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Article

Developing Policy for Urban Autonomous Vehicles: Impact on Congestion

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Abstract: An important problem for surface transport is road traffic congestion, which is ubiquitous and difficult to mitigate. Accordingly, a question for policymakers is the possible impact on congestion of autonomous vehicles. It seems likely that the main impact of vehicle automation will not be seen until driverless vehicles are sufficiently safe for use amid general traffic on urban streets. Shared use driverless vehicles could reduce the cost of taxis and a wider range of public transport vehicles could be economic. Individually owned autonomous vehicles would have the ability to travel unoccupied and may need to be regulated where this might add to congestion. It is possible that autonomous vehicles could provide mobility services at lower cost and wider scope, such that private car use in urban areas could decline and congestion reduce. City authorities should be alert to these possibilities in developing transport policy.

Keywords: road traffic congestion; autonomous vehicles; taxis; cities; urban

1. Introduction

The general deployment of Autonomous Vehicles (AVs) may lead to many changes in the operation of road networks and in travel behaviour. Recent reviews have begun to explore the consequences [1–12].

The hope is for better outcomes for citizens through mitigating the detriments associated with conventional vehicles, in particular air pollution, crash deaths and injuries, and delays due to road traffic congestion. We may also hope for improvements to the quality of journeys.

Automation would not directly affect vehicle emissions, whether carbon or noxious pollutants. However, it is likely that AVs will largely employ electric propulsion, both because this is being introduced generally for road transport and because the reduced mechanical complexity makes automation simpler to implement. Electric AVs would have zero tailpipe emissions, which would be beneficial for urban environments and for climate change (provided the electricity was not generated from fossil fuels).

Each AV model would need to demonstrate suitable performance as regards safe operation. At present, the regulatory regimes are relatively relaxed, permitting the testing of AVs on public roads. However, prior to general use it is to be expected that regulatory authorities will set safety standards appropriate to the different levels of vehicle automation, taking account of public acceptability. It is likely that safety standards for AVs would exceed those for conventional vehicles, and that AVs would be required to observe legal speed limits, such that overall road safety would be improved. There is a need to allocate responsibilities in the event of an incident in which injury or damage occurred, and for insurance arrangements to take this into account, recognising that improved safety performance would reduce the cost of insurance. While the need for such developments in safety regulation and insurance would require policy responses, this aspect will not be pursued here.

Arguably, the main challenge for surface transport is road traffic congestion, in that it is ubiquitous and has proved difficult to mitigate. Accordingly, a key question for transport policy concerns the possible impact on congestion of vehicle automation. To the extent that this or any other innovation may be expected to reduce congestion, it could be encouraged. On the other hand, regulation would need to be considered if congestion were likely to be worsened. And if the overall impact were judged to be neutral, then market penetration of AVs would be driven by user perceptions of benefits in relation to costs.

Accordingly, this paper addresses the possibilities for policy responses to the introduction of AVs as these seem likely to affect road traffic congestion. Given the very rapid development of the field and the considerable literature that has been published in recent years (a search of bibliographic databases by Cavoli et al. [3] yielded 50,000 results), references are selective and more recent, rather than comprehensive, chosen to illuminate the policy issues. Given the uncertainties about costs and timescales, the treatment is qualitative.

2. Road Traffic Congestion

Congestion arises in densely populated areas with high levels of car ownership. In this situation, road capacity is often insufficient to meet demand for all trips that might be made, particularly during the morning and evening commute. Some trips that might be made at a particular time are therefore not made—are suppressed or deterred—on account of anticipated delays. Those so deterred may change the time of travel, the destination (where options exist, as for shopping), the mode of travel, or may decide not to travel at all.

Congestion is therefore substantially self-regulating. As traffic grows, delays increase and some potential road users make other choices. For the same reason, congestion is difficult to mitigate. Measures that aim to get people out of their cars initially reduce traffic, but the resulting reduction in delays attracts on to the road other drivers who had previously been deterred by the prospect of delays, as argued by Givoni [13] in relation to the lack of impact of congestion charging in London. Similarly, increasing road capacity initially reduces congestion, but this makes road travel more attractive to those whose trips were previously suppressed, generating additional traffic—"induced traffic" [14,15]; hence the maxim that you can't build your way out of congestion, which is known from experience to be generally true [16].

A key constraint on daily travel behaviour is the limited time available within the 24 h of the day, given the many other activities that have to be undertaken. Evidence from surveys, both of travel behaviour and of time use, indicates that average travel time for settled human populations is about an hour a day, irrespective of income level, and that this has not changed over at least the period for which such surveys have been carried out, and probably over many centuries [17–20]. It is this time constraint that limits the increase in travel and therefore the increase in congestion.

Levels of traffic congestion vary from place to place, from city to city, depending on population density, road capacity, choice of alternative modes of travel, and traffic management technologies in use. We therefore need to consider how AVs might affect road use and travel demand, to assess the impact on congestion.

3. Performance of AVs

There are two routes to the development of vehicle automation—evolutionary and revolutionary. The evolutionary route is being pursued by the main vehicle manufacturers and involves developing a number of operational modes to assist the driver (known as Advanced Driver Assistance Systems, ADAS), such as adaptive cruise control, lane change assistance and automatic parking. These are generally introduced for high-end models, and gradually move down the product range to mass-market models. As more such systems are integrated, the role of the driver is reduced, with full automation the possible ultimate development. Before that point, there remains a role for the driver in circumstances where the automation cannot cope with road and traffic conditions. The design challenge is to be able alert drivers in time to take control, and to avoid too much trust being placed in partial automation, when decreased driver involvement may lead to loss of cognitive skills.

The difficulty in managing this handover of control reliably and safely leads some to conclude that the driver should never be in charge—the revolutionary route, the true driverless car, pioneered by Google (now branded Waymo). This approach requires the vehicle to operate without human control. There are various nomenclatures for specifying the degree of automation, for instance that of SAE International [21]. For policy purposes the key question is whether there is a driver in charge of the vehicle—if there is, little is changed. There are essentially two levels beyond driver assistance [22]:

- highly automated" vehicles in which a driver is required to be present and can take manual control at any time, although in certain situations the vehicle can offer an automated mode which allows the driver to disengage from the driving task and undertake other activities.
- fully automated" vehicles in which a driver is not necessary. The vehicle is designed to be capable of safely completing journeys without the need for a driver in all traffic, road and weather conditions that can be managed by a competent human driver.

Although there is widespread optimism that success will be achieved, particularly for high automation, what is not yet clear is the ultimate outcome: whether and when full automation—the driverless mode—will be demonstrated and validated as sufficiently reliable for general use.

Driver assistance, high and full automation involve autonomous vehicles that are essentially self-contained, although they generally communicate with the surrounding infrastructure for navigation purposes—using GPS for location, communicating location and speed of travel to providers of digital mapping and receiving route guidance. A further development involves AVs that are also connected vehicles—vehicles that communicate amongst themselves (V2V) to improve safety, smooth traffic flow and increase road capacity by reducing headways between vehicles, as discussed later.

The nature of the infrastructure is relevant for the performance of AVs. Segregated motor roads (freeways, motorways) are favourable for assistance systems that allow the driver to relax or to carry out other tasks. Lanes dedicated to AVs may be helpful, analogous to High Occupancy Vehicle lanes, particularly where V2V communications are used. Heavy Goods Vehicles (HGVs, trucks) can take advantage of V2V communications to operate as platoons, to reduce fuel costs and possibly driver costs. Separate lanes for AV cars and trucks may be necessary for reasons of safety and efficiency, which would limit these to wider highways. Vehicle entrance and exit from such highways would need to be managed safely. Another type of favourable context for AVs would be low speed operation where access by general traffic is controlled, for instance campuses, resorts, business parks, airports and other kinds of terminal.

Generally, it seems likely that the scope for dedicated road space for AVs would be limited, particularly at the earlier stages of deployment. Accordingly, most AV use would be on roads with mixed traffic—conventional, partially assisted and fully automated vehicles on main highways, plus bicycles and pedestrians on urban streets and local roads. It may be demanding to demonstrate sufficiently safe AV operation in such environments, particularly in historic towns and cities with narrow residential streets that have parked cars on both sides and too little space for vehicles to pass without negotiation. More modern urban settings with gridiron or similar road networks would offer more auspicious opportunities for general use of AVs.

Use of AVs would be affected by ownership, whether individual or shared in some form, for instances taxis, hired vehicles or car clubs. The evolutionary route pursued by the main vehicle manufacturers would fit the traditional model of individual car ownership. Indeed, for manufacturers of brands whose attractions are based on superior driving performance, the possibility of full autonomy would send a mixed message. Tesla, a new entrant to mass market vehicle manufacture, offers an electric car with an option for overnight home charging from solar-powered electricity generated during the day and stored in domestic batteries—consistent with personal ownership incentivised by near-zero running costs.

The revolutionary route to full automation offers the possibility of car-based door-to-door travel without individual ownership, in that empty vehicles could be summoned when needed and left when no longer required. Essentially this would be a taxi with a robot driver—a "robotic taxi". Conventional taxis are useful and would be more used if robots replaced human drivers at lower cost.

More generally, shared ownership spreads capital costs over much larger annual distance travelled, contributing to cost reduction compared with personal ownership, given that most cars are parked for some 95% of the day [23]. Electric propulsion of AVs would also reduce costs as battery costs decline, and because the simpler technology, operating at lower temperatures than internal combustion engines, is expected to extend vehicle life, increase reliability and lessen maintenance expenditure.

Altogether, the cost reduction obtainable with shared used electric AVs seems likely to make them economically attractive. However, vehicle sharing depends on the supply being able to meet demand, particularly at times of peak demand. Thus car club vehicles, which are shared by members, are not generally used for commuting, for which supply would be limiting [24]. So the attraction of shared use AVs may be limited, such that both personal and shared vehicles may be widely used, in proportions that would depend on factors such as availability of home parking and electric charging, and of alternative modes for urban travel under congested conditions.

4. Impact of AVs on Traffic

An AV takes the same amount of road space as a conventional vehicle of similar capacity. It is possible that AVs could operate at reduced headways (in platoons in the most extreme case) on narrower lanes, and could be more efficiently managed at junctions, thus increasing effective road capacity. A constraint would be how confortable occupants would be with short headways. The implications of varying levels of AV deployment and styles of behaviour have been explored in traffic simulation modelling (an example of a clear and detailed exposition is that of Atkins [25]). A recent review concluded that most such studies show little impact on traffic flow and capacity until relatively high penetrations of vehicles with high levels of automation (which would not be the case at best for many years); moreover, there is evidence of the potential for demand to rise as capacity increases, analogous with induced demand associated with new transport infrastructure [2] see also [26].

Vehicles equipped with ADAS or individually owned AVs operating in mixed traffic are therefore likely to be operationally neutral as regards traffic congestion. However, there could be wider impacts of driverless vehicles on demand for travel. Individually owned AVs could extend car use to those who are not able or qualified to drive, including children, older people and those with disabilities: this could increase the demand for car use, for which one upper-bound estimate is 14 per cent more vehicle miles travelled [27], potentially worsening congestion.

Individually owned AVs could offer new options to households, such as taking one member to work in the morning, returning unoccupied for use by others during the day, then travelling back to the workplace for the return commute trip. This might obviate the need for a second car for household use, but would double the distance travelled for work journeys. Analysis based on data from the US National Household Travel Survey suggests that average household ownership could be reduced from 2.1 to as few as 1.2 vehicles per household [28].

Use of driverless vehicles could allow occupants to engage in other activities, including working online. The ability to work online is likely to have contributed to growth of rail passenger numbers, which have doubled in the UK over the past 20 years. The ability to carry out activities other than driving while in a car could lessen the time constraint on personal travel, discussed above. This could result in increased distance travelled, which would add to traffic congestion, offsetting the potential again. The net impact is unclear.

Individually owned AVs could be expected in these ways to add significantly to overall distance travelled by car and hence to increased traffic levels. In contrast, AVs operating as robotic taxis would not be expected to have such an impact, given that conventional taxis travel without passengers between paid trips.

5. Impact of Shared Use

There are two aspects to vehicle sharing: shared ownership as discussed above, and shared use by unrelated people on a particular journey (shared use by friends, family and work colleagues is routine). Shared use by unrelated people—ride sharing—has been made generally feasible by smartphone apps, whether for shared taxis, such as UberPool and Lyft Line ridesharing, or for longer trips, such as BlaBlaCar and Waze Carpool. Such shared use is incentivised by lower costs. Shared vehicle use at present involves cars with drivers: if and when AVs are permitted for general use and drivers are not needed, costs could be further reduced, which would increase demand for sharing.

In the first instance, shared use increases car occupancy, which would be expected to reduce the number of cars needed to meet the travel needs of a given population and hence would reduce traffic congestion. However, reduced congestion would tend to attract trips previously deterred by anticipated delays. Moreover, the lower travel costs associated with shared use would be expected to attract passengers from public transport (transit), increasing demand for car and taxi use. So the net effect of shared use vehicles on congestion may not be substantial, given the self-regulating nature of road traffic congestion, as discussed above.

Digital platforms that employ smartphone apps to summon taxis are an important innovation in transport services. They represent a major step forward in provision of demand-responsive travel, which has generally been for the benefit of passenger with disabilities who require a door-to-door service (often known as Dial-a-Ride). Such platforms can be used to deploy a range of vehicle types and sizes to match supply with demand. If driverless operation becomes possible, costs would be reduced and the range of services extended. The relationship with regular public transport would need to be considered—whether competitive or co-operative—within a suitable regulatory framework, as discussed below.

6. Impact on Parking

As well as affecting moving traffic directly, AVs may have an indirect impact through lessening the need for parking space. Individually owned driverless vehicles could return home after the morning commute, as noted above, so not needing parking space at or near the workplace; a similar effect on parking space would occur if robotic taxis were to replace personally owned vehicles. Reduction in parking adjacent to the workplace would permit development opportunities for land no longer required. These could be substantial in cities where a considerable part of the central business district is dedicated to parking. And the reduced need for parking would reduce the contribution to congestion of vehicles in search of vacant parking spaces.

More generally, robotic taxis that are used for a substantial part of the day would need much less parking space than do individually owned vehicles, and such capacity as is needed could be on low-value off-street sites, thus freeing up kerbside space; such off-street parking would be suited for recharging electric robotic taxis. Reduction in the high demand for kerbside parking space in city centres would be helpful in lessening congestion arising from double parking by goods vehicles unloading and by taxis picking up and setting down. Freeing kerbside space in suburban residential streets with low levels of traffic would have little impact on congestion. On the other hand, reduced parking in narrow residential streets could help mitigate what could be a serious problem for AVs—negotiation between oncoming vehicles where there is too little space to pass side-by-side.

For conventional vehicles, parking involves finding a suitable space for a stationary vehicle. However, individually owned AVs might be programmed to cruise round the block while the owner was doing business. This would contribute to congestion, and might therefore need to be regulated in city centres and other areas prone to congestion.

A reduced need for parking may not be the only way in which AVs affect land use. The possibility discussed earlier that travel time constraints might be relaxed would allow longer distance commuting and hence housing development in more distant locations, resulting in more urban sprawl. However, the resulting additional traffic from such longer trips would add to congestion, thus reducing speed and lessening the benefit of longer journey times. It is possible that individually owned AVs would be particularly attractive to drivers who are already committed to long daily commutes through choices of residential and work locations.

7. Overall Impact on Congestion

Vehicles that are highly but not fully automated would probably not behave significantly differently from normal vehicles as regards their contribution to congestion. For fully automated AVs (driverless vehicles) there are factors that seem likely to operate both to increase and decrease congestion. Those that may add to congestion include: individually owned AVs travelling unoccupied on return trips or while "parked" on the move; increased demand for car use arising from those unable to drive; increased demand arising from the relaxation of the time constraint on daily travel if work can be carried out on the move; and increased demand for lower-cost robotic taxis by former users of public transport. Factors that might mitigate congestion include: possible scope for reduced headway and lane widths on dedicated highway lanes; some reduction in city kerbside parking; shared use of robotic taxis; and possibly less individual car ownership. However, all these factors would play out in the context of congestion that is self-regulating on account of the time constraints to which road users are subject, as discussed above.

To reduce traffic congestion substantially, it would be necessary to limit car ownership to within the capacity of the road network. This is the situation in rural areas of relatively low population density. The only large urban area where such limitation has been achieved is Singapore, where a high charge is made for the right to operate a car, such that ownership is about 100 per 1000 population, compared with more than 400 for most developed economies. This level of ownership allows the successful operation of electronic road pricing, which achieves consistent and adequate speeds on the road network.

A number of simulation modelling studies have been carried out to explore the scope for reducing urban traffic through sharing of vehicles. A study of a theoretical grid-based urban area indicated that one shared ownership AV could replace 11 conventional vehicles [29]. The International Transport Forum modelled the impact of replacing all car and bus trips in the city of Lisbon with fleets of shared vehicles, both shared taxis and on-demand mini-buses, plus existing rail and subway services; it was concluded that the travel needs of the population could be met without use of private cars in the urban core area and hence without congestion [30]. A simulation of travel demand in Austin, Texas, found that shared AVs could replace many if not all intra-urban trips in the ratio of 1 AV per 9 conventional vehicles, but with 8 per cent more vehicle-miles while unoccupied [31]. A study of taxi demand in New York City showed that 2000 vehicles (15 per cent of the taxi fleet) of capacity 10 or 3000 of capacity 4 could serve 98 per cent of the demand for taxis within a mean waiting time of 2.8 min and mean trip delay of 3.5 min [32].

These studies suggest that high levels of shared use vehicles could result in a substantial reduction in congestion, thus improving speed and reliability of road travel. The challenge is to reduce car ownership in societies where this is already high. In successful cities with growing populations, car use as a share of all trips tends to decline, since limited road capacity prevents any increase in car traffic. For instance, 50 per cent of all journeys in London in 1990 were by car, which reduced as the population has grown, currently to 36 per cent [33,34] with an ambition to reduce further to 20 per cent by 2040 [35]. So it may not be impossible to reduce urban car use to the point where alternatives, including shared surface transport, offer an improved service under reduced congestion.

8. Connected Vehicles

Adaptive Cruise Control, available in production vehicles, adjusts the gap to the vehicle in front using sensor data to vary speed. Connected (or Cooperative) Adaptive Cruise Control (CACC), an emerging technology, takes data from vehicles further ahead using vehicle-to-vehicle (V2V) communications, which allows shorter headways and attenuates traffic disturbance [36,37]. The shorter the headway, the less scope for driver control. In the limit, CACC allows platooning of vehicles on inter-urban roads—"road trains" involving vehicles in close proximity with a lead driver in control. The benefits of platooning include fuel economy resulting from lower aerodynamic drag, and improved traffic flow and capacity; these and the practical problems of safe implementation have been reviewed ahead of a UK trial [38].

The generality of drivers of AVs will, however, be able to choose the gap to the vehicle in front. It is not clear why, without an incentive, they would choose a gap smaller than that with which they are comfortable, which may not be much different from current headways. Accordingly, to increase road capacity by reducing headway there would need to be some incentive that would impact on individual drivers. This might be a road user charging regime that charged on the basis of the length of carriageway effectively occupied. Another kind of incentive to reduce headway would be dedicated lanes that are less congested and faster flowing than other lanes, analogous to High Occupancy Vehicle lanes on US freeways. Acceptable incentives would be needed if manufacturers were to go beyond equipping vehicles with the existing Adaptive Cruise Control. Manufacturers would be responsible for the safe functioning of AVs. Adding V2V or vehicle-to-infrastructure connectivity to reduce headway would exacerbate this responsibility by introducing functionality that depends on that of other manufacturers and suppliers and that increases the risk of security breaches.

More generally, connected vehicles operating at short headways would require reconsideration of the safety regime, which at present is concerned with the crashworthiness of individual vehicles. A system of connected vehicles would require consideration of fault modes at system level, for instance the consequences of faults in individual vehicles in a platoon and of faults in connectivity. It would not be surprising if there were trade-offs between headway and safety that limited possible increases in capacity.

The general application of V2V connectivity would need to follow on from the successful adoption of vehicle autonomy—because the benefits of such connectivity depend on response times of connected vehicles that are faster than achievable by a human driver. A question that arises is whether access to certain classes of roads should be limited to vehicles equipped with V2V technology. However, the efficiency gains from such dedicated infrastructure use would depend on widespread adoption of V2V communications, for which, as noted, there may be a lack of incentive for vehicle manufacturers to develop.

9. Implications for Transport Policy

There is considerable political interest in autonomous vehicles. A review of European and American policy reveals that governments are already playing an active role in supporting the technological development of AVs, based on expectations of a range of potential societal benefits that are yet to be proven or even demanded by the market [4]. The policy instruments available in the US have recently been reviewed [39].

As an example of policy development, the British government has stated its aim of ensuring that the UK is at the forefront of the testing and development of the technologies that will ultimately realise the goal of driverless vehicles [22]. The government has established a Centre for Connected and Autonomous Vehicles to support research, development, demonstration and deployment; is funding driverless car projects in four cities; has published codes of practice for on-road testing and for cyber security; and has introduced legislation into Parliament to clarify the liability of insurers when a crash involves an AV. This government support for AVs seems mainly motivated by considerations of industrial strategy since the transport implications are as yet uncertain. The outcomes of reviews and studies commissioned by the UK government provide no clear guide for transport policy, which is not surprising given the lack of evidence beyond that from pilot testing and simulation studies [1,3,25,40].

The potential contribution of AVs needs to be considered as one of four new technologies that will be important in meeting future demand for travel. In order of market maturity:

- Digital geography: digital maps and GPS location permitting route guidance and predictive journey times that take account of traffic congestion,
- Digital platforms to match supply and demand, for instance apps to hail taxis, which also allow shared trips at reduced cost, thereby achieving higher vehicle occupancy; extension to multimodal travel is under active development (known as Mobility-as-a-Service).
- Electric propulsion, which eliminates tailpipe emissions.
- Autonomous vehicles.

In this context, the key development for AVs is full autonomy—driverless vehicles able to operate in general traffic on all roads. Developments short of this seem likely to have little impact: driver assistance does not change the basic behaviour of the vehicles; and autonomy in limited circumstances, such as on campuses, would not have general impact. Given the maturity of existing road networks in developed economies, there would seem to be limited benefit in considering changes to the design of any new road infrastructure to accommodate AVs.

While the timing and even the feasibility of driverless vehicles operating in general traffic is unclear, it is nevertheless possible to anticipate the implications of such deployment.

Driverless shared ownership cars are essentially taxis with robot drivers—robotic taxis. They are not fundamentally different from taxis with drivers. Costs would be lower through not having a paid driver, making such services more attractive, thus increasing demand. Sharing by passengers would reduce charges further. Autonomous on-demand minibuses could fill the present gap between high capacity, low cost buses and rail services and low capacity, high cost taxis. In this context, the main impact of autonomy is likely to be cost reduction, permitting a wider range of publicly available services, particularly in areas of low residential density.

Driverless vans and trucks in general traffic are not fundamentally different from their conventional counterparts. Their practicality depends on being able to arrange for offloading at customers' premises.

In contrast, individually owned AVs are different from conventional vehicles in that they could travel without occupants, for instance returning to base after dropping the user at their destination, or "parking on the move" when no stationary parking is available. Such unoccupied vehicles would add to traffic congestion and their presence might need to be regulated in areas and at times when congestion was a problem.

The combination of the four technologies identified above, with AVs operating as taxis and minibuses, together with existing bus and rail services, could be the basis of substantially improved transport in urban areas.

The shift to electric propulsion will deprive governments of income from fuel taxes, used in part to fund the operation, maintenance and development of the road network. This suggests the need for some form of road user charging, familiar on toll roads and in some cities such as London, Stockholm and Singapore. London's central congestion charging zone generates revenues that are invested in the city's transport infrastructure. Taxis and private hire vehicles are currently exempt from the congestion charge, but need not be. There is scope for extending both the geographic area of charging and the classes of vehicles that pay, in order to achieve an optimal balance of the different kinds of transport provision. It would also be advantageous to shift from a daily charge on entering the charging zone to a charge based on distance. Such arrangements could be used to levy a higher charge on unoccupied individually owned AVs, to discourage their use under congested conditions.

The simulation studies discussed earlier suggest that more and better provision of alternatives to the private car would allow travel demand to be largely met by means other than the private car. In London's central congestion charging zone the composition of four-wheeled (or more) traffic is: private cars 22 per cent, taxis and private hire 39 per cent, goods vehicles 31 per cent, and buses and coaches 7 per cent (Table 6.6 of [34]). This indicates the significant scope for reducing traffic if private cars could be discouraged. The context is that for London as a whole, the share of journeys by public transport has grown from 25 per cent in 1995 to 37 per cent in 2015, while the share by private transport has fallen from 49 per cent in 1995 to 36 per cent in 2015 (Table 2.4 of [34]). This is largely due to road capacity constraints that have prevented any increase in traffic despite population growth, and investment that has added to rail capacity. The ambitious aim of the Mayor of London is to reduce the share of trips by car, taxi and private hire to 20 per cent by 2041 [35].

The four new technologies mentioned above would allow the development of the emerging concept and practice of Mobility-as-a-Service (MaaS), which is envisaged as offering seamless travel by modes other than the private car, booked and paid for on a smartphone app or other digital means (for recent consideration, see [41,42]). The potential reduction in private vehicles arising from the attractions of MaaS could reduce congestion and thus improve reliability and journey times, creating a virtuous circle.

These possible developments in mechanized mobility need to be placed in the context of concern about the increase of obesity in developed economies associated with sedentary lifestyles. While conventional public transport involves walking at each end of the journey, reduction in such exercise through growth of demand-responsive modes must be an anxiety, to be mitigated by the positive encouragement of the active modes of walking and cycling in the urban environment.

It will be for national governments to establish regulatory requirements for the safe and secure operation of AVs. Vehicle manufacturers will both create and respond to market demand. Authorities responsible for inter-urban roads will need to address the implications of a growing population of vehicles with varying levels of automation. It will be for cities to manage the urban deployment of AVs, using powers to regulate taxis, support public transport, manage traffic, and charge for road use. Cities and national governments should review the powers available for influencing traffic levels and compositions, in anticipation of the deployment of AVs.

10. Conclusions

There is at present much uncertainty about the impact of AVs, but also much wishful thinking about potential benefits. This paper has attempted to form a balanced judgement about the impacts on congestion, to the extent that this is possible ahead of real world experience, which may inform policy makers who see the need to address the issues.

It seems likely that the main impact of AVs on the urban transport system will only be seen when driverless vehicles have developed to the point that general deployment occurs on roads that accommodate mixed traffic, the timing of which is unclear. Given that the road network is open to all qualified users in vehicles that satisfy safety requirements, such deployment would be determined largely by demand from users and supply by manufacturers.

Driverless shared ownership vehicles would reduce the cost of taxis and increase demand, and a wider range of public transport vehicles would be economic. Driverless individually owned vehicles could add to traffic when unoccupied and their use in congested urban areas may need to be regulated.

Autonomous alternatives to the private car would reduce the cost of travel. As these alternatives develop, car ownership in urban areas may decline to the point at which congestion ceases to be the main problem for surface transport, a prospect that should encourage city authorities to plan for a driverless future.

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