Introduction

This chapter explores the role of technology in creating a functioning public transport system fit for societal needs and demands in the 21st century. These requirements are highly influenced by the conditions imposed by global urbanisation, demographic growth, extended life expectancy, climate change and sustainability challenges.

Ticket machines, smart cards, contactless payment, low floor buses, bus rapid transit (BRT) systems, light rail rapid transit systems, driverless metro, in-cab communication and navigation systems, radio-based communication systems for metro and articulated buses are examples of technologies that have evolved and enhanced public transport systems over the past five decades (see Figure 41.1). Ottawa, Curitiba, Bogotá, Vancouver, Lille, Singapore, Hong Kong and Paris have pioneered these innovations and, in doing so, inspired others across the globe.

The rapid digitalisation process experienced across all spheres of society, which is underpinned by the associated emergence of new technologies, is creating a wealth of opportunities enabling fundamental changes in how future transport systems are designed and implemented. This is encompassing all aspects of the system, but it is particularly significant in applications related to how vehicles are designed and operated, how infrastructure is deployed and managed and the types of transport services offered to citizens, as well as the format in which these are accessed. Examples include, but are not limited to, automation of vehicles, vehicle-to-infrastructure connectivity, smart corridors, shared mobility, micro-mobility and Mobility as a Service (MaaS).

Technology is also at the core of efforts to decarbonise transport systems, and this is even more so in the particular case of public transport, given the extent to which urbanisation is contributing to global climate and sustainability challenges. Progressively reducing dependency on internal combustion engines as the main propulsion system for vehicles; adopting efficient energy storage systems, both in vehicle and wayside and exploring novel vehicle concepts, for example, driverless pods and vertical take-off and landing (VTOL) aircraft, are all examples of initiatives aimed at significantly reducing the contribution of transport to greenhouse gas emissions (see also Chapter 40).

These issues are discussed in this chapter with an emphasis on technological trends applied to vehicle, infrastructure and public transport services in the context of digitalisation and decarbonisation.
Roberto Palacin

Digitalisation of public transport

The digitalisation of services is expected to have a profound impact on transport and mobility (Government Office for Science, 2019). Transport users in urban areas have become data points, creating a shift in the way mobility provision is designed, accessed and operated. Intelligent systems are providing a shift from a fragmented system of modal silos to user-centric mobility that integrates inadequately connected mode-based systems while allowing system-wide optimisation of networks and resources, that is, transport that fulfils the elusive goal of truly satisfied and empowered users while achieving optimal performance and minimising its impact on our environment. An ageing society, energy usage, carbon footprint, network resilience, health impacts and socioeconomic aspects are all key transport challenges being re-imagined through digitalisation.

At the core of the digital revolution is data and information sharing. This is creating a new set of challenges and opportunities. Table 41.1 summarises the key questions surrounding this issue and potential strategies on how to approach them.

The use of technology based on data sharing is not an exclusive result of the digitalisation process but, arguably, a precursor. A clear example is the use of smart cards in public transport (see also Chapter 33). While the technology has been known and ready since the late 1960s (Pelletier et al., 2011), the exponential growth of the internet and the increased sophistication of mobile communication technologies experienced since the early 1990s has contributed to their widespread use (Blythe, 2004). This expansion has created a new source of transport data that can be used to analyse travel behaviour, an essential part of increasing patronage for public transport and hence maximising its benefits. While quality of data might vary, it is recognised that smart card technology facilitates access to: (i) a large volume of individual travel data, (ii) continuous trip data for longer periods of time and (iii) a frequency of individual trips (Bagchi & White, 2005). These vast datasets allow the mapping of accessibility not just from a physical perspective but as the time taken to travel between desired origin and destination locations (Lei & Church, 2010).

The essence of the data collected today remains, for example, origin–destination, but its quality and accuracy are improving. Similarly, the constant evolution of technology and mobile telecoms is superseding smart cards with contactless payments, for example, bank cards and digital (mobiles) based on near-field communication (NFC) technology. However, the digitalisation of society in urban areas is putting a strain on data distribution networks and could act as a barrier to further development of public transport systems. Fifth-generation (5G) mobile networks are perceived as the answer to ever-increasing demand for data and data services. The rollout of autonomous vehicles and other technologies (discussed further subsequently) depends on 5G, which is expected to reach approximately 90% of market coverage depending on location.

Figure 41.1  Simplified timeline of some key technology innovations in public transport

![Simplified timeline of some key technology innovations in public transport](image-url)
### Technology for the future

#### Table 41.1 Opportunities and barriers surrounding data and information sharing in transport

<table>
<thead>
<tr>
<th>Effects, questions and issues</th>
<th>How is data affecting transport?</th>
<th>Will new transport modes change how data is used?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aggregated individuals’ travel data combined with secondary data analysis allowing insight into choices and behaviour while protecting privacy</td>
<td>Digital literacy and access to smartphones could create disparity and reduce accessibility to essential transport services, particularly in rural areas</td>
</tr>
<tr>
<td></td>
<td>The relationship between data generators exploiting (e.g. Google) and not exploiting their data (e.g. transport operators) and new entrants seeking data to develop new business models is key for generating meaningful value from transport data</td>
<td>Data monopoly by large stakeholders could create unfair advantage and lack of choice</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distributed ledger technology, for example, Blockchain, could enable access and control over data ownership rights by individuals</td>
</tr>
<tr>
<td>Will public’s attitude to data sharing change?</td>
<td>Increasing expectation of obtaining something in return for sharing data</td>
<td>Contactless and other payment methods, for example, ApplePay, could raise concerns about geolocation and privacy</td>
</tr>
<tr>
<td></td>
<td>Contactless and other payment methods, for example, ApplePay, could raise concerns about geolocation and privacy</td>
<td>Data security, privacy and extent to which new legislation, for example, general data protection regulations (GDPRs), could affect data sharing</td>
</tr>
</tbody>
</table>

*Source: Government Office for Science, 2017*

This could potentially be a handicap for mass adoption of connected autonomous vehicles (CAVs) (Government Office for Science, 2019) given their requirement for ultra-reliable and low latency communications, which can only be provided with very high-coverage 5G communication services, for example, 99% or over (Oughton & Frias, 2016).

Smart cities are enabled by data and information sharing. The presence of pervasive and ubiquitous computing and digitally instrumented devices across cities allow monitoring, managing and regulating of urban flows with mobile technology (smartphones, in-vehicle computers) engaging with this digital infrastructure and thus generating relevant data (Kitchin, 2014). A multitude of mobile applications are facilitating the development of new business models around shared mobility, for example, car-sharing, carpooling, bike-sharing and micro-mobility.

The idea of the digitalisation of public transport, however, is more than simply data sharing. Leviäkangas (2016) argued that the term is significantly reliant on the concept of intelligent transport systems (ITSs), defined as “the application of modern information and communication technologies to transport system”. ITSs go beyond data, encompassing the system as a whole, for example, operations, vehicles, infrastructure and services. Systems thinking is essential to unlock the possibilities of digitalisation and public transport not just from a service perspective but also from a technology development and selection approach. Digitalisation should not be seen as an external phenomenon, a disturbance, to which society must adapt but a dynamic process that must be embraced and framed to achieve transformation leading to sustainable and low-carbon societies (Creutzig et al., 2019; German Advisory Council on Global Change, 2019).
However, the state of advancement related to data sharing, digitalisation and ITS and their normalisation in urban conurbations during the 21st century is creating a unique opportunity for the deployment of technology applied to public transport vehicles, infrastructure and services, contributing to the realisation of true mobility fostering seamless integration of modes, liveability of cities and decarbonisation.

Decarbonisation of public transport

Decarbonisation can be understood as the removal or reduction of greenhouse gas emissions within a given system or a part thereof (Golightly et al., 2019). This is a critical societal challenge of our time, with the Paris Agreement of 2015 setting out a framework to limit global temperature rise to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C (UNFCCC, 2015). Transport is a significant contributor to the challenge, being responsible for around 20–25% of emissions, a quarter of which is generated in urban environments (European Commission, 2011). Figure 41.2 shows the evolution of the overall contribution of transport to global CO2 emissions based on fuel consumption data (see also Chapter 8).

Significant efforts are already taking place to advance the decarbonisation of mobility systems by deploying alternative propulsion technologies and integrating renewable energy sources with transport infrastructure (European Commission, 2016). New technologies related to energy and materials are enabling new forms of decarbonised transport, whilst mobile applications are generating a wealth of new mobility services (Hinkeldein et al., 2015). The emergence of new players with disruptive offerings, for example, micro-mobility, is creating a transitional phase from the traditional mobility marketplace. These are challenging traditional boundaries between public and private transport and will increasingly require the co-creation of mobility services by both traditional public and new private providers. Future global transport and mobility will be fundamentally affected by the need to create more resource-efficient, clean transport technologies and to deploy and maintain sustainable transport systems (Lennert & Schönduwe, 2017). This is particularly relevant today in the urban context with an urgent need to decarbonise public transport at the point of use for quality-of-air purposes but also as a whole system to meet global challenges.
The advent of new business models triggered by digitalisation, albeit in their infancy, is allowing the increase in capacity and efficiency of transport and energy systems, which in turn is contributing to decarbonisation (Canzler & Knie, 2016). This is linked to the essential prerequisite of having fully integrated public transport systems as part of any attempt to successfully decarbonise mobility. Technology has a fundamental role to play as part of a wider systems approach combining not just clean vehicles but also smarter operations, co-ordinated service offer, enhanced active mobility options and a policy framework that supports these initiatives, as well as the core ingredient of any decarbonisation strategy, that is, a modal shift from private to public transport.

Suggested strategies for the success of decarbonised mobility include: (i) ambitious limits on CO₂ emissions, (ii) compulsory pricing schemes for traffic and parking areas with exceptions for shared zero-emission vehicles and (iii) experiments with decentralised networks in field tests under realistic conditions (European Commission, 2016). The latter refers to co-operative ITS (C-ITS), where vehicles communicate with each other and with the infrastructure, removing the need for centralised control centres (Osaba et al., 2016). Technology is already playing a pivotal role in all of these approaches.

Whilst initiatives from national and supra-national organisations (e.g. European Commission, United Nations) are needed to create the conditions allowing the implementation of decarbonisation strategies, cities are essential for this to materialise. The Global Covenant of Mayors for Climate and Energy (GCoM) and the C40 Network are two examples of the relevance of combined urban efforts. GCoM is the largest global alliance for city climate leadership, built on the commitment of over 10,000 cities and metropolitan areas representing more than 800 million people, and is expected to achieve an estimated 2.3 billion tons CO₂e of annual emissions reduction by 2030 (Global Covenant of Mayors for Climate and Energy, 2020). The C40 network is a more executive global grouping of 94 megacities aiming at implementing commitments to deliver the goals of the Paris Agreement at local level using data, shared practice and specific programmes to achieve this (C40, 2020). An illustration of this is the Fossil-Fuel-Free Streets Declaration (October 2017), committing the signing cities to all-electric buses by 2025 and zero emissions in designated areas by 2030 (C40 & GCoM, 2017). Target dates for ending the sale of new internal combustion engines (ICEs) range from 2025 (Norway) to 2050 (e.g. Costa Rica) (Schwanen, 2019).

Designing for decarbonisation of public transport is a systems problem in which it is not just the performance of individual vehicles or their specific components that defines carbon impact but also the interaction between multiples of those across scales, often within an operational context (Golightly et al., 2019; Roskilly et al., 2015). Arguably, the three revolutions postulated by Sperling (2018), namely electrification, automation and shared mobility, are the basis for any successful attempt at decarbonising urban transport. The role of technology and public transport is core to this approach.

Vehicle technology trends

Automation

On-road vehicles

Self-driving cars once seemed a far-fetched idea from some distant sci-fi future, appearing as an exhibit at the 1939 New York World’s Fair (Sperling, 2018). Today’s road vehicles have a significant number of automated features, for example, cruise control, automatic braking, lane departure warning and correction systems. There are many different terms often used to
refer to vehicle automation. Connected, autonomous and driverless are examples. Connected vehicles use communication technologies enabling the exchange of information with other vehicles (vehicle-to-vehicle or V2V) and/or with the surrounding infrastructure (vehicle-to-infrastructure or V2I) (Clarke J & Butcher L, 2017). This is closely related to the taxonomy of driving automation levels, which allow for progressive engagement/disengagement of drivers as summarised in Figure 41.3.

Current driving assistance systems require driver engagement at all times, while future systems will gradually reduce the engagement levels. This can be translated to what is known as high automation and full automation. High automation requires the driver to be present and engaged with an expectancy to take full control in certain conditions, for example, bad weather. Full automation does not require a driver, as the vehicle is designed to be fully safe to complete journeys in any conditions (Department for Transport, 2015). For the purpose of this chapter, the term connected and autonomous vehicles (CAVs) is used to refer to all types of road vehicle automation covering levels 3 to 5.

The technologies that facilitate CAV deployment are varied. In broad terms, and focusing on the vehicle only, these relate to on-vehicle software and hardware, although dependencies with non-vehicle systems are part of their essential functioning, for example, communication networks. Table 41.2 summarises the main technologies related to crucial CAV aspects and their research status.

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**Figure 41.3** Levels of driving automation

*Source: Adapted from SAE International, 2018*
There is an abundance of trials related to the development of the technologies described previously, for example, Google’s Waymo and Uber, as well as already commercially available features such as Tesla’s *autopilot* (albeit only partially operational). Governments and private investors worldwide are exploring, testing and piloting technologies that will make automation a reality. In Europe, testing on public roads is legal in countries such as the United Kingdom, France, the Netherlands, Germany, Norway and Sweden. Oxbotica, a UK start-up, began on-road testing in 2018 for Level 4 automated grocery delivery vehicles, taxis and shuttles. In North America, companies such as Waymo are conducting extensive on-road pilots. Similar situations can be identified for Asian countries, namely China and Japan (Frost & Sullivan, 2019). Although estimates vary, it is not expected that these will be commercially available before 2030 or fully widespread before the 2040s (Government Office for Science, 2019).

What about public transport? Fleet operators are expected to be early adopters. Technology companies, car manufacturers, traditional public transport operators and governments have all launched mobility service projects using CAVs (Abe, 2019). Ride-sharing is an example of such services, for example, the Waymo One Program in the Phoenix area of the United States. Bus services, particularly BRT due to the segregated nature of its operation, are also likely early adopters of autonomous technology. For instance, in late 2019, a pioneering electric and autonomous 12-m bus demonstrator (Volvo technology operated by Keolis) took place in the Swedish city of Gothenburg (ElectriCity Partnership, 2020). The city of Edinburgh (UK) is

<table>
<thead>
<tr>
<th>CAV aspect</th>
<th>Related technologies</th>
<th>Observations and future research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors and monitoring systems</td>
<td>LIDAR, RADAR, cameras, ultrasonic, infrared, Inertial navigation systems (INS)</td>
<td>Sensor resolution is highly affected by weather conditions. Current and future research focuses on reducing such impact</td>
</tr>
<tr>
<td>Inter-CAV communications</td>
<td>Vehicle-to-everything (V2X), for example, vehicle-to-pedestrian (V2P), vehicle-to-network (V2N)</td>
<td>V2X is highly dependent on wireless technologies. 5G C-V2X (cellular-based V2X) is considered a promising future technology</td>
</tr>
<tr>
<td>Security</td>
<td>Virtual machine (VM), GPS</td>
<td>Passive attacks are mainly related to vulnerabilities of servers, while active attacks are associated with in-vehicle and road-level components, for example, jamming of antennas. Key research includes 5G C-V2X security and the development of auto security development frameworks (ASDF)</td>
</tr>
<tr>
<td>Traffic intersection navigation</td>
<td>Cooperative adaptive cruise control (CACC), cooperative vehicle intersection control (CCVIC)</td>
<td>Centralised navigation has demanding computational requirements but is highly reliable, while decentralised navigation is more flexible. Future systems are expected to use a combination of both, for example, navigation of intersections</td>
</tr>
<tr>
<td>Collision avoidance</td>
<td>Pre-collision systems (PCSs), predictive trajectory guidance (PTG)</td>
<td>Critical for autonomous collision avoidance is finding a suitable balance between fluidity (e.g. adaptive cruise control) and overall safety</td>
</tr>
</tbody>
</table>

Source: Bagloee et al., 2016; Elliott et al., 2019
expected to pilot a commercial service in the second half of 2020 on a 14-mile route crossing the Forth bridge using single-decker buses operating at level 4 autonomy (UK Research & Innovation (UKRI), 2020). Japan is testing self-driving ride-sharing services in Yokohama (Nissan) and autonomous buses in the suburbs of Tokyo as a feeder services to a station (Odakyu Railway) (Abe, 2019).

The possibilities to re-think public transport are also enhanced by autonomous technology using, for instance, shuttle pods. In Europe, the European Commission is funding a demonstrator project with a value of approximately €20m to run fleets of autonomous minibuses from start-up Navya in low to medium demand areas of four cities (Geneva, Lyon, Copenhagen and Luxembourg) and planning to have a further three so-called replicator cities applying the lessons learned (Avenue Project, 2020; European Commission, 2020).

The contemporary digitalisation process is facilitating the expansion of the on-road automation technologies described here. This is particularly relevant for aspects of secured data transmission and communication networks, for example, 5G. On-road automation cannot be imagined without non-fossil fuel propulsion technologies leading to cleaner air and decarbonised mobility. However, it could also lead to a rise in the number of journeys, increasing congestion, creating the opposite effect particularly during the transition phase where traffic will be a mix of vehicles with different levels of autonomy and powered by fossil and non-fossil-based propulsion systems.

**Urban rail systems**

Rail is best placed to become the backbone of greater levels of mobility due to its superior mass transit capability and energy efficiency related to the low resistance of the steel-on-steel contact. As early as the 1970s, rail was already expected to be the first transport system to be automated (Berwell FT, 1973). Today there are 69 fully automated lines in 44 cities from 21 countries across the world (UITP, 2019a), meaning that approximately one third of world cities with metros have automated lines. Powell et al. (2016) provides a good overview of the historic implementation timeline. As with on-road applications, the level of automation, known as grade of automation (GoA), is defined and standardised (IEC, 2009) depending on the human interaction requirements. Figure 41.4 provides an overview of GoA for metro.

The GoAs, in turn, are related to varied technology-based operations, as summarised in Table 41.3.

Automated metros are at the forefront of technological advance for guided systems. Varying grades of automation provide increasing advantages, for example, greater capacity utilisation and efficient use of resources. Automatic train operation provides more sophisticated control than manual driving, translating into a reduced energy consumption, lower wear and tear on the vehicles and increased ride comfort (Vuchic, 2014). Driverless trains (GoA4) are the ultimate level of rail automation, and while they are currently relatively niche, they are poised to be the norm in the not-too-distant future, influenced, in part, by advances in digital technology and the demands for decarbonisation of metropolitan areas.

**Propulsion**

**On-road vehicles**

As discussed previously, the climate emergency has increased the relevance of calls for the decarbonisation of transport in general and in particular in urban areas. A core aspect of this
approach is the search for alternative forms of propulsion that are non-dependant on burning fossil fuels. Introducing alternative transport vehicles is necessary in order to achieve objectives of decarbonisation, energy security and urban air quality (Offer et al., 2010). Chief amongst the emerging technologies being applied to on-road propulsion as an alternative to the internal

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic train protection (ATP)</td>
<td>A control system preventing trains from following each other at a gap that is less that the safe stopping distance. It is linked to GoA1 and requires the train to be manually driven.</td>
<td>London Underground</td>
</tr>
<tr>
<td>Automatic train operation (ATO)</td>
<td>Performs all functions along a given line. It is necessary for GoA2/3/4 and does not require a driver controlling the train. Drivers can have an oversight role and perform other safety-critical tasks, for example, open/close doors.</td>
<td>Hamburg, London, Singapore</td>
</tr>
<tr>
<td>Unattended train operation (UTO)</td>
<td>Needs a fully controlled and protected track. Required for GoA4, it can drastically increase capacity of a network.</td>
<td>Lille, Paris, Singapore</td>
</tr>
<tr>
<td>Automatic train supervision (ATS)</td>
<td>A system controlling the movement of all trains on a given line and/or network.</td>
<td>San Francisco, London</td>
</tr>
</tbody>
</table>

Source: Fraszczyk et al., 2015; Cohen et al., 2015; Vuchic, 2014, 2007
Roberto Palacin

**Table 41.4 Overview of charging technologies and strategies for electric buses**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description and charging strategy</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low power charging</td>
<td>Use of cable and plug-in. Suitable for <strong>overnight charging strategies</strong> when the bus is out of service at the depot. Requires large batteries.</td>
<td></td>
</tr>
<tr>
<td>High power charging</td>
<td>Use of conductive charging with physical connections for example, pole mounted pantographs. Suitable for <strong>overnight and opportunity charging strategies</strong> i.e. inductive or conductive charging at selected stops or at the head/end of the line. Allows for the use of smaller batteries suitable for high power charging.</td>
<td>Stockholm, Eindhoven, Barcelona, Vancouver, Shenzhen, Singapore</td>
</tr>
<tr>
<td>Fast charging</td>
<td>Use of inductive charging with a transfer of energy through a magnetic field. Suitable for single or <strong>combined depot and opportunity strategies</strong>.</td>
<td>Namur (Belgium), London (inductive trials)</td>
</tr>
</tbody>
</table>

*Source: Lin et al., 2019; UITP, 2019b*

Combustion engine are battery electric vehicles (BEVs), with hydrogen fuel cell electric vehicles (FCEVs) hailed as a future long-term sustainable option.

Putting aside BEVs for private and hire purposes, electric buses are the most promising of the alternative propositions for public transport. Approximately 385,000 electric buses are on the roads globally, with 99% of all electric buses located in China, representing circa 13% of the total global urban bus fleet (O’Donovan & Frith, 2018). In 2017, the Chinese city of Shenzhen completed the electrification of its entire fleet of 16,359 buses, becoming the first city in the world to do so (Lin et al., 2019). At the core of strategies for the mass deployment of electric buses is the battery technology which is linked to the charging technologies available and operational and the time penalties introduced by these technologies. Table 41.4 summarises these aspects.

The viability of any of the charging strategies described depends on the local conditions of the city and include location of depots, visual impact of charging equipment, possibilities for shared infrastructure, for example, private car charging.

**Urban rail systems**

Urban rail, namely metro, tram or commuter services, is regarded as an ideal solution to reduce the impact of urban mobility because of its great capacity, safety, reliability and excellent environmental performance (González-Gil et al., 2014; Vuchic, 2007). Urban rail systems are an agent of decarbonisation.

Energy use in urban rail systems may be typically classified into two categories: traction and non-traction consumption. Traction consumption accounts for the power required to operate the rolling stock across the system (González-Gil et al., 2014). Urban rail systems are already electrified. A number of technologies are being considered to take advantage of the current digitalisation and decarbonisation framework and enhance the already positive credentials of urban rail. Particularly relevant to the propulsion aspects are technologies aimed at optimising energy usage. These include energy storage systems (ESSs) and more efficient motors, for example, permanent magnet synchronous motor (PMSM). Table 41.5 summarises some of these technologies.
Table 41.5 Summary of main traction-related technologies for current and future application in urban railways

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy storage systems and units</td>
<td><strong>Batteries.</strong> High energy but low power density. Li-ion or NiMH are the most common. Suitable for various charging strategies and applications, for example, regenerative braking.</td>
<td>Nice Tram (France), Singapore MRT</td>
</tr>
<tr>
<td></td>
<td><strong>Electro-chemical double layer capacitors.</strong> Also known as supercapacitors or supercaps. Widely used due to high power density, fast response, high cycle efficiency and long lifecycle. Energy density is low.</td>
<td>Seville and Zaragoza trams (Spain), Hunan (China)</td>
</tr>
<tr>
<td>Flywheels</td>
<td>Attractive features for energy storage and recovery but limited commercial viability.</td>
<td>Los Angeles (wayside)</td>
</tr>
<tr>
<td>Permanent magnet synchronous motor</td>
<td>A promising alternative to the state-of-the-art asynchronous machines due to its very high efficiency of up to 97%.</td>
<td>Munich, Tokyo</td>
</tr>
</tbody>
</table>

Source: Adapted from González-Gil et al., 2014

An interesting approach that is gaining acceptance is the combination of some of these technologies due to their complementarity, for example, battery (low power, high energy density) and supercaps (high power and low energy density). The high cost of electrification and the visual impact on historic city centres is also driving a need for catenary-free tram systems, increasing the demand on these energy storage systems.

**Infrastructure technology trends**

To take full advantage of the benefits that digitalisation brings and to direct these for endeavours such as decarbonisation, a smart and efficient supporting infrastructure is paramount. While the focus of this section is on technology trends, it is important to acknowledge that technology alone will not be sufficient to tackle the issues surrounding mobility in urban areas or indeed increase significantly the patronage of public transport. These innovations need to be combined with understanding of human choice and effective policies that prioritise public transport over private cars.

The automation of public transport, both on-road or rail systems, requires the deployment of equally smart infrastructure. Table 41.6 provides an overview of future technology applications.

**Services technology trends**

New technologies promise the promotion of new mobility paradigms but technology enables rather than drives change (Mulley, 2017). This is also applicable to digitalisation. A topical development that has dominated the discourse amongst transport experts in recent years is...
Table 41.6 Overview of infrastructure themes and associated future technologies

<table>
<thead>
<tr>
<th>Infrastructure theme</th>
<th>Technologies and description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV charging infrastructure</td>
<td><strong>Fast charging.</strong> Three-phased up to 22 kW of power. Able to charge 80% of a battery in 1–2 h</td>
<td>Standard in service stations and fleet depots</td>
</tr>
<tr>
<td></td>
<td><strong>Rapid charging.</strong> Three-phased up to 43 kW or DC up to 50 kW as well as 175/350 kW if vehicle can accept this power. 80% charge in ~30min (15 min for 175 kW)</td>
<td>Dedicated charging stations, for example, Fastned network</td>
</tr>
<tr>
<td></td>
<td><strong>Super rapid charging.</strong> A version of rapid charging exclusive to Tesla vehicle owners</td>
<td>Tesla supercharger network</td>
</tr>
<tr>
<td></td>
<td><strong>Pole-mounted pantographs.</strong> Power capability includes 150, 300 and 450 kW</td>
<td>Hamburg, Vancouver, Montreal, Gothenburg, Singapore, Luxemburg</td>
</tr>
<tr>
<td>Co–operative intelligent transport systems</td>
<td><strong>Dynamic or Wireless Electric Vehicle Charging.</strong> Concept of a continuously charging vehicle for example, using electromagnetic induction via a wireless connection</td>
<td>Online electric vehicle (OLEV), Korea</td>
</tr>
<tr>
<td>Smart cycling</td>
<td>Sensors reacting to the presence of cyclists at crossings providing green lights for longer</td>
<td>“Warmth Sensor” in Rotterdam</td>
</tr>
<tr>
<td></td>
<td>Safety in tunnels by using sensors detecting movement and activating lights informing others of their presence</td>
<td>“Spinning lights” Copenhagen</td>
</tr>
<tr>
<td></td>
<td>Information at traffic lights indicating cyclist of speed adjustments to achieve a seamless flow at intersections</td>
<td>Flo, Evergreen, Netherlands, Green Waves Copenhagen</td>
</tr>
<tr>
<td>Urban rail</td>
<td>Communication-based train control (CBTC) allows for moving block operation, bringing trains much closer together, increasing capacity. Can be used in all types of operation, but it is essential for GoA3/4</td>
<td>Lille, London, Underground, New York Subway, Paris Metro</td>
</tr>
</tbody>
</table>

Source: ACEA, 2017; Cho et al., 2015; ElectriCity Partnership, 2020; Nikolaeva et al., 2019; UKEVSE, 2020

the concept of Mobility as a Service (MaaS) (see also Chapter 3). Many definitions have been offered but perhaps a clear way to describe it is:

a technology-enabled Mobility Management service where the customer interface and business back office are integrated. . . . MaaS concentrates on resolving the origin and destination requirements of the traveller through providing (usually) a number of options which vary by mode, time and cost.

(Mulley, 2017, pp. 247–248)
railway system providing easy, personalised and integrated future mobility

Figure 41.5  Digitally enabled rail system as part of future mobility
Underpinning the concept of MaaS is the way technology advancement facilitated by digitalisation can lead to easier sharing of mobility resources (Mulley & Kronsell, 2018). The integration of transport services in this way is agnostic of mode and allows for blurring the boundaries between public and private transport, redefining the very concept of public transport and providing, at least in theory, an opportunity for increased patronage.

Pooling of mobility services has greater potential than EVs to transform mobility. Sperling (2018) goes as far as stating that it is the “single most important strategy and innovation going forward for all passenger transportation”. Pooling is understood in the broader sense of the new mobility services such as Uber, Lyft, ZipCar and Co-Wheels rather than conventional carpooling, which some commentators consider “has been a failure”. This is linked to the three revolutions, that is, electrification, automation and shared mobility (ibid.). Interesting developments taking place now and suggesting a future pathway for urban mobility include the emergence of new services in cities under the umbrella term of micro-mobility, for example, one-way sharing, which involves free-floating fleets of bikes, e-bikes, e-scooters and cars. One-way electric car sharing has considerable potential due to its complementarity with air quality and decarbonisation strategies, the proliferation of mobile technology and the prospects of autonomous vehicles (Mounce & Nelson, 2019). The implementation challenges of these services are, arguably, linked to non-technology aspects such as regulation.

An exemplary illustration of the positive effects of free-floating fleet services is London’s car-sharing scheme, which has nearly a quarter of a million members, making it the second largest in the world, and aims at 1 million users, or 20% of the driving population, by 2025. Members drive less than car owners and use more public transport, walking and cycling (Polis, 2016). This is in line with research that highlights the relevance of these sharing systems as they integrate with public transport to become relevant elements in urban transport systems of the future (Mounce & Nelson, 2019).

Nevertheless, none of the promises that these new services and MaaS offer will be realised without a robust, reliable and capable mass transit system. For large and mega cities, this mainly means rail-based systems which also act as an agent of decarbonisation. A vision of such future system is depicted in Figure 41.5.

Conclusions

The main driver of innovation in transport is digitisation, and new mobility services accessible via smartphones are booming (European Commission, 2016). Technology advancement is being made possible by digitalisation enabling new opportunities to maximise the potential of shared services in public transport. This, in turn, is contributing directly to the all-important decarbonisation agenda.

Automation promises to play a crucial role in any future public transport system although full automation might remain a niche for the first half of the 21st century. In the interim, many of its features can and are bringing benefits to cities across the globe; for example, driverless metro systems are providing essential reliable, high-capacity and efficient mass transit.

Clean vehicles are a compulsory component in the quest for decarbonisation, and electric propulsion is core to that. New battery technology and economies of scale will facilitate the uptake, accelerated by policies banning petrol, diesel and hybrid vehicles.

Infrastructure supporting these technological innovations will transform the urban landscape, putting users and not cars at its core. Sensors, cameras and charging stations will all contribute to this change. The transformation is being completed by the increasing relevance of active mobility and micro-mobility and the realisation of the need for specific infrastructure interventions to
facilitate this. Examples of this include the development and deployment of sensors specifically designed to detect cyclist and pedestrians, vehicle-to-infrastructure interactive technology and traffic management protocols protecting vulnerable road users.

To realise this, there are promising areas of research underway which include, but are not limited to, the following:

- Ultra-highly reliable and secured sensors and wireless networks supporting mass deployment of autonomous vehicles;
- Navigation technology for autonomous vehicles for example, co-operative adaptive cruise control (CACC), co-operative vehicle intersection control (CCVIC);
- Safe deployment of technology for example, communication-based train control allowing grade of automation level 4 on mainline railways, for example, driverless mainline trains; and
- A new generation of batteries with much higher performance in terms of storage capability, power density, weight and cost, for example, batteries using solid-state materials and sodium-ion batteries.

Public transport services are being redefined by new paradigms such as MaaS, seeking the increased patronage, accessibility and integration of shared mobility facilitated by emerging digital technologies.

Systems thinking is essential to unlock the possibilities of digitalisation and public transport not just from a service perspective but also from a technology development and implementation approach. Accelerated decarbonisation goals cannot be achieved without this holistic view.

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