Transportation Research Part A 120 (2019) 17–30

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

On the potential for one-way electric vehicle car-sharing in future mobility systems

Richard Mounce*, John D. Nelson

Centre for Transport Research, School of Engineering, University of Aberdeen, Fraser Noble Building, Aberdeen AB24 3UE, UK

ARTICLE INFO

Keywords:
Car-sharing
Electric vehicle
Charging
Redistribution
Autonomous vehicle

ABSTRACT

City transport systems often struggle to cope with high volumes of traffic and become congested, despite the use of various traffic management strategies. The concentration of traffic around city centres results in pollution and poor urban air quality, although the increasing popularity of electric vehicles is helping ameliorate these effects. One reason for the growing momentum behind electric vehicles is the emergence of mobility operators such as car-sharing companies, who target users wishing to rent out vehicles on a short-term basis. There is currently rapid growth in one-way car-sharing, in which the vehicle can be dropped off at a different location to the pickup point. Crucially, one-way car-sharing gives the opportunity for travellers to utilise car-sharing in conjunction with other modes, such as public transport modes, for their journey provided the requisite intermodal connections are present. This paper looks at how one-way electric vehicle car-sharing systems have the potential to become important components of future city transport systems. The future role of shared autonomous vehicles is also considered.

1. Introduction

Towns and cities are very significant to transport, with larger cities being of greater significance. First, their large populations mean that many trips originate and terminate in cities. Secondly, they have numerous attractions, such as employment, retail and recreational facilities, which means that many trips by those living outside the city have their destination within the city. Many of these trips are facilitated by motorised transport and this means that there is generally a lot of traffic concentrated within cities. These high volumes of traffic in cities have been bolstered by the trend of urbanisation, i.e. a population shift from rural to urban areas. The United Nations have predicted that by 2050 about 64% of the developing world and 86% of the developed world will be urbanised, with nearly all global population growth from 2016 to 2030 being absorbed by cities (United Nations, 2015). This urbanisation will drive an increase in urban population density, resulting in an increasing amount of people requiring transportation in urban areas.

There are downsides to having large volumes of traffic in cities. These high volumes of traffic often lead to congestion, which amounts to a huge waste of time, energy and money. Emissions from traffic are a major contributor to greenhouse gases. High levels of traffic in cities has a major impact on urban air quality (Fenger, 1999). The adverse health effects of particulate matter are well documented and there are growing concerns regarding nitrogen dioxide (World Health Organisation, 2013). Other downsides include increased accident rates and noise pollution. In general, the extent of these problems is particularly striking in some of the larger cities in developing countries, but this is perhaps largely because cities in developed countries have had longer to refine their strategies for dealing with these traffic-related problems. Section 2 will outline a range of traffic management strategies.

* Corresponding author.
E-mail address: r.mounce@abdn.ac.uk (R. Mounce).

https://doi.org/10.1016/j.tra.2018.12.003
Received 1 December 2017; Received in revised form 3 November 2018; Accepted 4 December 2018
0965-8564/

Fulton et al. (2017) write about the three revolutions in urban transportation (the *3Rs*) of electrification, automation and sharing and in this paper we seek to draw out the benefits for car sharing that arise from this juxtaposition of these influences. Section 3 outlines the emerging trends in mobility that have the potential to significantly impact the way we travel in the future. One of these trends is the electrification of the motor vehicle industry and this is discussed in Section 4. Another trend is the development of autonomous (or driverless) vehicles and these are discussed in Section 5. Car-sharing, in which users make temporary use of vehicles, is a recent mobility trend that is discussed in Section 6. Finally, Section 7 will discuss the central focus of the paper: one-way electric vehicle car-sharing, in which users make temporary use of electric vehicles which they can pick up and drop off at different locations.

2. Traffic management strategies

City authorities employ a range of traffic management strategies to attempt to manage traffic and its related problems. These strategies include:

(1) *Car-free zones*. Car-free living is most easily satisfied in cities due to them affording better access to services and better public transport.
   (a) *Car-free cities*. There are several towns and cities across Europe which are completely car-free, e.g. Venice which utilises water transport and Mdina in Malta which does not allow motor traffic inside its city walls.
   (b) *Pedestrianisation*. Most cities do allow cars into their centres, but many cities do have pedestrianised zones, which are streets or areas for use solely by pedestrians (and perhaps also by cyclists in many cases). The first purpose-built pedestrian street in Europe was the Lijnbaan in Rotterdam, opened in 1953. Many European towns and cities have made part of their centres car-free since the early 1960s. The impacts of pedestrianisation are assessed in Hass-Klau (2014).
   (c) *Car-free neighbourhoods*. Underlying car-free neighbourhoods is the exclusion of traffic and non-ownership of vehicles. There is evidence that car-free neighbourhoods are friendlier and more socially cohesive (Ornetzeder et al., 2008).
   (d) *Car-free periods.* Many cities have had car-free days as a means of demonstrating the benefits to their citizens. The 22nd September is World Car Free Day. Bogotá holds the world's largest car-free weekday event covering the entire city.

(2) *Congestion charging*. Congestion charging is a form of road pricing, which involves drivers paying monetary fees to traverse some of the roads on the network. Economists have long advocated road pricing, but there is a debate about its economic efficiency (Raux et al., 2012). Road pricing ideally charges users the marginal congestion cost, which is the additional cost that users place on existing users (Button, 2004). Congestion charging attempts to deter road users from entering congested city centre areas by charging them a monetary fee, which can be fixed or variable (e.g. it might increase as the congestion increases). Another possible form for congestion charging is tradable congestion credits (Yang and Wang, 2011). Congestion charging can result in time savings for travellers (Raux et al., 2012) as well as lowering rates of car ownership in the long term. However, the successful implementation of congestion charging relies not only on its design and implementation, but also on its public acceptability (Jaensirisak et al., 2005). Probably the highest profile scheme is the London Congestion Charge, which was introduced in 2003 and remains one of the largest congestion charge zones in the world. The charge's primary aim is to reduce high traffic flow in the central area, but it has also raised investment funds for London's transport system (Li and Hensher, 2012).

(3) *Traffic signal control*. Traffic signal control can be an effective tool in managing traffic to achieve given objectives. These objectives might include minimising travel delays, maximising network capacity and managing queues. Intelligent use of traffic signal control should take account of the fact that changes to signal control settings impact upon travellers' route choices (Smith et al., 2015).

(4) *Low emission zones*. A low emission zone (LEZ) is an area from which vehicles emitting pollutants over a given threshold are restricted access to, e.g. hybrid vehicles may be allowed, but internal combustion vehicles would not be. There are also ultra-low emission zones (ULEZs), which have extremely low emissions thresholds; and zero emission zones (ZEZs), which do not permit any vehicle emissions at all (so only fully electric vehicles would be allowed and not hybrids, along with pedestrians, cyclists and fully electric public transport). The aim of LEZs, ULEZs and ZEZs is to improve air quality in the area. The first LEZs in Europe were established in Stockholm in 1996. More than 200 cities and towns in 10 countries around Europe already have in place or are preparing to introduce LEZs. The EU air quality directive (2008/50/EC) required the limit values for particulate matter and nitrous dioxide to be achieved by 2005 and 2010, but many European cities still exceed these limits, and so many cities have introduced LEZs to help meet these targets. Holman et al. (2015) investigated the effectiveness of LEZs in improving air quality.

(5) *Improvements to public transport and walking/cycling infrastructure*. The number of motorists in city centres can be reduced by making public transport more attractive since this will induce a modal shift away from the car. In terms of public transport, service reliability is a key factor for passengers (White, 2017). Intermodal connections are also important, since in replacing trips that might otherwise only be possible by car, it may be necessary to undertake these using multiple modes. An example of this is Park and Ride, in which drivers park outside of the city and take buses into the city centre. Provision of sufficient walking and cycling infrastructure is also important in encouraging use of these 'slow modes' instead of the car. The availability of new technology (especially apps accessed via smartphones) is also being used to promote public transport and active travel.

3. Trends in mobility

People need to travel for a variety of reasons, many of which have been present for thousands of years, e.g. to find resources and to socialise. The amount of time that people spend travelling has remained remarkably constant, but with the development of faster

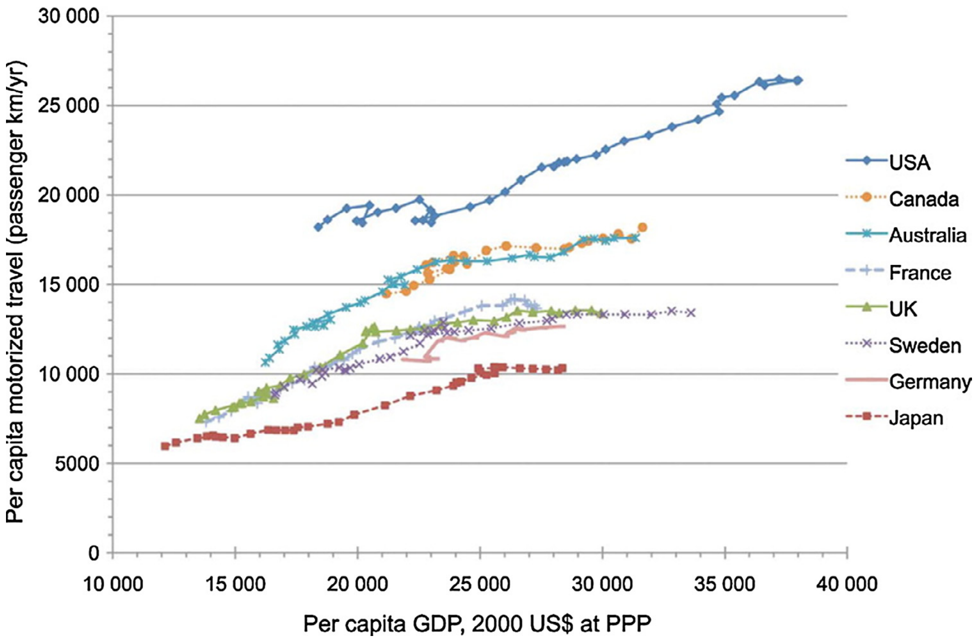

Fig. 1. Total motorized travel activity 1970–2007/08 (Millard-Bell and Schipper, 2011).

forms of transport, the distance that people travel on average has risen steadily. The invention of the motor car was an example of such a development: the number of privately-owned motor cars has grown inexorably since the 1950s, driving an increase in the distance travelled by motorised modes per capita, which has been rapid from the 1970s onwards across developed countries (Millard-Bell and Schipper, 2011). Fig. 1 shows how per capita travel by country has changed compared with per capita GDP. GDP growth has been the main driver of increased travel, partly as greater prosperity translates into rising car ownership. There are signs of a levelling out or saturation of total passenger travel since the early years of the twenty-first century. This levelling out has occurred when GDP is between $25000 and $30000 in most countries, and in the USA at a slightly higher income of about $37000. To some extent this saturation may be related to higher fuel prices since 2002, but this levelling out predated the rapid rise in the price of oil from 2007 to 2008. Commentators such as Metz (2010) suggest that this drop represents a saturation in travel demand although it is difficult to isolate the cause of the decline. Millard-Bell and Schipper (2011) provide evidence to suggest that growth in vehicle ownership, vehicle use and travel demand may have halted; they and others have coined the phrase ‘peak car’ (see Goodwin and Van Dender, 2013) and whilst the arguments around peak car continue, what is clear is that attitudes towards mobility are changing, in particular in relation to the dependence on the automobile (Quadract, 2016), as well as in relation to people’s changing lifestyles (see e.g. the MIND-SETS project[1]).

Changes in mobility are to a large extent being driven by developments in various enabling technologies. Developments in vehicle technology are the most obvious examples. The development of autonomous vehicles, or driverless cars as they are also known, is the most prominent, and these will be covered in Section 5. However, there are many other developments, which are much more widely deployed currently. These include various driver assistance technologies, for example cruise control; as well as advances in vehicle communications capabilities, such as onboard Wifi and vehicle-to-vehicle communications. In fact, in addition to developments directly in vehicle technology, it is developments in information communications technology which is driving changes in mobility. These communications technologies include the proliferation of mobile phones, global positioning systems (GPS) and the internet. These technologies converge in the smartphone, which is a mobile phone with an advanced operating system like that used by a personal computer but specialised for mobile and handheld use. Smartphones are now in common usage throughout the world, with around a quarter of the world’s population using them at present, with many developed countries having over half their population using them. Smartphones can provide information to travellers about the current state of networks and services, e.g. timetabled bus and train times as well as information about if and by how much specific buses and trains are delayed; as well as providing access to travel services, e.g. buying tickets, paying for parking etc. In addition, its global positioning system (GPS) capability affords it a variety of uses including for example route guidance.

The major current and developing trends in mobility are:

1. *The decline in car ownership in the developed countries*. There is evidence that car ownership has begun to level off in many developed countries (Millard-Ball et al, 2011; Goodwin, 2012) with car ownership rates often particularly dropping amongst younger people (Noble, 2005) and amongst millennials (Klein and Smart, 2017). Many young people are now acquiring a driving

[1] http://www.mind-sets.eu/.

licence much later than previously. Historically, the car-ownership saturation level was thought of in terms of everyone who wants a car having one, whereas the reality is that congestion is reducing the private car's appeal in many areas. Hence, there has been a shift from car ownership towards car access.

2. *The emergence in the motor car market of electric vehicles*. The adoption of electric vehicles (EVs) can contribute to improving air quality; in the UK for example, the diffusion of EVs into the mainstream vehicle fleet is regarded as a primary means through which the environmental sustainability of the transport system will be improved (Morton et al., 2016). Section 4 will give more detail about the electric vehicle industry.
3. *The rapid emergence of 'cars on demand'*. Kent and Dowling (2016) provide a useful typology for 'cars on demand' which they define as a form of transit involving collaborative use of the car which is characterised as largely based around ride or lift-sharing; and car-sharing or car clubs. Car-sharing is also hugely important to the issues above, since it has the potential to considerably reduce car ownership as well as reduce pressure on parking space (Kent and Dowling, 2016). More detail will be given on car-sharing in Section 6. Lift-sharing, also known as ride-sharing and car-pooling, is when one or more distinct groups of travellers make use of a single vehicle at the same time. It has been growing rapidly and has the potential to make a sizeable reduction in the number of cars on the road. It has been promoted in the US by the introduction of dedicated car-pooling lanes on highways. For an overview of lift-sharing see Furuhata et al. (2013). Lift-sharing is relevant because, like car-sharing, it is another less conventional form of transportation. However, lift-sharing tends to be more appropriate for long distance trips, particularly for commuting purposes, and therefore is not so much in competition with car-sharing, which tends to be more suitable for shorter journeys. The enabling role of technology has been critical and successful applications of new technology have been demonstrated by Transport Network Companies, such as Uber and Lyft; and in dynamic car-sharing, such as car2go (for more detail see Mulley and Nelson (2016)).
4. *The development of autonomous vehicles*. Belgium, France, Italy, the UK and the US are amongst the countries planning to operate transport systems for driverless cars. There are some hurdles to be overcome for autonomous vehicles to be deployed; these include public acceptability (in terms of the safety and reliability of autonomous vehicles) and issues relating to liability (e.g. in the case of an accident). Autonomous vehicles are very likely to be a disruptive technology, since they have the potential to radically alter the way the transport system functions (Department for Transport, 2015). More detail on autonomous vehicles will be given in Section 5.
5. *The potential shift towards 'mobility as a service' or 'mobility on demand'*. The fundamental idea behind Mobility as a Service (MaaS) is a shift in the way that transport or mobility is viewed from a physical asset to purchase (e.g. a car) to a customised service. This service would be available on demand and potentially incorporating multiple transport services from cars to buses (including demand-responsive and flexible transport) to rail (Transport Systems Catapult, 2015). This would lessen the need to own a vehicle or multiple vehicles as is often the case for families in the developed world). Much of the literature on MaaS appears to focus on a changing role for the car (Hensher, 2017), however it is important not to ignore the crucial role of public transport (both fixed-route and flexible) and shared transport such as car-sharing, lift-sharing and ride-sharing (US Department of Transport, 2017) in the delivery of MaaS.
6. *Developments in teleworking / virtual mobility*. The availability of affordable broadband internet access for both private residences as well as public spaces, via WiFi technology, has facilitated and encouraged growth in telecommuting in which employees are connected to their workplace without being physically present there. Growth in telecommuting has the potential to radically reduce the number of people who need to travel every day for commuting purposes, and since a high proportion of 'rush hour' traffic is for commuting, telecommuting could significantly contribute towards lowering congestion. At the same time, email and telecommunications make it possible for people to maintain more geographically-dispersed social and business networks, meaning that people may then have to travel further when they do meet people face-to-face (although this may be less frequently). So teleworking and virtual mobility may simply be contributing to a shift in travel patterns rather than a reduction in overall travel demand.

4. Electric vehicles and the global automobile industry

There has been rapid growth in vehicle production from over the last half century or so, with global production rising from around 11 million in 1961 to over 90 million per annum in 2015 (see Fig. 2). The growth of production in Asia has been significant and the emergence of China as the world's largest producing country in 2009 is particularly noteworthy (see Fig. 3).

There are over 1.2 billion vehicles on the world's roads today[2] and this figure is rising all the time due to increases in production. 95% of these vehicles are classified as light duty vehicles, which includes highway-capable passenger cars, trucks, and commercial vehicles weighing up to 10,000 lbs. The vast majority (currently around 96%) of these light duty vehicles utilise a conventional internal combustion engine powered by either gasoline or diesel. Hence, vehicles powered entirely using alternative power sources such as electric batteries or hydrogen fuel cells comprise a small share of the global vehicle fleet. However, there is a significant proportion of hybrid electric vehicles; these combine an internal combustion engine with an electric propulsion system to increase efficiency and performance. There is also a significant, and increasing, number of stop-start vehicles, which automatically shut down their engines when stationary for greater fuel economy. Plug-in electric vehicles include both plug-in hybrid electric vehicles (PHEVs) which are hybrid vehicles that can be charged from an electric power supply but have an internal combustion engine; and battery electric vehicles (BEVs), which are powered purely by their electric battery. Hydrogen vehicles are essentially electric vehicles with a

[2] http://www.oica.net/wp-content/uploads/total-inuse-2014.pdf.

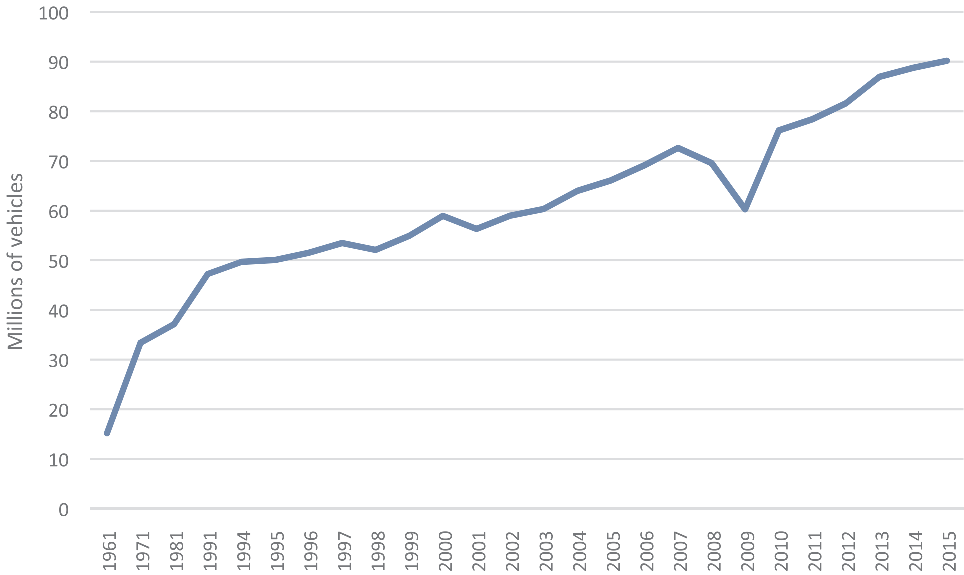

Fig. 2. Total world vehicle production (all vehicle types) (https://www.bts.gov/bts/archive/publications/national_transportation_statistics/table_01_23).

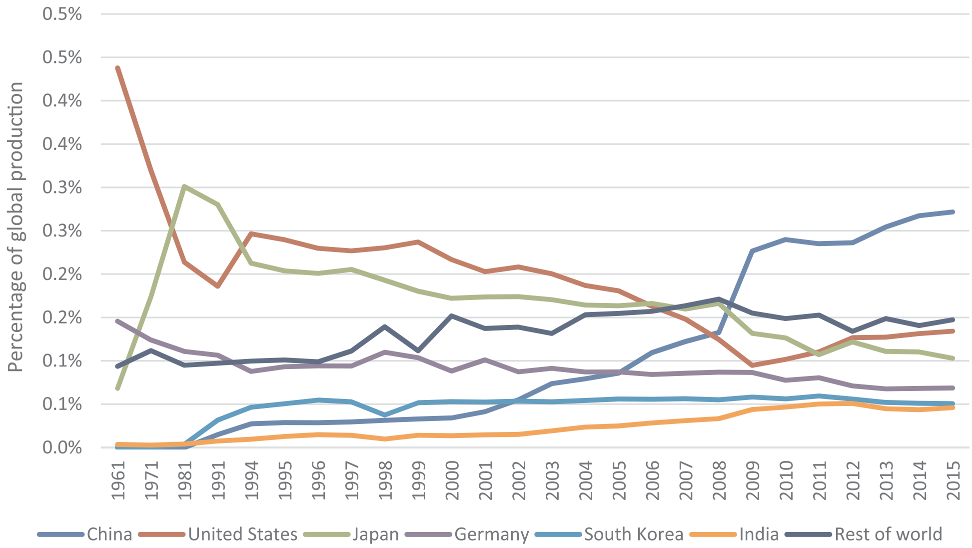

Fig. 3. Motor vehicle production by country (all vehicle types)3.

small onboard battery that is continuously charged from a hydrogen fuel cell that runs on hydrogen gas.

The internal combustion engine was not always the favoured engine used to power the motor vehicle. In fact, at the turn of the twentieth century there were more battery-operated electric motor cars in use in the USA than either steam or gasoline-powered (Hoffman, 1967). The severe range and speed limitations of storage batteries meant that it was not long before they went out of fashion. There was renewed interest in the USA in the 1960s and 1970s due, mainly due to the negative effects of air pollution and rising oil prices (Hoffman, 1967). However, they could not compete on price or performance with their petrol-fuelled counterparts and interest waned again. A renewed surge of interest in electric vehicles began in the early 1990s but was somewhat dampened by the subsequent rather limited progress in battery technology, meaning that consumers were not satisfied with range, function and price. On the other hand, hybrid vehicles flourished during the same period when electric vehicle take-up was faltering, with a noticeable example being the Toyota Prius.

Recently there has been new momentum for electric vehicles resulting from both technological advances as well as developments in the social context of car mobility (Dijk et al., 2013). One of the key factors has been climate protection policies and targets, motivated by political concerns about climate change. A landmark event in the development of such policies was the Kyoto Protocol, ratified in 2002 and in effect from 2005, which established targets for emissions of greenhouse gases for nations signing up to it.

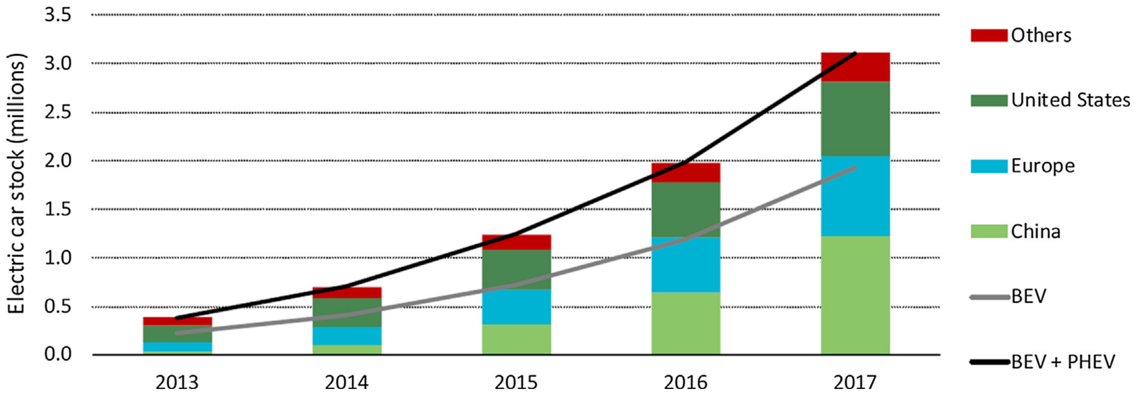

Fig. 4. Passenger electric car stock in major regions and the top-ten EVI countries (from Bunsen et al. (2018)).

Green and fuel-efficient vehicles were subsidised in the developed countries because of the Kyoto Protocol. These subsidies not only encouraged production, but also provided much-needed investment in research and development, which was particularly needed in the battery sector. Car manufacturers recognised that battery technology was the key to improving electric vehicle performance and so started collaborating with battery manufacturers. Electric vehicles started to become more affordable and their range was increasing to the point where it was becoming less of an issue. There has also been substantial investment in the charging infrastructure, which is vital to the practical operation and hence success of electric vehicles. Fig. 4 shows that the global electric car stock has been growing at an increasing rate over the last 5 years, as well as the emergence of China to become the country with the highest level of stock.

The ever-increasing efficiency of cars using the internal combustion engine, combined with their generally lower price, means that they will make up the majority share of the vehicle market for many years to come. However, a growing proportion of these vehicles will be stop-start vehicles. Also, electric vehicles are projected to gain a significant market share over the coming decades (Shepard and Jerram, 2015). Some key factors to the success of electric vehicles include:

1. *The degree of investment in the necessary infrastructure*. There needs to be sufficient charging points, in terms of coverage (so that consumers are reassured about not running out of fuel) and capacity (to support a larger number of electric vehicles on the road, particularly in and around cities where traffic is much higher).
2. *Developments in mobility*. The most relevant mobility trend to electric vehicles is the emergence of car-sharing (explored further in Section 7). Continued growth in car-sharing will boost the electric vehicle industry since it overcomes one of the main barriers in the high purchase price of electric vehicles. In addition, better systems of intermodality will also benefit the electric vehicle industry, because an electric vehicle may be used for part of a trip in conjunction with other modes; this is particularly relevant when viewed in the context of car-sharing which eliminates the need for parking once a user finishes with the vehicle. This leads directly to and expands the potential for car-sharing, particularly as technological advances can help address the demands of all age groups more effectively than in the past.
3. *Developments in the global car manufacturing industry*. There has been significant growth in automobile sales in developing countries. China is now the leading vehicle producer in the world[3] and has focussed much of its efforts on electric vehicle production. Electric vehicles require fewer parts than cars using the internal combustion engine (e.g. an engine or exhaust), meaning that the modular nature of car production poses less of a barrier to their production by emerging enterprises than for cars using the internal combustion engine.
4. *Energy sector and climate policies*. Peak oil is the point in time when the maximum rate of extraction of petroleum is reached, after which it is expected to enter terminal decline (Hirsch et al., 2005). There have been many predictions of when peak oil might occur, many of which have now been shown to be incorrect given that oil production has continued to grow, albeit slowly, mainly due to innovations in oil field technology. If production does start to slow, it will put upward pressure on oil prices. Electricity prices will rise too, but to a lesser extent. Climate policies are stimulating renewable energy generation and contributing to electric mobility, since transport emissions are a key source of greenhouse gases. In turn, the fact that renewable energy generation is characterised by intermittent supply suggests the opportunity for electric vehicles to be used to store such electricity, via smart-grid systems.

These factors contribute to several positive feedback mechanisms working in favour of electric vehicles (Dijk et al., 2013).

There is a rapidly developing market for lightweight electric vehicles. Lightweight vehicles have traditionally been Internal Combustion Engine powered vehicles built by small automotive companies and have mainly been targeted at users in rural areas. However, recently there has been a significant increase in the number of available options of lightweight electric vehicles.

[3] http://www.oica.net/category/production-statistics/.

Lightweight electric vehicle manufacturers are now targeting urban mobility and generally producing vehicles with electric drive systems built by major car manufacturers. Major examples of this new tendency are the Renault Twizy (4 wheeler L6 or L7 category), the Smart Fortwo Electric from Daimler, the Toyota Coms (4 wheeler) or iRoad (3 Wheeler). A broader offer is available from smaller actors, such as the Biro from Estrima or the electrified versions of the Aixam and Ligier-Microcar vehicles (Market leader in ICE driven quadricycles). The significance of lightweight vehicles and their potential for deployment in one-way car-sharing systems is explored further in Section 7.

5. Developments in autonomous vehicles

An *autonomous vehicle* is a vehicle that can sense its environment and navigate without human input. Autonomous vehicles are also referred to as *driverless vehicles* or *self-driving vehicles*; these terms imply the absence of a driver and hence the term autonomous vehicle covers a wide range of instances of vehicle-assisted driving and navigation, including autonomous road vehicles; autonomous light rail systems; autonomous aircraft and drones; autonomous maritime vehicles; and autonomous pods (such as the UK Transport Systems Catapult autonomous pods[4]). The focus here will be on autonomous road vehicles because it is the most relevant to the topic of car-sharing; the other forms of autonomous vehicles should certainly not be viewed as unimportant, e.g. Begg (2014) suggests that rail-based automation (used for both underground and overground services) will have the biggest impact on London over the next 30 years. The range in the level of autonomy stretches from full driver control to full vehicle control, with the middle ground including the driver maintaining overall control whilst delegating tasks to the machine, and the machine maintaining control until a situation demands human input, upon which the driver is alerted. There are several frameworks for heirarchies of levels of autonomy, but the SAE framework (SAE International, 2014) is the generally accepted framework with levels of autonomy ranging from 0 (*No autonomy*) to 5 (*Full autonomy*).

Autonomous vehicles utilise a range of technologies to sense their environment, including radar, lidar, video cameras, ultrasonic and infrared sensors. Radar, which utilises radio waves to detect objects, is employed in accident-prevention systems. Lidar, which measures distance to objects by illuminating them with laser light, is used in constructing a three-dimensional view of the vehicle's surroundings. Video cameras are also used in imaging, but are not as reliable lidar, particularly in adverse weather conditions. Infrared sensors can be used to provide effective night vision. Sensor fusion is the process whereby data from different sensors is combined to give an overall view of the vehicle's surroundings: this enables different sensor types to compensate weaknesses of other types. In addition to technologies that sense their external environment, autonomous vehicles are being equipped with technologies that can monitor the state of the driver to check that he or she is capable of resuming control.

The development of autonomous vehicles is now accelerating, but in fact has been happening for over fifty years (Vanderbilt, 2012), beginning with General Motors developing a vehicle that could steer automatically (albeit aided by electrical wires embedded in the road) in 1958.

Many companies have begun testing driverless car systems, including:

1. *Google*. Google entered the development of self-driving cars by employing researchers working on the DARPA Grand Challenges (which had been launched in 2002). Google fitted self-driving technology to both the Toyota Prius and the Lexus, which by 2012 had completed over 300,000 test miles on inter-urban free-ways in California and Texas. Subsequent testing has been in more complex urban environments, with handover between the automated system and a trained 'safety driver'. The Google car requires a human to programme in various aspects of external control like road signs, traffic lights, and so on, and it is not clear how well the system would operate in a novel environment where it might have to handle unexpected events such as temporary traffic lights or lane closures. A Google self-driving car caused a crash[5] in February 2016 by pulling out in front of a bus which was travelling at 15mph; the test driver in the car assumed that the bus would slow down to let the car out, so did not override the car's self-driving computer.
2. *Volvo*. Volvo is using technology called *Autopilot*[6], which can follow lanes, adapt speed, and perform merges autonomously. They have been running trials in Gothenberg (Sweden) in everyday conditions.
3. *Audi*. Audi is working on a fully autonomous drive system, i.e. aiming at a system that requires no human input. A self-driving Audi S7 Sportback completed a 550 mile 'piloted' drive from San Francisco to Las Vegas[7]. The Audi A8 will be capable of operating at Level 3, i.e. capable of handling some situations in full self-driving mode but will monitor the driver to ensure he or she is ready to resume control if needed.
4. *BMW*. BMW is focussing its research into autonomous vehicles on motorway driving and valet parking.
5. *Tesla*. Tesla is developing cars with increasing amounts of capability as and when they are available, unlike the major car manufacturers who are predominantly seeking to deliver a complete and fool-proof self-driving system. Tesla's ambitions suffered a setback following a fatal accident in 2018 involving one of its cars in autopilot mode[8].
6. *Uber*. Uber have recently been working on incorporating self-driving cars into their Uber fleet. Uber launched its first self-driving

[4] https://ts.catapult.org.uk/pods.
[5] http://www.bbc.co.uk/news/technology-35800285.
[6] http://www.volvocars.com/au/about/innovations/intellisafe/autopilot.
[7] http://www.ibtimes.com/audi-self-driving-car-completes-560-mile-trip-las-vegas-ces-2015-1775446.
[8] https://www.wired.com/story/tesla-autopilot-self-driving-crash-california/.

car services to a selected number of customers in Pittsburgh in September 2016. Uber has a fleet of Ford Fusion cars each equipped with 20 cameras, seven lasers, GPS, lidar and radar equipment, which enable it to create a three-dimensional map and keep track of its position. Uber also began using self-driving Volvo XC90 SUVs in San Francisco in December 2016, but these vehicles had their licence plates revoked a week later. Uber then moved the programme to Arizona where the cars are facilitating passenger trips, albeit with two engineers on board to monitor the vehicle's operation. In March 2017 Uber temporarily removed its self-driving cars from the roads after an accident which left one of the vehicles on its side. The accident occurred when another vehicle 'failed to yield' to the Uber car at a left turn[9].

Autonomous vehicles have the potential to deliver substantial benefits if delivered to the mainstream market. These benefits include:

1. *Time savings for drivers. Since* there will no longer be the need for the driver to keep his or her full attention on driving all the time, this will free up travel time for other use.
2. *Parking.* Parking assistance systems range from designated parking, in which the vehicle is capable of parking in a designated parking bay; to valet parking, in which the vehicle searches for and parks in an available spot on its own. By removing the need for manual vehicle parking and enabling automated driving following drop-off, parking space is freed up in city centres, which can be utilised for other uses.
3. *Improvements in road safety.* Collision avoidance and mitigation systems. These are systems that detect when a collision is going to occur and then engage automatic braking systems to prevent it (or mitigate the effects of a collision if a collision is unavoidable). Autonomous vehicles are more likely to maintain a safe distance to the vehicle in front and are better able to respond quickly.
4. *Cooperative driving.* The premise of this is that vehicles can communicate with each other, and potentially with elements of the road infrastructure (e.g. wireless controllers at intersections) to optimise traffic flow, reducing both congestion and emissions whilst increasing capacity.
5. *Increased access to personal transport for the mobility impaired and for those without a driving licence*. Since autonomous vehicles will not require a driver, they can provide additional mobility options for people who are mobility impaired (Harper et al., 2016). They will also provide mobility options for those without a driving licence (for example because they are too young).
6. *Ability to be used on a shared basis*. It is widely anticipated that Shared Autonomous Vehicles (SAVs) will likely provide inexpensive on-demand mobility services and could bring about the wider use of dynamic ride sharing (Krueger et al, 2016). Use cases for how autonomous vehicles might operate within the transport network are discussed below.

The benefits listed above can only be fully realised once a significant share of the vehicle fleet is automated, e.g. cooperative driving will depend upon most if not all vehicles being autonomous. Autonomous vehicles will need to overcome numerous barriers for this to happen, including:

1. *Homologation*. Autonomous vehicles may require legislation in order for them to be legally driven on public roads, depending on the country. The *1968 Vienna Convention on Road Traffic* (which has been ratified by 74 countries including most EU countries and Russia) and the *1949 Geneva Convention on Road Traffic* (ratified by 96 countries including the USA) include the requirements for every moving vehicle to have a driver, and also for that driver to be in control of his or her vehicle at all times. However, there was an amendment to the Vienna Convention ratified in 2014 which states that drivers should be allowed to take their hands off the steering wheel of self-driving cars[10].
2. *Liability*. If an autonomous vehicle is involved in an accident with a manually-driven vehicle, the manufacturer might be held accountable if there is a flaw in the way the autonomous vehicle is designed. In the case of an autonomous vehicle with a human driver present who is able to assume control of the vehicle, is there a responsibility for them to do so in certain situations?
3. *Ethical issues*. In the case where an accident becomes likely or unavoidable, should an autonomous vehicle prioritise its passengers over those outside the vehicle or should it prioritise more vulnerable road users such as pedestrians? (Goldhill, 2015).
4. *Interactions of autonomous vehicles with other road users*. There are issues around how autonomous vehicles might interact with other road users, including human-driven vehicles, as well as pedestrians and cyclists (who are often overlooked in current visions of future autonomous vehicle systems (Adams, 2015)). Human drivers negotiate their way through the road network not only by obeying the rules of the road, but also through situational awareness and non-verbal communications.
5. *Sufficiently advanced artificial intelligence*. The capability for a vehicle to be able to drive autonomously under predictable (albeit variable) conditions is one thing, but for an autonomous vehicle to be able to manage a variety of complex scenarios on the road that may arise only very infrequently is quite something else. To make the correct judgement in these complex scenarios requires far more cognitive ability than is available at this current time. In general, these complex scenarios arise more frequently in urban driving.
6. *Public acceptability*. There is a general assumption that people will accept and use autonomous vehicles (especially amongst manufacturers and policy-makers) but this will only be the case if their usefulness can be demonstrated and if people's perception of their safety and reliability is sufficiently high. People are generally favourable towards autonomous vehicles (Kyriakidis et al.,

[9] http://www.bbc.co.uk/news/technology-39397211.
[10] http://www.reuters.com/article/us-daimler-autonomous-driving-idUSKBN0DZ0UV20140519.

2015) and can see their potential usefulness particularly for motorway driving, in traffic congestion, and for automatic parking, but they are less convinced about their use for urban driving. Payre et al. (2014) found that many people were attracted by the potential of autonomous vehicles in avoiding impaired driving (e.g. driving whilst under the influence of drugs or alcohol).

7. *High costs to the user*. The current cost of autonomous vehicles is prohibitive for most users, e.g. a typical sensor suite for one of Google's autonomous Toyota Prius would cost over $100,000. Autonomous component technologies such as adaptive cruise control; lane keeping assistance; collision warning; blind spot monitoring; and parking guidance, are available individually at much lower cost. In general, consumers are willing to pay around a 5–10% premium to acquire these features, so it would seem that the cost of the in-vehicle technology required for autonomous driving would need to reduce to around this level before widespread adoption by consumers, and this will certainly be many years before the necessary economies of scale can be achieved. However, this is assuming the standard model of car-ownership, whereas we noted earlier that car-ownership trends are changing.
8. *Investment*. Significant investment will be needed across the road network in order for autonomous vehicles to be safely driven on them, including both physical and communications infrastructure. Intelligent infrastructure (Office of Science and Technology, 2006) will help facilitate the operation of autonomous vehicles; these will include RFID tags; sensors; GPS technology; 4G networks; WiFi; and artificial intelligence. Infrastructure specific to autonomous vehicles might include customised signage, electronic road markings and beacons that broadcast traffic information.

As well as the barriers listed above, there are also potential drawbacks to the implementation of autonomous vehicles. Drivers, such as truck drivers, taxi drivers and bus drivers may lose their jobs due to automation. There is also the possibility of increases in vehicle miles travelled (VMT), especially in the case of privately-owned autonomous vehicles (Zhang et al., 2018), which could circulate without passengers until needed (e.g. to avoid paying for parking). Policies restricting autonomous vehicles from travelling unduly without a passenger could help to prevent this.

Predictions about the future uptake of autonomous vehicles vary significantly. KPMG (2015) forecasts that Level 3 automation will start to pick up around 2020 and will be present in around 40% of the UK vehicle fleet by 2030, with over three-quarters of the total fleet being connected by 2030. This will be driven by production of connected and autonomous vehicles in the UK motor construction industry. The adoption rate of autonomous vehicles will depend on how quickly the barriers identified above are overcome and how quickly suitable use cases for them can be demonstrated. Use cases for how autonomous vehicles might operate within the transport network include:

1. *High-speed roads used exclusively by autonomous vehicles*. This use case is built upon the premise that autonomous vehicles can travel faster and closer together at higher speeds (in platoons), thereby realising large increases in traffic flow, and hence, in the effective capacity of such designated high-speed roads (which would likely be motorways). One of the key questions for the operation of such high-speed roads would be whether they would only be for autonomous vehicles or whether non-autonomous vehicles would also be allowed. It seems likely that non-autonomous vehicles would need to be catered for on such high-speed roads. Improving traffic flow on these roads would reduce inter-city travel times, and so benefit public inter-city coach services.
2. *Urban taxis*. One of the key problems for car drivers when visiting city centres is parking availability. This is not only a problem for the car-drivers themselves, but also impacts on everyone, by causing additional congestion (people driving around looking for car-parking spaces) and consequent use of space for car parks. Fully autonomous driving would ameliorate some of these problems since the vehicle would not need to be parked centrally for any length of time, but instead would just need a place to drop off its passenger(s) and then would be able to drive itself to a suitable car-park, such as a large multi-storey or underground car-park at a distance from the city centre. These autonomous urban taxis could function in a just-in-time manner, which would eliminate waiting time and parking, provided that the prevalence of autonomous vehicles leads to a more regulated and predictable urban traffic network. Urban taxis could be utilised to link with mass transit and other public transport systems, making the use of public transport more attractive (UITP, 2017). Highly efficient operation of these urban taxis would make car-ownership not so necessary for city residents, providing benefits to city centre life such as better use of public space and reclamation of front gardens (Skinner and Bidwell, 2016).
3. *Rural buses*. Most households in rural areas in developed countries already have a car out of necessity; autonomous vehicles could help to remove this necessity. Autonomous vehicles could be used in a demand-responsive and shared-use mode to facilitate door-to-door services for those wishing to access services in towns, as well as linking in with the public transport network for onward travel to larger urban conurbations.
4. *Autonomous deliveries*. The potential for the use of autonomous vehicles for last-mile freight is enormous and has been recognised by companies such as Amazon[11], who are researching and experimenting with the use of drones for deliveries. The use of autonomous vehicles for larger freight deliveries, e.g. vans and lorries, would enable more deliveries in city centres to be made off-peak and hence help to reduce congestion.

The invention and subsequent popularisation of the motor car over the course of the twentieth century ushered in a global system of *automobility* (Urry, 2004) in which most households in developed economies had access to a privately-owned car. Geels (2012) argues that automobility has emerged as the dominant *socio-technical* regime, coexisting alongside other longer-established yet subordinate regimes of public transport such as train, tram, bus; and slower modes such as cycling and walking. The adoption of

[11] http://www.bbc.co.uk/news/technology-38320067.

autonomous vehicles has the potential to be just as revolutionary to the transport system as in the case of the motor car.

The full benefits that autonomous vehicles have the potential to deliver might only be realised if there is a high degree of automation, but perhaps total automation is not necessarily to be aimed for (Dizikes, 2015). Vehicle automation combined with more intensive vehicle usage, e.g. through shared ownership, has the potential to deliver greater system efficiency and benefits to individuals. Car-sharing, detailed in the next section, has the potential to make this higher level of utilisation of cars possible.

6. The rise of car-sharing

Car-sharing is a model of car rental in which customers rent cars for relatively short periods of time, usually from a car-sharing operator who owns a fleet of vehicles and is responsible for their maintenance. Cars are massively underutilised: most cars are used to transport a single person and are used for less than an hour a day. Car-sharing can significantly increase the utilisation rate of cars and thereby reduce the costs of vehicle travel for individuals as well as for society (Shaheen et al., 1999).

There are clearly strong connections between car-sharing and car ownership. Car owners are much more inclined to make use of their own vehicle, which they have already spent money on, rather than choose a car-sharing option. They may also be reluctant to give up their vehicles leaving them reliant on a car sharing network where there is no guarantee that a vehicle will be available when needed, despite them being offered incentives to trade their car in when joining the scheme. However, the fact that car-sharing enables people to have access to a car without the need to own one makes it attractive to customers who make only occasional use of a car, since everything is on a pay-as-you-use basis and the associated costs of vehicle purchase; insurance; maintenance and depreciation; are all avoided. A car-sharing operator typically has a fleet of vehicles incorporating different types (e.g. sports car, passenger carrier, four-wheel drive etc.) and hence can cater to customers who want to make use of different vehicle types for different types of trip (including car owners).

Car-sharing can certainly contribute to reducing the number of cars on the road, since replacement rates can be as high as 15:1, i.e. 15 prior car owners can be accommodated by 1 car-sharing vehicle. However, this smaller fleet is utilised more intensively to facilitate the same number of trips: OECD (2016) showed on a simulation of the city of Lisbon that a vehicle fleet a tenth of the current actual size could be used to complete the same number of trips. In replacing private cars, many of which are parked in car parks or on public streets for long periods of time throughout the day, by car-sharing vehicles, which are much less frequently parked, increased adoption of car-sharing can result in a reduction in parking demand. Since parking availability is a key factor in travellers' decision-making when it comes to private car use, this can set up a negative feedback mechanism, since increased adoption of car-sharing results in higher parking availability and hence makes it more attractive to be a car owner. Therefore, the reallocation of such freed-up parking space is crucial in promoting car-sharing, and the use that it is dedicated for is crucial in making cities more liveable and more attractive as destinations (Skinner and Bidwell, 2016). Indeed, many building developers are now incorporating share-cars into their developments as an added value to tenants, and this is being promoted by municipal government bodies (Melia, 2014).

Car sharing is most common in urban areas with a good public transport network, suggesting that its success is linked to it being complementary to public transport rather than being in competition to it. It makes possible journeys that would otherwise only be possible using a car for the whole journey whilst also often eliminating the need for parking, increasing its attractiveness as a travel option. Travellers with a tendency towards car use may use car-sharing as a substitute for public transport, whereas those with a tendency towards public transport use are more likely to use car-sharing in conjunction with public transport rather than making the same journey by car. Ideally, car-sharing schemes would be fully integrated with the public transport system, so that there would be seamless transitions between modes, which would benefit the user.

The first known car-sharing programme was the Selbstfahrergenossenschaft in a housing cooperative that got underway in Zürich in 1948 (Shaheen et al., 1998), but there was no known formal development of the concept in the next few years. A much more ambitious project called the Witkar was launched in Amsterdam by the founders of the 1968 white bicycles project, and it endured into the mid-1980s before finally being abandoned. There was slow growth in car-sharing in the 1980s and the early 1990s, mainly of smaller non-profit systems. Zipcar, Flexcar (which was bought by Zipcar in 2007) and City Car Club were all formed in 2000. Several car rental companies launched their own car sharing services beginning in 2008, including Hertz, Enterprise and Avis. By 2010, when various peer-to-peer car-sharing systems were introduced, Zipcar accounted for 80% of the U.S car sharing market and half of all car-sharers worldwide, with 730,000 members sharing 11,000 vehicles by September 2012. Car-sharing has also spread to the developing world because population density is often a critical determinant of success for car-sharing and developing nations often have highly dense urban populations. At the time of writing there are hundreds of car-sharing operators in operation throughout the world. Car-sharing is particularly thriving in Germany, where there were 1.26 million car-sharing customers registered at the start of 2016.

In one-way car-sharing, the user picks up the vehicle from a station or some other location and drops it off at their destination. This often means that vehicles become unbalanced over time, i.e. end up in locations where they are not needed (Boldrini and Bruno, 2017). This then poses a problem of the operator having to redistribute the vehicles, which can be costly. The Autolib' car-sharing service offered its users an incentive (e.g. a free trip) to help redistribute its vehicles. One-way car-sharing has been around since the 1970s but has only recently started to gain widespread momentum (Shaheen et al., 2015).

In free-floating car-sharing systems, cars can be picked up and dropped off at any location. Generally, users utilise a smartphone app to locate available vehicles. The first free-floating car-sharing system was car2go, launched by the car manufacturer Daimler in 2009 in the city of Ulm, Germany, and offering a mixed fleet of electric and gasoline vehicles (Finkorn and Müller, 2011). Free-floating car-sharing is particularly suited to facilitating the first and last mile of multi-modal trips due to its increased flexibility. This flexibility makes free-floating car-sharing more attractive to potential users than station-based and zone-based car-sharing.

Another category of car-sharing is peer-to-peer car-sharing in which existing car users make their cars available for rent for short periods of time. An operator charges commission on transactions but does not have the overheads of vehicle acquisition, maintenance, etc. that standard car-sharing operators have.

A current trend is for car-sharing operators to offer combined services that provide both free-floating and station-based trips within one tariff. An example of this is Zipcar, which is currently planning to offer a wider variety of trip types, such as round-trip, one-way with and without parking, the option to travel between cities, etc.

The rise of car-sharing (and particularly one-way car-sharing) has been rapid, and there are many factors working in favour of car-sharing, However, for car-sharing to become more widespread, there needs to be significant investment in the necessary charging infrastructure (for electric vehicle fleets); and users' mobility and car-ownership patterns need to change. The success or failure of individual car-sharing schemes depends on several critical factors (Gordon-Harris, 2016):

1. *The presence of a good public transport system*. This is due to the complementary nature of the public transport network and car-sharing. In addition, a good public transport system lessens the need to own a car, which widens the potential customer base for car-sharing (since car-owners are less likely to utilise car-sharing).
2. *The car-sharing scheme needs to have the proper pricing structure*. Car-sharing should not be cheaper than public transport to avoid unwanted competition and ensure complementarity. There will naturally be some direct competition between car-sharing and public transport since car-sharing can offer greater convenience and flexibility. However, direct competition can be minimised through segmentation of public space and careful placement of car-sharing stations. Competition between a public transport option and a car-sharing combined with public transport option is healthy competition, since it increases traveller choice.
3. *Having urban populations of significant scale and diversity*. A high population density gives a higher number of potential users. Also, having a more diverse population in terms of living and working patterns may be advantageous to the practical operation of a car-sharing scheme, e.g. having a predominantly commuter user-base may cause problems with vehicle availability and distribution since vehicle demand is concentrated in space and time.
4. *The presence of adequate charging infrastructure*. There needs to be a critical mass of charging points for electric vehicle car-sharing fleets to operate, and this depends on securing the necessary finance to install them.
5. *Having space allocated for stations and for on-street parking*. If stations are considerable in size, locating them in areas where is space is limited, e.g. in or close to a railway station, could be problematic. Having access to on-street parking is a high priority for car sharing operators and the lack of on-street parking can be a significant barrier to expanding car sharing networks (Schwieger et al., 2015). In many established cities road space is constrained, so accommodating additional car-sharing parking and associated infrastructure can be challenging.
6. *Support from public authorities*. Public authorities can assist car-sharing operators by providing on-street parking space, investing in charging infrastructure, etc.

7. The potential for one-way electric vehicle car-sharing systems

There is considerable potential for one-way electric vehicle car-sharing systems due to synergies with air quality imperatives (aided by developments in electric vehicles), the rise of the sharing economy, the proliferation of smartphones and other enabling technologies, and the potential capabilities of autonomous vehicles. This section looks at existing one-way car-sharing systems and vehicles, as well as exploring the issues related to their deployment.

There has been appreciable growth in recent years in one-way car-sharing, both in terms of the number of operators and their levels of patronage (Shaheen et al., 2018). car2go is currently the largest free-floating car-sharing operator in the world with over two million registered customers[12]. It allows a user to undertake a one-way trip and drop the car on-street. Although there is synergy between car-sharing and electric vehicles, one-way car-sharing poses additional challenges for the use of electric vehicles due to the need for charging infrastructure. Also, the need for redistributing vehicles can pose a challenge in terms of the profitability of the scheme, e.g. Autolib' was a one-way car-sharing system in Paris which closed in July 2018 due to significant financial losses.

There are several electric vehicle concept cars under development designed specifically for one-way car-sharing. These include:

1. *MIT CityCar*. MIT CityCar is an urban all-electric concept car designed at the Massachusetts Institute of Technology (MIT). Initially they presented a foldable and stackable vehicle with the objective of gaining parking space, but later the concept was restricted to a purely foldable vehicle. The CityCar concept was designed as an all-electric four-wheel ultra-small vehicle (USV) for two passengers, and drive-by-wire driver interface. Each wheel is independently digitally controlled, with its own wheel motor, which enables them to move in different direction and speed and allows the wheels to rotate up to 120 degrees, allowing for 0-degree turn radius. This feature makes the CityCar suitable for urban conditions, as it can perform sideways motions for parallel parking, and O-turns instead of the conventional three-point turns. The CityCar was designed with a collapsible frame through a four-bar linkage that enables the vehicle to fold up for more compact parking, making it possible to stack three or four CityCars in the length of a traditional parking bay. Hiriko Driving Mobility, a Basque consortium, developed a commercial version based on the CityCar but was unable to bring the car to market.
2. *EO smart connecting car*. The EO smart connecting car[13] is an innovative concept car from DFKI (German Research Centre for

[12] https://www.car2go.com/media/data/usa/microsite-press/files/2m-member-car2go-na.pdf.

[13] http://robotik.dfki-bremen.de/en/research/robot-systems/eo-smart-connecting-1.html.

Artificial Intelligence) in Bremen. Its features include the ability to fold, turn on the spot and drive sideways. It will also have the facility to be mechanically coupled to form road trains. The road train can be shortened or lengthened on the move.
3. *EN-V (Electric Networked Vehicle)*. The Electric Networked Vehicle[14] is based on a technology co-developed between General Motors and Segway. The vehicles operate in convoy with the vehicles being coupled through approach platooning and can be driven normally or operated autonomously.
4. *ESPRIT*. ESPRIT is an EU-funded Horizon 2020 Green Vehicles project which developed a purpose-built, lightweight L-category electric vehicle with novel elements including the capacity for forming road trains of up to eight vehicles and the capability to charge the entire road train from a single charging point.

The success of one-way car-sharing systems hinges largely on vehicles being accessible when and where users need them: if a potential user needs to undertake a long journey on foot just to reach the vehicle then they will most likely look for other travel options. In one-way car-sharing systems, vehicles often accumulate in places where they are not required and there can be a lack of vehicle availability where demand is high. Boldrini et al. (2016) study the spatial and temporal patterns of station utilisation in a one-way car-sharing system. Clearly, there needs to be an effective redistribution system to ensure that vehicles are available when demanded by users. Vehicle redistribution can be carried out by the operator of the scheme or by its customers. Redistribution by the operator is generally expensive because it usually takes one employee to transport the vehicle to another location, as well as that employee potentially needing transportation to and from the vehicle to be redistributed. However, vehicles that can be connected together in road trains can be much more economically redistributed, e.g. the ESPRIT vehicle can form road trains of up to eight vehicles, vastly reducing redistribution costs. Redistribution by users is generally facilitated by incentivising users to undertake trips from locations with lower demand to locations with higher demand; this strategy was employed by Autolib'. The future development and proliferation of autonomous vehicles would synergise with car-sharing systems, since upon completion of their trips they would simply be able to drive back to the depot autonomously. That said, the autonomous vehicle technology would need to be fully capable of dealing with an urban environment, which is an essential capability in terms of car-sharing. Boldrini and Bruno (2017) simulate vehicle distribution done manually in road trains compared with autonomous redistribution.

Charging infrastructure is key to the operation of electric vehicle car-sharing. Most urban trips are relatively short distance, but the fleet of vehicles used by a car-sharing operator may have shorter range batteries than normal, so it is important that vehicles are charged when not in use. In terms of stations, charging, collection and drop off, the state-of-the-art is that most one-way car-sharing systems install a charging point in each one of their reserved parking spots or in popular locations where people want mostly to pick up or drop off vehicles. However, this approach is highly inefficient since most of the time the charging stations are not utilised because no vehicle is parked. Additionally, the charging points are normally available to any electric vehicle, meaning that they may be in use by non-car club members when they are required. In contrast to this, the ESPRIT system is designed so that charging stations can accommodate up to 8 vehicles which can all be charged concurrently whilst parked. This facilitates a significant reduction of the required number of charging stations, with a consequent reduction of deployment and maintenance costs, as well as a lower strain on the power grid. Battery loads are dynamically balanced so that charging is prioritised towards the front of the road train, ensuring that the lead vehicle is ready for the user to drive away when required. The capability for charging in road trains means that fewer charging facilities are needed compared to conventional charging.

Modelling prior to deployment of a one-way car-sharing system is informative in several key areas: to understand the effects of deploying a one-way car-sharing system in a variety of different urban and suburban configurations; understanding the potential shift in modal share which might be induced by the introduction of the system; and estimating whether the scheme will be viable in the long run. Modelling can give insights about how to optimally locate stations to maximise user availability and system efficiency (Biondi et al., 2016) or how to optimally redistribute vehicles (Weikl and Bogenberger, 2015). The model components required to evaluate the introduction of such a system might include a demand model, to estimate the demand for the car-sharing system; a supply model, to determine in the operation of the car-sharing system; and a business case model, to evaluate operating profits, cash flow, etc.

Homologation and legal requirements play an important role in the automotive industry. Vehicle manufacturers and their suppliers must comply with various legal and technical requirements which vary between different countries. Bringing new concept vehicles to market can be challenging since existing directives and regulations generally lack provisions for vehicles that include new technologies or concepts, making it difficult for individual approval items to fulfil the requirements of existing legislation. Car-sharing vehicles that are designed to operate in a road train must satisfy the regulations for operating both in single vehicle mode as well as in road-train formation, e.g. the ESPRIT single vehicle could be classified as vehicle type L7e-CP (heavy quadri-mobile for passenger transport) according to Regulation (EU) No 168/2013, however there is no applicable legal framework for the homologation of the ESPRIT road train.

Potential use cases for one-way car-sharing systems include:

1. *One-way trips within city centres.* These trips will generally be short and will be for a variety of trip purposes, e.g. commuting, shopping, tourism, etc.
2. *First and last kilometre trips*. For these trips one-way car-sharing will be used for part of the trip in conjunction with other modes. These first and last kilometre journey legs will mainly be between travellers' homes and suburban transport interchanges but

[14] The bubble car is back – Cheap, small and simple: an idea from the 1950s bubbles up again. The Economist. 2010–09-30.

could also be on business parks and campuses.

The introduction of one-way electric vehicle car-sharing has the potential to deliver the following benefits:

1. *Modal shift away from private car use*. The introduction and success of one-way electric vehicle car-sharing will result in a shift away from private car use.
2. *Improved urban air quality*. The modal shift from private cars, which are mostly polluting, to electric cars, which are not polluting, will reduce the amount of pollution from traffic.
3. *A better integrated public transport system*. One-way electric vehicle car-sharing can complement the public transport system provided there are the proper intermodal connections.
4. *Reduced pressure on parking*. The intermodal and one-way nature of one-way electric vehicle car-sharing should eliminate the need for parking once a user finishes with the vehicle. In addition, one-way electric car-sharing vehicles may be much smaller, which would result in significant space saving when they are parked, leading to an overall increase in capacity.

Finkorn and Muller (2011) and Martin and Shaheen (2016) have sought to quantify these potential benefits.

The success of one-way electric vehicle car-sharing systems will clearly depend on policies relating to their operation as well as to other aspects of the transport system. Some policies which could help one-way electric vehicle car-sharing in cities are:

1. *Low emission zones in city centres*. This will make electric vehicle car-sharing more attractive compared with running a conventional car, which would not be permitted to enter these zones.
2. *Restricting vehicle access to the most central areas of the city*. Purpose-built lightweight electric vehicles for car-sharing could be permitted to access these areas whilst conventional (larger) cars would be denied access. If there were lightweight electric vehicles designed specifically for one-way car-sharing in these areas, these would be an attractive option for getting around the city centre.

8. Conclusion

A shift from conventional vehicles to electric vehicles can contribute towards better air quality in urban areas, and the emergence of car-sharing operators is giving momentum to the uptake of electric vehicles. One-way car-sharing is growing rapidly, but vehicle redistribution can be a problem. One-way car-sharing concept vehicles that are under development have the potential to overcome this problem and deliver cost-effective and efficient car-sharing solutions; as well as reducing pressure on parking. In addition, these car-sharing systems have the potential to integrate with public transport, through intermodal connectivity, and become important components in city transport systems of the future. The ongoing development of autonomous vehicles has the potential to result in an even more efficient transport system by bringing benefits in a variety of usage scenarios.

Acknowledgments

This research was carried out as part of the ESPRIT project, which was funded under grant agreement no. 653395 of the European Union's Horizon 2020 research and innovation programme.

References

Adams, J., 2015. Self-driving cars and the child-ball problem: why Autonomous Vehicles are not the answer. http://essays.centreforlondon.org/issues/technology/selfdriving-cars-and-the-child-ball-problem-why-autonomous-vehicles-are-not-the-answer/.

Begg, D., 2014. A 2050 vision for London: What are the implications of driverless transport? London: Transport Times.

Biondi, E., Boldrini, C., Bruno, R., 2016. Optimal charging of electric vehicle fleets for a car sharing system with power sharing. In: Energy Conference (ENERGYCON), 2016 IEEE International.

Boldrini, C., Bruno, R., Conti, M., 2016. Characterising demand and usage patterns in a large station-based car sharing system. IEEE Smart City.

Boldrini, C., Bruno, R., 2017. Stackable vs autonomous cars for shared mobility systems: a preliminary performance evaluation. In: Proceedings of the IEEE 20th International Conference on Intelligent Transportation Systems, pp. 232–237.

Bunsen, T., Cazzola, P., Gorner, M., Paoli, L., Scheffer, S., Schuitmaker, R., Tattini, J., Teter, J., 2018. Global EV Outlook 2018: Towards cross-modal electrification. Int. Energy Agency. https://www.connaissancedesenergies.org/sites/default/files/pdf-actualites/globalevoutlook2018.pdf.

Button, K., 2004. The rationale for road pricing: standard theory and latest advances. Res. Transp. Econ. 9, 3–25.

Department for Transport, 2015. The Pathway to Driverless Cars: Summary Report and Action Plan. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/401562/pathway-driverless-cars-summary.pdf.

Dijk, M., Orsato, R.J., Kemp, R., 2013. The emergence of an electric mobility trajectory. Energy Policy 52, 135–145.

Fenger, J., 1999. Urban air quality. Atmos. Environ. 33 (29), 4877–4900.

Finkorn, J., Müller, M., 2011. What will be the environmental effects of new free-floating car-sharing systems? The case of car2go in Ulm. Ecol. Econ. 70 (8), 1519–1528.

Fulton, L., Mason, J., Meroux, D., 2017. Three revolutions in urban transportation: How to achieve the full potential of vehicle electrification, automation, and shared mobility in urban transportation systems around the world by 2050 (No. STEPS-2050).

Furuhata, M., Dessouky, M., Ordóñez, F., Brunet, M., Wang, X., Koenig, S., 2013. Ridesharing: the state-of-the-art and future directions. Transp. Res. Part B 57, 28–46.

Geels, F., 2012. A socio-technical analysis of low-carbon transitions: Introducing the multi-level perspective into transport studies. J. Transp. Geogr. 24, 471–482.

Goldhill, 2015. Should driverless cars kill their own passengers to save a pedestrian. http://qz.com/536738/should-driverless-cars-kill-their-own-passengers-tosave-a-pedestrian/.

Goodwin, P., 2012. Peak Travel, Peak Car and the Future of Mobility: Evidence, Unresolved Issues, Policy Implications, and a Research Agenda. Discussion Paper No. 2012-13 Prepared for the Roundtable on Long-Run Trends in Travel Demand. http://doi.org/10.1787/5k4c1s3l876d-en.

Gordon-Harris, S., 2016. On the factors affecting the potential development of one-way car sharing networks in cities. In: 44th European Transport Conference, 5th–7th Oct 2016, Barcelona, Spain.
Goodwin, P., Van Dender, K., 2013. 'Peak Car' — themes and issues. Transp. Rev. 33 (3), 243–254.
Harper, C.D., Hendrickson, C.T., Mangones, S., Samaras, C., 2016. Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly and people with travel-restrictive medical conditions. Transp. Res. Part C 72, 1–9.
Hass-Klau, C., 2014. The Pedestrian and the City. Routledge.
Hensher, D., 2017. Future bus transport contracts under mobility as a service regime in the digital age: are they likely to change? Transport. Res. A 98, 86–96.
Hirsch, R.L., Bezdek, R., Wendling, R., 2005. Peaking of World Oil Production: Impacts, Mitigation and Risk Management. US Department of Energy.
Hoffman, George A., 1967. Systems design of electric automobiles. Transp. Res. 1, 3–19.
Holman, C., Harrison, R., Querol, X., 2015. Review of the efficacy of low emission zones to improve urban air quality in European cities. Atmos. Environ. 111, 161–169.
Jaensirisak, S., Wardman, M., May, A.D., 2005. Explaining variations in public acceptability of road pricing schemes. J. Transp. Econ. Policy 39 (2), 127–153.
Kent, J., Dowling, R. 2016. The Future of Paratransit and DRT: Introducing Cars On Demand. In: Mulley, C., Nelson, J.D. (Eds). Paratransit: Shaping the Flexible Transport Future, Emerald.
Klein, N.J., Smart, M.J., 2017. Millennials and car ownership: less money, fewer cars. Transp. Policy 53, 20–29.
KPMG, 2015. Connected and Autonomous vehicles. https://assets.kpmg.com/content/dam/kpmg/images/2015/05/connected- and-autonomous-vehicles.pdf.
Krueger, R., Rashidi, T.H., Rose, J.M., 2016. Preferences for shared autonomous vehicles. Transp. Res. Part C 69, 343–355.
Kyriakidis, M., Happee, R., De Winter, J.C.F., 2015. Public opinion on automated driving: results of an international questionnaire among 5,000 respondents. Transport. Res. Part F: Traffic Psychol. Behav. 32, 127–140.
Li, Z., Hensher, D.A., 2012. Congestion charging and car use: A review of stated preference and opinion studies and market monitoring evidence. Transp. Policy 20, 47–61.
Martin, E., Shaheen, S., 2016. The impacts of car2go on Vehicle Ownership, Modal Shift, Vehicle Miles Traveled, and Greenhouse Gas Emissions: An Analysis of Five North American Cities. Berkeley, CA: Transportation Sustainability Research Center. http://innovativemobility.org/wp-content/uploads/2016/07/Impactsof car2go_FiveCities_2016.pdf.
Melia, S., 2014. In: Carfree and low-car development Parking Issues and Policies (Transport and Sustainability). Emerald Group Publishing Limited, pp. 213–233.
Metz, D., 2010. Saturation of demand for daily travel. Transp. Rev. 30 (5), 659–674.
Millard-Bell, Adam, Schipper, Lee, 2011. Are we reaching peak travel? Trends in passenger transport in eight industrialized countries. Transp. Rev. 31 (3), 357–378.
Morton, C., Anable, J., Nelson, J.D., 2016. Consumer structure in the emerging market for electric vehicles: identifying market segments using cluster analysis. Int. J. Sustain. Transport. 11 (6), 443–459.
Mulley, C., Nelson, J.D., 2016. Shaping the new future of paratransit: An agenda for research and practice. Transp. Res. Rec. 2542, 17–24.
Noble, B., 2005. Why are Some Young People Choosing not to Drive. Department for Transport, London.
Office of Science and Technology, 2006. Intelligent Infrastructure Future Project Overview. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/300334/06-522-intelligent-infrastructure-overview.pdf.
Ornetzeder, M., Hertwich, E.G., Hubacek, K., Korytarova, K., Haas, W., 2008. The environmental effect of car-free housing: a case in Vienna. Ecol. Econ. 65 (3), 516–530.
Payre, W., Cestac, J., Delhomme, P., 2014. Intention to use a fully automated car: Attitudes and a priori acceptability. Transp. Res. Part F 27, 252–263.
Quadract, 2016. Reviewing The Peak Car Debate. Posted at: http://www.quadract.com/reviewing-the-peak-car-debate/.
Raux, C., Souche, S., Pons, D., 2012. The efficiency of congestion charging: Some lessons from cost-benefit analyses. Res. Transport. Econ. 36 (1), 85–92.
SAE International, 2014. Automated driving: levels of driving automation are defined in new sae international standard J3016.
Schwieger, B., Victorero-Solares, P., Brook, D., 2015. Global Carsharing Operators Report 2015. Team Red International GmbH, Berlin, Germany.
Shaheen, S., Sperling, D., Wagner, C., 1998. Car-sharing in Europe and North America: past present and future. Transport. Quart. 52 (3), 35–52.
Shaheen, S.A., Sperling, D., Wagner, C., 1999. A short history of carsharing in the 90's. J. World Transp. Pol. Practice Vol. 5, No, 3.
Shaheen, S.A., Chan, N.D., Micheaux, H., 2015. One-way carsharing's evolution and operator perspectives from the Americas. Transportation 42 (3), 519–536.
Shaheen, S., Cohen, A., Jaffee, M., 2018. Innovative Mobility: Carsharing Outlook. UC Berkeley: Transportation Sustainability Research Center. https://doi.org/10.7922/G2CC0XVW.
Shepard, S., Jerram, L., 2015. Transportation Forecast: Light Duty Vehicles. Navigant Research.
Skinner, R. and Bidwell, N. (2016) Making better places: Autonomous vehicles and future opportunities. WSPPB and Farrells. http://www.wsppb.com/Globaln/UK/WSPPB-Farrells-AV-whitepaper.pdf.
Smith, M.J., Liu, R., Mounce, R., 2015. Traffic control and route choice; capacity maximization and stability. Transp. Res. Procedia 7, 556–577.
Transport Systems Catapult, 2015. Traveller Needs and UK Capability Study. https://ts.catapult.org.uk/wp-content/uploads/2016/04/Traveller-Needs-Study.pdf.
UITP, 2017. Autonomous vehicles: a potential game changer for urban mobility. http://www.uitp.org/news/autonomous-vehicles-urban-mobility.
United Nations, Department of Economic and Social Affairs, Population Division, 2015. World Urbanization Prospects: The 2014 Revision, (ST/ESA/SER.A/366).
Urry, J., 2004. The 'System' of automobility theory. Cult. Soc. 21 (4–5), 25–39.
US Department of Transport, 2017. Mobility on Demand: Operational Concept Report. Available at https://rosap.ntl.bts.gov/view/dot/34258.
Vanderbilt, T., 2012. Autonomous cars through the ages. http://www.wired.com/2012/02/autonomous-vehicle-history/.
Weikl, S., Bogenberger, K., 2015. A practice-ready relocation model for free-floating carsharing systems with electric vehicles – mesoscopic approach and field trial results. Transp. Res. Part C 57, 206–223.
White, P.R., 2017. Public Transport: Its Planning, Management and Operation. Routledge.
World Health Organisation, 2013. Review of the evidence on health aspects of air pollution- REVIHAAP Project Technical Report, Copenhagen.
Yang, H., Wang, X., 2011. Managing network mobility with tradable credits. Transp. Res. Part B 45, 580–594.
Zhang, W., Guhathakurta, S., Khalil, E.B., 2018. The impact of private autonomous vehicles on vehicle ownership and unoccupied VMT generation. Transp. Res. Part C 90, 156–165.