Review Article

Autonomous driving: a bird's eye view

Margarita Martínez-Díaz[1] ✉, Francesc Soriguera[2], Ignacio Pérez[1]

[1]*School of Civil Engineering, University of A Coruña, Campus de Elviña, s/n, 15071 A Coruña, Spain*
[2]*Barcelona Innovative Transportation (BIT), UPC-BarcelonaTech, Jordi Girona 1–3, 08034 Barcelona, Spain*
✉ *E-mail: margarita.martinez@udc.es*

Abstract: The introduction of autonomous vehicles (AV) will represent a milestone in the evolution of transportation and personal mobility. AVs are expected to significantly reduce accidents and congestion, while being economically and environmentally beneficial. However, many challenges must be overcome before reaching this ideal scenario. This study, which results from on-site visits to top research centres and a comprehensive literature review, provides an overall state-of-the-practice on the subject and identifies critical issues to succeed. For example, although most of the required technology is already available, ensuring the robustness of AVs under all boundary conditions is still a challenge. Additionally, the implementation of AVs must contribute to the environmental sustainability by promoting the usage of alternative energies and sustainable mobility patterns. Electric vehicles and sharing systems are suitable options, although both require some refinement to incentivise a broader range of customers. Other aspects could be more difficult to resolve and might even postpone the generalisation of automated driving. For instance, there is a need for cooperation and management strategies geared towards traffic efficiency. Also, for transportation and land-use planning to avoid negative territorial and economic impacts. Above all, safe and ethical behaviour rules must be agreed upon before AVs hit the road.

1 Introduction

Autonomous vehicles (AVs) are called to revolutionise not only the transportation sector but also society at large. Furthermore, they are expected to improve traffic safety and alleviate congestion while achieving a better driver (passenger) travel experience. Among others, carmakers, technological companies, researchers, and administrations have been working on AVs and their related aspects for a long time now. Outstanding progress has been made, although there are still technological problems to be solved. Meanwhile, doubts about the impact of AVs on society, economy, mobility, the environment, or other fields have also appeared. Despite being mostly considered as beneficial, there is general agreement that additional societal changes and proper government measures must accompany the AVs implementation in order to guarantee a complete success.

The complexity around autonomous driving is therefore enormous; every issue is broad and intricate and its interdependency with others cannot be overlooked. Researchers have tried to discriminate the relative importance of each issue and assess the impacts of increasing rates of AVs on the above-mentioned aspects. Both quantitative and qualitative methods have been used. However, there is no consensus on the conclusions reached so far, and neither the qualitative results nor the quantitative values proposed for parameters and thresholds should be taken strictly [1–3]. In this context, this paper presents a topic-by-topic comprehensive overview on AVs and their global effects on developed societies. Although the study is centred on passenger transport, most of the analysis can also be applied to freight transport. The final goal of the paper is to provide readers with a synoptic starting point to frame the narrower view of more specific research. Such a global view, gathered from on-site visits to top research centres in the field together with an exhaustive literature review, is a significant contribution which will help researchers, practitioners, and administrations to set up a framework where to place their contributions avoiding myopic approaches (see Table 1).

The rest of the paper is organised as follows. Section 2 expounds on all involved technological aspects. Section 3 analyses the expected impact of AVs on mobility, covering traffic efficiency and safety issues, among others. Section 4 details different social facets that could hinder the introduction of AVs in traffic flow, and also presents the aspects that support their implementation. Section 5 explains the expected influence of automated driving over land use planning, whereas Section 6 focuses on its effects on the environment. Legal and ethical issues regarding AVs are discussed in Section 7. Finally, several conclusions are outlined in Section 8. The paper ends with Acknowledgment and References sections.

2 Autonomous driving technological aspects

Although the idea of developing self-driving vehicles is not new [12–14], the lack of sufficient technological advances has thus far prevented their materialisation. In fact, despite the huge step forward experienced in the last decade, there are still technological challenges to face. This section is aimed at explaining the key technological aspects required to achieve an optimal driving environment based on AVs. Fig. 1 provides an overview of all the technological elements covered in the next subsections.

2.1 Vehicle automation levels

The vehicle's degree of autonomy is directly related to its technological complexity. The first thing then is to establish AVs classification according to their automation level. Different degrees of driving automation were first differentiated by the US National Highway Traffic Safety Administration (NHTSA) in 2013 [15], which defined five autonomy levels (from 0 to 4). One year later, the Society of Automotive Engineers released its standard SAE J3016:JAN2014 [16], updated in 2016 as SAE J3016:SEP2016 [17]. Six levels (from 0 to 5) are differentiated in this last reference, which has been worldwide adopted. Table 2 recaps the distinctive features of each level according to this standard, which in short splits the previous NHTSA level no. 3 into two more detailed sublevels. No significant differences exist between the original and the former SAE classification, but, in the later, each level is explained (and thus delimited) in greater detail.

To summarise, levels are distinguished according to who (i.e. the driver or the vehicle) is responsible for the management of the controls (braking system, steering etc.), the environment

Table 1 Literature review and contribution of the paper

Ref.	Main source of information	Technology[a]	Mobility[b]	Society[c]	Territory and environment[d]	Ethics and legislation[e]	Comments
present paper	scientific literaturein situ visitsown research projecttechnical reports	yes	yes	yes	yes	yes	comprehensive review of the state-of-the-art and practice, covering most of the related issues from an engineering standpoint, using information gathered from multiple sources
[1, 2]	scientific literature	no	yes	yes	yes	no	in deep literature review covering only some topics
[4]	technical reports	no	part	part	no	part	interesting informational works for non-professional readers. Lack of an engineering standpoint. Traffic management is overlooked
[5]	unknown	no	part	part	part	no	
[6]	unknown	no	no	part	part	no	political point of view. Regarding the mobility impacts, only safety is mentioned.
[7]	unknown	part	part	part	no	yes	political point of view. On-board technology and ethics are overlooked.
[8]	technical reports	no	part	part	part	no	a sort of outline. No considerations about traffic efficiency, safety, and impacts on land uses
[9]	scientific literaturetechnical reports	no	yes	part	part	part	interesting and informative. Key topics like technology and ethics are missing
[10]	unknown	no	yes	yes	part	part	general readers dissemination work. City-oriented. Traffic management and efficiency completely overlooked. Technology barely addressed
[11]	scientific literaturetechnical reports	part	part	yes	yes	part	all topics are covered in terms of costs. There is no explanation about the technological architecture of AVs. Lack of engineering standpoint in topics like traffic management and efficiency or safety.

[a]On-board vehicle technologies, communications, cloud, infrastructural needs.

[b]Mobility trends, global demand, traffic efficiency and management, safety.

[c]Economic impact, competitiveness, acceptability.

[d]Impact on land use, EVs, indirect environmental impacts.

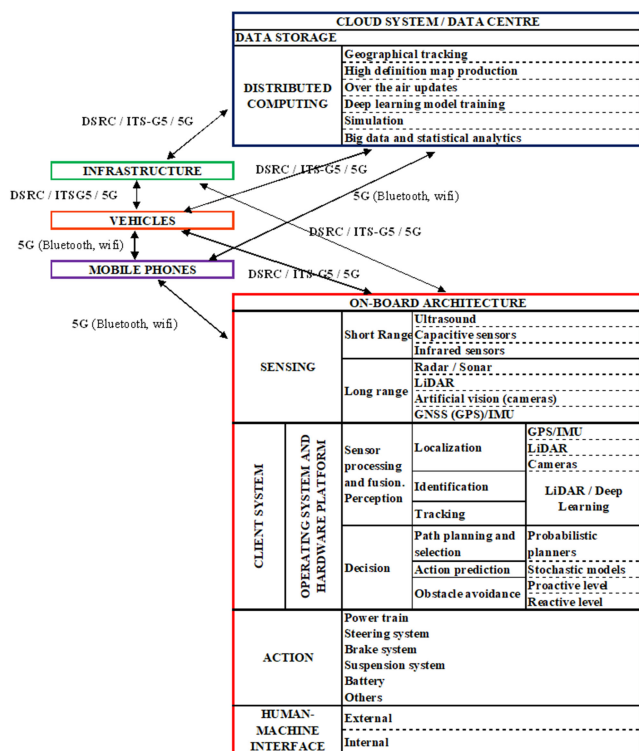[e]Ethics, liability, AVs testing, practical issues.

Fig. 1 *Autonomous driving technological architecture*

monitoring, and the global supervision of driving tasks. In addition, levels are also determined depending on the scenarios in which a particular distribution of responsibilities is suitable. Level 0 corresponds to fully manual driving. In level 1, a driver assistance system allows the vehicle to either steer or to accelerate and brake, always under the driver's supervision. Both tasks are entrusted to the vehicle in level 2, while the driver is still responsible for the driving assignment and for monitoring the driving environment. A drastic forward leap is made between level 2 and higher levels. From level 3 onwards, it is the vehicle which gathers data from the driving environment to identify both the path to follow and the possible obstacles. In level 3, the vehicle can control its longitudinal and lateral displacements in uncomplicated and well-referenced tracks. The driver is thus allowed to perform other tasks as long as it remains vigilant in case his intervention is necessary. In levels 4 and 5, vehicle duties include operational (steering, decelerating, braking, accelerating, monitoring) and tactical aspects (lane-changing, turning, signals observance, incident response etc.). Furthermore, in level 5 (full automation), the driver only has to decide the destination and waypoints (if not predetermined), regardless of the complexity of the scenario. On the contrary, in level 4 (high level of automation), the vehicle could ask the driver to regain control in complicated situations.

Despite the high prospects raised by advertisement campaigns promoted mostly by technological companies, carmakers do not expect to launch fully AVs in the short term. Apart from the experimental vehicles developed by companies like Waymo (Google), Apple, Baidu etc. and also by traditional automotive corporations, only Audi already offers a car (the new Audi A8 2019) that is ready to drive with SAE3-level autonomy in places where this is allowed by the traffic regulations. The new A8 model

will be equipped with the so-called Audi AI traffic jam pilot, which is able to drive the car on freeways and highways (i.e. where traffic directions are physically separated) at speeds up to 60 km/h. The key novelty of the vehicle is a camera that operates with artificial intelligence and creates a very accurate three-dimensional (3D) model of the driving environment. Furthermore, it includes special parking assist systems that park the vehicle either in parallel or perpendicular parking spots [18]. Although these features represent a technological advancement, it is true that the SAE3 level has only been partially reached. In fact, Audi participates with Opel, Daimler, and BMW in research projects aimed at extending the SAE3 level to usual speeds on highways, i.e. up to 120–130 km/h [19]. Most carmakers currently work on SAE3- and SAE4-level prototypes.

Taking an approximate average between different sources, it is predicted that SAE5-level vehicles could be available by 2035–2040. However, there is no consensus [4–6, 20]. The more optimistic predictions reduce this deadline by 5–10 years [5], while others increase it to 2075 [21]. Furthermore, the adoption of *ad hoc* widely accepted policies could be a much more intricate task than the development of completely reliable technologies. Covering fields from traffic management to social equity, their maturation will set the pace for the introduction of fully AVs [2, 4, 5, 7, 22, 23]. Additionally, the dates when AVs will be available and legalised will significantly differ from the later moment when they will represent a significant share of the vehicle fleet. Considering that their introduction will be progressive, a global scenario with a majority of self-driving vehicles is not expected before 40–60 years [5, 6]. AVs are likely to appear first in commercial fleets (e.g. taxis, commercial vans, shuttles etc.) and to work in limited environments (e.g. a closed city centre, a university campus etc.). SAE4-level vehicles will appear earlier, but they will represent a very small percentage of the total fleet [5].

2.2 The vehicle: on-board architecture

Despite differences among brands and models, the basic architecture of an SAE5-level AV has already been outlined. In fact, there is a lot of research on the subject coming either from private companies or public institutions [24–30]. This architecture is usually divided into four parts: (i) the sensing system, (ii) the client system, (iii) the action system, and (iv) the human–machine interface (HMI). Table 3 summarises the most relevant technologies used. All of them (and the used acronyms) are explained in the next subsections in more detail.

2.2.1 Sensing system: It plays a key role in automated driving. This system is basically made up of sensors and it is responsible for collecting all possible data from the vehicle environment, in any boundary conditions and in real-time. Sensors can be broadly divided into short range and medium/long range. Ultrasound, capacitive, or infrared sensors are short range. Their functionality and the interpretation of their signals are quite simple. On the contrary, medium/long-range sensors pose significant challenges, as each of them performs well in some conditions but is unadvisable in others [31]. This means that AVs must be equipped with different types of sensors, so that they complement each other: individual inefficiencies are compensated by means of data fusion. For example, the combination of the following medium/long-range sensors has produced promising results:

- *Radar and sonar*: both are mainly used as a last resort to avoid obstacles. They provide basically the distance and the speed of the nearest object in front of the vehicle path. These data do not require much processing and subsequent decisions are quickly transmitted to controls to perform emergency actions. One particular problem of the radar is that it lacks peripheral vision.
- *LiDAR*: it is a medium-range rotating laser with high accuracy even in bad weather conditions. It illuminates targets with pulsed laser light and measures the reflection times to calculate distances. LiDAR is mainly used to produce high definition maps, to localise moving objects, or to detect obstacles in front of the vehicle. The main problem with the LiDAR is that it provides a 'shape description' of the environment, which is not

Table 2 Summary of SAE automation levels

SAE level	Controls	Environm. monitoring	Driving superv.	Scenarios
0: all on	driver	driver	driver	all
1: hands on	driver	driver	driver	some
2: hands off	driver + vehicle	driver	driver	some
3: eyes off	vehicle	vehicle	driver	some
4: mind off	vehicle	vehicle	driver + vehicle	some
5: all off	vehicle	vehicle	vehicle	all

Table 3 Main on-board technologies of AVs

Technology	Subsystem	Key functions
ultrasound	sensing system	detection of very close obstacles. Very useful for parking assistance
capacitive sensors	sensing system	short-range detection of obstacles, detection of driver's fingers when approaching the internal interface
infrared sensors	sensing system	short-range detection of obstacles, especially in low-light conditions
radar	sensing system	short/long-range detection of obstacles, real-time tracking of their speeds, last chance for collision crash avoidance
sonar	sensing system	especially used for sudden obstacle avoidance. Good functioning with rain
LiDAR	sensing system	long-range accurate (3D) identification of obstacles, self-localisation, HD maps creation, navigation, tracking
artificial vision	sensing system	object recognition and tracking, detection of colours and fonts, interpretation of road markings and signs, generation of (3D) images of the vehicle's environment
GPS	sensing system	self-localisation, HD ground maps creation, navigation
IMU	sensing system	self-localisation, HD ground maps creation, navigation
hardware platform	client system	computing tasks (perception and decision) physical support
operating system	client system	data fusion and interpretation, decision-making
mechanical components	action system	execution of decisions
internal interface	human–mach. int.	passenger information, indications reception
external interface	human–mach. int.	communication with/warnings for external agents

sufficient to differentiate between individual entities. A normal LiDAR rotates at 10 Hz and takes 1.3 M readings per second.

- Artificial vision: AVs usually have eight or more cameras aimed at recognising elements and at the vehicle tracking (e.g. the lane path, traffic lights, pedestrians etc.). Cameras are affected by light changes and bad weather conditions. Furthermore, their data treatment is computationally intensive.
- GNSS (GPS)/IMU: the most used global navigation satellite system (GNSS) is the American GPS (global positioning system). Although the presence of buildings, tunnels etc. obstructs the signal and introduces noise, it can be considered as an accurate positioning system. However, GPS has long updating time intervals, which is undesirable when working in real time. A common solution to the problem is to use inertial measurement units (IMU) which supply frequent position estimates with coarse errors. Therefore, the combination of both systems provides accurate and frequent updates for vehicle self-positioning [29].

Despite the huge evolution of the sensing system in the last decade, it still needs to evolve to support the SAE5-level AV. Today, the goal of researchers is to design a sensor system that provides complete, updated, and accurate data at high speeds and in all possible weather and lighting conditions.

2.2.2 Client system: It represents the brains of the AV, with two main responsibilities. First, it must process all the collected data and extract meaningful information in order to interpret the environment (perception) and set the relative position of the vehicle. Second, it must decide on the next actions of the vehicle (decision).

Perception consists of three parts: positioning, detection, and tracking. All of them involve fusing data from different sensors with the support of HD maps. Data fusion is performed by algorithms that work at different levels: low, medium, and high. At the low level, raw data from similar detectors is combined to generate a bigger database that will be processed in later steps. At the medium level, pre-processed data from different sensors is fused. Finally, the fusion at the high level implies the final decision task, as it combines partial decisions taken according to perceptions coming from single sensors. Besides, deep learning techniques are being used for object recognition and tracking. This is a machine learning process using a neural network with different hierarchical levels. Deep learning turns out to be very appropriate to handle large amounts of data and achieves great accuracy without the need for human supervision. In fact, deep learning is surpassing traditional computer vision techniques.

Once the environment has been recognised and understood, effective and safe decisions must be taken and transmitted to the action system (see Section 2.2.3). The main parts of this decision task include action prediction, path planning and selection, and obstacle avoidance. The vehicle reproduces to some extent the human decision-making process. However, human reasoning is very flexible and able to adapt even to chaotic boundary conditions. This flexibility is not considered in traditional automatic systems, which are programmed to respond to typical circumstances or to follow a set of predefined rules [26]. For example, an AV programmed with strict rules could not make a lane change to leave a freeway in very dense traffic conditions. To include this flexibility, stochastic decision-making methods are considered. For instance, stochastic models combined with probability functions are used to predict the movements of the nearby vehicles or other moving agents. The next step is the path planning and selection, i.e. elaborating navigation plans in real time and in a changing and moving environment, which is probably the most difficult part. Deterministic methods and approaches which consider all the possible paths in order to choose the one with minimum cost are computationally intensive and unfeasible to be applied in real time. Approaches based on probabilistic planning aimed at optimising the success probability of the navigation plan are preferred. Finally, at least two obstacle avoidance mechanisms are implemented. The first one, proactive, anticipates dangerous situations by continuously predicting safety variables such as

minimum gaps with regard to other vehicles. If they are interpreted as risky, the system recomputes the path planning again, at least at a local level. The second mechanism is reactive and only applies when the first mechanism was unable to avert a collision. Mainly based on radar data, the vehicle overlooks control decisions underway and acts to avoid the obstacle. In any case, if one of the previous phases fails or returns inconclusive results, a conservative decision is taken, meaning that safety prevails to optimality.

The previous perception and decision tasks demand a very powerful hardware platform and an extremely advanced operating system. The hardware platform basically consists of processors and accelerators, for which dedicated companies (e.g. Intel, ARM, Qualcomm, Nvidia etc.) offer different solutions. For example, Intel develops platforms with a flexible architecture. This architecture usually includes central processing units, field-programmable gate arrays, and hardware acceleration technology for deep learning [31], which allow for both sequential and parallel processing. This partition is essential to handle the enormous computation workload involved in automatic driving. Most current AV prototypes have more than one compute box, as a backup in case one fails. This considerably increases the vehicle cost. Furthermore, each box consumes a large amount of energy and generates a lot of heat that must be dissipated. There is common agreement that the robustness of the system should be achieved without doubling the hardware. To that end, other solutions are being developed and tested. These include the research on system-on-chip solutions, i.e. tiny integrated circuits made up of a microcontroller with advanced peripherals like graphics processing units, connectivity components, coprocessors etc. These configurations require less space and consume less energy, but still they do not have enough data processing power. In this sense, it is explored the possibility of transferring some of the perception and decision tasks to the cloud system (see Section 2.4), relying on the communications network (see Section 2.3).

On its side, the operating system is the computing framework which integrates all the algorithms involved in the perception and decision tasks. Two main requirements must be fulfilled: (i) it must run and process the data extremely fast in order to respond with real-time decisions, and (ii) safety cannot be compromised, even in the case of partial or total failure. Operating systems coming from robotics and supported by the cloud system are being considered [29].

2.2.3 Action system: Made up by the mechanical parts of the vehicle (i.e. steering system, braking system, powertrain etc.), it executes the decisions of the client system. Although out of the scope of this paper, it is highlighted that this system no longer poses a problem.

2.2.4 Human–machine interface: HMIs are a combination of hardware and software that handle passenger-to-vehicle and vehicle-to-passenger interactions in real time. By interacting with the HMI, passengers obtain information about the driving performance and the environment and can also ask the AV to perform particular tasks by providing the inputs that the vehicle requires. HMI for fully AVs will be mainly informative and entertainment-related. They are conceptualised as minimalist, featuring inside and outside vehicle interfaces. The external interface, which primarily consists of light bars and points, would inform external agents in advance about the next movement of the vehicle. Passengers would receive this information and other related to the environment from the internal interface, with the sole purpose of making them to feel more confident with the automatic driving. The internal interface would also receive the passenger desires regarding entertainment or on-board conditions (e.g. inside temperature). A very welcomed HMI proposal was presented during the 2016 Grand Cooperative Driving Challenge in the Netherlands. The proposal removed most parts of the traditional cars HMIs (the steering wheel, pedals, gearshift etc.), and instead, it included a large touch monitor as well as separate controls for air conditioning and window management. The screen showed exclusively some information about the driving environment and only allowed the 'driver' to start and stop the system and to choose

the destination. In this design, any interaction with dynamic information systems, like entertainment or maps, relied on the use of personal mobile devices. Designers argued that, in this way, media could be personalised and adapted to the preferences of carmakers and users [30].

2.3 Communications

The generalised use of the adjectives 'autonomous', 'self-driving', or 'driverless' to describe vehicles with different autonomy levels (as presented in Section 2.1) is inaccurate and misleading. Note that the first two adjectives seem to indicate that future vehicles are called to drive on their own without any external support. Nothing could be further from the truth. As it will be discussed later on, society will only take advantage of self-driving vehicles if they behave cooperatively. In this regard, both vehicle-to-infrastructure (V2I) and vehicle-to-vehicle communications will play an essential role. The more global term V2X (vehicle-to-everything), which includes the former interactions as well as vehicle-to-person and vehicle-to-network communications, has also gained momentum in the last years.

V2I communications are essential for traffic management and AVs coordination. Firstly, the surveillance systems installed on the infrastructure must gather global and local data on traffic state, pavement conditions, weather etc. After these data are analysed in real time (either in a traffic management centre or in the cloud), they feed the underlying traffic flow models, and specific actions are suggested or imposed to a particular group of vehicles. Despite active traffic management strategies from real-time information already exist (e.g. real-time ramp metering, dynamic usage of hard-shoulders, activation/deactivation of HOV lanes etc.), today's indications need to be communicated via traffic lights or variable message signs, and their level of fulfilment depends on drivers' decisions. This interaction between the infrastructure and the vehicle will radically change in the future V2I cooperative environments. In this new context, the information provided by the infrastructure will be directly transferred to the vehicle controls using short-range wireless communication systems to automatically implement the optimal speeds, gaps etc. On their side, V2V communication allows interaction and collaboration among nearby vehicles without the intervention of a centralised entity. AVs exchange information locally allowing the coordination of their decision-making processes aiming to a smoother traffic. In this case, the AVs are also the surveillance elements and the structure of the traffic management is totally decentralised. This system's decentralisation together with the movement of the data sources makes more challenging the acquisition of the global perspective required for the implementation of network-wide traffic management strategies. Surely, traffic management will rely on a fusion of both, V2I and V2V, systems. In any case, establishing a powerful and reliable communications network is essential.

Moreover, there is a need for common communications standards shared among administrations, automakers, technological companies etc., to enable all possible interactions. Both short- and long-range communications are called to shape the so-called connected vehicle environments. Some work has already been done in this aspect. For example, in the USA, most efforts are devoted to dedicated short-range communications (DSRC). It is a two-way short-to-medium wireless communication technology based on the IEEE 802.11p standard, the 1609 Wireless Access in Vehicular Environment (WAVE Communication) protocol in the USA and the TC-ITS European Standards of the European Telecommunications Standards Institute [32]. The US Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz band in 2003 to be used by intelligent transportation systems (ITS) for vehicle safety and mobility applications [33]. In fact, US authorities completely rely on the suitability of DSRC for V2X interactions. They stress that its designated licenced bandwidth ensures secure, reliable, and high-speed communications. Specifically [34]:

- The fast network acquisition allows communication to be established immediately. This fact is critical, for example, for active safety applications.
- Messages are transmitted among applications in milliseconds, i.e. with very low latency.
- A high level of link reliability is provided, and thus information is delivered in spite of vehicle speeds, weather conditions etc.
- It can manage huge amounts of data: vehicles could have 360° awareness of the roadway conditions and of the nearby vehicles, as well as of the risks emerging at distances up to 300 km, without compromising the capacity of the communications network.
- Safety messages can have priority over any other message.
- Widely accepted standards which favour interoperability.
- Message authentication and privacy are guaranteed.

Furthermore, US authorities try to avoid sharing the 5.9 GHz spectrum for other purposes than V2X, as, for example, it is requested by telephone service providers; it is considered that any interference could cause an interruption or delay in the delivery of information, whose consequences could be critical. Other countries, like Canada, aim to allocate the same 5.9 GHz. spectrum in the context of the IEEE 802.11p standard for V2X in the short term [6].

The EU, for its part, harmonised in 2008 the use of the 5.875–5.905 MHz frequency band for safety ITS applications [35]. It is proposed a short-range wireless communication technology, the so-called ITS-G5, an evolution of the 802.11 wireless standards. In good conditions, its communication range reaches 1 km, although 0.5 km are considered as the reliable average. ITS-G5 was designed as a standalone system. However, the EU is currently not confident about the self-sufficiency of the network and tries to overcome some weaknesses which could also affect DSRC. For instance, ITS-G5 uses an *ad hoc* network topology (i.e. without a fixed structure) meaning that all the equipped agents, such as vehicles, motorbikes, bikes, pedestrians, infrastructures etc., can directly communicate with each other without going through an access point or base station. Given this network architecture, there is no superior entity who could manage an overload situation. Some proposals that suggested using different frequency channels in different European countries or prioritising particular communications were disregarded in favour of interoperability and equity. Only the highest priority for messages related to accidents is considered. In this context, the EU works on the implementation of a decentralised congestion control (DCC) of communications networks. DCC is the collective name of different techniques that try to avoid high network channel loads [36]. Different strategies are being tested: the restriction of the number of information packets generated by each vehicle, the reduction in the output power of vehicles' transmissions (i.e. this shortens the effective communication range), the shortening of the time period the information is available in the channel etc. All of them would act progressively, based on the real-time load of the channel. Initiatives to avert interferences among information packets are also on the table.

Besides the *ad hoc* wireless short-range communication networks, there is also an increasing interest in the use of mobile communications for V2X interactions (see Fig. 2). For mobile phone companies and, in particular, for some automakers, future 5G cellular networks could support additional services, like on-board mobile entertainment, while keeping the quality and security of V2X communications [37]. Furthermore, they value the fact that 5G is independent of the infrastructure to be advantageous, as its full implementation would be easier, faster, and cheaper than that of DSRC or ITS-G5. In fact, public administrations, like the *Dirección General de Tráfico* (DGT) in Spain, primarily opt for this kind of cellular communications because of the characteristics of the vast Spanish road network (>30,000 km in the primary road network, half of that composed of freeways). The costs for carmakers would also be lower, as the insertion of a single chipset in the vehicle would suffice. 5G technology is expected to be 100 times faster than current 4G LTE wireless technology [8].
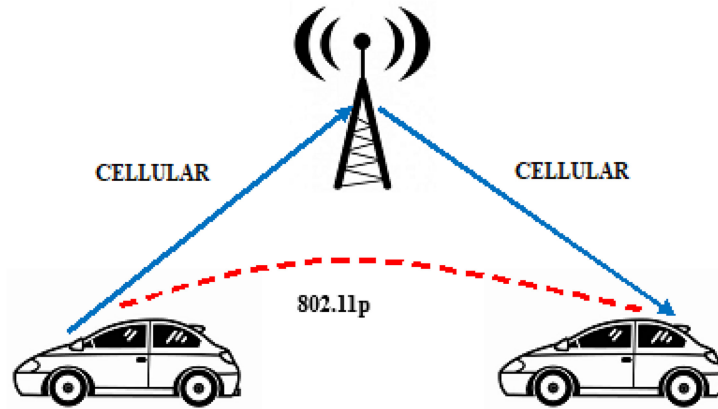
Fig. 2 *V2X communication systems: cellular device-to-device versus IEEE 802.11p short-range wireless system*
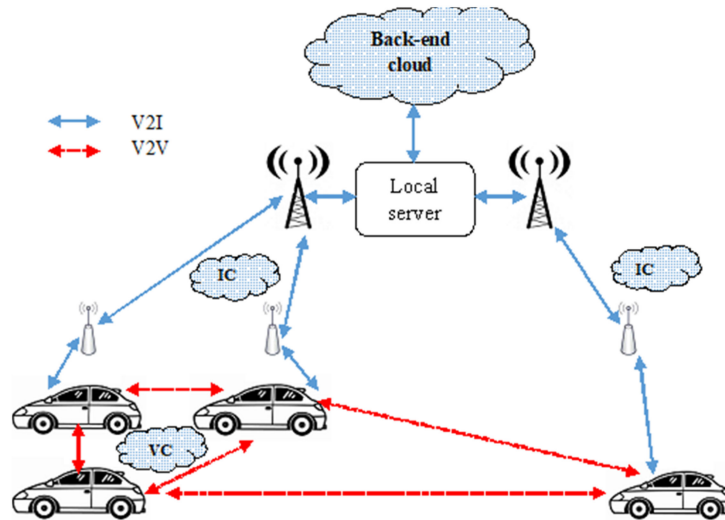

Fig. 3 *Example of VCN configuration [42]*

Despite the economic benefits of relying on 5G and on the current cellular communications' network, it is not expected that 5G will match all the requirements of V2X, at least in the short term. Experts opt for the higher level of reliability of DSRC or ITS-G5 systems [38], exploiting the fast and direct communications among 802.11p equipped devices via the random-access protocol [32, 39]. In spite of this, the EU is committed to support 5G, both for cellular communications and as a complement to ITS-G5 [40]. They aim at a hybrid communication system that includes multiple technologies and ranges [41]. The ITS Joint Programme Office of the US Department of Transportation is taking the same action.

2.4 Cloud requirements

Cooperative autonomous driving (CAD) is an extremely complex process that demands the reception, broadcast, and processing of large amounts of data, in addition to the ability to perform subsequent decision-making in real time. In this context, on-board equipment requires the support of an external computing system, such as a cloud platform. Ideas about the configuration, goals, and capacity of this platform have evolved in parallel to vehicle and infrastructure automation.

One option could be the configuration of a distributed cloud computing system among the vehicles sharing a road section. Each vehicle acts as a mobile node and creates a temporary and more powerful cloud with other vehicles within the area. Through this network, vehicles share data and their (limited) computational and storage resources [42]. This is the concept behind VANETs (vehicular *ad hoc* networks). They arose to support the growing number of wireless products that can be used in vehicles (mobile phones, long distance operating controls, tablets etc.) and currently are the foundation of V2V and V2I communications. AVs equipped with sensors, wireless communication modules, and processing and storing resources could cooperate with each other and with the infrastructure (via road side units – RSU) to support different applications related to safety, automated toll payment, traffic management, navigation, entertainment etc.

Although many administrations and research centres still work on the VANET concept [43], doubts about their ability to fulfil all the requirements of a CAD environment have arisen. For example, despite VANETS can involve a wide space range, vehicle movement causes each created network to be temporary, i.e. instable and of random size. Therefore, VANETs on their own do not always allow for the establishment of a reliable, sustainable, and effective global network to support applications. The next step in this direction would be to merge these temporary clouds with a traditional cloud, resulting in what is called a vehicular cloud network (VCN). Temporary clouds could be used for the simpler tasks, while the traditional cloud would provide larger storage capacities, ensure robust and efficient communications, and allow complex distributed processing [42, 44]. For example, VCN could update an HD map in real time (a key and challenging tool to correctly position vehicles), test new algorithms before their implementation in the client system, complement the deep learning models of the system etc. A well-accepted VCN architecture consists of a vehicular cloud (VC, a kind of VANET), an infrastructure cloud, and a back-end cloud [42]. Fig. 3 sketches this architecture, and Table 4 indicates the scope and possible applications of each of these components for an urban area. This is a favourable environment, because good communications as well as most of the vehicles with medium–low speeds are supposed to be guaranteed.

An even more advanced concept is that of the Internet of vehicles (IoV), which is derived from the idea of the Internet of things. IoV would be an open integrated network system composed

Table 4 VCN configuration

|	VCN component		
	Vehicular cloud	Infrastructure cloud	Back-end cloud
involved entities	vehicles	vehicles infrastructure	vehicles infrastructure global server
scope	local (VANET)	local (RSU surroundings)	large geographical area
examples of application in urban areas	video surveillance, tracking, parking assistance, vehicle safety, warnings,…	remote navigation, HD maps support, traffic management,…	extensive data storage, high-level computation, large bandwidth applications (e.g. multimedia)
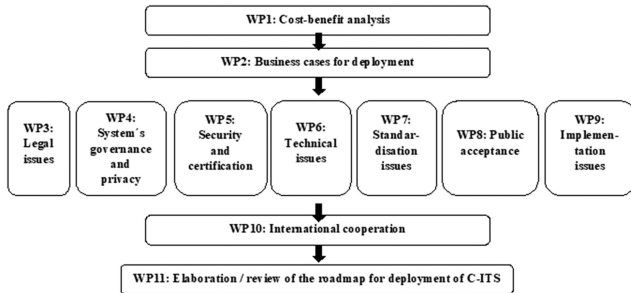
Fig. 4 *European C-ITS work packages*

Table 5 V2I day 1 and day 1.5 services of the European C-ITS platform

Services	Bundle[a]
hazardous location notification	2-motorway
road works warning	2-motorway
weather conditions	2-motorway
in-vehicle signage	2-motorway
in-vehicle speeds limits	2-motorway
probe vehicle data	2-motorway
shockwave damping	2-motorway
green light optimal speed ad./time to green	3-urban
signal violation/intersection safety	3-urban
traffic signal priority request by designated vehicles	3-urban
off-street parking information	4-parking
on street parking inf. and management	4-parking
park and ride information	4-parking
inform. on AFV/charging stations	5-smart routing
traffic information and smart routing	5-smart routing
zone access control for urban areas	5-smart routing
loading zone management	6-freight
wrong way driving	9-wrong way

[a]Bundles 1–3 refer to 'day 1' services. Bundles 4–9 refer to 'day 1.5' services. Those bundles not included in the table refer to V2V interactions.

of multiple users, vehicles, things (on-board sensors, infrastructures, management centres, the environment, mobile phones, computers etc.) and networks aimed at globally and continuously obtaining, processing, and managing all data in different ways and for different purposes, based on demands. IoV should be able to provide services to even a whole country without sacrificing the use of advanced techniques like deep learning, artificial intelligence etc. [45]. The complexity of setting up IoV is evident, and even if possible, it will not be available in the short term.

Most probably, the AV cooperative schemes that will be deployed first will be linked to V2I interactions where physical management centres will play an important role. In this context, a local station coordinates the information interchange among vehicles within its influence area and, if necessary, transfers data to nearby stations. Part of this information is processed and the (simplified) result is forwarded to vehicles. In other words, management centres do not only coordinate driving; they also help vehicles with their storage and computational tasks [46].

2.5 Infrastructural needs

Support from the infrastructure will be essential for the success of automated driving [5], and therefore, advances in vehicle automation must be accompanied by improvements in the infrastructure. For example, road signs and marking must be clear, properly located and in good condition, enabling vehicles to recognise lanes, speed limits etc. [47]. It would be also desirable to avoid sharp changes in slopes and curvatures to facilitate vehicle environment monitoring. While this could be achieved in the primary road network with a relative effort, in the vast network of secondary roads it will be specially challenging or even unfeasible, given the budget limitations for their disposal and maintenance.

The technological update of the infrastructures will also be necessary, consisting in the deployment of suitable V2I. A reliable and powerful V2I adapted infrastructure is considered to be the first step in making CAD possible. This adaptation will include (i) the adoption of a powerful and secure wireless communication system, (ii) the elaboration of standards that ensure interoperability, (iii) the development of data treatment protocols that guarantee privacy and prevent cyber-attacks, (iv) changes in legislation to include the former points, and (v) driver education seeking for proper responses to infrastructure warnings [48]. Administrations are making efforts in this direction. For example, the Directorate-General for Mobility and Transport (DG MOVE) of the EU promoted the creation of a multidisciplinary platform aimed at boosting an optimal cooperative driving environment in Europe. Shaped by European State governments (25%), automotive companies (17.50%), C-ITS relevant European associations (8.75%), service providers (8.75%), as well as insurance companies, regional and local governments, road infrastructure managers, telecommunications industries, user associations etc., the platform proposed in 2016 an initial roadmap for the implementation of cooperative intelligent transportations systems (C-ITS) in the EU [36]. Some particular working packages were defined to this end (Fig. 4). In this document [36], CAD was expected to come to reality in 2030. Its proposal for a gradual C-ITS implementation was more detailed (see Table 5). According to the trade-off between benefits and costs and to the maturity of the technology, they defined a list with the services that should be implemented in a first phase (i.e. 'day 1 services': bundles 1–3) and those which could wait for a second phase (i.e. 'day 1.5 services': bundles 4–9). Table 5 shows the V2I interactions considered. In their report from 2017, the degree of compliance of the former planning was assessed and more measures were implemented [41] to achieve a greater compliance.

For its part, the US Department of Transportation has its own plan to develop what is called 'The Connected Vehicle Path' (see Fig. 5) [49]. This includes the deployment of V2I and the V2V rulemaking, as the NHTSA will also regulate whether and when carmakers will have to install V2V technologies in new vehicles. In this plan, which arose when V2I deployment in the USA were in the early stages, 80% of the national intersections are expected to be V2I capable by 2040. Today, only small V2I tests have been carried out.

Besides the physical and technological update of the existing infrastructures, the idea of constructing smart roads specifically dedicated to AVs has also been considered. However, further analyses advise against them for the following reasons:

• Initially, when the penetration rate of AVs is low, only a small part of the driving population would benefit from the significant expenses incurred.

- The current road network in most developed countries is extensive and has good quality standards. The construction of additional networks would lead to their underutilisation and infringe upon the idea of a sustainable development.
- Traditional vehicles will be on the road for a long time. It has already been proven that a mixed environment with at least 30% of AVs sharing roads with human-driven vehicles would be beneficial from the point of view of traffic efficiency and safety [50].
- The high cost of smart roads could lead to problems of equity or segregation when deciding where to implant them. These issues can also arise when equipping current roads, although to a smaller extent.

3 Impact of self-driving vehicles on mobility

AVs will have implications for transport and mobility beyond safety and comfort improvement. In fact, they are called to boost a paradigm shift towards a more sustainable and conscious mobility. To date, research on automated driving has been mainly vehicle-centric and the influence of AVs on traffic efficiency, congestion, or mobility patterns has not been addressed with the same intensity. Although some studies have partially focused on these issues, many doubts remain. This section reviews the current state-of-the-art on these topics and highlights the knowledge gaps that require further research. The section is mainly focused on passenger transport.

3.1 New trend towards vehicle sharing

During the last decades, an increasing demand for sustainable development has grown in developed societies. What started primarily supported by young people has evolved to a transversal societal movement which has already reached administrations. The sustainable development is applied to all fields of human life, and also to transport and mobility, which are considered to be clearly unsustainable due to the high levels of congestion and pollution generated. Together with economical and practical reasons, the concern for sustainability fosters a change of mind, still in small niches of the urban society, in which vehicle usage is seen more profitable than vehicle ownership. This growing tendency is perceived by carmakers, who have invested huge efforts during the last 100 years in popularising the ownership of the car, and today are exploring new business models as mobility operators in addition to vehicle providers. From the perspective of the individual transportation (i.e. aside from the promotion of mass public transportation), a key objective is a better amortisation of passenger vehicles through sharing. In fact, private vehicles are parked for 95% of their life, on average. Several vehicle-sharing services have been proposed, which can be divided into two main groups: ride-hailing and car-sharing systems. In ride-hailing, users with partially common routes connect through a mobile app or a website to share a vehicle. This vehicle could belong to one of the passengers (e.g. BlaBlacar, Croove, Lyft) or to the company managing the system (e.g. Tesloop, Uber, myTaxi), which in any case receives an economic benefit. Car-sharing responds to a different concept. It is not a trip what is shared with other passengers, but a vehicle fleet which is made available for its shared use to the members of the community (e.g. Zipcar, Flinkster, Car2Go, DriveNow). While two-way car-sharing (i.e. when the vehicle must be returned to the same location of pick-up) can be seen as a car rental service, one-way car-sharing (i.e. single origin–destination trips) represents a new concept for urban mobility. Different system configurations for one-way car-sharing have already been put into practice. On the one hand, there are station-based systems, where users must pick-up and leave vehicles in predetermined stations. On the other hand, there are free-floating systems which lack stations. In this free-floating configuration, there is a delimited service area where users can find and leave the vehicle at any available parking spot. In both configurations, a reservation is usually mandatory. Payment is often made through a mobile app depending on the distance driven and the time the vehicle has been occupied. Some companies also offer flat rates. A
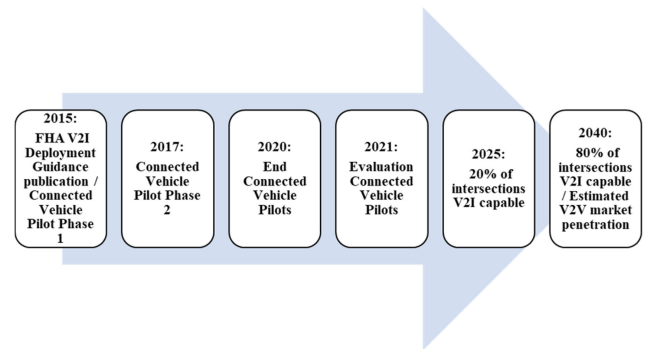

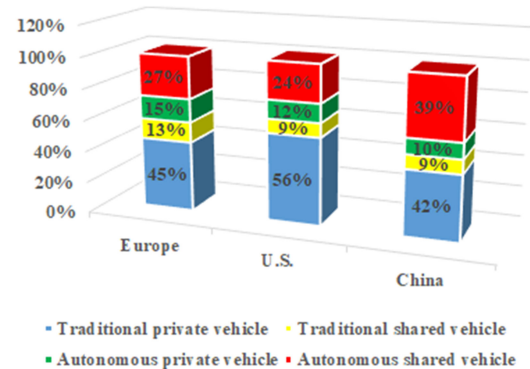**Fig. 5** *US DOTs connected vehicle path deployment plan*

Fig. 6 *Usage patterns for passenger vehicles by 2030*

more informal kind of two-way car-sharing system is peer to peer. In this case, there is not a company which owns the vehicle fleet, but private owners who rent their vehicles to others while they are not using them (e.g. Getaround).

Although currently <1% of the trips travelled in Europe correspond to car-sharing systems, it is expected that vehicle automation will boost their utilisation. On the one hand, traditional carmakers and start-ups have found a niche market in these services to become mobility operators, and the supply of car-sharing services is thus increasing. Furthermore, administrations conceive car-sharing as a means of reducing the vehicle fleet and thus parking needs and congestion to some extent. On the other hand, AVs are perfect candidates to support these services, as they are expected to be safe, efficient, electric, and autonomous. The autonomous attribute allows the self-distribution of vehicles within the service region, greatly simplifying operations and reducing costs of one-way car-sharing and hailing systems to very low values [9–11, 51, 52]. A recent detailed study estimated a cost of $0.20–0.40 per passenger and mile for an urban public system of shared electric AVs, with an average occupancy of three to six passengers. Obviously, higher costs are forecasted if users were to travel alone in the vehicles. Additionally, the high price of AVs will prevent general ownership. In this context, vehicle ownership is expected to decrease progressively in urban areas, while it could remain basically in rural areas or as a status symbol. Nevertheless, research has proved difficult to quantify the future usage of sharing systems, as it depends on many factors: service area, penetration rate of AVs, society welfare, public transportation supply etc. [53, 54]. Considering that SAE4-level vehicles are already suitable for implementing 'autonomous' sharing services restricted to a limited (mainly urban) area, and in accordance with their estimated penetration rates, approximate values have been obtained. Fig. 6 shows the average forecasts for 2030. According to them, China will lead the use of AVs integrated in sharing services and also the abandonment of vehicle ownership. On the contrary, the USA are expected to maintain quite a big rate of private vehicles, probably related to the dispersion of their population [5].

The adoption and popularisation of car-sharing systems is not free of risks. In the absence of an adequate planning and pricing of the service, it could become a competitor for collective public transportation systems. Some public transportation users could

decide to pay a bit more to travel more comfortably and shift to car-sharing or hailing options [55]. As collective transportation systems are more efficient in dense mobility environments and exhibit economies of scale [56], a reduction in their demand due to a shift to car-sharing options could imply a global increase in costs to satisfy overall mobility needs. This result would be contrary to the sustainability objective pursued. Possibly, this situation will be avoided by the implementation of the so-called mobility as a service (MaaS), also known as transportation as a service [57–59]. MaaS is a mobility solution that offers tailor-made travel sequences based on the individual user needs. A single mobile app or website combines transportation options from public and private providers, handling everything, from trip planning to payments. Users can pay either per trip or a monthly fee for a given limited distance. The MaaS concept can also be applied to freight transport and it is expected to spring up with vehicle automation. In this context of integrated transportation, self-driving buses will be competitive [60], and could also serve high demanded long-distance routes out of the area of operation of the previous on-demand services. Besides, current transportation modes will need to adapt to the new scenario: traditional taxis and mass public transports not integrated in sharing or MaaS will fall behind [6, 9, 60, 61]. Further research is needed to design these comprehensive on-demand transportation systems in a sustainable and cost-effective way. Some issues to overcome include the integration of the elderly or people with special needs, the coordination of the integrated modes to achieve a sustainable transportation system, and the extension of the service out of the cities [62].

3.2 Expected changes in travel demand

As discussed previously, vehicle ownership is expected to diminish in developed countries due to the high price of AVs and due to the introduction of sharing or on-demand mobility solutions. In fact, the vehicle fleet has been predicted to decline by 25% in the EU (from 280 to 200 M units) and by 22% in the USA (from 270 to 212 M units) by 2030 [5].

On the contrary, vehicle automation is expected to imply a 3–27% escalation in private car travel demand [2]. This expectation is primarily linked to the reduction in transportation costs (see Section 4.1) which will be translated to an increase in the number of kilometres travelled by car per person and day [63, 64]. Recent estimations predict this increase to be 23% in Europe, 24% in the USA, and 183% in China by 2030 [65]. The harmful effects of the increase in the travel demand by car could be attenuated by a simultaneous increase in the average occupation of AVs. Researchers foresee a change for passenger cars from the current 1.3 to 2.3–3 pax/car, depending on factors like the public transportation supply, the time of the day, and the pricing of AVs services [66–68]. Other reasons leading to an increase in car travel demand include the global population growth, the increase in the industrial and urban sprawl, and some induced demand (i.e. mode shifts from pedestrians or collective transportation users towards AVs) [69]. Surveys conducted in several US states concluded that this induced demand can be significant, as many trips would not have been made if public transportation or walking were the only options [70]. Additionally, AVs will extend the user spectrum to non-drivers, minors, elder people, or people with special needs. In the USA, the increase in the annual vehicle miles travelled (VMT) of people older than 19 years related to these groups is expected to reach 14% [65]. Finally, there will also be empty vehicle trips driven either by private AVs to park themselves or by shared AVs between successive clients.

3.3 Traffic management in the era of AVs

Despite the efforts made by traffic administrations, congestion continues to be a severe problem, especially around big cities and industrial areas. Automation could help to improve this situation as long as vehicles share data and their objectives aiming to benefit the entire system. In other words, cooperation between AVs will be essential for traffic efficiency in the era of AVs. However, vehicle automation has initially focused on safety and comfort, leaving traffic management and coordination aside. AVs' driving (in this

section, AV refers to SAE3 or higher levels) is being designed based on very conservative parameters. For example, the headway (i.e. time period between the passages of two consecutive vehicles) is usually set around 2 s, while for an average human driver, this is 1 s or less [71]. The values adopted for other AVs' design parameters like the acceleration rate, braking capacity, space gap etc. also contribute in shaping a much less aggressive driving behaviour of AVs with respect to human driving. Obviously, this contributes to safety and comfort, but the consequences over traffic efficiency would be detrimental. In addition, uncoordinated AVs would make 'selfish' decisions. They would choose their routes, individual speeds, lanes, lane-changing etc. overlooking possible disturbances to other vehicles and to the efficiency of the network as a whole. In this context, researchers predict a progressive reduction in the average freeway capacity with the increasing penetration rates of AVs. Freeway capacity could be reduced from the typical 2300 to ∼1700 vehicles/hour/lane upon mass penetration of AVs [72]. Although more aggressive design parameters of AVs would attenuate the problem, this is not a feasible solution as comfort and the acceptability of aggressive AVs would be seriously compromised.

On the contrary, traffic could become more efficient if AVs cooperate. AVs cooperation consist in the exchange of information with the objective of making decisions from a global perspective, prioritising the performance of the whole system over individual benefits. It has been proven that AVs cooperation would be beneficial even in a mixed environment, i.e. with cooperative autonomous vehicles (CAVs) sharing roads with traditional vehicles. A penetration rate of 10% of CAVs could already lead to significant traffic efficiency improvements, reducing the total time spent traveling by 30–40% with respect to the same demand without CAVs [50, 73]. The main reason for this efficiency improvement lies in the reduction in traffic instabilities (i.e. 'stop and go' traffic, shock waves) [72, 74], attenuating the capacity drop phenomenon (i.e. the capacity loss at the traffic breakdown and start of congestion).

The pinnacle of this effectiveness is achieved if CAVs are able to constitute platoons, i.e. 'road trains' in which they drive with very small space gaps at high speeds, as if they were physically linked. This would not only result in vehicles occupying less space on the road, but also it would enable higher flows without jeopardising safety [75, 76]. An early and renowned test of the concept was performed in 1997 under the PATH (Partners for Advanced Transit and Highways) program of the UC Berkeley. Even with the technological difficulties of the moment, platoons were proven to be advantageous in freeways and highways. More recently, simulations have shown that, in mixed traffic, platooning would lead to improvements in traffic efficiency if the average speeds are over 50 km/h, but not in congestion. In this last case, dedicated lanes for platoons could be advisable, provided that at least 40% of vehicles were AVs able to form platoons [77]. Dedicated lanes could be shared with the other vehicle with preference (e.g. high occupancy vehicles, public transportation, emergency services etc.). The decision of activating and deactivating the dedicated lane should be taken in real time, depending on traffic conditions [78, 79]. Further research is needed regarding dynamic traffic management in the presence of AVs. For example, in a mixed traffic environment with AV platooning, the platoon spacing, speed, length, creation/dissipation procedures etc. should be carefully designed to achieve maximum efficiency and avoiding disturbances to other vehicles, like the obstruction of merges or diverges.

In contrast with technological development where field tests with prototypes are possible, research on traffic management with the presence of AVs must rely on simulation. As automated driving with a significant penetration rate and in real traffic is not yet a reality, most of the research works use traffic microsimulators to replicate this environment. Microsimulators model the behaviour and trajectory of individual vehicles and with great detail. However, two main problems arise: firstly, these models include many calibration parameters, some of them without a physical interpretation, and secondly, it is not possible to calibrate them with real data, because the real scenario has not been achieved yet.
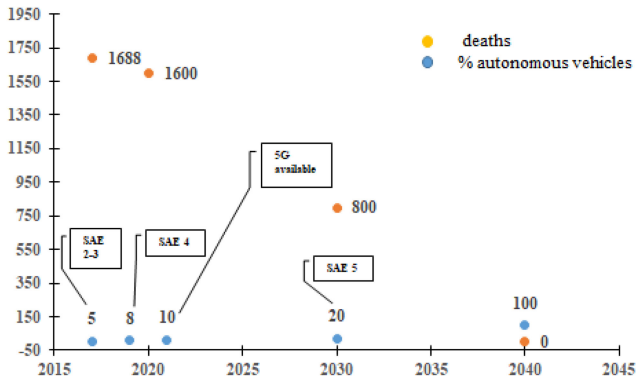
Fig. 7 *Spanish traffic administration (DGT) safety vision of an autonomous and connected mobility*

This means that results from the microsimulation should be taken with caution. An alternative consists on using mesosimulation. This is to model the traffic behaviour at a more aggregate level using as few parameters as possible, but still keeping the main attributes which characterise the traffic scenario under analysis. For example, in the AVs platooning context, segregated lanes and different vehicle types are attributes needed to be kept in the mesosimulation. Note that these attributes are not considered in typical macrosimulators, where only average sectional flows, densities, and speeds are modelled.

3.4 AVs and safety evaluation

According to the EU GEAR 2030 High Level Group, which addresses the key trends and challenges of the European automotive industry, 90% of road accidents come from human errors [80]. Thus, autonomous driving should contribute greatly to the reduction in road accidents and fatalities.

In line with Fig. 7, presuming that all vehicles in Spanish roads are able to cooperate by 2040 and optimistically assuming SAE5-level AVs, there would be no accidents [81]. Although very significant safety improvements are expected with the implementation of AVs [23, 75, 82], most experts recognise that the so-called vision zero (i.e. no accidents; a concept which emerged in Sweden in 1997) is too ambitious and optimistic. Inevitably, very complex situations will arise in which AVs will not be able to avoid accidents. There are also opinions claiming that safety improvements due to AVs will be negligible due to factors like slow human adaptation or hardware and software failures. For example, if risk perception decreases when using an AV, passengers could be more prone not to use seat belts, cyclists or pedestrians could act less cautiously etc. Also, the increase in the total driven kilometres implies more exposure to risk, and even if the accident rate decreases, the total number of accidents could vary little.

In spite of the previous arguments, it needs to be recognised that AVs will coexist and travel together with traditional vehicles for an extended period of time. This means that during this transitional period, accidents will not happen only due to AVs own crash modes, but also due to the uncertainties and disturbances introduced by the imperfect human driver behaviours. In such context, the evaluation of the safety performance of AVs must consider the interaction with traditional vehicles. This is a challenging task because probe AV's are few and expensive, and the rate of occurrence of dangerous driving situations is low. This means that evaluation by means of naturalistic field operational tests (N-FOT) [83], where data are measured from a group of equipped vehicles during extended periods of time in non-intrusive conditions, requires a huge number of probe vehicles and long periods of time. Although several N-FOT are being conducted, mainly in the EU and in the USA [84–86], this is far from being an efficient evaluation approach.

Several evaluation alternatives are being proposed. For instance, stochastic models can be constructed from a single sample of N-FOT data, from which to conduct Monte-Carlo experiments to simulate millions of driving scenarios. In this approach, it is critical to determine the amount of N-FOT data needed to calibrate the models. Insufficient data may lead to inaccurate models, while too many data affect the experiment costs. The scheme proposed in [87] systematically estimates how many naturalistic data are needed in order to model driver behaviour from a statistical perspective. This approach is used in [88, 89] in order to evaluate collision warning and avoidance systems, or in [90], where a method for testing and evaluating lane departure correction systems at low cost is proposed. Still, and although the budget for the evaluation experiments can be dramatically reduced, the frequency of dangerous situations is low and huge databases are required.

Lately, the accelerated evaluation concept has been applied to the safety evaluation of AVs in a mixed traffic environment in order to reduce the amount of required data (i.e. implying time and money). The method is still based on a stochastic model of mixed traffic, constructed from N-FOT experiments and calibrated through an iterative search for optimal parameters. However, the simulation of different scenarios is 'accelerated' by modifying (i.e. skewing) the density probability functions involved, in order to promote riskier behaviours. The obtained 'amplified' results, together with the modifications applied to the probability density functions, are used to replicate the statistics that would be obtained in a real-world environment. To that end, importance sampling theory and cross-entropy methods are generally used. The accelerated evaluation concept has been successfully applied in the evaluation of forward collision control systems in car-following scenarios [91, 92] and also in lane changing scenarios, when AVs need to react to vehicles cutting in [93, 94].

The test matrix approach is another evaluation alternative, where some test scenarios are selected using the information from traffic accident databases [95]. The benefits of this approach include the repeatability and reliability of the evaluation, without being intensive in resources (i.e. neither monetary nor temporal). However, the selection of the test scenarios and their relationship with the real-world conditions is always questionable. Moreover, because the test scenarios are fixed and predefined, AVs could be programmed to perform adequately in these conditions, while the general performance in the real and broader number of possibilities would be misevaluated. In order to partially solve these problems, the worst-case scenario evaluation has been proposed, where the most dangerous scenarios for a given AV design are identified using model-based optimisation techniques [96]. However, these methods do not take into account the frequency of occurrence of such worst-case situations and, therefore, they do not really evaluate the risks in a real-world environment. Furthermore, comparisons between different designs would not be fair.

In another order of events, from the security perspective, experts warn that AVs and V2X communication in general are vulnerable to terrorism in the form of malicious hacking. Malware could be massively spread and infect many connected vehicles at once [6, 97, 98]. For example, vehicle perception of the environment could be deliberately altered. Less dangerous would be the use of ransomware to block vehicles until owners pay a ransom [8]. Administrations are taking very seriously these risks, and, for example, the UK has recently issued eight cybersecurity principles for carmakers. They request redundant vehicle systems in order to be resilient to attacks. In other words, vehicles must be able to appropriately respond in the case of an attack during their entire lifespan. Recommendations also exhort all involved sectors to work altogether to this end [99]. Although this type of guidelines set noble objectives, zero risk does not exist. Like in any other field, there exists a trade-off between the cost of reducing the risk and the cost of not doing so. The accepted risk level should be the one that minimises total costs, knowing that the quantification of these costs is more a political than a technical issue.

4 Social impacts of autonomous vehicles

Although all impacts of AVs have, to some extent, a social implication, this section specifically addresses considerations regarding the AVs' social acceptability. As their impact on the
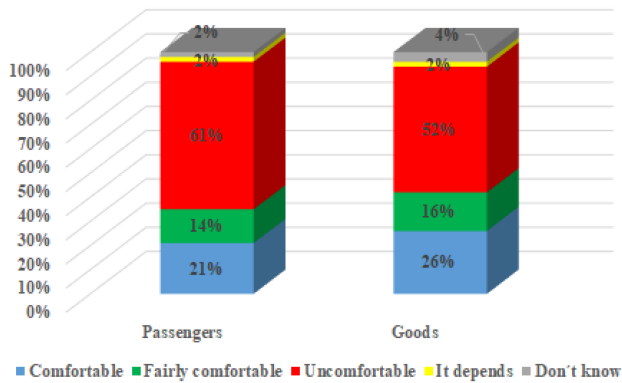
Fig. 8 *Driverless vehicles acceptance in the EU (2015)*

labour market and economy greatly influence the popular opinion, these are analysed first.

4.1 Impact on economy and competitiveness

The expected positive impacts of vehicle automation on economy are mainly due to two factors: the reduction in the transportation costs and the reduction in the value of travel time. The latter is related to the possibility of using the travel time to perform other tasks and will only take place with SAE5-level vehicles [64, 100]. The reduction in the cost of transportation will be the most relevant impact of AVs on economy, and will be due to: (i) better vehicle amortisation due to their more intensive use through sharing, (ii) lower staff costs due to the automatisation of the driving task, (iii) reductions in energy consumption (see Section 6), and (iv) shorter travel times due to a more efficient traffic management and the elimination of the need to travel in the vehicle while looking for parking. As a result, this will contribute to the punctuality and stress reduction in workers and thus, to productivity. In conclusion, the lower transportation costs will benefit the economic competitiveness of the society [5].

Regarding the labour market, the automotive industry is expected to deal with the vehicle fleet reduction in areas like the EU or the USA, by incentivising a continuous fleet renewal and by diversifying their business activities. Future AVs shared vehicles will be used more intensively, which will probably shorten their lifespan. The faster obsolescence of technology will also contribute to a more frequent renewal. Conversely, the smaller number of accidents will partially compensate for this shortening. In conclusion, it is even possible that despite a smaller fleet, the number of car registrations per year increases. Recent estimations push the increase in the number of registrations to 34% in the EU and 20% in the USA by 2030. In other markets like China, both the fleet and the registrations would rise due to increasing population rates and urbanisation processes [5].

In addition, the automotive industry is aiming not only to be a vehicle provider but also a global mobility operator. This process has already started, and, for example, Porsche Automobil Holding SE, the largest shareholder of Volkswagen, recently bought the PTV Group, a technological company which develops software for transportation planning and management. On their side, Daimler AG, who assembles Maybach, Mercedes-Benz, and Smart, has also started providing mobility services under brands like Car2Go or myTaxi, as well as digital services through AutoGravity and Mercedes Pay.

Inevitably, AVs will affect the labour market. Traditional jobs in the transportation sector, beyond that of drivers, are expected to disappear. For example, traditional mechanical workshops will die out with the reduction in the accident rate and because of their inability to repair fully AVs. However, new opportunities will appear, mainly linked to new technologies, optimisation, big data analysis, traffic engineering, transportation planning etc. For instance, experts in informatics and electronics, who are able to repair and maintain the new AVs hardware and software, will be in high demand. Driving schools could subsist with a different role once the conditions that new 'drivers' must fulfil are set (see Section 7.3).

4.2 AVs' acceptability

AVs are in the spotlight and the prevailing belief is that people will tend to welcome the safety and comfortability improvements that they will bring. However, opinions are not so favourable when people are directly asked whether they would feel comfortable travelling in an AV. According to a survey conducted in 2015 by the EU in 23 Member States (Fig. 8), 61% of the Europeans would feel uncomfortable, being the respondents from Cyprus and Greece the less fond of AVs. On the contrary, 21% would be confident. A majority (52%) still felt uncomfortable when asked about AVs transporting goods, although the rate of supporters increased in this scenario (26%) [101].

The previous survey focused on the potential passenger perception. However, AVs will interact with other road users (e.g. traditional drivers, cyclists, pedestrians) whose acceptability cannot be overlooked. In this regard, an investigation conducted in the UK in 2016 concluded that AVs were perceived as a 'somewhat low risk' mode of transportation in general. However, when compared with traditional vehicles, pedestrians thought they would be safer while passengers considered them riskier. Gender and age seem to have an influence, showing that male respondents and young people exhibit a greater acceptability [102]. Opinions of cyclists, bikers, and drivers of traditional vehicles must also be considered in future studies.

A more detailed research analysed, not only the general attitude towards AVs, but also the willingness to use them in different scenarios. Seven hundred and twenty-one commuters from North America and Israel were asked about their commuting preferences between: (i) continue using their individual traditional cars, (ii) buying (at an affordable price) a private AV, or (iii) sharing an AV of a commercial fleet. From all the factors considered, only the driving pleasure, the environmental concern and a general positive attitude towards AVs played a significant role. According to the results, 44% of the respondents would not change their routines with the appearance of AVs. Students, long-distance commuters, and people with higher education level were more enthusiastic about AVs. Also, it is interesting to note that 25% of the respondents would not use shared AVs even for free [103]. Although the study had some initial limitations (a small number of participants, only commuters etc.), it allowed reaching the conclusion that information (basics about automated driving, risks, benefits etc.) and educational campaigns (current traffic-related problems, environmentally friendly behaviour etc.) will be essential to reach sustainable mobility patterns supported by AVs.

The acceptability of AVs by collectives for which individual mobility is currently restricted is less ambiguous. Non-drivers, people with special needs, or the youngest and oldest branches of the population are relatively keener on using AVs [65]. In fact, advanced in-vehicle technologies have already extended the period over which the elderly can drive safely and comfortably. Their full integration in AVs will lead to further improvement for all these sectors of society [104].

Finally, it needs to be considered that the implications of AVs in privacy and in the modification of the labour market have been identified to disenchant mainly middle-aged and older people.

5 Territorial impact of autonomous driving

The relationship between land use and transportation is unquestionable; individual mobility has traditionally contributed to urban growth and urban sprawl. In 2008, >50% of the world's population was living in cities and this percentage is expected to increase to 70% by 2050. Cities expand because of the combined effect of a growing affluence of people, a change in lifestyles, and a reduction in transportation costs that allows, for instance, living further away from the working place. Not all the consequences of urban development are positive: many cities suffer from severe congestion and 75% of the anthropogenic greenhouse gases emissions come from cities. Experts claim that, unlike what has been happening so far, the urban form, configuration, and dynamics must determine mobility schemes [105]. Therefore, the introduction of AVs in urban environments must be planned from a global perspective. In this comprehensive approach, population
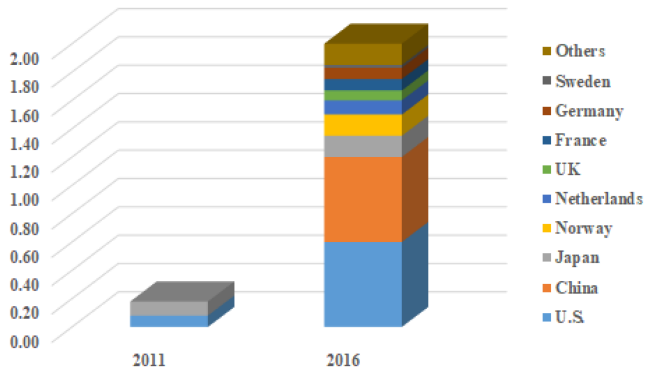
Fig. 9 *EVs stock evolution*

densities, urban shapes, and land uses must be considered, so that the new mobility patterns derived from vehicle automation provide the desired accessibility while promoting a sustainable use of the territory. In the absence of such planning, most studies predict an increasing city sprawl in line with the rise in VMT [61, 106, 107].

The impacts of urban sprawl as a result of the introduction of AVs can be reduced as long as planners develop designs that (i) reserve enough space for green, leisure, or agricultural-oriented areas and (ii) relieve city centres. In this regard, AVs could reduce the demand of daytime parking in cities, not only because the vehicle fleet will diminish, but also because parking slots could be shifted to peripheries. As the human presence in parking areas will be negligible, their configuration could also change, looking for a better space utilisation. Dedicated 'parking belts' just outside of the working areas might accumulate 90–97% of all commuter AVs [107, 108]. Thus, these released empty urban spaces could be humanised. Conversely, traffic streams of empty AVs driving from city centres to their daytime parking locations would imply some costs in terms of congestion, energy consumption etc.

Additionally, land use changes are expected to cause some increase in the rents at central locations accompanied by an equivalent decrease in the periphery. These changes have been quantified to be of the order of 30–40% [107]. Besides, well-connected rural areas will gain accessibility in an automated driving environment [61]. Again, the positive effects of automation on the territory are subject to more sustainable mobility patterns in which mainly private owners and companies should aim to share vehicles at higher occupancies.

6 Environmental impact of autonomous driving

Today, the environmental impacts of transportation, related to the local air quality and the global warming are a major concern. For example, the UE has been implementing different measures to reduce transportation greenhouse gases emissions by >60% by 2050, taking the 1990 levels as a reference [109]. Road transport is the largest contributor to air pollution, primarily due to the use of fossil fuels as energy resources. Therefore, efforts are concentrated on traffic management and vehicles' energy efficiency. Although AVs are expected to increase VMT, they would possibly contribute to significant environmental improvements as they are going to be electric and they will drive efficiently [110, 111].

6.1 Electric and other sustainable vehicles

The conversion from petrol to electric engines has already started as a consequence of societal environmental concerns. Electric vehicles (EVs) produce zero emissions at the point of use and are less noisy than conventional fuel-powered vehicles. Being practically inexistent in 2011, the global (i.e. battery electric and plug-in hybrid electric) EVs stock in 2016 exceeded 2 M vehicles (Fig. 9), of whom 750,000 were pure electric, which represents a huge leap. Norway is the world leader with 29% of its vehicle fleet being electric, while China, accounting for >40% of EVs sold in the world, is by far the largest EV market. It is expected that 55% of new cars built by 2030 in the EU will be fully electric and 40%

hybrid. Vehicle automation will push even forward the penetration of EVs, as SAE4- and SAE5-level vehicles will be mostly electric.

However, several issues must be solved in order to achieve the generalised use of EVs. One of the main problems is the range anxiety due to the limited battery capacity. Although the problem is technologically solved and car batteries with ranges up to 600–700 km are already available, their high prices make vehicles unaffordable for many drivers. This situation is expected to change in the short term. In fact, lithium battery prices dropped 77% on average since 2010 [112]. Another problem is the lack of sufficient charging points. To that end, most administrations are devising investment plans for their deployment, together with networks of charging stations that are being developed by private car manufacturers. In fact, charging stations increased worldwide by 72% since 2015. Emerging technologies like wireless (or inductive) charging systems are also under development [8].

It is expected that EV prices will diminish together with their penetration rate. When the acquisition cost is no longer a barrier, maintenance and operational costs will be more relevant for the purchaser. Regarding maintenance costs of EVs, batteries are expensive and must be replaced approximately every 150,000 km. The remaining costs are 35% lower than that of traditional vehicles. In all, EVs increase the maintenance costs approximately by 28%. On the contrary, operational costs, i.e. energy consumption, insurance fees, exemptions etc. [60], are favourable to EVs. Nevertheless, new policies will be necessary when EVs become more competitive. Current subsidies mainly come from fuel taxes, which will diminish in line with the sales of conventional engine vehicles. Applying taxes based on the distances travelled is one of the alternatives on the table [113], which in addition would promote vehicle sharing.

The generalised introduction of EVs will also urge to face the global planning of the energy supply. The electric energy needs in a future environment with a majority of EVs would be huge. Thus, current supply would be insufficient and energy prices could rise. The capacity of EV as energy storage devices could be used to laminate demand and mitigate this impact. Besides, battery manufacturing will significantly grow, and the availability of cobalt, lithium, and other related materials at a reasonable price and fair trade must be ensured. Battery recycling must be fostered to this end and to avoid environmental contamination.

Gas is an alternative to electricity to power the vehicles. Compressed natural gas (GNC) (i.e. methane stored at high pressure) and biogas capture most of the current market in this sector. Other solutions like LNG (liquefied natural gas) or HCNG (natural gas mixed with hydrogen) have a much lower penetration rate. Most automakers already offer gas models of their vehicles, although the vehicles still maintain the petrol tank. These early models are said to have a quieter and softer driving while maintaining their power and performance. Motors last longer, and maintenance needs are reduced. In addition, 1 kg of GNC supplies the same energy as 1.5 l of petrol, and the economic and environmental benefits with respect to fuel-engine vehicles are noticeable. In this regard, biofuel GNC vehicles emit 25% less CO_2 and 87% less NO_x and particles on average. One of the main drawbacks of gas-powered vehicles is the need for space for the second tank, which is generally placed under the boot bottom. This is related to the current lack of gas stations, which makes necessary the petrol tanks to ensure the reliability in the energy supply. In Europe, this problem is expected to be solved by a new European directive. In spite of the advantages of gas-powered vehicles when compared with the traditional ones, they are mostly seen as an intermediate step or a complement to EV, which are the primary focus.

6.2 Indirect environmental improvements of AVs

Beyond the direct impact of the substitution of fossil fuels as the main source of energy in transportation, a well-managed automatic driving context would involve indirect benefits for the environment, especially considering those vehicles that will still rely on combustion engines. Fuel consumption and traffic pollutant emissions increase in congestion with 'stop and go' driving

behaviour (i.e. with continuous accelerations and decelerations) and also with high speeds [114, 115]. Consequently, traffic efficiency and an adequate management of speed limits would reduce traffic-related pollution. Dynamic traffic management strategies like dynamic speed limits or congestion charging, aimed at ensuring a smooth and fluent driving, are already being applied [51, 116–122] and are expected to intensify with the introduction of AVs. AVs will also allow a robust and generalised application of eco-driving, consisting in providing vehicles with real-time advice regarding speed, acceleration, and deceleration levels and other driving parameters with the goal of optimising their energy consumption and emissions levels. Research on eco-driving, including eco-routing and taking advantage of V2X, has already demonstrated its potential [123–128]. The benefits of such strategies would be enhanced in a cooperative driving environment. However, only a generalised optimal management could compensate the expected VMT increase [8, 129].

7 Ethics and legal issues

The time when fully AVs will be widely introduced in the market might depend more on the promulgation of all the required laws than on the overcoming of the current technological and operational challenges. Liability in the case of an accident is the most controversial topic, in which ethics and economic interests play a role, although other aspects must also be considered.

7.1 Ethics of AVs

SAE5-level vehicles will have to make decisions that imply human (and material) losses, and moral dilemmas will arise. The philosophical approaches used so far in fields like law or in the army are being applied to find acceptable solutions. For example, consider the 'tram problem' [130], originally introduced to analyse the ethics of abortion, and brought to a new life by automatic driving. The dilemma is presented when a tram enters a track where five men are working. The driver has no time to warn anybody but could direct the tram towards a side track where only one person is working. In other words, the driver can choose who is going to die. Should the driver deviate so that only one person dies? In this case, he would take part in the death of one person. If the driver does nothing, five people would 'accidentally' die. Which is the most ethical choice? AVs will face similar situations. For example, think about a child that suddenly crosses a two-lane road out of a pedestrian crossing. An AV would have to decide whether to run over it or to deviate towards the opposing lane or to a side wall, thus endangering the lives of the vehicle occupants. Governments and research centres are addressing these complex ethical issues [131–133]. They try to enact globally accepted laws that can regulate AV programming. Two main ethical trends are on the table: deontology and consequentialism. The first one is a vision 'without consequences' of human moral decision-making. Deontology (from Greek, meaning 'duty') holds that actions are not justified by their consequences. Reasons other than good results determine the correctness of the acts. However, for the consequentialists, the correctness of an action is determined by the 'goodness' or 'utility' (broadly speaking) associated with its consequences.

The German Ethical Guidelines, released in 2017 [132], are the first official recommendations that address AVs ethical issues. Twenty statements are proposed which constitute a starting point for further analysis and legislation. In fact, the guidelines will be reviewed after 2 years of application to make the necessary changes or additions derived from experience. The proposed ethical guidelines remark:

- If an accident cannot be avoided, human safety takes precedence over animals and property. In case humans are involved anyway, the action that harms less people prevails. Furthermore, software cannot prioritise among individuals on the basis of age, gender, race, physical attributes, or any others.
- Before the SAE5 level arrives, the ultimate decision and responsibility lies in the human sitting in the driver seat, as

control will be immediately transferred to him in complex situations. If he fails to react, the vehicle must simply try to stop.
- AVs should have a kind of 'black box' that continuously records events, including who is in control at any given time. If an AV is involved in an accident, an independent federal agency must carry out an investigation to determine responsibilities.
- Everyone who drives a vehicle of any automation level must be legally validated as being qualified to perform this task.
- Drivers and passengers retain the rights over the personal information collected from vehicles. No one can use these data without their permission.
- People must understand all implications of AVs for society. Education on the principles upon which AVs operate should be incorporated into school curriculums.

From these guidelines, it is deduced that data management is another important issue that requires an ethical treatment. Three main goals are pursued with respect to data management: (i) interoperability, (ii) cyberattack hindering, and (iii) respect for user privacy and rights. While the first two goals are more technical, although all the stakeholders will need to reach an agreement on to what level (and costs) these objectives need to be assured, it is the data privacy what is more controversial. The usage of private data out of the original scope of traffic coordination (e.g. police follow-up, corporate control, people behaviour analysis, commercial purposes etc.) generates debate. Note that society already complains about the indiscriminate use of mobile phone data, street camera images, personal Internet searches etc. Considering the large amount of data involved in cooperative automated driving, consensual solutions, informative campaigns, and ethics in data treatment will be essential.

7.2 Civil liability and insurances

While it is clear that liability in the case of material or personal damage lies in the driver up to SAE3-level vehicles, doubts arise with SAE levels 4 and 5. At first, liability would be transferred to the AV manufacturer, as long as the vehicle was used within its design limits and the owner fulfilled the corresponding update and maintenance requisites. At least, annual updates of hardware and software will be necessary [15]. However, laying all the blame on automakers could be unfair, and it would delay or even prevent self-driving vehicle manufacturing [134, 135]. Liability in the event of an accident could fall on carmakers, but also on the manufacturer of one particular component, on the technician who assembled this component, or on the software developer etc. Another challenging scenario to cover is that of a mixed environment with traditional vehicles and AVs sharing roads. For example, consider a two-lane road where the driver of a manual vehicle suddenly enters the opposite lane and travels against a coming AV. Common sense would say that this driver holds the responsibility of a possible accident, but also AVs are supposed to be able to avoid any crash. Thus, liability needs to be analysed together with the ethical principles considered. The existence of an 'event data recorder' box is essential to enable investigations in this regard. Some action has already started to address liability issues. For example, the European Parliament approved an initiative exhorting the European Commission to define liability rules on robotics, and particularly on AVs [136].

Insurance companies will also play a role. The insurance costs for owners of AVs are expected to be low, and mainly related to repair needs [137]. In this context, insurance companies will change the focus of their business from drivers to areas like product liability (carmakers) and cyber security (software developers, commercial fleets etc.).

7.3 More legal issues

More regulations will be necessary, even before SAE5-level vehicles are brought to the market. Current legislation of individual countries and also international agreements do not allow full automation. For example, 74 countries reached an agreement on road traffic in Vienna, 1968, in the United Nations Economic and
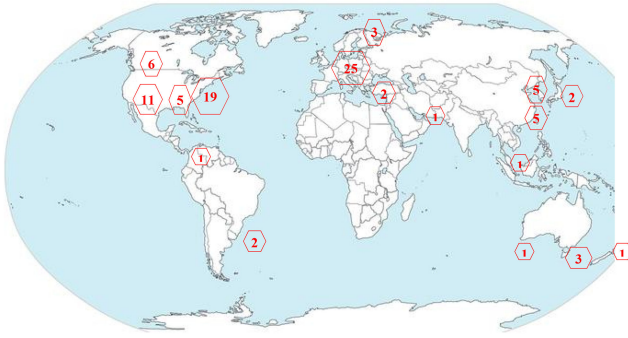
Fig. 10 *Bloomberg's Global Atlas on AVs trials in cities (adapted from [140])*

Social Council's Conference on Road Traffic [138], which came into force in 1977. Among many other regulations, it states that drivers are always responsible for controlling their vehicles. The amendment of this convention and its acceptance by the involved parties needs to be addressed first. The United Nations Economic Commission for Europe already started the modification of this agreement in 2014, but it is still uncompleted. Another example is the Regulation No. 79 of the Economic Commission for Europe of the United Nations, which indicates that automated steering must be automatically disabled, and the driver warned if the vehicle speed exceeds 10 km/h [139]. These kinds of regulations, which are shared by many codes of particular countries, are against the philosophy of autonomous driving or even of collision avoidance systems and need to be revised.

On the vehicle manufacturing side, there is a need for legislation aimed at the testing of vehicles with high autonomy levels. In 2011, the US state of Nevada became the first jurisdiction in the world where AVs could be legally operated on determined public roads under certain safety and performance standards. For example, the presence of a person behind the steering wheel and at least one additional passenger was mandatory. Nevertheless, this step forward helped Google to test their first AVs. Today, 25 US states have legislation in this regard. In California, >40 companies hold permits to test AVs since first trials in 2014, and a revised regulation allowing tests without any person in the vehicle is expected for 2018. The first European trial took place in the UK in 2013, with similar conditions than that of Nevada. The country is expected to allow road tests of SAE5-level cars by 2019. Many other European countries have been taking steps in this direction, as well as other Asiatic countries like China, Japan, Singapore etc., which have also developed their own rules on the topic. China is a particular case, as it takes advantage of not having ratified the Vienna Convention of 1968. A good overview of the state of the practice in this regard is presented in the recently developed 'Global Atlas of Autonomous Vehicles in Cities' [140]. The atlas shows the cities where AVs are being tested and those that are preparing themselves to embrace them in the next decade (Fig. 10). Details about the trials are also available. Only 53 cities all over the world hold this privileged status. From them, 35 cities are already housing pilot projects, while projects are developed in 18 more.

Traffic authorities must also decide if a driver's licence is necessary to be in charge of a fully AV. In case a licence is considered to be still mandatory, the requisites to obtain it should be focused on driving rules and technology usage. Recommendations in this regard have been published by the German Parliament [132] or by the NHTSA [131]. In both cases, a driver licensing programme is proposed which should provide the driver licence endorsement that authorises the operation of AVs. In their opinion, licence issuances should be conditioned to pass a test on safety in a connected and automated driving environment and to the completion of a training course provided by the manufacturer and previously approved by the traffic administration. This licensing process should provide at least an understanding of the basic operation and limits of AVs, and knowledge on how to resume control in the event the vehicle cannot continue to operate automatically.

These are not the only aspects that require further legislation. Many other regulations will be necessary. Among others:

- Traffic efficiency would depend on the establishment of *ad hoc* management strategies, whose rules must be defined and regulated.
- Data treatment must follow a strict protocol in order to respect privacy and prevent terrorism. Legal agreements among countries would be desirable.
- Mandatory AVs technical inspections should be defined.
- Vehicle maintenance or repair will demand the intervention of *ad hoc* trained technicians. Requirements to enable them to perform these tasks, as well as possible liability in the case of later accidents, must be regulated.

8 Conclusions

Currently, mobility is linked to huge externalities like accidents, congestion, and pollution. Being conscious of the unsustainability of the present model, all the implied sectors are making substantial efforts to develop a new archetype in which mobility will be safe, efficient, environmentally friendly, and inclusive. Mobility is a multidisciplinary field with a large scope of influences, and the evolution towards this new scenario will be progressive, full of difficulties, and over a long time. In spite of this, AVs are called to be the agent of change. Future vehicles will be: (i) fully autonomous, (ii) connected, (iii) shared, and (iv) electric. In this context of technological evolution, this paper provides an overview of the different topics that must be considered to effectively take advantage of AVs in the next future. Firstly, the current state-of-the-practice of the related technologies is analysed. Secondly, their impacts on mobility patterns and traffic efficiency as well as on safety are assessed. Furthermore, implications for land use, the environment, economy, and competitiveness are also covered. Finally, population's acceptability as well as ethics and legal issues are faced. Several clear conclusions have been drawn from the former analysis, namely:

- Significant technological improvements have been reached so far. In fact, mass production of SAE4-level vehicles will be possible in the short term. However, the leap to fully AV will take much longer, as vehicles should be able to perform the entire driving task under all boundary conditions.
- AVs will bring a much safer driving environment. However, some failure probability will always exist. Robust communications, cloud systems, and infrastructure equipment to support safe driving do not represent a technological problem but require significant investment.
- AV impact on traffic efficiency will be important. On the one hand, mainly due to the lowering of the transportation costs and the extension of the user spectrum, automation will lead to an increase in the number of vehicle-kilometres travelled. Sharing systems used at high occupancy or MaaS schemes must be promoted to attempt to reduce the vehicle fleet and thus avoid an increase in current congestion or pollution problems. On the other hand, dynamic management strategies must be designed aiming to AVs coordination (e.g. vehicle platooning). System-wide optimisation can only be achieved if AVs behave cooperatively.
- AVs will boost an increase in competitiveness, which is primarily linked to lower transportation costs.
- The labour market will be affected by AVs, and some traditional professions are expected to disappear, while other profiles related to technology, data treatment, creativity etc. will be demanded.
- AVs acceptability is still low, especially among people over 50. Safety and privacy concerns are the main pros and cons, respectively. Informative campaigns will be necessary.
- AVs will foster urban sprawl. Land use policies aimed at limiting this effect and preserving sufficient green areas will be needed. Conversely, city centres are expected to gain space, as parking lots will move to the peripheries.

- Most future vehicles will be electric. This fact could lead to an enormous reduction in traffic pollutant emissions and noise. Notwithstanding, additional changes in the energy sector will be necessary, such as obtaining a sustainable primary source of energy, improving charging systems, developing policies aimed at battery reuse etc.
- Discussion on the ethics of AV and the development of new legislation will be essential. In fact, both will probably determine when fully AVs come to the market. Although many points of current legislation must be modified, those including ethical decisions are more intricate. Some administrations have proposed general guidelines in this regard, but specific rules aimed at directing vehicle behaviour in the case of danger should be agreed upon by all countries. Civil liability is also being discussed and will lead to new insurance models.

In summary, AVs have the potential to immensely improve mobility while restraining some current undesirable impacts like congestion or environmental pollution. Important advances have been made in recent years by all the related sectors. However, complex issues remain. Thus, the introduction of AVs must be developed guided by research and under a multidisciplinary environment in which stakeholders, administrations, researchers, population etc. cooperate.

9 Acknowledgments

10 References

[1] Milakis, D., van Arem, B., van Wee, B.: 'The ripple effect of automated driving'. Proc. BIVEC-GIBET Transport Research Day, Eindoven, The Netherlands, May 2015, pp. 1–3

[2] Milakis, D., van Arem, B., van Wee, B.: 'Policy and society related implications of automated driving: a review of literature and direction for future research', *J. Intell. Transp. Syst.*, 2017, **21**, (4), pp. 324–348

[3] Nieuwenhuijsen, J., Almeida Correia, G.H., Milakis, D., *et al.*: 'Towards a quantitative method to analyze the long-term innovation diffusion of automated vehicles technology using system dynamics', *Transp. Res. C, Emerg. Technol.*, 2018, **86**, pp. 300–327

[4] Litman, T.: 'Autonomous vehicle implementation predictions: implications for transport planning', Victoria Transport Policy Institute, January 2018

[5] Kuhnert, F., Stürmer, C.: '*Five trends transforming the automotive industry*' (PriceWaterhouseCoopers, Frankfurt, Germany, 2018), pp. 1–48

[6] Tkachuk, D., Dawson, D., Bovery, P., *et al.*: 'Report of the standing Senate Committee on Transport and Communications of Canada. Driving change: technology and the future of the automated vehicle', 2018

[7] TRB.: '*Strategies to advance automated and connected vehicles*' (US National Academy of Sciences, Washington, DC, USA, 2017), pp. 1–12

[8] Shaheen, S., Totte, H., Stocker, A.: 'Future of mobility. The white paper', UC Berkeley, UCConnect, 2018

[9] Fagnant, D.J., Kockelman, K.M.: 'Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations for capitalizing on self-driven vehicles', *Transp. Res. A*, 2015, **77**, pp. 1–20

[10] Bloomberg Philanthropies and the Aspen Institute: 'Taming the AVs: a primer for cities', 2017

[11] Report of the JRC Science Hub of the European Commission: 'An analysis of possible socio-economic effects of a Cooperative, Connected and Automated Mobility (CCAM) in Europe', 2018

[12] da Vinci, L.: 'Codex Atlanticus', folio r812

[13] Illing, W.: '*Utopolis*' (Der Bücherkreis, Berlin, Germany, 1930)

[14] Geddes, N.B.: '*Magic motorways*' (Random House, New York, NY, USA, 1940)

[15] US National Highway Traffic Safety Administration: 'Preliminary statement of policy concerning automated vehicles', US Department of Transportation, 2013, pp. 1–14

[16] J3016:JAN2014: 'Taxonomy and definitions for terms related to On-road motor vehicle automated driving systems', Society of Automotive Engineers, 2014

[17] J3016A:SEP2016: 'Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles', Society of Automotive Engineers, 2016

[18] 'Der neue Audi A8'. Available at http://www.audi.com/de/models/der-neue-a8.html, accessed 6 February 2018

[19] 'Kooperatives hochautomatisiertes Fahren'. Available at http://www.ko-haf.de/startseite/, accessed 6 February 2018

[20] Jiménez, F.: '*Intelligent road vehicles: enabling technologies and future developments*' (Elsevier, Oxford, UK, 2017)

[21] Shladover, S.E.: 'The truth about self-driving cars', *Sci. Am.*, 2016, **314**, (6), pp. 52–57

[22] Mladenovic, M.N., McPherson, T.: 'Engineering traffic justice into traffic control for self-driving vehicles?', *Sci. Eng. Ethics*, 2016, **22**, pp. 1131–1149

[23] Koopman, P., Wagner, M.: 'Autonomous vehicle safety: an interdisciplinary challenge', *IEEE Trans. Intell. Transp. Syst.*, 2017, **9**, (1), pp. 90–97

[24] Ling, C., Juan, J., Li, K.: 'Active collision avoidance system for steering control of autonomous vehicles', *IET Intell. Transp. Syst.*, 2014, **8**, (6), pp. 543–549

[25] Bharadwaj, S., Murthy, S., Varaprasad, G.: 'Detection of pothole in autonomous vehicle', *IET Intell. Transp. Syst.*, 2014, **8**, (6), pp. 550–557

[26] Okumura, B., James, M., Kanzawa, Y., *et al.*: 'Challenges in perception and decision making for intelligent automotive vehicles: a case study', *IEEE Trans. Int. Vehicles*, 2016, **1**, (1), pp. 20–32

[27] Li, B., Du, H., Li, W.: 'Trajectory control for autonomous electric vehicles with in-wheel motors based on a dynamics model approach', *IET Intell. Transp. Syst.*, 2016, **10**, (5), pp. 318–330

[28] González, D., Pérez, J., Milanés, V., *et al.*: 'A review of motion planning techniques for automated vehicles', *IEEE Trans. Intell. Transp. Syst.*, 2016, **17**, (4), pp. 1135–1145

[29] Liu, S., Tang, J., Zhang, Z.: 'Computer architectures for autonomous driving', *IEEE Comput. Archit. Lett.*, 2017, **50**, (8), pp. 18–25

[30] Benderius, O., Berger, C., Malmstem, V.: 'The best rated human–machine interface design for autonomous vehicles in the 2016 grand cooperative driving challenge', *IEEE Trans. Intell. Transp. Syst.*, 2017, **1**, (1), pp. 20–32

[31] Jiménez, F., Naranjo, J.E.: 'Improving the obstacle detection and identification algorithms of a laserscanner-based collision avoidance system', *Transp. Res. C: Emerg. Technol.*, 2011, **19**, (4), pp. 658–672

[32] FHWA-JPO-15–28: 'Status of the dedicated short-range communications technology and applications' (US Department of Transportation, 2015), pp. 1–26

[33] FCC-03-324: 'Report and Order-Amendment of the Commission's Rules Regarding Dedicated Short-Range Communication Services in the 5.850–5.925 GHz Band (5.9 GHz Band)', 2003

[34] US Department of Transportation: 'ITS-JPO Strategic Plan 2015–2019', 2014

[35] 2008/671/EC: 'Commission Decision of 5 August 2008 on the harmonised use of radio spectrum in the 5875–5905 MHz frequency band for safety-related applications of Intelligent Transport Systems (ITS)', 2008

[36] C-ITS Platform: 'Final report', 2016

[37] Intel Go Autonomous driving solutions. Product brief: 'Autonomous driving, accelerated', 2016

[38] Lee, J., Brian, B.: 'Investigating communications performance for automated vehicle-based intersection control under connected vehicle environment'. Proc. IEEE Intelligent Vehicles Symp., Seoul, Korea, June–July 2015, pp. 1342–1347

[39] Filippi, A., Moerman, K., Daalderop, G., *et al.*: 'Ready to roll: why 802.11p beats LTE and 5G for V2X', Internal Report for Siemens, 2015

[40] COM(2016) 588.: '5G for Europe: an action plan', European Commission, 2016, pp. 1–11

[41] C-ITS Platform: 'Final Report Phase II: Cooperative Intelligent Transport Systems, towards cooperative, connected and automated mobility', 2017

[42] Ahmad, F., Kazim, M., Adnane, A., *et al.*: 'Vehicular cloud networks: architecture, applications and security issues'. 2015 IEEE/ACM 8th Int. Conf. Utility and Cloud Computing (UCC), Limassol, Cyprus, 2015, pp. 571–576

[43] Zeadally, S., Hunt, R., Chen, Y.S.: 'Vehicular *ad hoc* networks (VANETs): status, results, and challenges', *Telecommun. Syst.*, 2012, **50**, pp. 217–241

[44] Gerla, M., Lee, E.-K., Pau, G.: 'Internet of vehicles: from intelligent grid to autonomous cars and vehicular clouds'. 2014 IEEE World Forum on Internet of Things (WF-IoT), Seoul, South Korea, 2014, pp. 241–246

[45] Yang, F., Wang, S., Li, J., *et al.*: 'An overview of internet of vehicles', *China Commun.*, 2014, **11**, (10), pp. 1–15

[46] Milanés, V., Godoy, J., Pérez, J., *et al.*: 'V2I-based architecture for information exchange among vehicles'. 7th IFAC Symp. on Intelligent Autonomous Vehicles, Lecce, Italy, September 2010

[47] Bosetti, P., da Lio, M., Saroldi, A.: 'On curve negotiation: from driver support to automation', *IEEE Trans. Intell. Transp. Syst.*, 2015, **16**, pp. 2082–2093

[48] GAO 15-775: 'Vehicle-to-infrastructure technologies expected to offer benefits, but deployment challenges exist', US Government Accountability Office, October 2015

[49] United States Government Accountability Office: 'ITS: vehicle-to-infrastructure technologies expected to offer benefits, but deployment challenges exist', in '*vehicle-to-infrastructure technologies*' (Nova Science Pub Inc., Washington DC, 2016, 1st edn.), pp. 1–50

[50] Guériau, M., Billot, R., El Faouzi, N.-E., *et al.*: 'How to assess the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies', *Transp. Res. C, Emerg. Technol.*, 2016, **67**, pp. 266–279

[51] Burns, L.D., Jordan, W., Scarborough, B.: 'Transforming personal mobility', Technical Report. The Earth Institute, Columbia University, 2013

[52] Friedrich, M., Hartl, M.: 'MEGAFON-Modellergebnisse geteilter autonomer Fahrzeugflotten des öffentlichen Nahverkehrs', Research report. Universität Stuttgart, Institut für Strassen- und Verkehrswesen, Stuttgart, 2016

[53] Fagnant, D.J., Kockelman, K.M.: 'The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios', *Transp. Res. C, Emerg. Technol.*, 2014, **40**, pp. 1–13

[54] Chen, T.D., Kockelman, K.M., Hanna, J.P.: 'Operations of a shared, autonomous, electric vehicle fleet: implications of vehicle and charging infrastructure decisions', *Transp. Res. A, Policy Pract.*, 2016, **94**, pp. 243–254

[55] Gehrke, S.R., Felix, A., Reardon, T.: 'A survey of ride-hailing passengers in metro Boston', Metropolitan Area Planning Council Boston, 2018, pp. 1–19

[56] Daganzo C.F. Public Transportation Systems: 'Basic principles of system design, operations planning and real-time control, institute of transportation studies', University of California, Berkeley, 2010

[57] Linares, M.P., Montero, L., Barceló, J., *et al.*: 'A simulation framework for real-time assessment of dynamic ride sharing demand responsive transportation models', Winter Simulation Conf. (WSC), Washington, DC, USA, January 2016, pp. 2216–2227

[58] Djavadian, S., Chow, J.Y.J.: 'An agent-based day-to-day adjustment process for modeling 'mobility as a service' with a two-sided flexible transport market', *Transp. Res. B, Methodol.*, 2017, **104**, pp. 36–57

[59] Matyas, M., Kamargianni, M.: 'A stated preference experiments for mobility-as-a-service plans'. 5th IEEE Int. Conf. on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Naples, Italy, June 2017, pp. 1–7

[60] Bösch, P.M., Becker, F., Becker, H., *et al.*: 'Cost-based analysis of autonomous mobility services', *Transp. Policy*, 2018, **64**, pp. 76–91

[61] Meyer, J., Becker, H., Bösch, P.M., *et al.*: 'Autonomous vehicles: the next jump in accessibilities?', *Res. Transp. Econ.*, 2017, **62**, pp. 80–91

[62] ITS International: 'Authorities look to MaaS for new solutions and cost savings'. Available at http://www.itsinternational.com/sections/transmart/features/authorities-look-to-maas-for-new-solutions, accessed 15 February 2018

[63] Correia, G.H., van Arem, B.: 'Solving the user optimum privately owned automated vehicles assignment problem (UO-POAVAP): a model to explore the impacts of self-driving vehicles on urban mobility', *Transp. Res. B, Methodol.*, 2016, **87**, pp. 64–88

[64] Milakis, D., Snelder, M., van Arem, B., *et al.*: 'Development and transport implications of automated vehicles in the Netherlands: scenarios for 2030 and 2050', *Eur. J. Transp. Infrastruct. Res.*, 2017, **17**, (1), pp. 63–85

[65] Harper, C., Hendrickson, C.T., Mangones, S., *et al.*: 'Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly and people with travel-restrictive medical conditions', *Transp. Res. C, Emerg. Technol.*, 2016, **72**, pp. 1–9

[66] International Transport Forum: 'Technical Report: Urban mobility system upgrade: how shared self-driving cars could change city traffic', OECD, 2015

[67] Martínez, L., Viegas, J.M.: 'Assessing the impacts of deploying a shared self-driving urban mobility system: an agent-based model applied to the city of Lisbon, Portugal', *Int. J. Transp. Sci. Technol.*, 2017, **3**, (1), pp. 13–27

[68] European Federation for Transport and Environment: 'Does sharing cars really reduce car use?', 2017, pp. 1–8

[69] Lamondia, J.J., Fagnant, D.J., Qu, H., *et al.*: 'Shifts in long-distance travel mode due to automated vehicles and travel survey analysis', *Transp. Res. Rec.: J. TRB*, 2016, **2566**, pp. 1–10

[70] Clewlow, R., Shankar, G.: 'Disruptive transportation: the adoption, utilization, and impacts of ride-hailing in the United States', Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-17-07, 2017, pp. 2–38

[71] Diakaki, C., Papageorgiou, M., Papamichail, I., *et al.*: 'Overview and analysis of vehicle automation and communication systems from a motorway traffic management perspective', *Transp. Res. A, Policy Pract.*, 2015, **75**, pp. 147–165

[72] Ntousakis, I.A., Nikolos, I.K., Papageorgiou, M.: 'On microscopic modelling of adaptive cruise control systems', *Transp. Res. Proc.*, 2015, **6**, pp. 111–127

[73] Arnaout, G., Bowling, S.: 'Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp', *J. Ind. Eng. Manage.*, 2011, **4**, (4), pp. 699–717

[74] Delis, A.I., Nikolos, I.K., Papageorgiou, M.: 'Macroscopic traffic flow modelling with adaptive cruise control: development and numerical solution', *Comput. Math. Appl.*, 2015, **70**, (8), pp. 1921–1947

[75] Gong, S., Shen, J., Du, L.: 'Constrained optimization and distributed computation based car following control of a connected and autonomous vehicle platoon', *Transp. Res. B, Methodol.*, 2016, **94**, pp. 314–334

[76] Lioris, J., Pedarsani, R., Yildiz, F., *et al.*: 'Platoons of connected vehicles can double throughput in urban roads', *Transp. Res. C, Emerg. Technol.*, 2017, **77**, pp. 292–305

[77] van Arem, B., van Driel, C.J.G., Visser, R.: 'The impact of cooperative adaptive cruise control on traffic-flow characteristics', *IEEE Trans. Intell. Transp. Syst.*, 2006, **7**, (4), pp. 429–436

[78] Roncoli, C., Papamichail, I., Papageorgiou, M.: 'Model predictive control for multi-lane motorways in presence of VACS'. Proc. 17th Int. IEEE Conf. Intelligent Transportation Systems (ITSC), Qingdao, China, October 2014, pp. 501–507

[79] Maiti, S., Winter, S., Kulik, L.: 'A conceptualization of vehicle platoons and platoon operations', *Transp. Res. C:Emerg. Technol.*, 2017, **80**, pp. 1–19

[80] GEAR 2030: 'Final report', 2017

[81] Arriola, J.J.: 'Circulación de vehículos autónomos: retos legislativos', *Carreteras*, 2017, **216**, pp. 18–27

[82] Kockelman, K., Avery, P., Bansal, P.: 'Implications of connected and automated vehicles on the safety and operations of roadway networks: a final report', Center for Transportation Research, Texas Department of Transportation, 2016, pp. 1–249

[83] FESTA-Consortium: 'FESTA handbook version 2 deliverable T6.4 of the field opErational teSt supporT action', Eur. Commission, Brussels, Belgium, 2008

[84] LeBlanc, D., Sayer, J., Winkler, C., *et al.*: 'Road departure crash warning system field operational test: methodology and results'. Univ. Michigan Transp. Res. Inst. (UMTRI), Ann Arbor, MI, USA, UMTRI-2006-9-2, 2006

[85] Victor, T., Bärgman, J., Hjälmdahl, M., *et al.*: 'Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT) Phase 1: Final Report', Chalmers, Goteborg, Sweden, 2010

[86] Sayer, J., LeBlanc, D., Bogard, S., *et al.*: 'Integrated vehicle-based safety systems field operational test final program report'. Nat. Highway Traffic Safety Admin. (NHTSA), Washington, DC, USA, DOT HS 811 482, 2011

[87] Wang, W., Liu, C., Zhao, D.: 'How much data are enough? A statistical approach with case study on longitudinal driving behavior', *IEEE Trans. Intell. Vehicles*, 2017, **2**, (2), pp. 85–98

[88] Lee, K.: 'Longitudinal driver model and collision warning and avoidance algorithms based on human driving databases'. Univ. Michigan, Ann Arbor, MI, USA, 2004

[89] Woodrooffe, J., Blower, D., Bao, S., *et al.*: 'Performance characterization and safety effectiveness estimates of forward collision avoidance and mitigation systems for medium/heavy commercial vehicles', Univ. Michigan Transp. Res. Inst., Ann Arbor, MI, USA, UMTRI-2011-36, 2014

[90] Wang, W., Zhao, D.: 'Evaluation of lane departure correction systems using a regenerative stochastic driver model', *IEEE Trans. Intell. Vehicles*, 2017, **2**, (3), pp. 221–232

[91] Zhao, D., Peng, H., Bao, S., *et al.*: 'Accelerated evaluation of automated vehicles using extracted naturalistic driving data'. Proc. 24th Int. Symp. Vehicle Road Tracks, 2015, pp. 1–9

[92] Zhao, D., Huang, X., Peng, H., *et al.*: 'Accelerated evaluation of automated vehicles in car-following maneuvers', *IEEE Trans. Intell. Transp. Syst.*, 2018, **19**, (3), pp. 733–744

[93] Zhao, D., Lam, H., Peng, H.: 'Accelerated evaluation of automated vehicles safety in lane-change scenarios based on importance sampling techniques', *IEEE Trans. Intell. Transp. Syst.*, 2017, **18**, (3), pp. 595–607

[94] Huang, Z., Lam, H., LeBlanc, D.J., *et al.*: 'Accelerated evaluation of automated vehicles using piecewise mixture models', *IEEE Trans. Intell. Transp. Syst.*, 2017, **19**, (9), pp. 1–11 (Early Access)

[95] Aust, M.: 'Evaluation process for active safety functions: addressing key challenges in functional, formative evaluation of advanced driver assistance systems', Chalmers Univ. Technol., Goteborg, Sweden, 2012

[96] Ma, W.H., Peng, H.: 'A worst-case evaluation method for dynamic systems'. *J. Dyn. Syst. Meas. Control*, 1999, **121**, (2), pp. 191–199

[97] Douma, F., Aue, S.: 'Criminal liability issues created by autonomous vehicles', *Santa. Clara. Law. Rev.*, 2012, **52**, (4), pp. 1157–1169

[98] Petit, J., Shladover, S.E.: 'Potential cyberattacks on automated vehicles', *IEEE Trans. Intell. Transp. Syst.*, 2015, **16**, (2), pp. 546–556

[99] 'The key principles of vehicle cyber security for connected and automated vehicle -GOV.UK'. Available at https://www.gov.uk/government/publications/principles-of-cyber-security-forconnected-and-automated-vehicles/the-key-principles-of-vehicle-cyber-securityfor-connected-and-automated-vehicles, accessed 28 February 2018

[100] Cyganski, R., Fraedrich, E., Lenz, B.: 'Travel time valuation for automated driving: a use-case-driven study'. 94th Annual Meeting of the Transportation Research Board, Washington, DC, USA, January 2015, pp. 1–19

[101] 'Special Eurobarometer 427: Autonomous Systems-European Commission'. Available at http://ec.europa.eu/commfrontoffice/publicopinion/archives/ebs/ebs_427_en.pdf, accessed 28 February 2018

[102] Hulse, L.M., Xie, H., Galea, E.R.: 'Perceptions of autonomous vehicles: relationships with road users, risk, gender and age', *Saf. Sci.*, 2018, **102**, pp. 1–13

[103] Haboucha, C.J., Ishaq, R., Shiftan, Y.: 'User preferences regarding autonomous vehicles', *Transp. Res. C*, 2017, **78**, pp. 37–49

[104] Eby, D.W., Molnar, L.J., Zhang, L., *et al.*: 'Use, perceptions, and benefits of automotive technologies among aging drivers', *Inj. Epidemiol.*, 2016, **3**, pp. 1–20

[105] Barceló, J.: 'Paradigm changes: from smart cities to wise cities and the role of transport models'. CYTED Workshop 2016, Santiago de Chile, Chile, October 2016

[106] Heinrichs, D.: 'Autonomous driving and urban land use', in Maurer, M., Gerdes, J.C., Lenz, B., *et al.*: '*Autonomous driving: technical, legal and societal aspects*' (Springer, Berlin, Heidelberg (Germany), 2015, 1st edn.), pp. 213–231

[107] Zakharenko, R.: 'Self-driving cars will change cities', *Reg. Sci. Urban. Econ.*, 2016, **61**, pp. 26–37

[108] Zhang, W., Guhathakurta, S., Fang, J., *et al.*: 'Exploring the impact of shared autonomous vehicles on urban parking demand: an agent-based simulation approach', *Sust. Cities Soc.*, 2015, **19**, pp. 34–45

[109] COM/2011/0885 final: 'Energy roadmap 2050', European Commission, 2011, pp. 1–20

[110] Greenblatt, J.B., Saxena, S.: 'Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles'. *Nat. Clim. Chang*, 2015, **5**, pp. 860–863

[111] International Energy Agency: 'Global EV outlook 2017. Two million and counting', OECD/IEA, 2017

[112] Bloomberg New Energy Finance: 'Electric Vehicle Outlook 2017', Bloomberg Finance, 2017

[113] 'Energy Technology Perspectives 2017'. Available at http://www.iea.org/etp/, accessed 1 March 2018

[114] Barth, M., Boriboonsomsin, K.: 'Real-world carbon dioxide impacts of traffic congestion', *Transp. Res. Rec., J. Transp. Res. Board*, 2008, **2058**, (1), pp. 163–171

[115] Ding, Y., Rakha, H.: 'Trip-based explanatory variables for estimating vehicle fuel consumption and emission rates', *Water, Air Soil Pollut.: Focus*, 2002, **2**, (5–6), pp. 61–77

[116] Psaraki, V., Pagoni, I., Schafer, A.: 'Techno-economic assessment of the potential of intelligent transport systems to reduce CO_2 emissions', *IET Intell. Transp. Syst.*, 2012, **6**, (4), pp. 355–363

[117] Grumert, E., Ma, X., Tapani, A.: 'Effects of a cooperative variable speed limit system on traffic performance and exhaust emissions', *Transp. Res. C: Emerg. Technol.*, 2015, **52**, pp. 173–186

[118] Zohdy, I.A., Rakha, H.: 'Intersection management via vehicle connectivity: The intersection cooperative adaptive cruise control system concept', *J. Intell. Transp. Syst.*, 2016, **20**, (1), pp. 17–32

[119] Ji, Y., Hu, B., Hill, G.*, et al.*: 'Signal coordination scheme based on traffic emission', *IET Intell. Transp. Syst.*, 2016, **10**, (2), pp. 89–96

[120] Grote, M., Williams, I., Preston, J.*, et al.*: 'Including congestion effects in urban road traffic CO_2 emissions modelling: do local government authorities have the right options?', *Transp. Res. D, Transp. Environ.*, 2016, **43**, pp. 95–106

[121] Soriguera, F., Martínez, I., Sala, M.*, et al.*: 'Effects of low speed limits on freeway traffic flow', *Transp. Res. C, Emerg. Technol.*, 2017, **77**, pp. 257–274

[122] Wua, K., Chena, Y., Ma, J.*, et al.*: 'Traffic and emissions impact of congestion charging in the central Beijing urban area: a simulation analysis', *Transp. Res. D: Transp. Env.*, 2017, **51**, pp. 203–215

[123] Barth, M., Boriboonsomsin, K.: 'Energy and emissions impacts of a freeway-based dynamic ECO-driving system', *Transp. Res. D, Transp. Environ.*, 2009, **14**, (6), pp. 400–410

[124] Barkenbus, J.N.: 'Eco-driving: an overlooked climate change initiative', *Energy. Policy.*, 2010, **38**, (2), pp. 762–769

[125] Park, S., Rakha, H, Ahn, K.*, et al.*: 'Predictive ecocruise control system: model logic and preliminary testing', *Transp. Res. Rec., J. Transp. Res. Board*, 2012, **2270**, pp. 113–123

[126] Ahn, K., Rakha, H., Park, S.: 'Ecodrive application: algorithmic development and preliminary testing', *Transp. Res. Rec., J. Transp. Res. Board*, 2013, **2341**, pp. 1–11

[127] Yang, H., Jin, W.L.: 'A control theoretic formulation of green driving strategies based on inter-vehicle communications', *Transp. Res. C, Emerg. Technol.*, 2014, **41**, pp. 48–60

[128] Yang, H., Rakha, H., Venkat, M.: 'Eco-cooperative adaptive cruise control at signalized intersections considering queue effects', *IEEE Trans. Intell. Transp. Syst.*, 2017, **18**, (6), pp. 1575–1585

[129] Wadud, Z., MacKenzie, D., Leiby, P.: 'Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles', *Transp. Res. A, Policy Pract.*, 2016, **86**, pp. 1–18

[130] Foot, F.: 'The problem of abortion and the doctrine of the double effect in virtues and vices', *Oxford Rev.*, 1967, **5**, pp. 5–15

[131] NHTSA: 'Federal automated vehicles policy', National Highway Traffic Safety Administration. US Department of Transportation, 2016, pp. 1–116

[132] BMVI Ethics Commission: 'Automated and connected driving', German Federal Ministry of Transport and Digital Infrastructure, 2017, pp. 1–36

[133] 'Massachusetts Institute of Technology, MIT (2017). Moral Machine'. Available at http://moralmachine.mit.edu/, accessed 22 February 2018

[134] Marchant, G.E., Lindor, R.A.: 'The coming collision between autonomous vehicles and the liability system', *Santa. Clara. Law. Rev.*, 2012, **52**, (4), pp. 1157–1169

[135] Hevelke, A., Nida-Rümelin, J.: 'Responsibility for crashes of autonomous vehicles: an ethical analysis', *Sci. Eng. Ethics*, 2015, **21**, (3), pp. 619–630

[136] 'Recommendations to the Commission on Civil Law Rules on Robotics, 'Mady Delvaux' – European Parliament', http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+REPORT+A8-2017-0005+0+DOC+XML+V0//EN, accessed 26 February 2018

[137] Thierer, A.D., Hagemann, R.: 'Removing roadblocks to intelligent vehicles and driverless cars', *Wake Forest J. Law Policy*, 2015, **5**, pp. 339–391

[138] Vienna Convention on Road Traffic: 'United Nations Economic and Social Council's Conference on Road Traffic', 1968

[139] Regulation No. 79 of the Economic Commission for Europe of the United Nations (UN/ECE): 'Uniform provisions concerning the approval of vehicles with regard to steering equipment, revision 2', 2008

[140] 'Global Atlas of Autonomous Vehicles in Cities – Bloomberg Philanthropies and the Aspen Institute'. Available at https://avsincities.bloomberg.org/, accessed 26 February 2018