International Transport Forum

Cooperative Mobility Systems and Automated Driving

Summary and Conclusions

167

Roundtable

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Cooperative Mobility Systems and Automated Driving

Summary and Conclusions of the ITF Roundtable on
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Introduction

There is currently a clear trend towards the implementation of cooperative automated driving capabilities; whilst the projected time-scales, technology options and use cases involved vary, policy makers need to prepare their responses to these developments without delay. Mainstreaming of shared-use mobility services, particularly in large urban areas is trending in parallel with shared ownership of vehicles. The convergence of these developments may provide the business case for early large-scale adoption of vehicle automation technologies.

Many research and demonstration projects for systems and technologies using automated driving are being carried out in ITF member countries. Projects cover many research areas, including human behaviour, vehicle design, and supporting infrastructure and examine a range of issues. An overview of developments in technologies, regulation and policy is therefore timely. The potential for mobility solutions such as car sharing, car pooling, and ride sharing to meet urban transport demand is attracting increasing attention. We might now be seeing the first waves of a radical change in the format for car use and ownership and overall mobility provision in urban areas.

In multi-modal journeys the last-mile is crucial. Lack of convenience and personal safety concerns for this trip segment often deter modal shift. Conventional public transport is in most cases unable to provide last-mile transport, particularly at low-demand times and low density locations. Here in particular, shared mobility concepts and vehicle automation have the potential to radically improve service provision, enabling a paradigm shift for urban mobility.

Shared mobility is still a relatively new field, therefore business models and preferred technologies are still in flux. According to an analysis described in TCRP Research Report 188, current systems and services include the following; bike sharing, car sharing, demand responsive transport systems, fixed-route systems, micro-transit, mobility on demand, para-transit, private shuttles, public transport, ride sharing, carpooling, ride sourcing, ride splitting, dynamic carpooling, and specified public transportation. In the same study shared mobility is generally defined as a wide range of transport services having in common that they are shared among users.

The cooperative element in vehicle automation relates to the use of and system reliance on vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication. This communication relies on 5.9 GHz DSRC or widespread 5G implementation for its time-critical, safety-critical messages. Cooperative automation is the continuation of the Cooperative Intelligent Transport System (C-ITS) approach of adding vehicle-to-everything (V2X) communication to a developing and maturing technology. V2X communication is defined as the passing of information from a vehicle to any entity that may affect the vehicle, and vice versa (i.e. combining V2V, V2I, and going beyond). Thus real-world implementation may depend on the provision of supporting roadside infrastructure, which raises the question of whose responsibility this will be and where funding will come from.

Definition of terminologies is required to discuss automation of road vehicles. Whilst a variety of different technology options, application environments and business models is possible, a useful categorisation can be made based on the roles and responsibilities of the driver and/or passenger in the vehicle.

According to the updated SAE International (formerly US Society of Automotive Engineers) “Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles”, the varying levels of automation are to be classified as follows:

Table 1. **Summary of SAE levels of driving automation**

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	OEDR		
Driver* performs part or all of the *DDT						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* (“*System*”) performs the entire *DDT* (while engaged)**						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Table Note: Dynamic Driving Task; OEDR = Object and Event Detection; ODD = Operational Design Domain; ADS = Automated Driving System

Based on the above concepts and definitions, the discussion at the roundtable centred on the wider issues surrounding the use of SAE levels 3-5 cooperative vehicle automation for enabling a variety of potential shared mobility concepts, with a focus on last-mile public transport in urban areas.

As Shladover and Bishop (2012) note, road transport automation systems are not ends in themselves but are a means of satisfying needs to improve transport operations or driver comfort and convenience. Specific systems will be designed to achieve different goals, and those different goals are likely to point toward very different designs.

These goals could include combinations of the following:

- Enhancing driving comfort and convenience.
- Improving productivity or quality of life by freeing up time currently consumed by driving.
- Reducing vehicle user costs.
- Improving vehicle user safety or broader traffic safety.
- Reducing user travel time.
- Enhancing and broadening mobility options, giving users more flexibility.
- Reducing traffic congestion.
- Reducing energy use and pollutant emissions.
- Making more efficient use of existing road infrastructure.
- Reducing the cost of future infrastructure and equipment.

One simple means of understanding the opposing approaches to initiating the deployment of automation was defined by Walker-Smith (2014):

- **Everything Somewhere** (e.g. the Google car): very high functionality (Level 4) in a constrained geographical area due to the need to constantly update mapping and limit the interactions with potentially hazardous (higher speed) traffic. Also, given the high functionality, it is likely that the fleet would need frequent servicing and testing to ensure safe operation is maintained; this is also facilitated by geographic constraints.
- **Something Everywhere** (e.g. automotive Original Equipment Manufacturer OEMs): this is the classic incremental approach, in which systems are brought to market that are capable of operating on “any” road (of a certain type, at least) regardless of geographic area.

Another approach is advocated by some OEMs, which could be termed the **something eventually everywhere scenario**. This includes sections of roadway being individually approved for automated operation by the OEM and/or public authorities based on availability of map information and potentially by modifications to the supporting infrastructure as required by public safety agencies and/ or the automation system developers. This may entail the vehicle travelling the route first to collect map information to support the on-board system.

Box 1 shows an overview of the key factors for both vehicle sharing and vehicle use (of privately owned vehicles) based on user survey.

Box 1. **Overview of factors for vehicle sharing and vehicle use (privately owned vehicles)**

Key factors for vehicle sharing (KiM, 2015):

- Political and administrative support from the municipality.
- Big fleet size and variety of vehicles and providers, often in combination with highly urbanised development.
- Ease of use; this is increased by quick access to the shared vehicles via apps and automatic payment of parking fees, among other things.
- Coordination and integration of the vehicle sharing to public transport.
- Marketing and profiling.

Key factors for vehicle use (Steg, 2005):

- Instrumental motives: may be defined as the convenience or inconvenience caused by car use, which is related to, among other things, its speed, flexibility and safety.
- Symbolic or social motives: people can express themselves and their social position by means of (the use of) their car, they can compare their (use of the) car with others and to social norms.
- Affective motives: refer to emotions evoked by driving a car, i.e., driving may affect people's mood and they may anticipate these feelings when making travel choices.

Overview of the range of service concepts investigated

The concept of automated cars can be traced back to the 1939 World Fair in New York and the General Motors (GM) "Futurama" exhibit, which amongst many other future visions included the concept of an automated highway system. Since then this has been a firm element of a vision of the future in popular culture. But given that this was then the anticipated progress within the next 25 years, i.e. to 1964, actual developments in this field have somewhat lagged. Nevertheless, 1949 saw the first experiments with a remote-controlled car in cooperation between GM and the Radio Corporation of America (RCA).

It was during the 1980s that real progress with vehicle automation was made, enabled by breakthrough developments in computing, sensor and communication technologies. In 1986 a collaborative project between Caltrans and UC Berkeley started the California Partners for Advanced Transit and Highways (PATH) programme. This programme has carried out a wide range of transport research, including one of the earliest vehicle automation projects. At the same time the EU-funded PROMETHEUS Project

(Programme for European Traffic of the Highest Efficiency and Unprecedented Safety) developed and tested similar concepts and technologies in Europe.

Developments in this space accelerated in the new millennium with automation and platooning demonstrations in the US and in Europe. A series of EU-funded projects (CyberCars, CyberMove, NetMobil, and CityMobil) looking specifically at automated urban shared mobility started in 2001. The DARPA Challenges in the US between 2004 and 2007 gave a further boost to R&D efforts, enhancing public visibility.

It was with Google's announcement in 2010 to test and develop an automated car (now Waymo), that the automated car achieved "hype-status". Governments, cities, and companies around the world are now competing for leadership in this field. While a large number of systems and technologies are being tested and demonstrated, providing a wealth of data and information, it is still too early to tell which specific solutions will eventually emerge.

Despite this uncertainty, it is essential for policy makers to be ready to positively influence these developments in the transition period to the automation of transport; the transition did not perhaps start at the New York World Fair in 1939 but has begun now. The use of this technology to provide shared mobility concepts in urban areas can be identified as a key trend based on on-going research projects, demonstrations and studies.

A significant element here is the recent development in big data analytics coupled with smart-phone apps. This concept also has the potential for providing more sustainable mobility and, by increasing average vehicle occupancy rates, reduced numbers of vehicles on the road. This in turn could potentially decrease congestion and free up parking spaces for more appropriate use (ITF, 2015), at least to the extent that the space is not occupied by pent up demand for more road traffic.

Overview of existing systems and technologies

One of the first real world applications of Automated Vehicles (AVs) was the ParkShuttle in the Rivium Business Park near Rotterdam in the Netherlands. Open to the public in 1999, this was a shared, automated shuttle carrying passengers on a loop with a number of stops connecting offices to nearby public transport interchanges. A similar system connecting the long-stay car park with the main terminal building of Schiphol airport has been set up as a multi-year demonstration, which ceased operation after the end of the trial period. Both systems, although segregated from other traffic on some parts of the route, were able to operate safely with manually driven vehicles and pedestrians in controlled but mixed environments. The Rivium system has been extended, with second generation vehicles, and is still operational today. Similar kinds of shuttles are now being tested around the world (e.g. in Paris, Las Vegas, Singapore) with about 10 different suppliers present in the market.

Most of these systems share similar parameters, including:

- Low speeds: operational speeds are often below 15 km/h, but higher speeds are possible depending on segregation, as maximum levels of jerk for emergency braking needs to be adhered to for safety reasons.
- Simple and controlled environments: to minimise interaction with other traffic, vehicles operate e.g. in pedestrian zones, university campuses, etc..
- Significant infrastructure: there are varying levels of separation from other traffic.

- **Supervised operations:** whilst it is not necessary to have operations staff inside the vehicle, a staffed remote operations centre is necessary.

In a transition period and while full automation is not yet fully proven and costs are high, introducing SAE level 1-3 automation (i.e. still with a driver present) for public transport vehicles could be an interim solution enabling enhanced performance, e.g. precision-docking at stations, operation at minimum headways, or allowing narrower lanes, etc. at comparatively lower costs. Box 2 shows the set of vehicle and service categories developed as part of the EU-funded CityMobil project that describe different vehicle and service concepts (EC, 2012). As implementation of these systems progresses, categories might be merged or replaced by new concepts, or prove to be less applicable.

Box 2. **CityMobil vehicle and service concepts and respective definitions**

- **Cybercars:** fully automated road vehicles for individual or collective transportation of people and goods, for specific areas with little or no interaction with other vehicles.
- **Personal Rapid Transit (PRT):** small fully automatic vehicles operating on guide ways, segregated from pedestrians and other traffic.
- **Advanced City Vehicles (ACV):** integrating zero or ultra-low pollution propulsion and driver assistance systems, allowing integration into car-sharing services.
- **High-tech buses:** buses on rubber wheels, operating like a tram on lanes with light infrastructure using electronic guidance either fully automated or assistance functionalities.
- **Dual-Mode Vehicles (DMV):** using conventional vehicles, supporting both fully automated and manual driving. They represent a potential migration path from traditional cars to AVs.

Operational design domain restrictions and dependency on infrastructure

Until true SAE level 5 vehicles are on the market, i.e. vehicles that can perform all driving tasks (everything) under all conditions in all settings (everywhere), vehicle manufacturers and fleet operators will have to put certain Operational Design Domain (ODD) restrictions in place to mitigate system and/or vehicle limitations. These ODD constraints include geography, road type, speed, and weather conditions; in addition system capability and maturity will also require a certain dependency on supporting infrastructure for safe operation.

Restrictions will have to be formulated and enforced by policy makers and regulators, and conflict may arise between realistically achievable ODDs and actual operational or commercial requirements. This is also dependent on timescales, with government requiring time for developing type-approval regulations and regulating new transport services that raise issues similar to Transportation Network Companies (TNC), such as Uber or Lyft.

The public perception of safety plays a key role in this context, conceivably causing a situation where more restrictive than necessary (as suggested by industry and research) constraints on system operation are put in place, possibly creating excessive burdens on vehicle manufacturers and system operators. There is evidence from some automated metros in cities around the world where either a “driver” is still present despite automated operations or a decision to move towards automated operations was reversed due to concern over public perception of safety.

In the case of shared mobility systems, there would then be concern over the economic viability of a system with a large number of small automated shuttles retaining (for a certain period of time) a manual operator, particularly as savings in personnel costs would be a key motivator for introducing such a scheme in the first place. The dominant challenge for the developers of the technology will then be to demonstrate convincingly that their technology has reached a level of maturity that it is capable of operating safely in a shared (unprotected) ODD without human operator supervision. This is a challenge that has yet to be met by any of the technology developers.

In addition to ODD considerations, specific requirements for accompanying infrastructure may occur:

- Charging infrastructure: if electric vehicles are used, a likely option for a number of reasons, then designing and providing the necessary charging infrastructure (offline, or online e.g. at stops or junctions), scheduling of charging of vehicles, and routing to charging stations needs to be considered as part of the overall service planning.
- Communication infrastructure: vehicle and system operation options will depend on provision and level of connectedness using wireless technology (e.g., DSRC and eventually 5G). This is particularly important with the emergence of both smart infrastructure with embedded sensors and the Internet of things. With increasing importance of digital infrastructure there is the need to ensure the robustness of system (data protection and privacy) and of data coverage. A central control or supervisory system with reliable communication systems will be needed for public transport fleets.
- Other physical infrastructure: in the transition period, but possibly beyond, physical infrastructure might still be required; this includes varying levels of segregation between automated vehicles and other traffic, while technology lacks the maturity to allow negotiating highly complex environments. We might therefore see separate lanes, different types of barriers to limit access to parts of the network and special provisions for junctions; potential negative effects on urban design including visual intrusion and the risk of community severance need to be carefully considered.

Operating principles, vehicles, and user interfaces

The underlying operating principles for such a system will likely be based on both size and density of urban areas; with the assumption that cities, rather than more rural areas, would be the appropriate geographical setting for shared services. Long-distance services that connect urban centres may be feasible, but private companies will focus on highly dense urban areas, as the operation of vehicle fleets will likely depend on investment into mapping.

The vehicles to be used are likely to have the following common characteristics:

- Electric propulsion: The control mechanism and actuators involved in automated operation make electric propulsion the likely option for AVs. The environmental performance of electric vehicles, with lower noise levels and no emissions at the point of operation, would further suggest their use. Also, mandating EVs for specific vehicle fleets, e.g. public transport, is a viable policy option to positively influence the transition period.
- Light-weight vehicles: Traditionally the vehicles used in existing applications are relatively flexible and light-weight vehicles from non-conventional vehicle manufacturers. An immediate concern for a more wide-spread deployment of these types of vehicles would then be their safety performance. Addressing this might involve development of specific standards to ensure

the necessary road safety levels, particularly in mixed traffic with heavier and larger manually operated vehicles.

- **Tailor-made vehicles:** whilst potentially being based on a generic base or chassis, the vehicles are likely to be required to be tailored to local characteristics in order to ensure success of the system. These include cultural and geographical characteristics, business model used, customers targeted (e.g. general public, tourists, elderly/disabled, etc.), as well as the site of the systems (i.e. private or public). Specific care needs to be taken to make both the vehicles and the system as a whole accessible to disabled, including mobility impaired, wheelchair users, and the blind.

Care needs to be taken for the design of all internal and external user interfaces for:

- **Booking a service:** a smart-phone, app-based platform needs to be in place, which can be understood and used by all passengers independent of individual characteristics, which might otherwise prevent them from accessing mobility services. These may include: social background, age, IT literacy, or having physical impairments. Alternative means of access will also be needed for those without access to smart phones.
- **Accessing and using the vehicle:** a system needs to be in place for users to be guided through the process, including finding the access point, recognising the booked vehicle, gaining access, and once on-board being reassured of the pre-booked destination, and being advised on the route and any intermediate stops. In addition all back-office function for billing and multi-modal ticketing need to be designed and implemented;
- **Interactions in mixed operation:** AVs need to be able to communicate with other vehicles and road-users, including pedestrians and cyclists, in mixed-use environments. Use cases for this can include: negotiating narrow congested areas, giving way or asking others to give way and preparation for turning, etc. Likely communication channels are displays or lights on the outside of the vehicle and/or with targeted messages on users' smart phones. This is particularly important in the transition period when movements and behaviours of AVs are not yet intuitive to those around them.

Matching service concepts and operational environments

Having discussed a broad range of service concepts, operational designs, domain restrictions, infrastructure dependency, operating principles, vehicles and user interfaces, the next step is to explore how specific service concepts can be matched to specific operational environments, on a detailed local level as well as across continents and cultures.

Further research and development work is required in the areas below as is real-world experience of rolling out systems on a larger scale before we can confidently move forward;

- **Specific technology development:** sensor technology and specific software components (potentially including artificial intelligence) need to be further developed to ensure safety under all environmental conditions and in complex urban settings, using connectivity for deep learning. Further data also needs be gathered and shared openly during testing and demonstration to engender a move towards a more data-driven and thus sufficiently flexible regulatory regime;
- **Relationship with existing multi-modal public transport:** the emergence of new mobility solutions using AVs might make it necessary to rethink the term "public transport", as the multi-modal system and service offer will increasingly consist of both public and private elements; "collective transit" could be a more appropriate term. It will become increasingly necessary to incorporate this technology and new public transport investments need to include a business case analysis that considers AVs. Many transit agencies assume that they will be managing smaller, automated on-demand vehicles.
- **Transport/ urban planning and policy:** the transition needs to be managed in such a way that unintended consequences (e.g. increased traffic, modal shift to less green modes) can be avoided. Much of the discussion centres on services in urban areas, but mobility provision in lower density and rural areas also needs to be investigated. It would be useful to focus on specific transport problems to be solved, rather than using a purely technology-driven approach. It is unclear at this point how AVs would fit into the mobility-as-a-service approach, offering multi-modal alternatives to car ownership or its relationship to road user charging schemes aimed at nudges toward using greener modes. Furthermore, changes to travel demand and effects on land use need to be considered.
- **Communication and public image:** there is an assumption (although yet unproven) that connected and automated transport systems will increase traffic safety, but in public discourse the expectation often appears to be that the introduction of this technology will not just decrease accident rates, but completely avoid crashes; this would appear unrealistic and the public as well as policy makers need to be made aware of this to ensure unrealistic expectations do not hinder the implementation of a technology that should be an improvement on the status quo. The media and the way it portrays these systems will play an important role.

Urban planning and policy background

Different actors that may drive early uptake of these technologies can be identified. This includes: industry (traditional car manufacturers, IT sector innovators, or partnerships of both) which pushes specific products and services into the market, the public sector based on transport needs, and, perhaps most importantly for the first highly visible implementation, individual champions with vision and a political agenda. In the past, demonstrations have been driven more by research, industrial development, marketing needs and industrial policy, rather than in response to specific transport purposes or needs.

AV technology could entirely take over urban mobility (in some environments), but the more likely scenario is that it will contribute to the existing multi-modal transport systems, with a specific importance for the first-mile/ last-mile feeder functions; thus improving the overall quality and comfort of services. Moreover, different operational environments will require different solutions; some of them better suited to AVs, some less; e.g. dense cities might be more appropriate for high-capacity collective modes but suburban areas might benefit from completely new transport options, as an alternative to the private car.

AVs can become enablers in redefining streets and achieving more liveable cities. Minimum parking requirements are today the standard in many cities, there is a chance to modify this with shared mobility modes. In the urban context, denser environments with payment-based management of parking spaces can further incentivise uptake of rides sharing systems.

Potential negative effects of AV technology and shared mobility concepts need to be taken into account. The promise of greatly reduced congestion might well be reversed, instead inducing traffic through lower prices for mobility and a release of latent demand. Such effects are typical of investments in new or upgraded road infrastructure, i.e. capacity increases tend to be short-lived, as travel behaviour changes as a result of improved travel times, with people switching modes and routes, quickly leading to a return of similar congestion levels with the overall increase in vehicle-km travelled.

Another key concern is that if AVs provide door-to-door services and enable other activities to be done while travelling, this could lead to commuting time being considered useful rather than lost time, which would have a strong influence on housing choices. It could lead to increased urban sprawl with AVs allowing users to live further away from places of work, tolerating much longer (but more useable) travel times.

Automation is thus likely to increase pressure on road space and the tendency for sprawl in the long term will make effective congestion management through road pricing increasingly important. Fortunately the same technology that facilitates automation also facilitates dynamic road pricing. Automation also highlights the importance of governments redoubling efforts to integrate land use and transport planning.

Geographical, societal cultural differences

The expert discourse on implementation of vehicle automation for shared urban mobility applications often over-simplifies the situation, advocating a “one-size-fits-all” solution but a series of factors will have a bearing on how such a system is to be designed in order to be accepted by the targeted users (Box 3).

It is important to note in this context that none of these points; particularly not the views, customs, and perceptions of the public, are fixed, but rather have to be seen as being dynamic, changing based on various events and over time and generations/ cohorts. Also current trends need to be scrutinised in order to avoid drawing the wrong conclusions by only looking at parts of the picture without a broader view.

One example is the observation that millennials in dense urban areas are increasingly moving from vehicle ownership to shared mobility schemes, potentially heralding the death of the privately owned car. But there is evidence that this cohort marries, settles down and has children considerably later than previous generation, and at that time there is then a move to car ownership; this additional information points to very different conclusions. Focusing on urban millennials who work in the information-based economy also ignores their counterparts in the vocational trades, the older generations and those who live in low-density suburban and rural areas, whose attitudes toward vehicle ownership are much less likely to change substantially.

Box 3. **Geographical, societal, and cultural factors for automated vehicle implementation**

- Social, societal, and demographic factors
- Economic level and income distributions
- Car ownership levels and car culture
- Existing layout, size, and density of the urban form
- Characteristics of the built environment
- Specific requirements for mega-cities
- New cities, green-field and brown-field developments
- Current transport modal provision and share
- Legal and regulatory frameworks in place
- Cultural aspects relating to e.g.;
    - IT and technology literacy
    - Perception of safety and trust
    - Driver behaviour
    - Environmental awareness
    - Views on privacy.

The above considerations all point to the need for designing and implementing tailor-made solutions taking into account all local, wider regional, as well as national characteristics. Once the first systems emerge, a case-study based analysis will be able to take this important discussion forward, ideally leading to a best practice guides detailing the lessons learnt and helping to match specific solutions to specific types of local and wider challenges.

Industry sectors and business model options

There is a potential for shared AV services to drive new, efficient, high-quality urban development patterns with low car and low carbon characteristics and a high quality of life (e.g. street space useable for children, etc.). AVs can also be part of economic development, particularly in the context of property development in urban areas, where e.g. in large urban areas in North America new high-end developments now often feature an “Uber waiting room” for residents; beyond these trends there is also the potential for integration of new housing into mobility-as-a-service memberships and with specific facilities such shared vehicle parking areas, etc.

For AVs to be a part of the overall travel chains fare integration is required, i.e. as a prerequisite for last-mile solution, but also for door-to-door systems, which will not be the sole provider of mobility, but will compete with other modes and providers, based on different pricing regimes, levels of service, and other factors. The following industry sector involvements and cooperation projects for testing and demonstrating AV technology in this space are first examples to emerge.

Box 4. **Automated vehicle system examples**

- Google/ Waymo: full automation in specific geo-fenced areas, using very high definition inch-precision maps of the area the vehicles are expected to use, in addition to on-board systems, some computation is performed on remote computer farms.
- EasyMile: a low-speed urban shared-mobility shuttle currently being demonstrated in small highly controlled environments with little interaction with other traffic, demonstrations are being carried out in Paris, and in sites in the Netherlands and North America.
- nuTonomy: recently launched its highly automated taxi service as a pilot project in Singapore (still supervised by safety drivers), their vehicles use formal logic to decide their paths in terms of motion, manoeuvrability, and speed.
- Uber and Volvo: Uber started testing the concept of driverless (although in the trial period a driver was still inside the vehicle at all times, to take over in case of unforeseen circumstances) shared mobility service provision in the city of Pittsburgh.
- Uber and Daimler: recently announced a strategic partnership, through which Daimler will provide tailor-made vehicles to Uber to be eventually used as a highly automated ride-sharing (i.e. driverless) system.
- Ford: recently announced plans to offer highly a fully automated (level 4) high-density, high-volume ride-hailing application in geo-fenced parts of urban areas area in some cities by 2021; the operational design domain limitations for this system have not yet been determined.
- Drive Me Project: large-scale pilot project in Level 4 automated driving backed by the Swedish government where 100 self-driving Volvo cars will be driven on specific designated sections of public roads in Gothenburg. The aim is to study the benefits to society of highly automated driving.

Government action will affect how automated vehicles will impact society

There is substantial excitement about the potential of automated vehicles (AVs) and their impacts on society. Their promotion and media coverage has fed public hopes that AVs will improve road transport and alleviate a series of stubborn problems. Governments share these hopes.

In setting out it's pathway to AV implementation, the UK's Department for Transport (DfT) set out the following impacts of AVs (DfT, 2015):

They will make driving easier, allow people to be more productive and offer greater mobility to a wider range of people than ever before. They will also help improve road safety, reduce emissions, and ease congestion. As a result they could provide significant economic, environmental and social benefits, including improving social inclusion.

At the same time, there are risks. Making driving easier could increase demand for road transport and make living further from city centres more attractive. This may result in AVs exacerbating congestion and urban sprawl.

Many of the expected impacts of AVs such as improving safety, reducing congestion, providing more equitable access to mobility, congestion and urban sprawl accrue to society as a whole rather than the people who produce or use AVs and the services they provide. The result, in economic terms, is externalities or public goods. Markets have a poor history of controlling negative externalities, sustaining positive externalities and protecting public goods, as these are side effects of profit-maximising activities. As a result, we cannot assume that markets alone will provide AVs in a fashion that has the impacts the public and policy makers desire. Rather, regulations are likely to be necessary to ensure society can capture the benefits of AVs (OECD, 2008: 6).

Assuming AVs will provide overall benefits to society, effective regulation provides a foundation that benefits all AV stakeholders including developers and users. Effective regulation gives consumers protection and confidence that they can purchase AVs and use the services they provide safely, even if they have little knowledge about them. In turn, this provides a market for developers to sell into. Also, effective regulation provides certainty, reducing developers' investment risk and encouraging the innovation necessary to make AVs a reality. Finally, effective regulation allows governments to influence how people behave in order to capture benefits and avoid negative consequences to society.

Regulating highly automated vehicles

AV technology is still largely experimental (Cohen and Cavoli 2017: 6). AVs that can operate on a broad range of public roads without a human driver are still years away (Isaac, 2016: 12-13; Shladover, 2017). Ford intends to have high-volume, SAE level 4 automation capable vehicles in commercial operation by 2021 (Ford, 2016). However, SAE level 4 vehicles are likely to be limited to a specific and narrow operational design domain (ODD). They are unlikely to operate in automated mode beyond some combination of; low speed, relatively small geographical area, less complex environments, segregated lanes, specific weather and road conditions and times of day.

Under current circumstances, such vehicles are unlikely to be able to operate efficiently in the dense urban environments where the opportunities for safe, more accessible and less congested transport that

AVs promise are most desired (Cohen and Cavoli, 2017). For that, technology that allows AVs to have wide ODDs would be necessary. Using the most optimistic estimates, we are still decades away from that technology (Isaac). Some estimates suggest that we will not see such AVs until around 2075, if ever (Shladover, 2017).

Despite the uncertainty, several jurisdictions have moved quickly and taken significant steps towards developing regulatory frameworks for AVs. Several factors seem to be incentivising policy makers to move relatively quickly.

Improved road safety is, perhaps, the highest public policy priority for AV deployment. The US National Highway Traffic Safety Administration (NHTSA) has estimated that the driver is the critical cause of 94 per cent of crashes (NHTSA 2015). AVs would eliminate human drivers and, in turn, are hoped to eliminate many of these crashes. Also, as computer processors have faster reaction times than human drivers, they are hoped to avoid a series of collisions that human drivers cannot. In turn, AVs are expected to significantly reduce fatalities and injuries, improving road safety (Cohen and Cavoli, 2017).

There are also other incentives. Providing a favourable regulatory environment for AVs may attract manufacturers and related businesses to particular locations, improving economic development in that area. Also, there may be political dividends from a jurisdiction being perceived to be at the forefront of exciting new technologies.

Regardless of the incentives, as the examples below demonstrate, AV regulation has been heavily influenced by the uncertainties surrounding the technology and its potential. Policy makers and regulators seem keen for the technology to succeed. In particular, they are aware of AVs' potential safety benefits. However, they do not know if, when or how AV technology will be deployed. Therefore, regulators seem keen to ensure that their jurisdictions do not inhibit the development of AVs and have been motivated to move relatively swiftly to remove potential regulatory barriers. At the same time, policy makers seem concerned about the safety issues that may arise from having AV technology in public spaces.

While the uncertainty around AVs and when they will enter operation presents a challenge, it has also provided opportunities to different jurisdictions to experiment and take different approaches. As a result, there are already many examples of good AV regulatory practice. Across the ITF's membership, different jurisdictions are at various stage of AV regulatory development.

Research and preparation

There are various ways policy makers and regulators can prepare for AVs. Some important preparatory steps have included funding research, skilling staff in AV issues or, as in the case of the UK Department for Transport's Centre for Connected and Autonomous Vehicles, creating a specialist unit that can lead on AV issues across all of government.

Auditing existing motor vehicle regulatory frameworks has also proven useful in preparing for AV introduction. Australia, Germany, the UK and US have all used this systematic approach. In particular, the UK Department for Transport (DfT) and the US National Highway Traffic Safety Administration (NHTSA), have focussed on identifying existing regulations that create barriers to the development of AVs and potential amendments that would create greater certainty and encourage the AV take-up (DfT, 2015; NHTSA, 2015; Volpe, 2016).

The Australian National Transport Commission's (NTC's) audit process has been held up as a particularly good example of how to approach such audits (Maheshwary, 2016). Over 2016, the NTC worked with

Australian state and territory governments (who have central responsibility for vehicle regulation) and other stakeholders to comprehensively audit all Australian jurisdictions' regulations affecting AVs.

The audit covered a wide range of issues including:

- Measures for testing AVs
- Legal definitions:
- What it means to "control" a vehicle
- Who is/ is not the "driver" of a vehicle.
- Safety assurance
- Vehicle design standards
- Liability
- Data.

The resulting reports (NTC 2016a-c) have identified current legislative barriers to the testing and operation of AVs at SAE levels 4 and above and specified the reforms that are necessary to address them. The final report goes further, setting timelines, specifying the reforms that are necessary in the short, medium and long term (NTC, 2016b).

The timelines recommended are based on current evidence as to when particular technologies are expected to mature. Also, importantly, the report is cognisant that Australia will cease to produce vehicles locally in the near future. As a result, it places a strong focus on harmonising AV regulation with international standards, especially those that are negotiated under the Convention on Road Traffic.

In 2016, Ministers adopted the final report (NTC, 2016a), and the NTC is working on the following to further develop a national framework for AV regulation:

- Develop national guidelines to support automated vehicle trials.
- Clarify who is in control of a vehicle with different levels of driving automation.
- Develop a comprehensive performance-based safety assurance regime for increasingly automated vehicles.
- Remove regulatory barriers in Australian Road Rules and other transport laws that assume a human driver.

Non and quasi regulatory approaches

ITF's Corporate Partnership Board (CPB) has previously advocated the avoidance of premature regulation. It pointed to the substantial uncertainty around AV technology and what future innovations may develop as a reason to be cautious and avoid regulation that may hinder future development. In turn, the CPB recommended that jurisdictions engage in informal dialogue with AV developers to ensure safe AV testing in their jurisdictions (CPB, 2015).

Several jurisdictions have adopted approaches consistent with these views. NHTSA's Federal Automated Vehicles Policy (NHTSA, 2016) is perhaps the best known quasi regulatory approach to dealing with AV safety. The policy is not binding, but gives a detailed insight into how NHTSA may approach regulating AV safety when regulations are made. It sets out fifteen areas in which it would assess the safety of AVs:

- Data recording and sharing
- Privacy
- System safety
- Vehicle cyber security
- Human machine interface
- Crashworthiness
- Consumer education and training
- Registration and certification
- Post-crash behaviour
- Federal, state and local laws
- Ethical considerations
- Operational design domain
- Object and event detection and response
- Fall back (minimal risk condition)
- Validation methods.

NHTSA's policy does not set specific standards. Rather, it focusses on the testing processes AV developers would need to pursue and the evidence they would need to provide, effectively delegating the safety case to AV developers. This approach has some similarities with existing type approval and self-certification approaches in the EU and US respectively. It has been recommended as one way to overcome the uncertainty around how to define or demonstrate appropriate safety standards for AVs, by educating regulators and the broader public about AVs' capabilities and limitations (Walker-Smith, 2015).

It is also different from NHTSA's approach for granting exemptions from vehicle safety standards, which requires a developer to demonstrate that the exempted vehicle is at least equal to the overall safety level of non-exempt vehicles (NHTSA 2015). However, NHTSA has also recommended use and possibly expansion of the existing exemption process for early implementation of limited numbers of highly automated vehicles, before they have a more comprehensive regulatory process developed (NHTSA, 2016).

There are also examples of governments using informal discussions to enable AV testing. On 20 October 2016, Otto (an automated truck developer) made the first commercial AV delivery, shipping a product across Colorado in the US as a one-time demonstration. Colorado's laws and regulations do not expressly authorise or prohibit the operation of AVs, as they do not address the scenario at all. While AVs are not specifically regulated in Colorado, local authorities worked with Otto to develop a framework to ensure the delivery took place safely (Savage, 2017).

This included Otto initially testing its AV off public roads, providing Colorado regulators with contingency plans and off road test data, certifying the safety of the vehicle, demonstrating appropriate insurance and successfully completing five successive test drives without human intervention (but with continuous human monitoring and supervision). In addition, Colorado regulators inspected the vehicle and conducted a company safety audit of Otto. By working together, Colorado and Otto were able to successfully develop AV protocols that satisfied all stakeholders, but which remain flexible as AV technology develops.

Reinterpreting existing regulatory frameworks

Regulatory reform can be slow, especially where it involves international coordination or agreement (such as if amendments to the 1949 Geneva Convention on Road Traffic or the 1968 Vienna Convention on Road Traffic are perceived as necessary), or changes to national laws are needed. As a result, other measures may be necessary to avoid holding back AV testing. In many motor vehicle regulatory frameworks, concepts such as the “driver” and “control” of a motor vehicle are central. While these usually assume that a human driver will control the vehicle, sometimes this implication is not made express. This creates room for expansive interpretations. For example, while it was originally designed with a human in mind, the term “driver” could include multiple drivers or operating software (Walker-Smith, 2014).

The UK has taken a somewhat different policy approach that allows AV testing while working within existing requirements for a human driver. For the time being, the operation of an AV should always involve the presence of a human driver (who may be inside the vehicle or outside of it, i.e. a remote driver) who is ready, able, and willing to intervene at any time.

As a result, DfT found that concerns about an operating system controlling a vehicle do not arise. Therefore, the entire existing motor vehicle regulatory framework operates as it normally does (DfT, 2015). This approach allows the testing of automated vehicle technologies, as it does not define the extent to which driver intervention is needed, though the UK recognises that regulatory reform may be required to support the deployment and use of such technologies without the presence of a human driver.

Another approach that makes use of existing regulatory frameworks has involved the use of exceptions, especially for vehicle design requirements, such as compulsory steering wheels and pedals. In Germany, the federal government sets vehicle safety standards. However, state governments are empowered to grant exemptions. These powers have been used to allow AV testing to occur in Germany, provided there is a driver in the driver’s seat (DfT, 2015).

However, exemptions can have limitations. Often, they are not intended to allow indefinite non-compliance for a large number of vehicles and can take months or years to obtain (NHTSA 2016). For example, NHTSA exemptions require developers to limit sales of exempted vehicles to 2 500 per annum (NHTSA 2015). As a result, this mechanism will only have limited use as the number of vehicles which do not comply with existing regulations grows.

Legislation and regulation

Since 2011, some jurisdictions have been updating their motor vehicle regulatory frameworks to deal with AVs. Several US states, France and Germany have all enacted legislation specific to AVs. At the international level, amendments have been made to the Convention on Road Traffic, with further amendments currently under discussion.

While there are differences in regulatory frameworks, many of those enacted to date have similar elements, including:

- Definition of what constitutes an AV and automated driving.

- Requirement for AVs to abide by all existing road rules at all times.
- Developer responsibility for what occurs while the vehicle is in automated mode.
- Express legalisation of testing AVs on public roads, subject to conditions, such as:
    - Obtaining a permit to test an AV on public roads
    - Requirement for a human driver to be present to take over manual operation at any time
    - Minimum insurance requirements
    - Obtaining further approval before commercial deployment.

Existing approaches will not be appropriate for long

The cautious approach many regulators have taken to date is prudent, given the current uncertainty. It provides a space in which to test AV technology and gather real world data and evidence. Regulators will be able to use this data and evidence for future policy making. However, there are also limits to this approach. As the technology approaches deployment, issues that a cautious approach leaves unanswered will need to be dealt with. There are at least two issues that will need to be addressed in the near future:

- How safe must an AV be to obtain commercial deployment approval?
- Current regulatory frameworks can only stretch so far.

How safe is safe enough?

Perhaps the most important issue that must be dealt with relates to how safe must an AV be before regulators will allow it to be commercially deployed. Many jurisdictions' AV regulatory frameworks are unprepared to deal with this issue. At present, Florida is the only jurisdiction that has AV legislation which permits commercial deployment without a specific permit. All other jurisdictions with AV-specific legislation either limit AVs to testing or require a specific permit for deployment. However, many have not yet developed the requirements for that permit. California is the jurisdiction closest to settling requirements for AV deployment. It is currently consulting on the second draft of its requirements for a permit to commercially deploy AVs. That draft effectively adopts the safety assessment approach in NHTSA's AV policy, delegating the safety case.

In regimes designed for human driven vehicles, mechanisms that allow exemptions from motor vehicle standards may be called upon to provide a path to AV deployment. For example, NHTSA can exempt a limited number of vehicles from US Federal Motor Vehicle Safety Standards, provided a vehicle is safer overall than a vehicle which complies with the standards. Arguably, there are advantages to using this standard for AVs. AV developers would have a target for the level of safety they need to meet, providing greater clarity than they currently have. Also, the overall nature of such a standard might be flexible, allowing AV deployment using a broad range of technologies and approaches, so long as they improve road safety.

While the flexibility in NHTSA's exemption processes and California's draft legislation has advantages, it can also create uncertainty. By having an overall standard or delegating the safety case, these regulatory approaches effectively leave the safety decision at the discretion of the relevant official, and their subjective judgement. In turn, they continue uncertainty around how safe will AVs need to be before they are allowed to be commercially deployed. Determining how safe an AV must be to obtain approval for deployment is challenged by both public perception and technical issues.

Unrealistic expectations may hinder AV deployment

Existing public perceptions and hype relating to AVs can raise desires for safety standards that are impractical. Most jurisdictions require AVs to comply with all road rules at all times. Further, substantial attention has been given to the fact that the driver is the cause of more than 90 per cent of collisions (NHTSA, 2015; Cohen and Cavoli, 2017). A lot of attention has been given to NHTSA's findings in the context of AV deployment. As AVs would eliminate human drivers, they are hoped to eliminate all of these collisions.

Also, as computer processors have faster reaction times than human drivers, they are hoped to stop or avoid a series of collisions that human drivers cannot, even where the other party is at fault. Further, there is evidence that the community is unlikely to be particularly forgiving of AV malfunctions. Together, these factors would place relatively high expectations on the level of safety AVs will be able to provide. They would need to comply with all road rules at all times and avoid as many collisions as possible, regardless of which party is at fault.

Improving road safety is a central public policy goal for AV deployment and safety standards should be high. However, using these expectations as a basis for the safety standards AVs will need to meet prior to obtaining a deployment permit could have negative consequences. AVs may avoid many errors human drivers make and may have faster reaction times than human drivers, however, avoiding almost all collisions seems unrealistic. Further, complying with all road rules and being able to stop and avoid collisions where others are at fault is likely to require almost constant stopping or very low speed.

As a result, regulatory safety standards set to meet high public expectations may delay or prevent AV deployment. Alternatively, as the CityMobil2 experiment demonstrated, requiring AVs to meet such high safety standards may severely limit the geographical range and speed of their ODDs and require almost constant stopping. In turn, AVs may prove unpopular with consumers as meeting safety requirements makes them deliver a driving experience that is disadvantageous compared to human driving.

This dilemma is an unavoidable outcome of the current immaturity of the AV technology. The technology needs to be improved to achieve the capability of providing a useful transportation service without degrading traffic safety. Attempts to short-circuit the regulatory process to promote early implementation of systems that are not yet mature will produce adverse safety events, which are in turn likely to produce a public backlash that will delay the eventual widespread implementation of AV technology.

The public perception issues discussed above highlight how regulators, and industry need to better integrate their work. In particular, there would be benefits from more integrated work to raise public awareness of realistic capabilities and limitations that can be expected from AVs. It would be unfortunate if AVs that could improve road safety are unable to be deployed because they cannot meet an even higher standard or cannot do so without making the driving experience undesirable. Instead it is desirable to set public expectations more realistically, through education about AV capabilities and the impacts of requiring them to meet particular safety standards, especially on the driving experience.

Equally, regulators could put greater effort into increasing the standard for human drivers. At present, there are high levels of non-compliance with road rules among human drivers. Increasing enforcement, such as through greater implementation of electronic enforcement mechanisms, would change the driving experience for human drivers in a way that may make AV driving more competitive (Walker-Smith, 2015).

An absence of testing mechanisms makes deployment approval harder

At the technical level, there are challenges developing tests to demonstrate AV safety. For various products, but especially motor vehicles, the product must be subjected to and pass tests that objectively demonstrate the product's compliance with relevant safety standards. At this point, there are no methods to develop such tests for AVs and their components. However, AV sensors continue to have significant limitations, and there is no way to prove the safety of the software that interprets the sensor data and makes decisions about driving behaviour. Both of these issues point to the likelihood that the AVs will cause new crashes of their own, the frequency of which cannot be predicted with any certainty.

Much of the objective evidence presented currently about AV safety appears to be at the higher level. It relates to how often a human driver testing an AV intervenes in the driving task or how many miles AVs have travelled without a fatal collision. However, these are not necessarily good indicators of safety. Testers have varying tolerances for intervention and the data on distance travelled safely is not particularly deep.

As discussed above, current regulatory regimes leave decisions about AV deployment to officials, who hold broad discretions. Given likely negative public responses to AV collisions, it seems unlikely that officials would be willing to approve AV deployment in the absence of better, objective evidence about safety. Arguably, there is room for more information sharing and research to better develop the ways in which AV safety can be tested and demonstrated.

Current regulatory frameworks can only stretch so far

To date, AV regulatory frameworks largely rely on a hybrid approach (Walker-Smith 2016) that effectively stretches existing motor vehicle regulatory frameworks to apply to AVs. For example, the term “driver” might be amended to include operating software or an AV developer. There are several advantages to this approach. It is consistent with industry views that prefer adapting existing frameworks over creating new frameworks that may lock in a standard that is too high or too low (CPB, 2015).

It is a relatively easy mechanism by which to ensure that AVs conform to the same norms as human driven vehicles that currently dominate on the road, especially in relation to road rules. It also reflects the history of transport regulation. When automobiles first appeared on public roads, they were required to comply with norms applying to the then dominant transport mode – horses.

While a hybrid has advantages, it also presents challenges. Stretching existing frameworks can be a relatively blunt mechanism with unintended consequences. Existing road rules have been drafted for a human driver, with human capacities that responds to human incentives. Applying these to operating software may require the application of concepts and mechanisms that are not appropriate. For example, just as two miles per hour speed limits were not appropriate for automobiles, safe following distances based on human reaction times may be too conservative for AVs.

Motor vehicle legislation also often uses criminal law as the mechanism to ensure compliance with road rules. For minor offences, this often involves relatively small fines, while more serious offences require proof of intent and penalties include imprisonment. Arguably, these mechanisms are not well adapted to AVs, where compliance with road rules is likely to be a function of how the AVs software and hardware are operating and liability is likely to fall on a corporation. There is also no clear analogy to the process of licensing drivers and the process for determining which party is at fault for a crash when the driving decisions are being made by proprietary computer software that is only understood by its developer.

Importantly, stretching existing frameworks does not change the detailed requirements that present barriers to AV development and deployment. For example, the Vienna Convention on Road Traffic was recently amended to deem vehicle systems which influence the way vehicles are driven to be in conformity with requirements for all vehicles to have a driver (UNECE, 2014 and 2016). However, the detailed regulations made under the convention remain un-amended. These include barriers to AVs including requirements that vehicles be designed to allow a driver to override an advanced driver assistance steering system and a limiting it to 12 kilometres per hour (Lutz, 2016).

For the time being, the hybrid approach many jurisdictions have used has been sufficient to create a space for AV testing. This may continue for a period at the commencement of AV deployment, perhaps even until AVs reach a critical proportion of all motor vehicles. Up until that point, it is appropriate that AVs comply with the norms of human driven vehicles. This was the approach taken as cars gradually replaced horses.

During this period, the difficulties arising from a hybrid approach may not be widespread. However, using a hybrid approach to regulate AVs seems unsustainable. As AVs enter deployment, policy makers and regulators will need to revisit motor vehicle regulatory frameworks and either fully adapt existing frameworks or develop a single regulatory framework that applies well to both AVs and vehicles with human drivers or a separate regulatory framework for AVs. In particular, it seems likely that road rules will need to change to reflect the capabilities of AVs and compliance mechanisms will need to shift from an ex-post criminal enforcement approach to an ex-ante product safety approach.

Regulating the impacts of automated vehicle technology

The current regulatory focus is on Automated Vehicle (AV) technology, rather than the broader impacts AVs may have on transportation. In 2015, the ITF's Corporate Partnership Board (CPB, 2015: 6) found it "could not find evidence of anticipatory regulatory action addressing the potential use cases that could result from large-scale deployment of highly autonomous vehicles, such as the provision of quasi-public transport or taxi-like operations."

This largely remains the situation today. Even the most recent AV legislation in the US State of Michigan provides little guidance in relation to the adoption path or use cases for AVs or how to approach their impacts. The only measure addressing impacts is a provision that allows AV developers to operate their vehicle to provide ride sourcing services (SoM, 2016).

Traditionally, policy makers have taken a gradualist approach to regulation in the road transport sector, regulating or taking other action in response to a development that is perceived to necessitate it. But, as deployment of AVs approaches, there are arguments for a more proactive approach with a broader focus. Beyond regulating the technology itself, some argue that government should seek to anticipate the impacts of AVs and develop plans to ensure that society is appropriately prepared (Cohen and Cavoli, 2017; 19). There is a range of areas in which AVs could impact society. This final section focuses on the impacts and mobility policy implications that arise from different AV use scenarios.

As with AV technology, uncertainty surrounds the potential impacts of AVs and the evidence is mixed. However, academic literature has provided some insight into likely scenarios relating to the impacts of AVs. Two different, likely scenarios emerge (Cohen and Cavoli, 2017; 9-12; Isaac, 2016; 7-12). Both scenarios agree that AVs are likely to bring substantial road safety benefits, could allow those who cannot drive (the un-licenced, children, the elderly and people with certain disabilities) to use a car without needing a driver and might reduce the time and financial costs of vehicle transport by removing human drivers. Beyond this the two scenarios differ markedly on what the impacts of AV introduction will be.

The first scenario involves AVs giving rise to shared mobility and collective efficiency. This scenario focusses on AVs providing mobility as a service. Shared use AVs would substantially reduce levels of individual vehicle ownership. These AVs could provide last-mile services that integrate into, and potentially complement, existing mass transit systems. Alternatively, the price reductions AVs create may favour door-to-door services, competing with bus services and, potentially, mass rail transit. Smartphone technology would provide the mechanism to access the vehicles and data analytics would allow service providers to maximise routing efficiency and convenience.

Services could be provided by ride-sourcing companies like Uber and Lyft or public authorities. Because ride sharing may be encouraged in this scenario, it could lead to better efficiency of the road network by reducing the number of vehicles, optimising public transport (thanks to automated public transport) and freight movement and freeing parking space (Cohen and Cavoli, 2017; 11). A shared mobility (i.e. ride-sharing) model would need fewer vehicles to satisfy existing road transport demand, creating opportunities to reduce congestion and emissions and reclaim road space for other purposes.

Some recent evidence is providing hope that consumer preferences are starting to change in a fashion that would allow a shared mobility scenario to develop organically. Improvements in IT platforms and the spread of smartphones have enabled substantial quality and efficiency improvements for shared mobility services, especially ride sourcing. These, combined with regulatory changes, have lowered the cost of these services for many consumers. For some consumers, shared mobility services can now provide on demand, reliable transport at a price that is a competitive substitute for individual vehicle ownership. Further, there is some evidence that ride sourcing customers more frequently travel with companions (Rayle et al., 2014), replacing the need for individual vehicle ownership and increasing vehicle occupancy. Also, Uber has stated that approximately 20% of its trips worldwide are taken using its shared ride sourcing service, UberPool.

The introduction of AVs is hoped to provide a catalyst for the expansion of shared mobility and especially shared ride sourcing services. Ford’s plan is to deliver AVs for ride-sourcing service rather than for individual ownership, at least initially. As AVs remove drivers and the costs associated with them, AVs have the potential to make ride sourcing (including shared ride sourcing) cheaper. At least one study predicts that, at entry into operation, the per mile cost of ride sourcing using an AV would be less than the per mile cost of owning an AV (Johnson and Walker, 2016).

If the above evidence signifies the beginning of a shift in consumer preferences, a shared mobility scenario may well arise organically. This would reduce the need for governments to take action to promote such a scenario. Also, as consumer preferences would have shifted in favour of shared mobility, any necessary regulatory changes would likely be less controversial than they are at present.

Equally, however, a shared mobility scenario may not arise organically. There may be a business as usual scenario. It focusses on the continuation of individual mobility, with or without private vehicle ownership. The vast majority of manually driven vehicles would eventually be replaced by AVs that are owned and operated in much the same manner as human driven vehicles are today. At best, car use would remain stable. But the lower costs and increased accessibility that AVs bring also create potential for increased demand for vehicle use. Similarly, there is the potential for "zero passenger trips" such as an AV circling rather than finding parking or someone using their private AV to return an item borrowed from a friend. All of these factors would increase vehicle kilometres travelled, taking up the additional road capacity AVs might provide, exacerbating congestion and emissions. They would also likely make it easier to travel further, increasing the potential for further urban sprawl.

As with the shared mobility scenario, there is evidence to support the likelihood of a business as usual scenario. One study in San Francisco (Rayle et al., 2014), a relatively mature ride sourcing market, raises questions about the extent of changing consumer preferences and raises questions about ride sourcing being used as a last mile service. It found that, like other shared mobility customers (Shaheen et al., 2014; Dill et al., 2014), ride sourcing customers are a relatively narrow group. On average, they tend to be more urban, wealthier, have higher education levels and own fewer vehicles than the average consumer. This raises questions about whether shared mobility is really able to expand to become a mainstream or dominant approach to mobility.

Also, a shared mobility scenario relies heavily on private ride sourcing and ride splitting services. To be a viable substitute, these services would need to generate a reasonable return to investors at prices that are cheaper than the generalised cost of private vehicle ownership. For at least some consumers, that would require ride sourcing/splitting prices that are lower than they are today. However, a number of ride sourcing/splitting service providers subsidise fares and/or are yet to provide a return to investors (Bogage, 2016). This raises questions about the sustainability of existing ride sourcing prices, let alone the ability to reduce them further. It also raises concerns about the validity of predictions relating AV ride sourcing prices to current prices. In turn, it is not clear what the price of AV ride sourcing will be and whether it will be competitive with private AV ownership.

Finally, while we cannot predict the purchase price for AVs, AV developers would want to maximize their investment returns. As a result, they would have an incentive to grow markets. Arguably, this favours a low margin high turnover model that utilizes economies of scale to spread research and development costs across as many units as possible. Such an approach is more likely to promote a business as usual scenario.

Most commentators expect the ultimate outcome to lie somewhere between each of these scenarios. They consider that different scenarios will evolve, depending on differing transport needs in different contexts and how suitable shared or individual mobility is to the relevant context. For example, a shared mobility scenario seems more likely to arise organically in dense urban areas, where individual vehicle ownership may already be low and public transport options are already of a high standard. Alternatively, they consider that a business as usual scenario may exacerbate issues such as congestion to a point where there is a transition to a shared mobility scenario at a relatively late stage of AV development (KiM, 2017).

However, they also consider a shared mobility scenario is likely to occur in a more limited number of places in the absence of government intervention (Isaac 2016, p. 9). As a result, they also expect that where exactly the future lies will turn, in part, on the effectiveness of regulation and other government interventions that influence the adoption path for AVs (Cavoli et al 2017, p. 102). In turn, there have been calls for government to start taking preparatory action to avoid the negative consequences of a business as usual scenario (CPB, 2015; 7).

There are numerous regulatory options available to governments that wish to avoid the negative consequences of a business as usual scenario and capture the benefits of a shared mobility scenario. Key measures include (Isaac, 2016; 30-31):

- Charging for the use of road space per mile, on the basis of the marginal cost
- Taxing vehicle travel
- Levies for road travel in and around areas of congestion (charges can vary by time of day, congestion levels and/or vehicle occupancy)
- Limiting public parking and/or charging for it at a commercial rate (that can vary by time of day)
- Limiting the number of vehicle registration permits and allocating them by auction
- Reallocating parking space as pick up and drop off zones.

These measures target the price of individual mobility, aiming to internalise the cost of road transport. By requiring road users to pay the full costs of their road use, such as the costs of maintaining infrastructure or congestion, these measures would provide incentives for all road users to ration their road use more efficiently. Shared mobility services (especially multi-modal, shared and last-mile services) would be more competitive under these regulatory options. Shared mobility users could flexibly shift between modes, split the increased costs with other users and avoid parking facilities. As a result, under these regulatory options, shared mobility services prices would likely increase by less than individual mobility prices. In turn, they would be more competitive with individual mobility.

Many of these options have been available to government for a number of years and none are contingent upon AV deployment. For example, Singapore has had road pricing since 1998, London's congestion charge commenced in 2003 and Stockholm's congestion tax commenced in 2007. Where these options have been implemented, they have had positive impacts on congestion, provided funding for mass transit improvements and incentivised changes in consumer preferences to other, more efficient modes of transport. However, they have also increased road transport costs to consumers, reduced the value of consumers' sunk investments in private vehicles and can be criticised for restricting freedom of movement and being inequitable to consumers who have poor access to other transport modes. As a result these are significant reforms that tend to be controversial and take substantial time to implement. For example, a congestion charge for London was first proposed in 1963, 40 years before it was implemented. They would also be more likely to obtain public acceptance in response to an existing problem, rather than in anticipation of problems that might arise in the future. As a result, while they are theoretically economically elegant and an increasing number of jurisdictions are adopting them, implementing measures that seek to internalise the costs of transport will face substantial challenges in many jurisdictions where travellers are accustomed to widespread personal vehicle use, especially in advance of AV deployment.

Given the challenges in some jurisdictions, they may wish to consider actively encouraging a shift in consumer preferences towards shared mobility more than discouraging private personal vehicle usage with punitive measures (relying more on "carrots" than on "sticks"). Governments can use regulatory and policy measures to remove barriers and facilitate the expansion of shared mobility services, effectively lowering their price and making them more competitive with individual mobility.

Last-mile shared mobility services can be facilitated through better integration of fares and information across transport modes. Transit authorities can move away from closed loop payment systems that require a specific card/ticket that they administer, to open loop payment systems that link to users' bank cards or mobile payment systems. Alternatively, they can integrate closed loop payment systems with other shared mobility services. For example, the Chicago Transit Authority (CTA) has integrated fares with IGO, a car sharing service. Consumers can use the same fare card to use CTA's mass transit services and IGO's car sharing service. Similarly, apps such as Nimbler can provide consumers with directions that integrate different modes of shared mobility, such as bike and mass transit. Practices such as these make using shared mobility services easier and, in turn, more competitive with individual mobility. Ideally, they would be expanded to allow consumers to plan multi-modal shared mobility trips, using real-time information and a single payment.

Equally, governments can remove existing barriers to shared mobility services. For example, California's Public Utilities Code prevents fares being levied on an individual basis, requiring them to be levied on the basis of vehicle mileage or time of use (CPUC §5401). Charging on an individual basis effectively prohibits ride splitting services, such as UberPool and Lyftline. The California State Legislature is currently amending legislation to remove this barrier.

All of the measures above can and, arguably, should be implemented prior to AV deployment. Doing so would assist to shift consumers' preferences towards shared mobility before AV deployment further reduces the cost of individual mobility. In turn, this may make it easier for governments to implement more ambitious reforms, allowing them to capture the benefits of a shared mobility scenario and prevent the negative consequences of a business as usual scenario from arising, rather than requiring regulators to attempt to reverse them after the fact.

Conclusion

The potential for automated vehicles (AVs) to improve road safety and mobility while reducing congestion has generated substantial excitement. However, most experts agree that society's ability to capture these benefits and minimize negative impacts depends on the presence of effective regulatory frameworks. At present, it is difficult to develop the necessary regulatory frameworks as AV technology is largely experimental (Cohen and Cavoli, 2017), creating uncertainty about how AVs will operate, how consumers will use them and how they will affect society.

In such uncertain circumstances, the current lack of a rush to regulatory action is appropriate. In the next two years, some small scale commercial operations are likely (ITF, 2017). However, a transition to mass use of AVs that are able to operate on a broad range of public roads will take decades (Isaac, 2016; Shladover, 2017). In the meantime, current vehicle safety regulations can be stretched adequately (albeit imperfectly) to accommodate the early commercial deployment of AVs. In turn, regulators will be able to use real world evidence (rather than speculation) to take action at a later stage to ensure that AVs are deployed safely.

Stretching existing regulatory frameworks will not be sufficient in the long term. Once AVs reach a critical proportion of all motor vehicles, regulatory frameworks that reflect the capabilities of AVs and the nature of the industry will be necessary. In particular, it seems likely that road rules will need to change and compliance mechanisms related to them will need to shift from an ex-post criminal enforcement approach to an ex-ante product safety approach. In the meantime, the research and non-regulatory or quasi-regulatory approaches some ITF members have adopted provide useful examples of short term good practice in relation to AV safety.

While road safety is a key concern for AV deployment, there is increasing evidence that regulators need to start preparing for the broader impacts of AVs on society. Many of the potential benefits from the introduction of AVs are dependent on mass use of shared mobility services. Experts consider, in the absence of regulatory interventions, this scenario is likely to be limited to dense urban areas, where individual vehicle ownership may already be low and high quality public transport is already available. Outside those areas, the lower costs and better accessibility that AVs should bring can be expected to drive increased demand for vehicle use. This rebound effect is likely to absorb any road capacity initially freed up by replacing the use of conventional vehicles, potentially exacerbating congestion and emissions. Increased urban sprawl as a result of the large scale use of AVs is also a concern.

The problems associated with un-priced use of infrastructure (such as congestion) exist regardless of the presence of AVs and there are numerous regulatory options available to deal with them. These measures (such as congestion charging) target the price of individual mobility, aiming to internalise the cost of road transport. In turn, these regulatory options make shared mobility services more competitive with individual mobility, regardless of when they are implemented. Arguably, these measures should be implemented now, to assist in shifting consumer preferences towards shared mobility and improve existing transport problems, before AVs make individual mobility even cheaper. In turn, societies may capture the benefits that AVs offer and mitigate their negative impacts before they arise. Otherwise, regulators will need to attempt to remedy problems after they have arisen.

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Cooperative Mobility Systems and Automated Driving

Automated vehicles could make roads safer as well as reduce congestion. Whether society will be able to capture these benefits while minimising negative impacts depends on effective regulation of self-driving vehicles. The technology is still largely experimental and mass use is likely to take decades. Today's regulatory frameworks can stretch to accommodate early deployment, but they will not be sufficient in the long term. This report reviews the range of existing service concepts for automated driving systems and technologies, the operational environments they require and assesses the need for regulatory action.

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