction with other public space users.

Designing physical infrastructure for automated-proof interactions

Like other public space users, automated vehicles operate in public space and interact with physical infrastructure. Ongoing deployments show that AVs, can more or less independently operate on already existing roads, depending on their level of automation. The road network is the largest physical infrastructure deployed in the world. Yet, it is not unitary in nature: roads' dimensions, shapes and states differ depending on the type of road (e.g. highway, forest track) and specific administrative context (e.g. regions, countries, etc.) pertaining to applicable standards, markings, etc. It is important to note that roads were designed and built with the characteristics and needs of human drivers and road space users. (ITF, 2023b). As highlighted by experts interviewed within the context of this project (Annex 1), it is unlikely that fully autonomous, i.e. SAE Level 5 vehicles, will be achievable in the short- and medium-term, considering the variety of roads and situations and the specific characteristics and limitations of AVs.

Physical infrastructure constitutes a common ground for public space users within cities. Among the diversity of roads, urban roads and streets there is a sub-category specifically designed to accommodate multiple uses, not only vehicular traffic. AVs in urban settings will thus have to interact with many diverse urban space users. Street characteristics play a mediation role in ensuring safe interactions between public space users (Qi et al., 2024).

This section will discuss how street design, equipment, and less tangible actions on speed management can improve interactions between AVs and other public space users. It will also assess why there is not a systematic need for an AV-specific adaptation of streets to enable safer interactions.

Automated vehicles using existing roads

AVs can and have been deployed on existing road infrastructure. AVs rely on onboard technology designed specifically to meet this challenge (ITF, 2018a, 2023b). AVs host a variety of sensors to sense the environment and are supported by software to enable the processing of the information present in public spaces. For example, cameras will be used to see and read traffic signs and lights and to look for the direct environment of the vehicles. Lidar sensors (i.e. light detection radar) are used to assess AV surroundings precisely (ITF, 2018a).

However, the use of existing road infrastructure poses specific challenges to safe AV deployment in some instances (ITF, 2023b). On poorly maintained parts of the network, or where the machine-readability of roadside markings or signage is degraded, AVs will not be able to discern key operating inputs. Safe AV operation may be significantly hindered if the digital representation of these signals is incomplete or inaccurate (i.e. via digital maps or infrastructure to vehicle signalling). For example, the absence of lane markings or poorly signalled rules (i.e. a traffic light hidden by a tree) can lead automated vehicles to adopt risky and unlawful behaviours. Public authorities in charge of road management should ensure that streets are self-explaining (to both humans and AVs) and well-maintained. Experts interviewed for this report (Annex 1) agreed that the progressive deployment of AVs will likely result in a shift in funding needs from new infrastructure to maintenance.

AVs also face their own limitations concerning existing infrastructure. Changing road conditions (e.g. snow, rain, fog, etc.) can reduce AVs' ability to discern their environment and negatively impact their operation

(Kotilainen et al., 2021; Zhang et al., 2023). Snowstorms, for example, can hinder visibility to cameras, degrade LIDAR capacity to sense AV surroundings and lead to inaccurate predictions or decisions (Meng et al., 2023). Additionally, lane markings can be obscured in dusty or snowy areas, thus reducing AVs' ability to correctly perceive the road.

Public authorities should prioritise the maintenance and readability of public spaces, as this will benefit not just automated vehicles but also public space users as a whole (Tengilimoglu et al., 2023). These efforts should be prioritised in areas where multiple users are expected to interact with AVs. Actions to ensure the proper delineation of street markings, lighting of interactions-intensive areas, and road surface quality will be necessary. Yet such actions might be unobtainable financially in the short term, considering both the state of the road network and public finances in a wide range of countries (Tengilimoglu et al., 2023).

Street-friendly automated vehicles rather than automated vehicle-friendly streets

The current physical design of the road infrastructure and streets is not a barrier to AVs and there is no evidence that AVs will require such a radical transformation of the road network in cities (ITF, 2023b). This contrasts with the advent of automobiles, where the progressive increase of their speed required the adaptation of local roads, the separation of pedestrians from motorised traffic, and the construction of large and dedicated physical infrastructure. In the short–to medium–term, SAE Level 3 and 4 AVs can safely and efficiently operate within pre-defined operational design domains (ODDs) and on well-defined parts of the road network. Deployments might happen on different types of roads (e.g., highways and low-speed streets).

Nevertheless, the deployment of AVs will impact streets, even if it does not entail a redesign of infrastructure. Land-use impacts will likely vary depending on AV deployment pathways (ITF, 2015b; Silva et al., 2021). As highlighted by modelling work from ITF (2015b), the deployment of a shared AV fleet combined with high-capacity public transport is associated with a sharp decrease in the number of vehicles necessary to accommodate the same travel (-89.6%) and in parking requirements (-94.4%) compared to a baseline scenario. This increase in shared transport use and shift away from private vehicle use would allow local authorities to reallocate available public space to accommodate other transport modes or uses. For example, by increasing pavement space, installing bicycle tracks, creating logistics distribution hublets (i.e. movement), or other non-mobility uses such as parklets (i.e. places).

Cities create value for people, not for the vehicles they occupy. Accordingly, if public authorities adopt a human-centric approach to ensure that AVs enable them to attain their public policy objectives, especially regarding the use of public space, AVs should adapt to urban settings and not the opposite. Thus, authorities should encourage AV manufacturers and fleet operators to deploy shared fleets instead of privately owned AVs. Such an approach will in turn contribute to AVs' acceptability (Silva et al., 2021).

Designing infrastructure for safer interactions between all users

Street design has a universal scope: it impacts all public space users. Street design will continue to play a role in easing interactions between all public space users. As highlighted by several experts during interviews for this project (Annex 1), enabling safer interactions with AVs will be possible by designing roads, roadsides, and vehicles in a way that ensures universal access (ASLA, 2017), minimises conflicts and crashes, and reduces kinetic forces if a crash happens (ITF, 2018a, 2022a). Speed management measures rely heavily on street design and prevent the occurrence and severity of conflicts between different public space users, including AVs.

Street design as tangible infrastructure for automated vehicles

Streets and all public space should be designed as self-explanatory to all users. Automated vehicles should be able to read their environment and extract information salient to their safe operation as much as any other public space user. Theeuwes and Godthelp (1995) noted that the self-explanatory dimension of an infrastructure refers to its capacity to encourage safe behaviour simply with design elements. The physical environment cannot be seen separately from public space users; they have a reciprocal relationship. Several multi-dimensional design elements can directly influence public space user behaviour.

Street design should have an emphasis on protecting the most vulnerable public space users. In cities, these efforts should consider the wider street elements of public space (i.e. pavement, crossings, non-vehicular areas) rather than focusing on road space alone. This entails a shift from a car-oriented approach to a more holistic design approach in interaction-intense areas, accounting for the needs and safety of other public space users (Welle et al., 2015). Pedestrians, cyclists and users of micromobility are among the most vulnerable road space users, while motorised vehicles are the source of greatest danger due to their mass and speed (European Commission, 2019, 2021). As one user of the public space among others, automated vehicles should adapt to such design principles.

Streets create different possibilities of actions for users depending on their capabilities (Debatin Neto and Graeff de Oliveira, 2024). Street design communicates perceived action possibilities to users and how they can occur in space (Furman, 2017). Integrating affordance-based design approaches in street design will be crucial to maximising public space users' possibilities. For example, traffic calming measures constitute intentional public space arrangements that improve traffic safety. At the same time, affordances are multiple: the same action can support several activities. In this regard, traffic calming measures can enable several possibilities. Physical barriers such as chicanes, tighter turns, and speed bumps encourage speed reduction. Visual cues (i.e. coloured lanes, lane markings) can encourage safer behaviour by influencing driving behaviour and reducing confusion. Welle et al. (2015) provide a taxonomy of actions to enable safer interactions. Among these, actions to provide dedicated and protected facilities (i.e. bicycle tracks, pedestrian-only areas) can be distinguished from actions aiming at reducing conflicts through improving the infrastructure's readability (i.e. lane marking, signalling, channelling). Physical barriers and visual cues should be implemented primarily at intersections, seen here as planned points of interaction and potential conflicts (FHWA, 2021). Candappa et al. (2015) identify Safe Intersection Design Principles and provide a comprehensive taxonomy of intersection planning actions for Safe-System compliant interactions (Box 6).

Box 6. Principles and examples for Safe-System compliant intersections

Candappa et al. (2015) identify different principles that enable safe intersections across a wide range of road types for all users. These principles are relevant in the context of AV deployment and, to some extent, applicable to all types of urban roads:

- In general, **speed should be limited to 30 km/h through intersections in mixed-used areas**: 90° perpendicular collisions above this limit are usually expected to exceed what is tolerable by the human body.
- In **physically unseparated areas like streets, public authorities should cap speeds at 30 km/h or protect public space users.** Capping speed is more cost-efficient, considering the potential spatial constraints and costs that apply to the protecting all public space users, wherever they may be using streets (i.e. not just on roads).
- **Avoid perpendicular (90°) impact angles**. Reducing the impact angle reduces lateral kinetic energy. At higher speeds (i.e. 70 km/h), halving this angle to 45° can reduce the energy transfer to below what is tolerable by the human body.
- **Limit points of conflict at intersections**. A design approach reducing permitted movements via lane marking for vehicles within the same intersection will automatically reduce the number of conflict points. Authors note that a typical intersection presents 32 conflict points to a driver, compared to 8 conflict points for a roundabout.
- Finally**, promote active mutual responsibility**. Interaction design should promote mutual responsibility rather than prioritising a unique mode over the others. This will reduce unexpected and often aggressive behaviours at intersections from less advantaged public space users (e.g., jaywalking, etc.).

The authors identified several intersection design approaches that are compliant with these principles. Among them are approaches well aligned with the Safe System principles (i.e. Cut-Throughs, Turbo roundabouts) to those more moderately aligned, such as elevated stop lines (i.e. a pedestrian crossing on a bumper, raised intersections). Cut-throughs and Turbo roundabouts usually implies a stronger redefinition of lane marking to reduce the points on conflicts, while the elevated stop lines tends to focus on reducing speed.

Source: Adapted from Candappa et al. (2015).

While alternative design approaches relying on physical barriers and visual cues enable safer interactions, their implementation may be challenging (Candappa et al., 2015). First, in dense areas, implementation might be limited by spatial constraints. Implementing extensive street redesign strategies in such areas can potentially create interferences and disrupt interactions in the long term (e.g. construction). Similarly, their implementation can be expensive. Finally, from a public acceptance perspective, important changes should be evidence-based and supported by strong political leadership. This implies pre- and post-data collection on the performance of design interventions.

Speed management as intangible infrastructure for automated vehicles

Speed is a serious source of danger. When combined with mass it directly contributes to the kinetic forces released in crashes. Speed was found to have contributed to respectively 30% and 29% of total fatal crashes in Europe (in 2019) and in the United States (in 2022) (European Commission, 2019, 2021; ITF, 2015a; NSC, 2022). Speed can be enabled or limited by street infrastructure design. The infrastructure supporting speed management is multidimensional, made of tangible elements (i.e. road design, speed limit signs, speed radar) and intangible elements (i.e. traffic rules, driver behaviour).

Speed management strategies are associated with several positive outcomes in interactions. A Seattle-based study found that the decrease of default speed on arterial roads (from 50 km/h to 40 km/h) and non-arterial roads (from 40 km/h to 30 km/h) was associated with a reduction of 17.2% of all crashes involving fatal, disabling, or evident harm on other public space users (Hu and Cicchino, 2024). Furthermore, in urban areas, lower speeds are associated with positive impacts on the quality of life for other public space users and residents (ITF, 2018b).

Reducing speed is also associated with safer interactions amongst public space users, including those operating vehicles, and, eventually, AVs. It gives public space users more time to collect and process information and to act on that information by adopting a safe speed thus reducing hard braking and lowering the kinetic energy that contributes to the probability of fatalities in a crash.

Reducing speed is associated with more time to collect and process information.

This time buffer can potentially allow automated vehicles to make safer decisions. High speed reduces reaction time available to unexpected events (European Commission, 2021). Reaction time is directly related to the distance required to stop a vehicle: the less reaction time available, the less distance a vehicle will have available, and the harder the braking deceleration required, to stop safely. Irrespective of speed, the average human reaction time, going from stimulus to action, is approximately under one second in optimal situations (i.e. no impairment and vigilant driving). For partially automated vehicles (SAE level 3), the disengagement of the automation mode, either manually or automatically, is associated with higher reaction times. Dixit et al. (2016) estimated that this reaction time was 0.83 seconds on average. The authors note that this result varies depending on the type of disengagement and the road type and design. In this context, lower overall speed means that AVs would have sufficient time to react safely to unexpected events.

Reducing speed is also associated with a decrease in distance travelled to stop in optimal conditions.

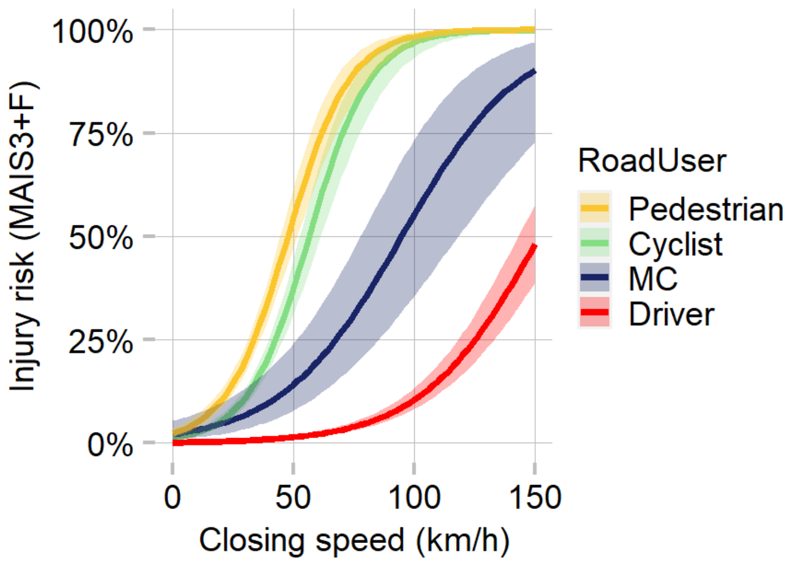
In interaction-intense areas of cities, reducing braking distances will reduce the occurrences of crashes. In non-rainy situations, lowering speed from 50 km/h to 30 km/h allows the total stopping distance - the distance travelled during reaction time and braking - to be halved from 62 m to 30 m. For a standard vehicle (5-metres long), applying a 30 km/h rule means that the vehicle stopping distance will be equal to six times the length of the vehicle, while 50 km/h implies a stopping distance of more than ten times the length of the vehicle.

Reducing speed reduces kinetic energy accountable for high numbers of fatalities.

Lowering speed will reduce the kinetic energy transferred in crashes. Safe speed management strategies should ensure that the energy transfer among crash opponents remains below biomechanically tolerable levels (Candappa et al. (2015). In that context, public authorities should reduce speed limits to 30 km/h in areas that do not provide segregated or protected space for other public space users. Speed of 30 km/h has several benefits: first, it drastically reduces the likelihood of a serious injury if a crash happens (Figure

7); it brings the vehicle's speed close to other public space users' speed, which improves road safety; and it allows the street network to accommodate more users. Vehicle design is another important factor to consider: injuries to vehicle occupants and other road space users may increase in frequency and severity due to vehicle characteristics (e.g. absence of airbags or safety belts, physical design or weight).

Figure 7. Vehicle closing speed and injury risk



Source: Lubbe et al. (2022).

Notes:Closing speed refers to the rate at which two bodies (i.e. vehicle, user) approach each other. It is calculated by adding their respective speeds. The closing speed for vehicles going in the opposite direction at 100 km/h will be 200 km/h.

Lubbe et al. (2022) notes "*A 10% risk of sustaining at-least-serious injuries corresponds to a closing speed of 29 km/h for pedestrians, 44 km/h for cyclists, 48 km/h for motorcyclists, and 112 km/h for car drivers*."

Aligning tangible and intangible infrastructure

Local authorities should consider street space interventions in an integrated manner and that efforts to reduce speed limits are associated with a transformation of the road space to ensure the clarity of the new speed. The consistency between street design and targeted street speeds is crucial to building credibility and encouraging public space users to comply with the rules (Box 7) (ITF, 2022b, 2022c). This can be further promoted through education and the evidence-based setting of speed limits. Local authorities should call for a default speed limit of 30 km/h in urban areas with interaction-intensive settings to reduce these inconsistencies. Establishing these speed limits should go together with a Safe system-compliant design approach.

Box 7. Good Street framework: Principles to align tangible and intangible infrastructure

The Good Street framework is a design approach aimed at integrating traffic safety, accessibility and accessibility. It acknowledges that streets are not only just a car space and, moreover, not a vehicular space. A Good Street design should consider the street's different functions and ensure user cohesion. Under this framework, two fundamental principles highlight how street design and speed are related:

- First, the **legal speed of vehicles should be dependent on street characteristics, not on those of the vehicle**. Logical design enforces the expected behaviours from users in the space.
- Second, **vehicle mass and speed should form the basis for determining which part of the network vehicles are permitted or not**. This principle ensures that the masses and speeds within a space are homogeneous, thus improving traffic safety and maximising street space use.

Source: Adapted from Immers et al. (2020).

As noted by CIHT (2024), there is limited guidance and definition for local authorities to ensure consistency between street design and speed limits. National authorities should support local authorities in ensuring they have access to the necessary guidance and skills to ensure the consistency between street design approaches and speed management decisions. Several countries provide such documents to local authorities (Cerema, 2017; DfT, 2013). In the United Kingdom, the Speed Limit Appraisal Tool provided by DfT (2013) guides local authorities on making more transparent and consistent decisions over speed limit settings and assessing the impacts of changes in speed limits.

Digital infrastructure as a crucial enabler of safe urban interactions

Digital infrastructure plays a central role in supporting the deployment of AVs (ITF, 2023b). This digital infrastructure allows the flow of data between AVs and other elements such as maps, other vehicles, or other stakeholders. Digital maps, communications between AVs and their environment, and machine-readable regulations are crucial elements of this data infrastructure which enable safer interactions between AVs and other public space users in cities.

Digital representations of the environment

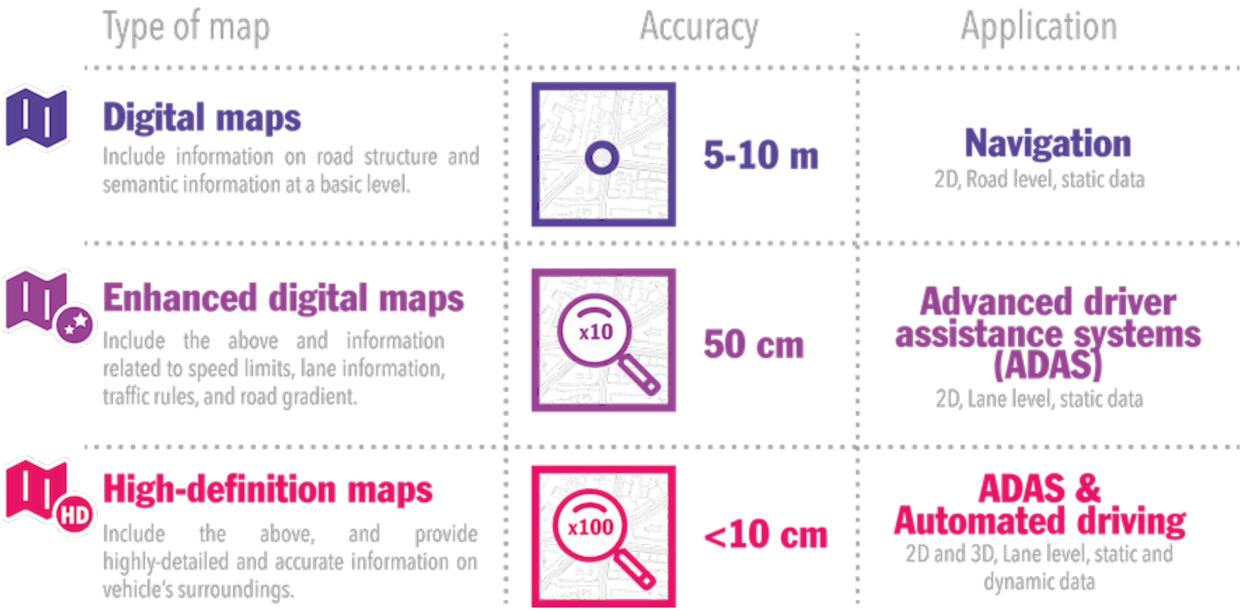
Maps enable users to understand their environment and make better-informed decisions about their actions within that environment. Maps can represent several elements. For urban maps, the street network will often be represented alongside buildings surrounding it. Paper maps were initially digitalised using geographic information systems (GIS). GIS is enriched by map and elevation data from satellite imagery and precise digital positioning data from global navigation systems technology (GNSS). Navigation systems relying on digital maps enable a broad range of public space users to plan optimal routes, often considering a variety of additional information (e.g. traffic, infrastructure quality, price).

Understanding the role of maps in enabling safer interactions between AVs and other public space users requires understanding how digital maps work and how AVs rely on them.

How digital maps work

Maps have different levels of precision and accuracy (Figure 8). Although high-definition maps supporting AV operation are digital, not all digital maps can support AV operation. The development of the internet and new technologies have enabled high-level digital mapping initiatives. These have been mostly led by private stakeholders such as Baidu, Microsoft, Google, HERE, and Apple (Johnson and Scassa, 2023) and by the crowd-sourced Open Street Map initiative. These initiatives primarily relied on open data shared by governments or volunteered by individuals; they extended their scope beyond government data. They usually represent road structures and semantic information at a very basic level. Their accuracy is insufficient to enable advanced driver-assistance systems (ADAS) or automated driving capabilities (Elghazaly et al., 2023). Enhanced digital maps, including lane-level information, speed limits and road curvature, enabled certain ADAS functions such as lane positioning. Yet, their applicability remains limited for automated driving functions. (Charroud et al., 2024; Elghazaly et al., 2023; ITF, 2023b).

Figure 8. Digital maps and their specifications

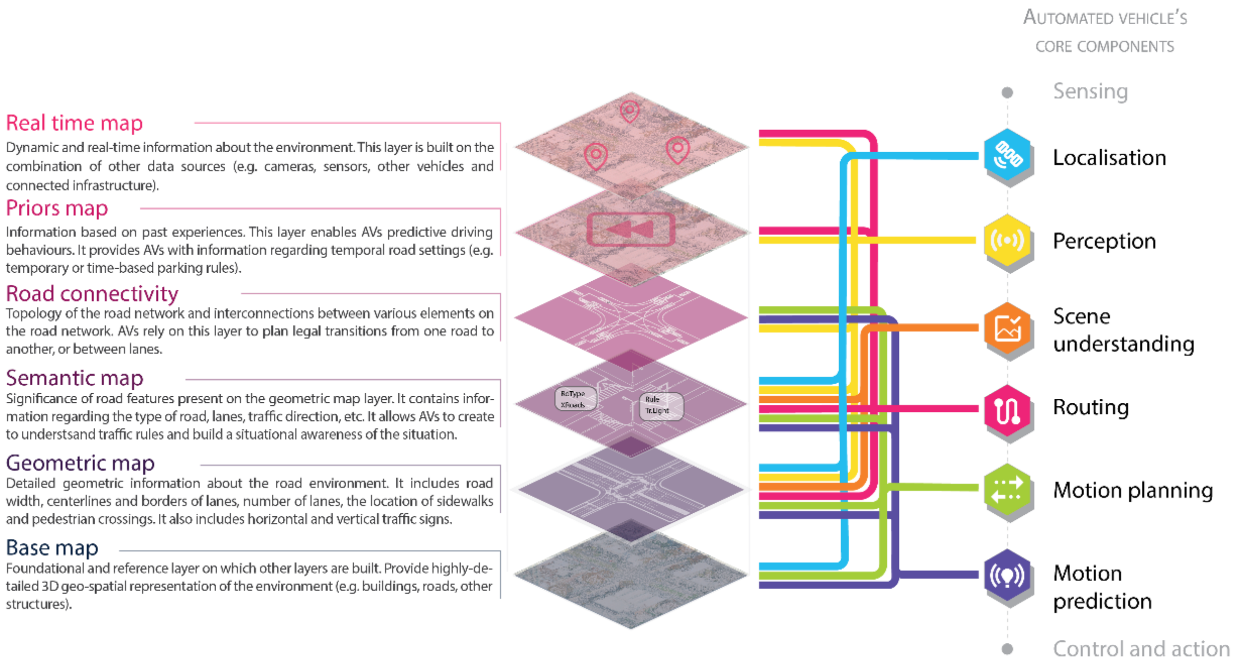


Source: Adapted from Elghazaly et al. (2023).

High-definition (HD) maps provide AVs with more accurate (i.e. sub-centimetre level) information on their environment (ITF, 2023b). Detailed maps contain information regarding the static environment surrounding the AV, such as buildings, roads, lane markings and traffic lights. Compared to high-level maps, HD maps provide information regarding the topology, the curvature of an intersection, lane width, etc. They provide information regarding objects that may not be discernible by AV sensors because of occlusion (Bao et al., 2023). Finally, unlike high-level maps, HD maps contain semantic features which provide AVs with more context regarding the vehicle's surroundings (i.e. where it can turn, which lane it should use, and where it can stop) (Efland and Rapp, 2019).

Safety-critical applications (e.g., automated driving) require accurate precision regarding the vehicle environment and real-time awareness of it. HD maps are expected to facilitate the deployment of AVs (Elghazaly et al., 2023). HD maps include the necessary information for automated vehicles to operate accurately in complex environments. There are multiple high-definition maps on the market, but no commonly agreed standard for them (Bao et al., 2023; Elghazaly et al., 2023). HD map structures tend to reflect the diversity of data sources. They are not a monolithic entity but rather composed of several layers, each representing a block of information about the driving environment (Elghazaly et al., 2023). This layered approach of HD maps also enables the accessibility of information by AV components (Figure 9).

Figure 9. High-definition maps layers



Source: Adapted from Charroud et al. (2024); Elghazaly et al. (2023); Bao et al. (2023).

What makes a good map: spatially accurate and updated information

Like conventional maps, digital maps can be wrong or outdated. They can inaccurately or incorrectly represent information. In urban settings, where information is omnipresent, inaccuracies can lead to complex situations. The inaccurate positioning of an object on a map can lead to positional or speeding errors and result in unsafe driving. The density of public space use makes accurate mapping crucial to enable safer interactions between different public space users. The main difference between high-level maps and high-definition maps lies in their capacity to provide accurate and timely spatial data (Charroud et al., 2024). Precision in space and time is crucial for AVs to safely navigate streets. Spatial accuracy without updated data can significantly degrade safe AV driving performance, particularly in dynamic environments such as cities where public space characteristics are constantly evolving.

The quality of digital maps lies in their capacity to be updated regularly to reflect changes in the environment (i.e. road closures, construction of a new infrastructure, etc.). AVs benefit from spatially accurate and updated maps to facilitate their interactions with other public space users. Such updates can enable AVs to adapt their path (i.e. repositioning or rerouting) or their behaviour (i.e. speed reduction), thus facilitating their safe operation in a dynamic environment (Fischer et al., 2018).

How AVs use maps: a supportive but not exclusive reference

Maps provide a pre-existing or pre-built representation of the environment (Charroud et al., 2024). By relying on pre-built maps, automated systems can address issues before the vehicle faces them. However, AVs do not solely rely on digital maps to perceive their environment. AVs collect real-time information using embedded sensors and cameras. Point-cloud maps generated using LiDAR technology provide a three-dimensional representation of the vehicle's line of sight environment (i.e. what can be seen by the

LiDAR sensor). Video sensors also read the line of sight environment in various visual wavelengths (natural colours to infrared). Various frequency radio detection and ranging (radar) sensors are also deployed on automated or semi-automated driving platforms providing information on the short- to long-range driving environment (Ignatious et al., 2022; ITF, 2018a). Additionally, communications between connected vehicles (i.e. vehicles able to communicate with other systems outside of the car) and AVs can provide additional situational awareness to AVs (Charroud et al., 2024).

AVs are just as reliant on maps, as they are on sensors. Humans have an advantage over single sensor-based automated vehicles (ITF, 2018a). However, other communication features in vehicles provide additional information that can complement limitations of maps or sensors. Addressing this gap requires combining sensed output data from different sensors through sensor fusion. Sensor fusion has been deployed in various AV trials and experiments (ITF, 2018a). Cross-checking between the different layers allows AVs to distinguish static and dynamic road elements, leading to close or often better results than humans when it comes to perception. For example, LiDAR will provide additional support to AVs in sensing other users, dynamic objects, and environmental conditions (e.g. rain) that are not represented on digital maps. This redundancy is crucial as it enhances the vehicle's ability to make sense of the existing environment and provides extra safety if one of these components fails or provides inaccurate data.

Sensor fusion requires agreement from the different sensor systems, including maps, to initiate an action (NHTSA, 2016; Schoettle, 2017). In interaction-intense areas, users can often be in the field of view of an AV for a limited time before a potential impact. These risks can potentially be reduced through the integration of additional inputs from other vehicles and the infrastructure.

However, in certain conditions, humans will still outperform fused sensor signals. Humans show better results at adapting to local and sociocultural norms (Chandra et al., 2020). Theory of Mind describes humans' ability to infer others' behaviours by observing them (Cuzzolin et al., 2020). This process is key to hot cognition, a process of information involving emotional and social cognition. Compared to humans, AVs show cold cognition where the information process is independent of social and emotional consideration. Hot cognition is central to understanding movement in cities, described here as a physical and social object. In urban settings, humans can anticipate the actions of other users based on subtle social information and on their understanding of human psychology.

Maps matter as long as you can read them

Maps should provide their users with accurate and reliable information. However, accurate information is only useful when it is correctly processed. While humans can fail at reading a map, AV difficulties lie elsewhere. What is not directly visible on a map can also be important. Useful information may be hidden or contained in another map or reference system. In some cases what is missing from a map (e.g. things that are not present in mappable space) may be as important as what is in the map to understand context. Experts interviewed for this report (Annex 1) highlighted that people generally assess several environmental cues to assess what is likely to occur or happen in any given space. For example, children are likely to be present in the vicinity of schools at least twice a day at fixed times. Similarly, drivers can have a reasonable expectation to come across alcohol-impaired people in the vicinity of bars late at night. While this contextual information is not encoded in maps, it plays a crucial role in reading the driving environment and ensuring safe interactions. Unlike AVs, humans can infer such contextual knowledge based on their personal or socialised experience.

Efforts to accurately capture urban environments, or a reasonable proxy for them, are being made in mapping solutions. For instance, enabling AVs to have access to other sources of information, such as school opening and closing times and areas where AVs are likely to encounter impaired public space users, can help, as well as develop more robust machine-learning protocols that are integrating such context-based information. This information is often publicly available but should be deliberately integrated into detailed maps or machine learning datasets. Public authorities should also ensure that such information is readable directly or by proxy in the street environment. This could be directly using specific signage when applicable (e.g. traffic signs signalling people with disabilities close to the hospital) or indirectly through a holistic design approach to ensure that AVs adopt safer behaviour.

Reliable and robust maps require decent investment

Public space users, including AVs, are looking for reliable information provided by trustworthy sources of information when using maps. Whether the data and data provider can be trusted are closely related. Historically, maps were created and maintained by public authorities to support decision-making processes (Johnson and Scassa, 2023). Public authority approaches to mapping can be top-down (i.e. led at the central government level) or bottom-up (i.e. mapping efforts rely on the integration of local government data) (Harvey and Tulloch, 2006).

Several countries have decided to establish and maintain a foundational map to support AV operations. In 2015, the Korean government began the creation of high-definition maps of its national network (MOLIT, 2020). Private companies did this by mapping major highways and motorways to survey the road network. The Korean Ministry of Transport (MOLIT) worked with the Korean National Geographic Information Institute to introduce the production of HD maps during maintenance procedures to ensure the automatic update of the maps following construction or maintenance works. These maps are already made publicly available for public and private entities to use.

Government oversight, control, standardisation or audit of high-definition mapping and its components can ensure that the information provided is reliable. Public authorities considering such initiatives to increase the trust in high-definition mapping should mindfully consider the costs, both direct and indirect, associated with it. In Korea, the cost estimation per kilometre for a government-produced HD map averaged USD 1 600 in 2015 (ITF, 2023b). Similarly, experiments led in Australia using LiDAR-based data collection on a 10-kilometre section of the roadway found that the cost per kilometre exceeds AUD 1 500. A network-wide digitalisation of urban roads (149 000 km of roads) would require approximately AUD 225 million in funding. Additional funding is necessary to maintain and update the map, as well as investment in capacity building to ensure that the map can be interpreted and that the data is updated regularly.

Digital communications between automated vehicles and their environment

Adapting vehicles to access digital networks has significantly helped the automation of driving functions for AVs. Telecommunication technologies, among other channels, enable direct communication with other vehicles, infrastructure, vulnerable road users, etc.. Wireless network connectivity is an essential to achieve high AV performance, complementing the information that sensors provide. Connectivity enhances AV effectiveness, and real-time communication between users provides better co-operation and safer streets.

Taking stock of what exists: Standardisation vs. interoperability of communications

To have a thorough understanding of their environment, connected vehicles can communicate and exchange information with users and devices that employ the same technology. At the most generic level, vehicles can have vehicle-to-everything communications (V2X). V2X is comprised of several sub-communication technologies including (Alalewi et al., 2021):

- Vehicle-to-network communication (V2N): Communication using cellular networks to access or share information (e.g. 4G-5G or dedicated short-range communication - DSRC)
- Vehicle-to-infrastructure communication (V2I): Bidirectional exchange of information between the vehicle and road or roadside (e.g. traffic signalling) infrastructure
- Vehicle-to-vehicle communication (V2V): Bidirectional and real-time communication directly with other equipped vehicles in the traffic environment
- Vehicle-to-cloud (V2C): Communication with cloud-based servers and services (e.g. vehicle diagnostics services, over-the-air software updates, etc.).

V2X communications have numerous applications based on co-operation, safety, and efficiency. Co-operative driving changes how cars move in cities and other urban environments. Connected vehicles can notify other users through short-range communications of their intent to change lanes, cross intersections or overtake vehicles. Communication with pedestrians, cyclists and other road users is also possible through wireless networks, helping connected vehicles to identify and safely interact with these users, though the safety of these users should never depend on this type of communication. Traffic safety can be improved by leveraging digital network connectivity. Connected vehicles exchange information with other users about crashes on the road, emergency services, and other safety-related traffic information, such as poor road quality or bad weather conditions. When deployed on a large scale, digital communication technologies can potentially improve the efficiency of overall traffic flow. Connectivity allows for better traffic control and vehicle fleet management.

V2N and V2I communications are especially important for AV deployment since they allow AVs to get help in emergencies and to better understand their environment. AV technology has enabled driverless urban transport services such as robotaxis and self-driven shuttles. These driverless services require a constant connection to the internet. In an emergency, the Operational Control Centre must always be reachable to handle malfunctioning and teleoperate the vehicle in failsafe mode. In a crash, the AV must be able to reach the centre to notify remote controllers of the collision and have them send help if necessary (ITF, 2023a). Communication with physical and invisible infrastructure is essential to interact with traffic regulatory signals and access data-rich geolocation systems.

Various digital networks and telecommunication technologies have enabled essential communication channels for AVs. Co-operative Intelligent Transport Systems (C-ITS) cover different short-range communication technologies that facilitate communication and co-operation between vehicles, infrastructure, and other users. They can also connect vehicles with traffic managers, improving information dissemination and efficiency. The short-range nature of these technologies provides low latency rates, which is crucial for preventing fatal crashes and guaranteeing traffic fluidity. Long-range connectivity is equally important for AVs. It offers two-way communication between users and the wider network, granting AVs access to digital infrastructure and software. Standardisation of these technologies has been an essential step in ensuring their success and interoperability.

Short-range communication

Various technologies enable short-range communication for connected and automated vehicles. They are essential to ensure seamless interaction and co-ordination among vehicles and infrastructure in close proximity.

Dedicated short-range (DSRC) communication

Dedicated Short-Range Communications ITS Generation 5 (DSRC/ITS-G5) is a Wi-Fi-based technology that allows for direct communication between vehicles and other users employing the same technology nearby. It provides excellent support for accident-imminent safety applications due to its low latency. DSRC technology also enables traffic and vehicle management systems, making it ideal for C-ITS applications. Even though the signal is stable at low altitudes and when surrounded by buildings, it has some limitations in congested areas or urban highways where vehicles drive fast and change several network topologies (Ahangar et al., 2021). IEEE Standard for Wireless Access in Vehicular Environments (WAVE) presents the fundamental specifications of this technology and incorporates the vehicle communication system IEEE 802.11p.

Cellular vehicle-to-everything (C-V2X) communication

C-V2X technology has emerged in recent years to provide short-range communication between users and devices using the same technology. It uses 4G Long Term Evolution (LTE) and 5G standards, which were established by the Third Generation Partnership Project (3GPP) and were developed to replace the DSRC. C-V2X communication operates using two modes. Mode 3 allows for long-range communications via the LTE interface and 5G, a newer and faster mobile technology. Mode 4 enables V2V communication using the PC5 interface. Mode 4 reduces latency, which is critical for C-ITS time-sensitive applications. The release of the C-V2X technology created great traction, and its benefits proved essential for connected vehicles. Cellular short-range technology provides a reliable connection for vehicles driving at high speeds and is reliable in dense traffic conditions. However, experts argue that its cybersecurity vulnerabilities might be an issue, especially when considering its use for AVs.

The project Fifth Generation Communication Automotive Research (5GCAR) in Europe showed the benefits of incorporating 5G into C-ITS. The consortium of the automotive industry and the mobile communication industry showcased two applications of mobile technology in 2019. First, it optimised lane-merge co-ordination on highways by sharing current state data with a central traffic planner. Second, it showed how co-operative perception allows vehicles to communicate with VRUs (Abdelkader et al., 2021).

Mobile technology and long-range communication

Mobile networks are composed of base stations which are connected to the wider network through fibre-optic cables and radio links. These base stations allow nearby users to communicate with each other and access content on the wider network. Before the release of the 5G technology, 4G LTE offered connectivity at lower latency and with some capacity constraints. For these reasons, 4G connectivity was not fit-for-purpose for data-intensive and time-sensitive applications like AVs. Some of these limitations were solved by 5G, and later 5G New Radio (5G NR) which offer support for various AV-relevant applications, like high-definition maps and vehicle software updates.

In the early stages of AV deployment, there will be an increasing need for bandwidth. Control centre to AVs requires the transmission of multiple video streams over the network. Bandwidth demand will further increase in case of major traffic disturbances involving various AVs (ITF, 2023b). The roll-out of 5G solutions has been concentrated in high-demand areas, such as cities. However, the development of the new generation of mobile connectivity in rural areas or small urban centres will require further investment.

Box 8. Assessing the need for long-range communication in cities

Connected technology can keep vehicles up-to-date with the information they need to safely operate on infrastructure. Within the rail sector, long-range signals primarily exist to accommodate the distance required for a train to stop. Trains can take several kilometres to come to a complete stop, which in turn requires a signalling system that can provide advance warning to train drivers. Also, trains' high speed can hinder drivers' capacities to correctly read trackside signals.

Such situations may not be replicated in cities. Connecting traffic signals in cities requires important investments from local authorities. At low speeds (i.e. 30 km/h) AVs should be able to operate on sight, i.e., rely on their sensors and digital maps as the perception distance rarely exceeds the stopping distance.

Interoperability

Network interoperability is vital to ensure better coverage and leverage each network's advantages. Recent efforts have been made to find a hybrid solution using Wi-Fi and mobile technologies to provide better coverage and improve vehicular wireless communication. The C-ROADS initiative joins European Member States and road operators to enhance C-ITS services. The initiative encourages the inclusion of on-board fusion technologies to provide a seamless flow of information regardless of the location of the vehicle and telecommunication infrastructures nearby (C-ROADS, n.d.).

The most promising hybrid communication cases leverage already deployed communication technologies, such as 4G for long-range and ITS-5G for short-range communications. Backward compatibility with these hybrid communication use cases must be considered when deploying future standards and technologies. 5G mobile connection further improves long-range communications and provides interoperability with other mobile networks, enabling seamless interoperability with the 4G network. Once it is widely deployed, 5G connectivity will be part of the mix of networks available for connected vehicles, together with other promising technologies, such as satellite communications.

Automated vehicle data is a form of safety infrastructure

Data shared by AVs and connected elements in the urban environment are crucial to enabling safer interactions. One AV's data can enable another AV to adopt a safer behaviour. In this regard, public authorities should consider data shared by AVs and connected elements of the urban environment as a new form of digital infrastructure (Star, 1999). Infrastructure can be defined as the basic systems that enable societies to function effectively. With the advent of automated mobility, these data streams are expected to play a crucial role in enabling AVs' safe and efficient operation. AVs are both users and agents of this new form of infrastructure: they operate in the physical environment, relying on data they collect from different sources while, at the same time, generating data on their surroundings as they move forward.

Automated vehicles generate valuable data on crashes and near-crashes. This data is required by public authorities to enable a thorough investigation of crash factors and to provide data to further improve safety policies (NHTSA, 2022). Antifragile systems improve after each failure (Taleb, 2014).An antifragile approach in the context of AVs ensures that the lessons learned after each crash or near-crash improve overall system safety. The aviation sector already applies an antifragile approach. The aviation community learns from each crash and improves overall safety performance via the mandatory sharing of post-crash data from aircraft manufacturers and operators to public authorities. aviation. Similarly, data collected in component stress tests inform airplane design decisions.

An antifragile approach applied to the transport system would require data from crashes and near-crashes, from both automated and conventional vehicles, to be shared with the different system stakeholders (i.e. car manufacturers, public authorities, infrastructure managers, ITS operators, etc.). In the European Union, Event Data Recorders are mandatory on all cars as of July 2024 thus establishing the factual basis for post-crash forensic investigations, the results of which can improve overall safety (Service-Public.fr, 2024). The non-personal data produced from these devices forms part of overall safety infrastructure for road transport. Considering AV data as an infrastructure renders the system safer and can be shared with other stakeholders.

A holistic approach to automated vehicle cybersecurity

The complexity of AVs arises from their nature as cyber-physical systems which, in turn, creates certain new vulnerabilities. AVs rely on different technologies (e.g. artificial intelligence, machine learning) and infrastructure (e.g. physical and digital infrastructure) to operate. While threats can either be intentional (i.e. malicious attack) or unintentional (i.e. unpredictable malfunctioning, inaccurate or biased data, etc.), their consequences can impact both vehicle passengers and other public space users' safety. Dede et al. (2021) distinguished two types of attacks: evasion and poisoning attacks. Evasion describes actions aimed at manipulating the AI system's input (i.e. data) to alter the output decision. Poisoning attacks aim to compromise the trained models' performance to create a malfunctioning behaviour.

Targeted physical perturbations of objects within the urban environment have led to vehicles' incorrect predictions (ITF, 2019). Such adversarial attacks can affect AVs' recognition capacities by altering a traffic sign (Eykholt et al., 2018) or by confusing AVs by adding fake rules (Bell, 2024). Attacks can also target input data from digital maps and AV sensors. The impacts of such attacks on vehicle trajectory constitute a critical threat to safe interactions in cities. The cybersecurity of geolocation services will become ever more crucial as the number of automated vehicles and intelligent infrastructure relying on these services grows (ITF, 2023b).

AVs must have robust abilities to mitigate malicious attacks for safe and reliable interactions between different public space users in cities. Cybersecurity should be considered holistically. Like the Safe System Approach, a cybersecurity approach should acknowledge that the different components on which AVs rely to operate can fail. Public authorities should develop a comprehensive cybersecurity framework for automated vehicles (ITF, 2018a). DfT (2017) published a list of principles to ensure the robustness of AVs against cyber threats. The fourth principle emphasises the role of collaboration across the different stakeholders and suppliers at every level to assure that their cybersecurity processes are robust enough. The framework is targeted to a wide audience: the principles apply to both the automotive industry and stakeholders involved in AV deployment or manufacturing (i.e. connected vehicle and ITS ecosystems).

Because cyber-security extends to all relevant subsystems of AVs, not just the vehicle as a whole, cyber-security strategies should treat risks at a sub-component and sub-system level. As noted in ITF (2018a), discussions around AV cybersecurity vulnerabilities share similarities with other complex systems in the transport sector (e.g. aircraft, trains, metro) or other sectors (e.g. nuclear power plants). The common denominator to these complex systems is the isolation of core safety-critical components from non-critical components on both hardware and software levels. Redundancies are built to support critical component performance, even in degraded conditions. These critical subsystems include steering control and speed management (i.e. acceleration and deceleration) for AVs. These subsystems should be isolated from the others with independent processors, system memory and architecture, and separated and independent power supply. Furthermore, the robustness of the operation system's cybersecurity should be thoroughly vetted, and secured protocols should be implemented for handling updated policies of AV systems. A fundamental governing principle of AV safety is that vehicle safety should never *rely* on V2X communication, but only be *augmented* by it.

Public authorities should also mitigate risk factors beyond but related to cybersecurity. By reducing speed in interactions-intense areas of cities, public authorities can reduce the potential damages caused should a malicious attack target an AV. Speed reduction constitutes a cost-efficient measure to mitigate the adverse impacts of system failures.

Digital regulations for automated vehicles

Rules implemented by governments condition interactions between different public space users. They constitute a form of often invisible infrastructure that enables society to function. But while humans can choose whether or not to comply with rules, AVs cannot: they must follow established rules. The progressive deployment of AVs may require translating existing laws into a machine-readable format to make them easily interpretable by automated systems.

Machine-readable regulations provide a reliable and accurate source of regulatory information. Encoded rules can reduce regulatory ambiguity should an AV make an incorrect perception of their environment. They also create redundancies between different sources of information for AVs: if AV sensors fail to capture a change in traffic rules, geolocated machine-readable regulations can constitute a backup and trustworthy source of information.

Small differences in local rules should not result in a significant change in vehicle behaviour. Standardised machine-readable regulations could accelerate the safe deployment of AVs in cities and across them, and they can foster consistency across different jurisdictions (Newcomb, 2018). Ideally, public authorities should directly communicate their regulatory intent in machine readable format but interim solutions can already be leveraged even where public authority capacity to do so is lacking. For example, INRIX's AV Road Rules Platform (2018) aims to facilitate the translation of road regulations into a machine-readable format and its transmission to AV operators. This programme asks that AVs comply with both static (i.e. speed limits, turn restrictions, directions, geofencing) and dynamic rules (i.e. rules that are dependent on the time of the day or a day of the week) (INRIX, 2018).

Rules are not monolithic: they might evolve throughout a day or following a transformation of the public space. Updating and maintaining machine-readable regulations is critical. Discrepancies between real-world (e.g. traffic signs, speed limits, etc.) and machine-readable regulations could lead to conflicting situations between AVs and other public space users. Connected infrastructure could support real-time updates to traffic rules. Public authorities will need technical skills to develop and maintain accurate machine-readable regulations. Legal experts and AV ecosystem stakeholders could ensure consistency between rules and that machine-readable rules align with the technological capabilities of AVs.

Annex 1. Experts interviewed

The project team conducted interviews with experts to collect their insights, gain an in-depth understanding of the current state of interactions between automated vehicles and different types of road users, foresee potential developments in this field, and assess existing and future limitations that must be addressed.

Experts interviewed:

- Hatun ATASAYAR, Project manager, Kuratorium für Verkehrssicherheit (KFV)
- Olivier CARSTEN, Professor of Transport Safety, University of Leeds
- Debargha DEY, Postdoctoral Researcher, Cornell Tech
- Yee Mun LEE, Senior Research Fellow, University of Leeds
- Ruth MADIGAN, Senior Research Fellow, University of Leeds
- Gustav MARKKULA, Chair in Applied Behaviour Modelling, University of Leeds
- Sina NORDHOFF, Postdoctoral Researcher, ITS Davis
- Eetu PILLI-SIHVOLA, Lead, Digitalisation of Transport, VTT
- Martin RUSS, Managing Director, Austria Tech
- Dajiang SUO, Assistant Professor, Arizona State University
- John WALL, Senior Manager Road Safety Technology, New South Wales

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Lost in Transmission

Communicating for Safe Automated Vehicle Interactions in Cities

As automated vehicles (AVs) are increasingly deployed, they are expected to introduce a paradigm shift in transport. In cities, the transition from the current state of interactions between users – where human-to-human interactions prevail – to situations where humans will interact with more or less automated vehicles will likely impact how other public space users interact with road vehicles. The interpretation of other public space users' intent, the physical infrastructure, and digital elements play a crucial role in influencing AV interactions with other public space users.

This report provides principles and recommendations to ensure the communication of necessary information for the best interaction between public space users and automated systems. It assesses how meaningful information regarding public space and its use can be encoded and transmitted to AVs and how automated systems can acquire and use information to guide their actions and safely and beneficially manage interactions.

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