An Autonomous Vehicle Strategy for the Greater Cambridge Partnership

April 2020

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1. Introduction

Purpose

This report has been prepared for the Greater Cambridge Partnership (GCP) by Professor John Miles of the University of Cambridge Department of Engineering. The purpose of the work was to take a forward look at the opportunities and barriers related to the use of connected, autonomous, vehicles within the public transport system for Greater Cambridge. This work took note of the changes in public perception, regulatory environment, and commercial models which are now beginning to evolve.

Objective

The objective is to help shape the Greater Cambridge Partnership (GCP) public transport strategy over the coming 10-year period.

Scope of Work

This report looks primarily at the Greater Cambridge area, but also considers medium-distance inter-urban travel and rural connections across the wider regions of the Cambridge and Peterborough Combined Authority (CA).

The scope of work specified by GCP included the following specific workpackages:

1) Horizon scanning out to 10+ years. This workpackage included the development of a high level overview which maps the technology, regulatory, and business landscapes as they might evolve over that period.
2) An assessment of vehicle electrification and other 'adjacent' transport/information technologies and the effect they might have on future development pathways for autonomous public transport systems.
3) The definition of a range of future transport scenarios, with a comparative evaluation of their benefits and dis-benefits.

Structure of the Report

The report begins with a horizon scanning summary of the autonomous vehicle space in Chapter 2, and a summary of adjacent technologies in Chapter 3.

The legal and regulatory state of readiness is surveyed in Chapter 4, and the technological and business state of readiness is surveyed in Chapter 5. Based on these two chapters, a family of credible future scenarios, with timescales, is sketched in Chapter 6.

Chapter 7 reviews the opportunities for, and barriers to, future progress from the GCP/CA perspective and Chapter 8 proposes a 10-year vision for GCP/CA which is designed to capitalise on the perceived opportunities. Conclusions and recommendations are presented in Chapter 9.

2. Horizon Scanning

We are currently experiencing a stark shift in the transportation sector as new mobility solutions such as ridesharing, carsharing, microtransit and micromobility expand across the globe and Mobility as a Service (MaaS) models emerge in various markets. At the same time advances in autonomous vehicle (AV) technology promise to increase the speed of change, with pilot deployments in cities taking place world-wide. These shifts are having, and will continue to have, dramatic impacts on urban planning, design and development. They will affect travel patterns and mode choice and, in turn, will affect land use, land values, streetscapes, and neighbourhood design. All of this will have implications for public equity, the environment, and the economy.

In this section, we scan the horizon for developments in the fields of autonomous and electric vehicle technology that are likely to have a material impact on our public transport systems in the coming decade.

2.1 Setting the Scene

The development of autonomous vehicles and their control systems has progressed at a very fast pace over the past 10 years. The arrival of the ‘tech’ companies in the automotive space has brought with it a wave of disruption and has provoked some rapid advances in the fields of both electric and autonomous vehicles. The technical and cultural differences between the main protagonists are extreme and, as a result, there are clashes of style and expectation which accentuate the tensions and make the prediction of future performance very difficult to read.

Over recent years, the major breakthroughs in the fields of both Electric Vehicle (EV) and Autonomous Vehicle (AV) technologies have been delivered by the disruptors (e.g. Tesla and Google/Waymo), but the incumbent car manufacturers (the ‘OEMs’) are now responding strongly. A wave of new EV’s is scheduled to arrive in the showrooms over the next three years from the major OEM’s and, in the field of AV’s, a swathe of alliances, mergers, and acquisitions has taken place which now blurs the line between the ‘disruptors’ and the ‘incumbents’. An illustration of some of the recent alliances and takeovers is presented in the diagram below (*source: The Economist)* and a brief summary of what has been happening may be found in Appendix 1. below.

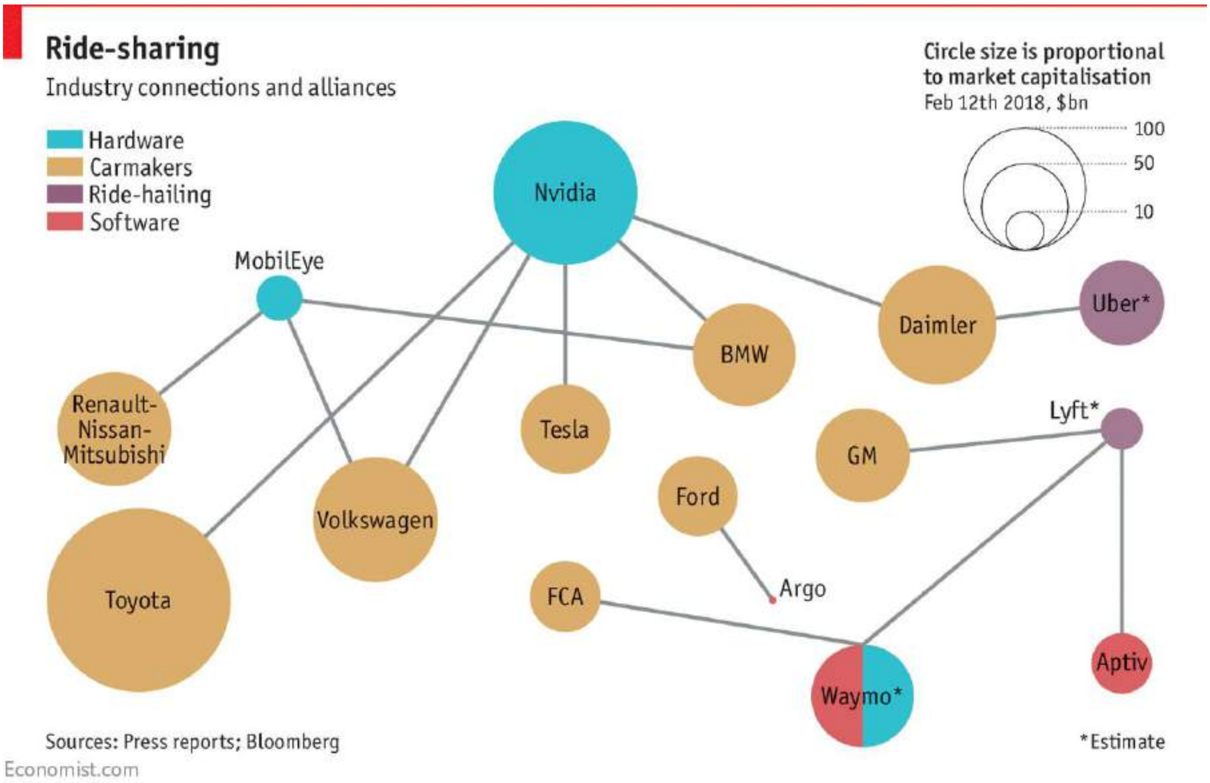


Fig 2.1 There has been a wave of alliances, mergers, and acquisitions over the past 5 years and further, even more dramatic, events are likely to unfold over the next 5 years

The picture is further complicated by the rapid development of the enabling technologies – sensors, actuators, software control systems, etc. The cost of LIDAR sensors has fallen by a factor of 10 since they were first adopted at the heart of the sensor arrays on the first autonomous vehicles. But, during that same period, vision-based systems (cameras) and millimetre-range radar have arrived on the scene with the potential to displace LIDAR sensors altogether. The cost of radar and camera-based systems is typically much lower than LIDAR systems, so the implication here is that sensor arrays will get both cheaper and more capable with the passing of time. Coupled with parallel advances in computing and communications, the case that we can assume a future in which unlimited on-board compute power, data storage, and sensor capability are available at affordable prices seems compelling.

This turmoil is not limited to the technology space alone. It is spilling over into the more general fields of service provision and freight/goods delivery. This is witnessed by the recent activities of companies like Uber, Lyft, and Amazon in the markets for electric bikes &,scooters, home deliveries, and even food take-away services. The last category has added some other interesting new-comers to the field of autonomous transport; Starship from Lithuania, for example, is currently running demonstration services in several cities around the world for short-range home delivery of light goods and take-away food.

Fig 2.2 New Services and Business Models – Autonomous Take Away Food Deliveries

As a result of these very rapid technical and commercial developments, it is very difficult to make predictions about the speed and scale of future take-up with any real confidence. Expert opinions vary widely but, despite the many uncertainties, there is a surprising degree of agreement on a few fundamental points:

1) Most experts agree that driverless technologies are coming and their arrival, at scale, is
2) inevitable within the next 30 years. Differences of opinion regarding the rate of arrival, and the technical detail of the intermediate steps, mainly exist because it is so difficult to frame the right questions to ask. (For example, there is a huge difference between the idea that *some* driverless cars will be on our roads and will be able to operate freely under *certain* conditions, and the idea that *all* cars will be fully driverless and can operate on the full extent of our road system *anywhere, any time, and under any conditions*). The answers offered by experts when asked these questions generally reflect the nuances of how the questions have been framed.

3) Most experts agree that vehicles with limited autonomous capabilities will become commonplace within the next 5 years. Confidence on this question is high because it is, essentially, a continuation of the process which has seen increasing degrees of ‘driver assist’ creeping into production cars over the past 25 years. This process began with the introduction of cruise control, and continued with the development of more sophisticated features such as adaptive cruise control, lane keeping, blind spot detection, automatic parking, collision avoidance, driver fatigue monitoring, etc. The integration of these formerly separate systems will enable new vehicle models to move to a new level of intelligent capability relatively seamlessly. The line between ‘advanced driver assist systems’ (ADAS) and ‘semi-autonomous systems’ is therefore very blurred.

In summary, the take-up of autonomous vehicles, and the associated displacement of conventional vehicles, could follow the pattern as shown in Fig 2.3 below.

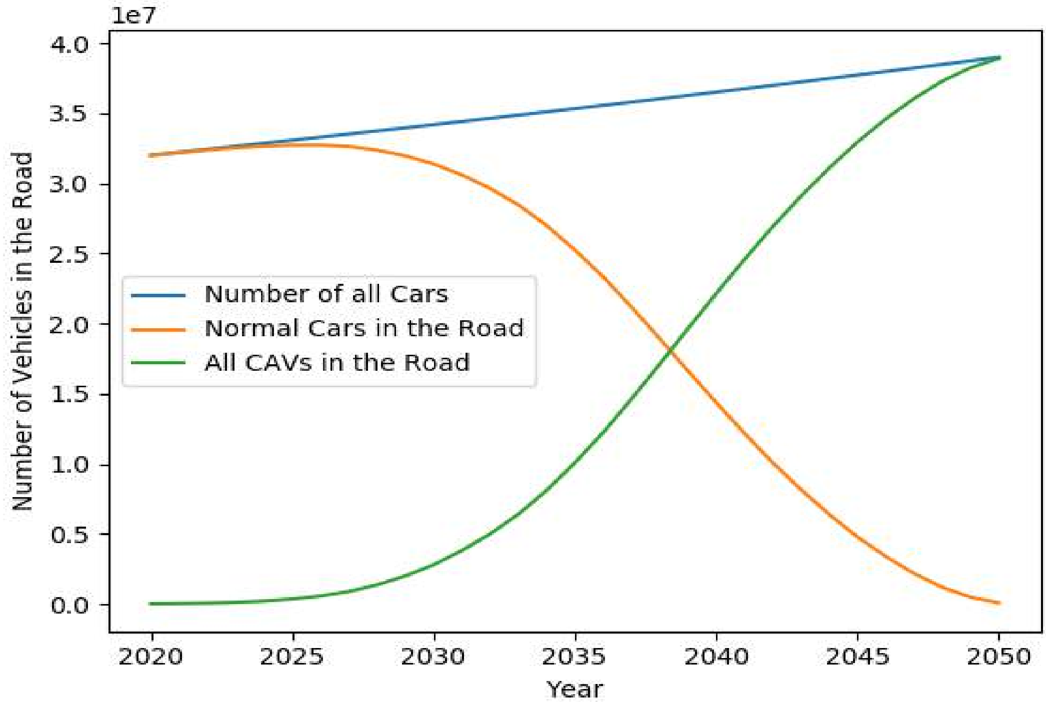


Fig 2.3 CAV's are expected to displace conventional vehicles in the total vehicle parc over the next 30 years

2.2 The Definitions of Autonomy

Defining the intermediate steps on the path between conventional vehicles and fully autonomous vehicles is an important part of setting a framework of expectation. The Society of Automotive Engineers of America (SAE) has developed an approach which defines six levels of autonomy, and this has become widely accepted as the language of autonomy throughout the automotive world. The SAE framework is illustrated in Fig 2.4 below. It should be noted that the current 'best in class' capabilities incorporated in purchasable vehicles (e.g. the Tesla) already meet the definition of SAE Level 2. The defining characteristic up to his level is that the driver is *always* responsible for whatever happens on the road and must intervene spontaneously in the event of emergency or malfunction. These automatic features are therefore classed as 'Driver Assist' rather than 'Autonomous', but their importance as stepping stones along the path to full autonomy should not be underestimated.

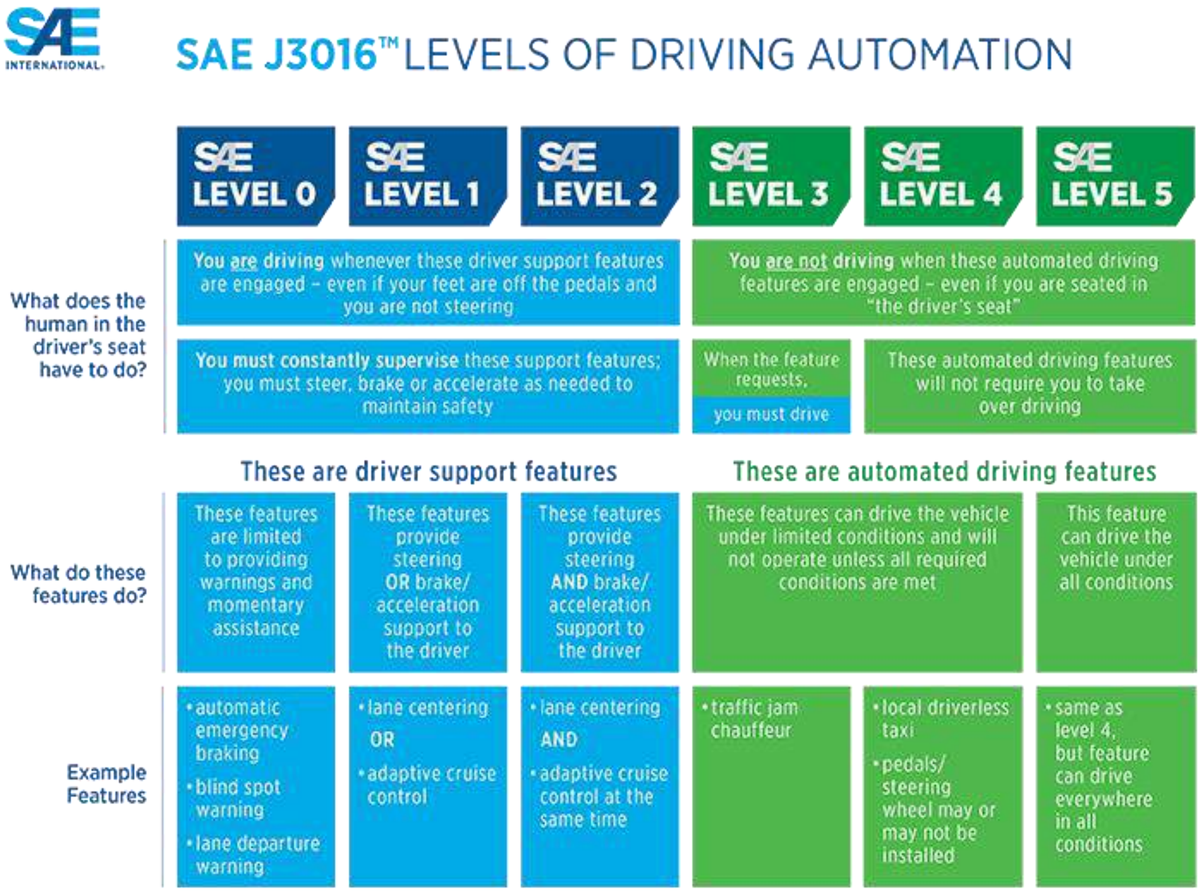


Fig 2.4 The SAE's 6 Levels of Autonomy

The SAE levels have been described by the Law Commission of England and Wales as follows:

Level 0 – No automation. The human driver performs all aspects of all driving tasks, even when these are enhanced by warning or intervention systems.

Level 1 – Driver assistance. The driver assistance features can carry out either the steering or acceleration/deceleration.

Level 2 – Partial automation. The driver assistance features can carry out both steering and acceleration/deceleration. The driver is responsible for monitoring the driving environment and must remain engaged **at all times.**

Level 3 – Conditional automation. The driving automation features can perform all driving tasks but a human "fallback-ready user" is expected to respond appropriately to "a request to intervene". The fallback-ready user must be receptive to a handover request or to an evident system failure, but is not expected to monitor the driving environment.

Level 4 – High automation. The driving automation features can perform all the driving tasks within their "operational design domain" or ODD (for example, motorways only). There is no expectation that the human user will respond to a request to intervene when the vehicle is operating within the ODD. If the limits of the system are exceeded, the system will put the vehicle into a "minimal risk condition", such as a safe stop.

Level 5 – Full automation. This is identical to Level 4 except that the driving automation features are not limited by an operational design domain. Instead they are capable of performing all driving functions in all situations that a human driver could.

The Law Commission goes on to elaborate on two terms of art which are implicit to these classifications.

Minimal risk condition

The SAE define this as the condition to which the user or system brings the vehicle "to reduce the risk of a crash when a given trip cannot or should not be completed". For example, a minimal risk condition may entail "bringing the vehicle to a stop in its current travel path" or "a more extensive manoeuvre designed to remove the vehicle from an active lane of traffic". However, at present there are no standards for what might qualify as minimal risk. The minimal risk condition may be achieved either by the human user (in Level 3 systems) or by the automated driving system (in Level 4 systems and above). This is a crucial difference between Level 3 and Level 4. Level 3 systems rely on the human user to be the "fail safe". By contrast, Level 4 systems do not require a human user to intervene to ensure safety.

Operational design domain

The operational design domain refers to the conditions in which the vehicle is designed to function in automated mode. They are set by the manufacturer and include the environmental, geographic, time-of-day, traffic, infrastructure, weather and other conditions under which an automated driving system is specifically designed to function. Thus, conditions may relate to a type of road (such as a motorway); a place (such as a city); a speed (such as under 12 km per hour); or weather (such as "not in snow").

2.3 The Arrival of Connected and Autonomous Vehicles on our Streets

As has been described, there is general agreement that Connected and Autonomous Vehicles (CAV's) will take an increasing fraction of the total market share to the point where these vehicles could become ubiquitous by 2050. Within that broad overview, however, there lies a much more complex sub-picture which is illustrated in Fig 2.5 below. In this figure, the arrival of CAV's is sub-divided into a series of waves which describe the arrival of first generation, second generation, and third generation vehicles. Each generation occupies a time-frame of around 10 years (two vehicle development cycles) and is defined as follows:

Gen 1 vehicles (first appearing in the early '20's) represent the first wave of vehicles to have genuine autonomous capabilities. These will embrace Levels 3-4 on the SAE scale and they will enable the driver to relinquish control of the vehicle under certain prescribed conditions (*conditional autonomy).* Under Level 3, the vehicle may return control to the driver at any time. Under Level 4, the vehicle will always retain control, but this level of functionality will only be available under certain limited scenarios (e.g. motorway driving, or in urban traffic jams on geo-fenced routes). The algorithms which are used under vehicle control conditions will exhibit 'cautious' driver behaviour, erring strongly on the side of safety over any other consideration. Because of this, if such vehicles ever come to dominate the total vehicle parc, congestion would probably be aggravated rather than alleviated. However, this is extremely unlikely to happen because the second generation of more capable CAV's will arrive too quickly.

Gen 2 vehicles (first appearing in the late '20's or early '30's) represent a maturing of the technology. In this scenario, Level 3 has disappeared and the technology lies exclusively at Level 4. The control algorithms will represent 'confident' driving styles, reflecting greater levels of confidence amongst the technology deliverers. Once engaged, these systems will not require the driver to intervene, even in emergencies. But they will only be activated under certain prescribed conditions (e.g. within clearly defined geo-fenced zones, or under weather conditions which preclude extremes). These vehicles will offer many advantages to drivers who make regular journeys on motorways and urban trunk roads, and they might enable limited driverless transport services to be offered within certain restricted areas. But they will not enable 'driverless cars' (or taxis /buses) to operate without limitations across the urban and rural landscapes.

Gen 3 vehicles (first appearing in the late 30's) represent the arrival of true Level 5 autonomy. In this scenario, the driver is *never* required to intervene and the vehicle takes sole responsibility everywhere and at all times (unless knowingly disengaged by the driver for 'pleasure driving' purposes). The control algorithms will represent 'very confident' driving styles and, for this reason, the large-scale penetration of the market by these vehicles could lead to significant reductions in congestion – maybe as much as 20% (Ref: "Connected and Autonomous Vehicles: Assessing the Likely Effects on Urban Congestion", UK Autodrive, 2018).

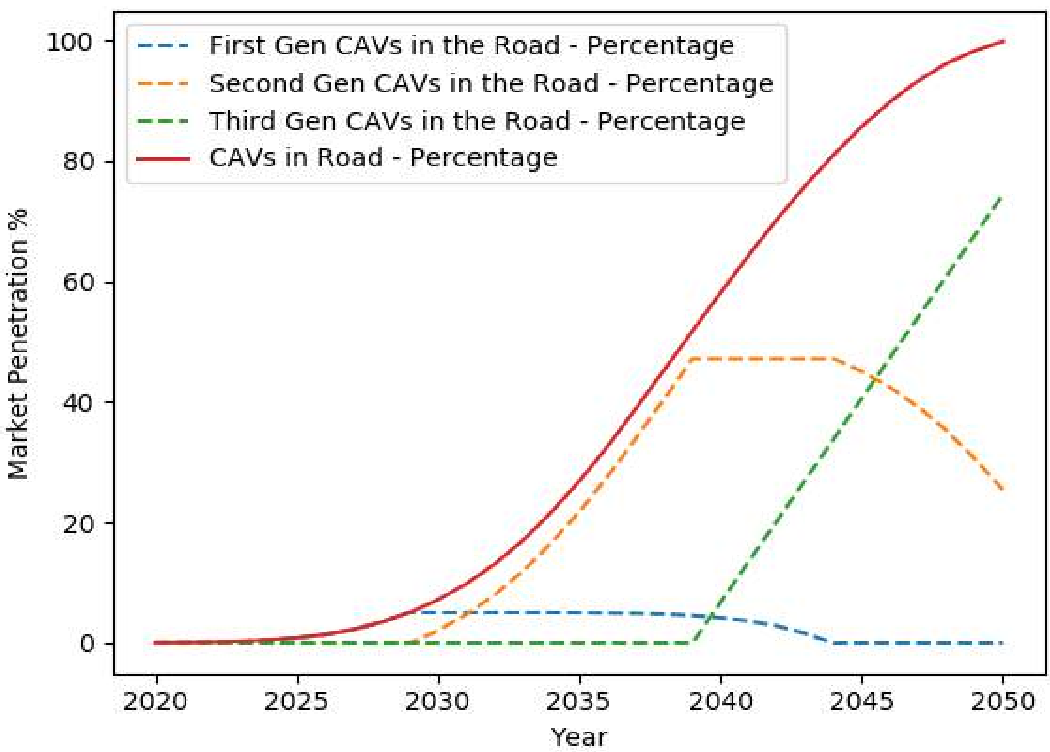


Fig 2.5 CAV's will arrive in a series of 'Generation Waves' between now and 2050

2.4 Cases of Special Interest

All of the above has been addressed from the perspective of road-going cars. These vehicles are being developed by the mainstream motor manufacturers and their new ‘Tech-challengers’, and their mission is to develop road-going vehicles with total capabilities at all speeds and under all driving conditions. Whilst there is a great deal of benefit to be gained from successful road-going vehicle developments, there is little room for GCP/CA to take a pro-active stance in this space.

However, there is an important sub-set of special cases in which the GCP/Combined Authority could take an active position. These cases are more specialised and therefore of less interest to the major motor manufacturers. As a consequence, there is more room for smaller, more agile, players to participate in the technical development programmes and there are some interesting near-term opportunities for CAV’s to make a positive contribution to solving our pressing transport problems.

2.4.1 Low-Speed Autonomous Transport Systems (L-SATS)

These systems are designed to operate at low speeds in either segregated or mixed pedestrian spaces. They are not road-going vehicles and, because of this, the technology challenges for the vehicles and control systems are much reduced. Small vehicles moving at low speeds have limited passenger transfer capacities, and so these systems typically fulfil niche requirements where the target passenger transfer rate lies well below 1,000 passengers per hour per direction (pphpd).

L-SATS sub-divide into two distinct categories:

1) Fixed path (segregated) systems
2) Free-roaming systems

Examples include driverless shuttles carrying multiple passengers providing public transport services along defined pathways (fixed path systems), and small driverless pods operating freely amongst pedestrians in designated zones within city-centres or hospital/university campuses (free roaming systems). Fig 2.6 illustrates the two cases.

(a) (b)

Fig 2.6 Low Speed Autonomous Transport Systems (L-SATS): (a) Fixed Path System (b) Free-Roaming System

In terms of the technology required, free-roaming systems are much more difficult to deliver than fixed path systems. This affects the horizon to effective deployment. Fixed path systems are already in public service in several places around the world (notably the 'ULTRa' system at Heathrow and the '2getthere' system in Rotterdam, illustrated above). The current T-CABS programme in Cambridge represents an intermediate case where the majority of the service runs on a fixed (and segregated) path, but the 'turn-round loops' at the end-points are performed in mixed traffic spaces.

Free roaming systems are not deployed in useful service anywhere in the world at the time of writing, although there are a few very slow, cautious, systems in operation which use the commercially available Navya and EasyMile vehicles. At the time of writing, these are more of an 'attraction' than a useful public transport service; it is unlikely that a truly free-roaming system will be deployed in a useful public transport application any sooner than the mid-20's (for a more detailed discussion on likely deployment timescales, see Section 5.1).

2.4.2 Fast Segregated Autonomous Transport Systems (F-SATS)

F-SATS are high speed, fixed-path, autonomous systems which run on strictly segregated pathways. They are, essentially, 'driverless buses', using road-based autonomous technologies driving rubber-tyred, steerable wheels on segregated concrete/tarmac pathways. In principle, they are a logical development of trams and Light Rail systems, but they cannot run in the mixed traffic conditions which are a common-place requirement for trams.

F-SATS are likely to be much cheaper to deploy than conventional tram/Light Rail solutions because they have no need for line-side power, rail-standard signalling systems, and steel rails mounted in the road. They are likely to be best-suited to passenger capacities in the range 1,000 – 5,000 pphpd which is significantly less than the economic 'sweet spot' for tram/Light Rail systems which, typically, lies in the range 5,000 – 10,000 pphpd.

There is plenty of evidence that the transition from steel wheel on steel rail to rubber tyre on concrete is credible. There are several driverless mass transit systems in France and other countries where rubber-tyred vehicles have been running for many years. One of the first such systems, developed by Matra, opened in 1983 in Lille, and others have since been built in Toulouse and Rennes (illustrated below). At the 'heavy' end of the scale, Paris Metro Line 14 runs on rubber tyres and was automated from its beginning (1998). Paris Line 1 was converted to automatic in 2007–2011.

Fig 2.7 The Driverless, Rubber-Tyred, Rennes Metro

The French examples look more like trains than buses, but the autonomous nature of their operation, and their use of rubber tyres, mark them out as forerunners of the more advanced *F-SATS* concept which is suggested here.

The MicroMetro system proposed for the Cities of Cambridge, Milton Keynes and Oxford (illustrated in Fig 2.8). is an example of a 'pure' *F-SATS* concept. In addition to its use of autonomous technology and rubber-tyred vehicles, it aims to reduce the surface disruption and carbon footprint of constructing the mass transit infrastructure by reducing the scale of the vehicles and their associated systems. The cross-sectional dimensions shown in Fig 2.8 (b) illustrate this point. The vehicle is very compact when compared to a conventional bus or tram, and the supporting infrastructure is correspondingly much smaller. The fixed infrastructure cost (civils element) is strongly related to size and, as a result, it is estimated that these 'Ultra-Light Mass Transit' systems could be built at approximately half the price of a conventional tram/LRT solution.

The cross-section dimensions of AVRT are close to those of the Glasgow Metro, and it is proposed that this approach could be used in tunnels as well as on the surface. The use of small-bore tunnels has the potential to reduce the cost of tunnelling to affordable levels and this opens the way to accessing the centres of cities and large towns in a manner that has not been cost-effective before. Collateral benefits arising from the adoption of tunnelled solutions include a reduced need for reconfiguration of the surface topography (demolition of buildings and re-routing of utilities) and a very much reduced level of disruption to traffic during the construction period.

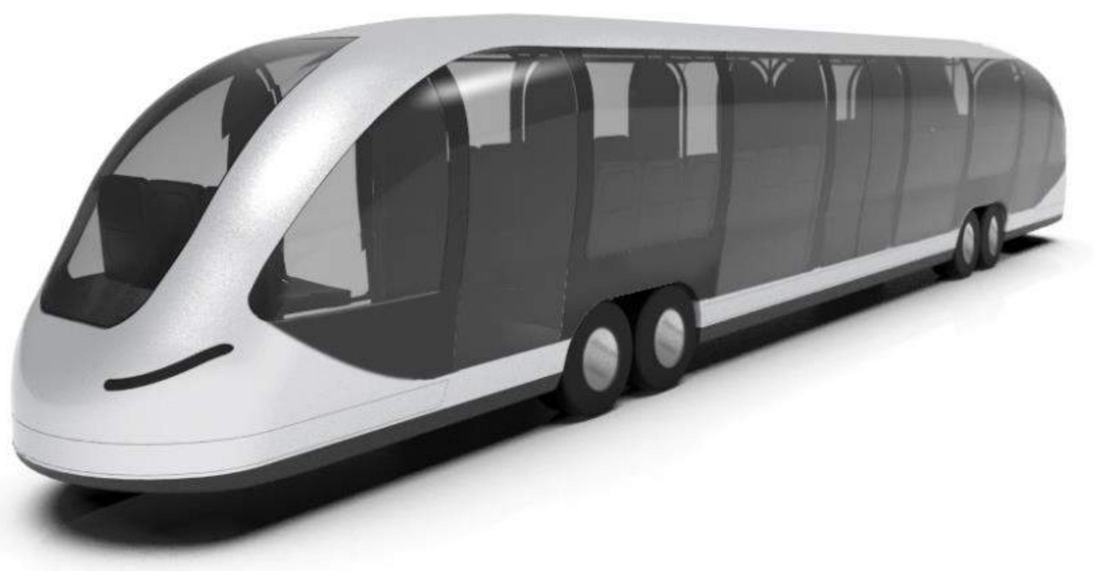


Fig 2.8a 'MicroMetro' – a New Concept of Ultra-Light Mass Transit Designed to Minimise Surface Disruption and Carbon Footprint

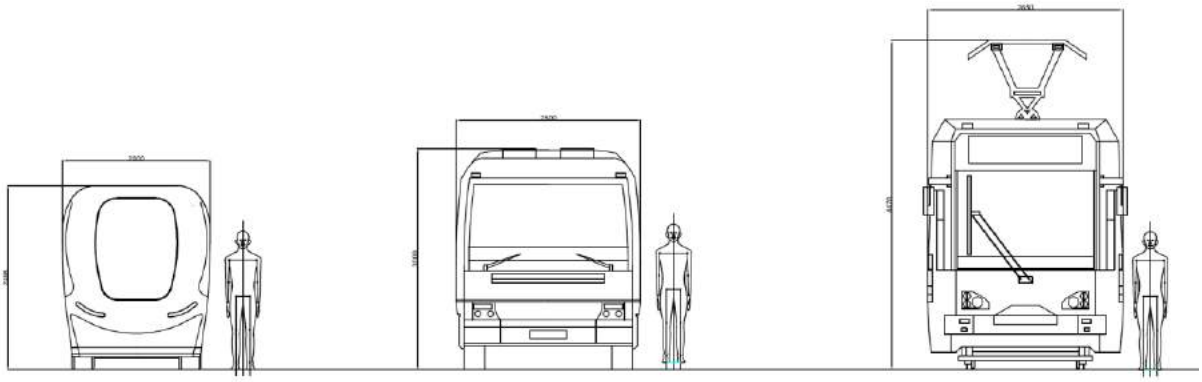


Fig 2.8b Cross Sections Comparing MicroMetro (at left) with a Conventional Single-Deck Bus and a Tram.

2.4.3 Tram and Light Rail

Tram and Light Rail systems have a long history of application to public transport. The two terms are often used interchangeably but, strictly, there is a clear distinction between them. Light Rail systems only run within unique corridors which are strictly segregated from road-going traffic. Trams, on the other hand, run in defined lanes on the open road for all, or part, of their journeys. The 'semi-segregated' nature of a tram makes these systems separate from, and technically more difficult to deliver, than the *F-SATS* systems described in Section 2.3.3.

Nevertheless, as a result of the historic popularity of trams, several of the well-established systems providers have already developed highly automated and (even) driverless systems which are designed to work in mixed space. These examples generally rely on fixed markings on the road surface to guide them along pre-determined paths. This type of tram is sometimes referred to as a ‘trackless tram’. The CRIC system being trialled in ZhuZhou, China, illustrated below, is one of the most recent examples. Although it is described as ‘autonomous’, the presence of a Safety Driver is clearly visible and to date, unlike the Paris Metro (a strictly segregated system), the system has never functioned in public service without a Safety Driver.

Fig 2.9 The ZhuZhou ‘Trackless Tram’

Despite the driverless technology and battery powered traction, the trackless trams most recently appearing are large vehicles with dimensions which make them less like the *F-SATS* ‘Micro-Metro’ concept described in the previous section and more like the conventional tram and light rail systems.

2.4.4 Drones

A rash of electric powered aircraft developments has hit the headlines over the past few years, ranging from straightforward conversions of conventional light helicopters to electric power (*e.g. the Sikorsky Firefly*) to purpose-designed aircraft like those proposed by Airbus, Velocopter, and Aston-Martin. Electric propulsion with its fly-by-wire architecture lends itself to automatic control, and several (but not all) of these new aircraft are intended to operate in driverless mode. The Velocopter is currently going through the process of becoming certificated for transport operations in Dubai, and the company intends to achieve certifications in Europe as well. This will be a slow process, but the potential is clear.

Fig 2.10 Autonomous Electric Powered Light Aircraft are Attracting a Lot of Attention

2.5 Safety

Safety is a critical issue. Autonomous transport systems will not become mainstream without the trust of the travelling public and the endorsement of the regulatory authorities. There is some precedent for autonomous vehicles being deployed in public service (for example, the ULTRA system at Heathrow, and the Paris Metro line 14). At the time of writing, there is no system which offers a public service which has approval to operate without restriction on the open highway or in a public space.

The burden of proving safe operation under all circumstances for Level 5 vehicles is enormous. The industry is of the view that this task requires a new approach to gaining approvals, because of the almost infinite combinations and permutations of circumstance which have to be considered. OEM's and others are working on new methods of gaining approvals based on simulation but this is, as yet, a very new field of activity.

In the meantime, the regulators and other authorities are making their own progress. The recently passed UK Automated and Electric Vehicles Act (2018) marked a milestone in autonomous vehicle developments. The UK Code of Practice for trialling self-driving vehicles on public roads (CCAV, 2019) and the British Standards Institute's PAS 1880/1881 (2020) publications are another sign of progress. All these documents are discussed in greater detail in Section 4.2

Developing safety cases for Level 4 vehicles running on segregated pathways presents a much more straightforward challenge. The examples of ULTRA and the Paris Metro line 14 cited previously illustrate the practicability of achieving this goal. Even here, it is not always straightforward. The Docklands Light Railway operates a public service without a driver, but a DLR employee is on-board at all times. (It is not clear, however, whether this is a human-factors consideration, or a Safety Case requirement).

2.6 Cyber-Security

This represents a special sub-case of the general safety considerations. There is a great deal of concern around cyber-security, hacking, terrorist activities, etc, and public transport systems are attractive targets for people with mal-intent.

The ideal solution is to make the autonomous control system an ‘island’, with no points of access from the outside. This means that 100% of the vehicle situational awareness and decision-making capability has to be delivered using on-board sensing and computing systems. This may preclude an attacker from entering the system via a vulnerable portal, but it also precludes any form of connection between the vehicle and the outside world. Valuable situational information from infrastructure-based sources cannot be taken advantage of and, more significantly, safety over-ride systems operated by a remote system supervisor cannot be implemented. At first sight, this makes it impossible to comply with the Code of Practice referred to in Section 2.4 above.

In the absence of ‘islanding’, very sophisticated technologies and strategies must be implemented to reduce the levels of risk to acceptable proportions. The British Standards Institute (BSI) has recently issued a ‘Publicly Available Specification (PAS) on this subject (PAS 1885, 2018).

3. The Impact of Adjacent Technologies

Autonomous vehicles sit within a distinct and fast-moving segment of the technology and product development spectrum. But they are not an island of development, and several adjacent segments of technology/product development have the potential to inter-act and enhance, or detract from, the ultimate benefits which might be delivered.

A particular confluence of interest exists around the three overlapping areas of **C**onnected, **A**utonomous, **S**hared, and **E**lectric (CASE). This, and other significant adjacencies, are discussed in this Chapter.

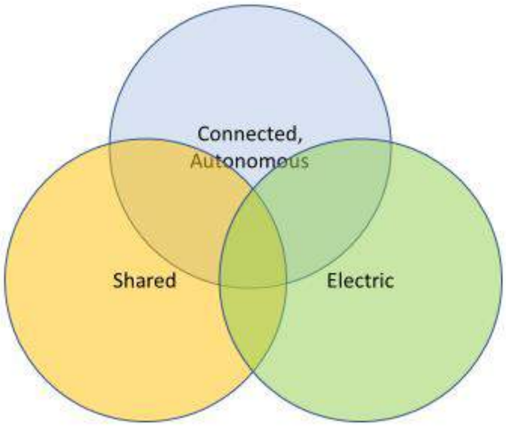


Fig 3.1 C.A.S.E. – the Confluence of Connected, Autonomous, Shared, and Electric Technologies

3.1 The Electrification of Vehicles

The tasks of developing electric vehicles and autonomous vehicles are often conflated but, whilst overlapping, the two are separate lines of technology development. There is no reason why an autonomous vehicle should be an electric vehicle and, whilst long term developments are likely to see these activities combine, most of the first and second generation autonomous vehicles are likely to be vehicles with conventional ICE/hybrid powertrains.

This section highlights a range of different electric vehicle developments which have relevance to the remit of improving public transport in the area of responsibility for GCP/Combined Authority.

3.1.1 Cars

A number of new electric cars from mainstream manufacturers are poised to enter the market over the next three to four years. These include vehicles from Volkswagen, Audi, Mercedes, Jaguar-LandRover, Ford and others. A good example is the Kia e-Niro (pictured below) which has just been launched.

(a) (b)

Fig 3.1 The Kia e-Niro (fig a) and its peer vehicle, the conventional Kia Niro (Fig b)

The e-Niro compares favourably with its conventional peer; it has a range of around 230 miles and the cost premium is only around 25%. This means the increased capital cost of the vehicle could be recovered through the reduced cost of fuel by an average driver over a period of around 6 years. For high-mileage drivers (taxi drivers, for example), the increased capital cost might be recovered within 3 years. This economic equation marks a major improvement over previous electric vehicles (which were often 50% - 100% more expensive than peer vehicles and had no hope of recovering the increased capital cost within the lifetime of the vehicle).

As a result, the e-Niro is widely regarded as the first affordable, mass produced, electric vehicle which can provide anything approaching the flexibility and capability of a family-sized conventional car. In particular it, along with the other imminent new-comers, offers a new possibility for zero tail-pipe emissions in the Private Hire business (a major element of public transport provision in Cambridge).

3.1.2 Buses

There has been a growing body of experience in the use of electric buses over the past 5 years. London has over 200 electric buses on the road, and numerous other UK cities have smaller fleets. Some of these vehicles have been in service now for more than 5 years, and (generally) the experience has been good. The business case is easier to make for buses than cars, because of the high vehicle mileages which are typical. There are, however, some important difficulties which stand in the way of immediate and widespread migration to electric buses. Meeting the daily range requirements, and providing surplus power for heating, can be particularly problematic.

These requirements can be met in two ways. First, the bus can simply be fitted with a bigger battery. This is the best solution, until the size of the battery required becomes too heavy and too expensive. At that point, other approaches need to be considered and ‘Opportunity Charging’ is an attractive alternative. In this approach, the bus receives charge whilst it is out on its daily route operations, with high-power chargers located at the route ends. This means that the battery can be downsized, with consequent savings in cost and weight. The approach can use cable-connect, overhead pantograph, or road-surface mounted Induction Power Transfer techniques (IPT, or ‘wireless’ systems).

Fig 3.2 A wireless charging system (120kW units) has been in daily use in Milton Keynes since 2014

Wireless charging has been demonstrated using Induction Power Transfer (IPT) over the past 5 years in Milton Keynes, London, and several cities in Continental Europe and East Asia. The oldest operational examples of IPT technology are now nearly 20-years old and can still be seen operating in Genoa and Turin. There are almost no range or power limitations which can't be overcome using Opportunity Charging, and this means that electric heating can be provided in addition to long range.

The downside of adopting Opportunity Charging on any bus route (using any of the available technologies) is the need to install charging infrastructure at the route ends. This does not pose insuperable problems and, in fact, it opens up the possibility of developing attractive new business models for Local Authorities and commercial bus service providers (see Chapter 5). Nevertheless, the installation of charging infrastructure in the public domain takes most bus operators outside their traditional comfort zones and this introduces an impediment to immediate adoption.

3.1.3 Other Public Service Vehicles

There are other public service and urban freight vehicles which could be incorporated in a 'zero tail-pipe emissions strategy'. These include dust-carts and light delivery vehicles used for the delivery of on-line grocery orders. Both vehicle types can be shown to be operable from a technical standpoint but, at the time of writing, they do not represent the lowest cost commercial option. It is possible that the GCP/Local Authority could introduce local requirements which 'nudge' the operators in the direction of using electric vehicles but, without this, these operations are unlikely to become commonplace in the near future (within 3-5 years).

3.1.4 Electric Bikes, Scooters, and PLEV's

Fig 3.3 Electric Bikes and Scooters have become very popular with urban commuters.

There has been an explosion of activity in this area, and the tech companies that have introduced the dock-less bike concept have been able to achieve stellar valuations (Lime, the electric bike provider from West Coast USA, has a market valuation of GBP 3Billion at the time of writing).

Light personal transport devices such as scooters, Segways, and ‘hoverboards’ have become known as Personal Light Electric Vehicles (PLEV’s). These devices open up a range of new personal mobility options, but there are some serious attendant regulatory problems which are currently getting in the way of wider take-up (see Chapter 4)

Fig 3.4 Personal Light Electric Vehicles (PLEV’s)

3.2 <u>Shared Transport Systems</u>

Shared transport systems have become very topical in recent years. They offer a very attractive proposition, because they deal directly with two of the key disadvantages of road transport – namely, congestion and pollution. If more people could be persuaded to share rides, there would be fewer vehicles on the road and the emissions signature per passenger mile would be significantly reduced.

There are two types of ‘shared ride’ within modern transport definitions. The first is one in which a car-owner willingly shares his/her vehicle with others, either by offering lifts or by offering the vehicle for use in his/her absence. The second is one in which a fleet operator runs a service in which customers willingly share the same vehicle (i.e. multiple riders in a taxi or a small, on-demand bus). Sharing taxi rides has been popularised in the press by the ‘Uber-Pool’ type of service, but it has not proved to be particularly popular. (Sharing rides in close proximity with strangers in a small vehicle is, apparently, an unattractive proposition). The small on-demand bus, on the other hand, seems to be much more acceptable - probably because the vehicles are bigger and more spacious.

There is nothing new in the idea of ride-sharing, but it has never (yet) caught on. Dial-a-Ride, an early form of On-Demand Bus, was introduced in the 1970’s and has been sporadically around ever since. But no Dial-a-Ride service has ever delivered a commercial profit and most of those that still operate are subsidised and (worse) require advance booking. This means these services are very limited and they are inconvenient to use. As a consequence, the levels of public take-up have been poor. This contrasts sharply with the levels of take-up for Private-Hire (taxi) services which, although 5 – 6 times more expensive than a bus fare for a single journey (Section 5.2.4) , are highly popular in cities all over the UK and abroad. (The obvious examples are Uber and Lyft, but many UK-based private-hire companies pre-date their better known American peers and have been very successful for many years. Panther Cars in Cambridge operate entirely commercially and run a fleet of over 700 vehicles to provide a comprehensive local on-demand service.

The advent of modern computing, communications, and information systems has the potential to re-balance this situation. Fleets of on-demand vehicles can now be managed far more effectively than the old dial-a-ride fleets in the 1970's and it seems feasible (but it is not yet proven) that small buses could run on-demand services that are as cheap as a conventional bus and as convenient as a taxi. Via-Van is a well funded start-up and is probably the most recognised brand in this space, having been operating in New York and several other cities around the world for several years. If these pilots prove to be successful, this type of flexible service could have massive implications for short-medium distance public transport provision. (See also Section 6.1.3)

3.3 Renewable and Distributed Energy

In the long-run, the widespread uptake of electric vehicles will probably cause us to consume around 50% more electricity than we currently consume at national scale. Conversion to electrical heating, and the projected growth in the UK population, will combine with electric vehicles to to mean that our national electricity generation, transmission, and distribution systems will, eventually, need to double in size (or more) to keep pace with these new sources of electricity demand. This problem is not likely to manifest itself in the short-term (5-10 years) because the current levels of market penetration for electric cars and heating systems is very small. And, even when the levels of demand begin to pick-up, the transition to the 'new energy' model will be relatively slow because the average life of a private car is 13 years, and a domestic gas boiler lasts 10-12 years. It will therefore take many years for these new classes of vehicle or home heating device to put 'life-threatening' pressure on the national power infrastructure.

Nevertheless, the capital-intensive and time-consuming nature of building new generation and transmission/distribution capabilities at national scale means that it is not too soon to be examining the possibilities for introducing new, greener, alternatives to the conventional centralised generation model. The UK government's obligation to reduce carbon emissions to 20% of 1990 levels by 2050 has underlined the need for new thinking and provoked interest in the development of alternative generation/distribution models.

Renewable energy (wind, solar), generated in relatively small 'packets' which are connected to the grid at multiple locations, is receiving a lot of attention and the County Council, with its 33,000 acres of agricultural land, is in an ideal position to participate in this type of distributed generation development. There are already good examples of local generation within the GCP/CA area – Soham Solar Park generates a peak level of 12 MW of electricity, and the Energy Recovery Facility (ERF) at Peterborough generates around 8MW from waste materials. More recently, a 1MW solar facility has been opened at the St Ives Park and Ride site.

The Cambridgeshire and Peterborough Authorities are currently giving energy a high priority and the Cambridgeshire and Peterborough Corporate Energy Strategy was published in June 2019. This identifies opportunities for generating and distributing renewable energy within the area and opens the way for further renewable power generation at Park and Ride sites. It also encourages electric vehicle take-up via the installation of better charging infrastructures across the region. The strategy also declares the Authorities' willingness to engage with private industry to co-fund projects, and cites the Soham Wind Farm and Peterborough ERF as successful examples. This has positive implications for developing a similar approach in the transport area (see Section 5.3).

Fig 3.5 (a) 33,000 acres for wind farm development? (b) 12MW solar farm at Soham

A particular opportunity which is relevant to the subject matter of this report lies in the generation and distribution of wind and/or solar power to electric vehicles at large Park & Ride sites. The County Council is already engaged in the development of a solar farm at the P&R in St Ives, and several other possibilities of this type exist. These sites provide an ideal opportunity to pursue an integrated energy and transport policy, although such schemes are seldom financially viable at present without government subsidy or some other form of gap funding.

Fig 3.6 The 1MW solar farm at St Ives Park & Ride

3.4 Communications Infrastructure

There is some debate about the extent of need for the public communications infrastructure. Most of the big OEM's are pursuing strategies which mean their vehicles will not need to rely on data feeds from outside sources (the so-called 'Orphan Vehicle' approach). This route is being pursued because of vulnerability to cyber attack and because of safety arguments which revolve around the critical dependence on connection at a time of urgent need (for example, when navigating complex, busy, urban junctions or travelling at high speed on crowded motorways). If these Orphan Vehicle strategies bear fruit, there will be little need for Local Authorities to provide significant communications infrastructure for the benefit of connected and autonomous vehicles. Rather, the Local Authority will need to focus on making sure that normal, visual, cues are fully up-to-date and clearly marked (this means road markings, direction signposts, speed limit signage, etc).

However, not every industry participant agrees with the Orphan Vehicle philosophy. Many argue that some level of hybrid operation will be most efficient, with on-board vehicle systems being supplemented by a continuous stream of 'situational awareness' which is sourced from all forms of infrastructure-based equipment (traffic signals, cameras, congestion monitors, etc). Under these circumstances, a very reliable communications infrastructure, with low latency and very high bandwidth, would be essential. Indeed, in the short to medium term, such a communications infrastructure will be even more important, because the full-blown Orphan Vehicle approach will take a long time to develop and perfect.

On balance, therefore, it would seem prudent for Local Authorities everywhere to be well informed in this sphere and make efforts to upgrade their public-facing data and communications infrastructure whenever the opportunity arises.

3.5 Passenger Information Systems

The key to transforming public transport lies in making it more convenient to use. User convenience can even trump cost as the key mode-selection criterion, as the strong market for Private-Hire demonstrates. (Private Hire is significantly more expensive than using the bus, yet the number of passenger miles delivered by Private Hire firms now exceeds that delivered by bus services in many UK cities).

An essential part of the route to displacing the car therefore, lies in making it more convenient for the user. An important part of this is the provision of first-class traveller information systems and services. These services should be available to all members of the public and should include, at minimum:

- Real-time location details for all relevant public or private transport vehicles which are to be found within a prescribed distance of the traveller.
- The ability to compare alternative end-to-end transport options for a journey which is being planned.
- The ability to make choices and to book/pay for transport services spontaneously where a hand-held device is being used.
- Personal guidance along all steps of the journey where a hand-held device is being used. (With suitable adaptation for people with hearing or other disabilities)
- The ability to tap-in and tap-out of service offerings where a hand-held device is being used.

Such systems have developed rapidly over the past 5 years. In some large cities (London, for example) systems like CityMapper have almost reached this level of service provision. But this is not true for the much larger number of 'Tier 2' cities in the UK. This is because the level of local knowledge and local system inter-connection required to provide a useable service demands bespoke developments, and this is not always attractive to a commercial system developer.

There is, therefore, a *prima facia* case for Local Authorities to become engaged with traveller information system suppliers to promote the development of bespoke local products or (better) the development of localised versions of the more popular apps which are already widely available. On the basis that many second-tier cities face the same problem, and in light of the importance of traveller information systems in enabling bigger plans to succeed (i.e. displacing the car as the primary means of urban mobility), it is worth considering the formation of a Local Authority consortium to promote/sponsor the development of an app (or apps) dedicated to the provision of local travel planning information systems. This consortium would exist to provide a public good, rather than to develop a profit-making product. GCP/CA could consider taking a lead in this area.

4. The Legal and Regulatory State of Readiness

The arrival of the new CASE-related technologies and business models has created a dramatic change in the transport landscape. As a result, the legal and regulatory state of readiness is uncertain. There is a clear need to re-assess the frameworks which govern public transport and our use of vehicles on the roads. In this section, the nature of the problem at hand is summarized, and extracts from official texts are provided on those issues which are of greatest importance to GCP in the context of enabling publicly accessible autonomous transport systems. As is the case with all simplifications and summaries, the extracts provided in this section do not tell the entire story. This material is provided only for the purposes of scene-setting; the reader must consult the full texts whenever a decision of substance needs to be made. Links are provided to assist with this process.

In many cases, the transport disruptors present challenges which appear to pit public benefit against regulatory intransigence. The resolution of such dilemmas is not easy. The current legal and regulatory frameworks are there for good reasons and their provisions should not be changed or discarded without careful consideration. To be done well, the process requires a reversion to the basic principles which sit behind our current laws and regulations and this, inevitably, will take time.

4.1 Public Benefit versus Regulatory Intransigence?

The ‘PLEV dilemma’ provides a simple illustration of the nature of the problems at hand. In the UK, electric kick scooters (e-scooters), hoverboards, and Segways are classified as a PLEV’s, or Personal Light Electric Vehicles, and they are currently illegal on British roads or pavements. These forms of personal transport are, however, becoming increasingly popular with the public and a groundswell of public acceptance is being fuelled by the arrival of firms which initially flooded the US market and are now coming to the UK.

The e-scooter is a particularly good example of the current legal oddities. e-scooters are not subject to taxes or registration, but neither are they legal for use anywhere other than private land in the UK. This is because they are motorised and have no pedals – so they are illegal for use on cycle lanes and pavements, and because they are low-powered they are illegal for use on the road. At the time of writing, commuters who wish to embrace this new method of urban travel are (technically) at risk of possible arrest and a fine of up to £75.

Other European countries are taking a more progressive approach. In France a PLEV can go up to 25km/hour in a cycle lane, while Austria and Switzerland additionally extend this to road use. In France and Germany a PLEV can also go up to 6km/hour on the pavement. Three scooter hire services were recently granted licences in Paris and their popularity in crowded European cities has even led to a suggestion from Volkswagen that it will introduce its own hire service in Berlin before long.

The oddity of this position is further underlined by the fact that GoPeds (scooters powered by a small petrol engine, as illustrated next to an e-scooter below) are treated as mopeds in UK law and may therefore be used on the road provided they are road-legal, taxed and insured. (The rider must, however, be over the age of 16 and wearing a helmet).

Fig 4.1 (a) Go-Ped. A road legal vehicle (b) e-Scooter. Illegal on road and pavement

There are, apparently, no plans to amend the law on electric scooters in the UK but, as our cities grapple with congestion, air-quality, and climate change, it appears unhelpful that electric scooters and other PLEV's should suffer the blanket ban which currently applies.

4.2 The Centre for Connected and Autonomous Vehicles (C-CAV)

Despite oddities of the type highlighted in Section 4.1, the UK government has, in general, taken a very progressive position with regard to the development and proving of autonomous vehicles. There is a clear desire at high levels for the UK to be seen as a world leader in this sphere, and this includes positioning the UK as one of the leading international locations for testing and developing new autonomous vehicles.

Part of the government's work in this field has been to establish C-CAV (the Centre for Connected and Autonomous Vehicles). This Centre spans several government departments, and mirrors the very successful organizational model created by OLEV (the Office for Low Emission Vehicles, which also spans several different government departments). Since its formation, C-CAV has been responsible for sponsoring a great deal of industrial R&D, developing guidance on testing for autonomous vehicles, defining standards, and creating legal/regulatory approaches.

Key outputs from C-CAV in the recent past include publication of a Code of Practice for trialling autonomous vehicles (Feb 2019), and a consultation paper from the Law Commission on the safe deployment of self-driving vehicles (June 2018). The latter was the first output from The Law Commission of England and Wales and the Scottish Law Commission who were commissioned by C-CAV to conduct a three-year review to prepare for the introduction of driving laws for self-driving vehicles.

In addition, working with Department for Transport, C-CAV have been working at the Global Forum for Road Traffic Safety (UNECE WP1) and World Forum for Harmonization of Vehicle Regulations (UNECE WP29) on the global framework for self-driving vehicles. Specifically, the UK helped produce the Resolution on the Deployment of Highly and Fully Automated Vehicles in Road Traffic. https://www.unece.org/fileadmin/DAM/trans/doc/2019/wp1/ECE-TRANS-WP-1-2018-4-Rev3e.pdf

Perhaps most significantly, C-CAV has worked to create the first UK legislation on self-driving cars (The Automated and Electric Vehicles Act, 2018). This Act sets out, amongst other things, a new framework for how motor insurance for self-driving cars will work.

Headlines from C-CAV's activities that are particularly relevant to the interests of GCP are set out below.

<u>Cautionary Note</u>: **The following sections are provided as a high level overview for the convenience of the reader only. The original documents may be accessed via the links provided. A thorough reading must be conducted and, if necessary, professional advice sought, in advance of any specific activities being undertaken.**

4.2.1 Consultation on the safe deployment of self-driving vehicles.
(https://www.lawcom.gov.uk/project/automated-vehicles/)

The Centre for Connected and Autonomous Vehicles (CCAV) has asked the Law Commission of England and Wales and the Scottish Law Commission to undertake a far-reaching review of the legal framework for automated vehicles and their use as part of public transport networks (including on-demand passenger services). The term 'Automated Vehicles' as used in this project refers to vehicles that are capable of driving themselves without being controlled or monitored by an individual for at least part of a journey. The scope of work also includes issues arising at the boundary between self-driving vehicles and widely used driver assistance technologies such as cruise control.

The Law Commission is considering responses to their second consultation paper at the time of writing. They will launch a third consultation later in the 2020 and produce their final recommendations towards the end of 2020.

The purpose of the consultations is summarised by the Law Commission as follows:

We have been asked to review the UK's regulatory framework to enable the safe and effective deployment of automated vehicles. It is part of a package of reforms, which builds on the work of the Centre for Connected and Autonomous Vehicles (CCAV) and others. We have three objectives. The key objective is safety. We consider how safety can be assured both before and after automated driving systems are deployed. Secondly, we aim to provide clear allocations of liability in both civil and criminal law. Finally, we wish to remove any unnecessary blocks which might delay the benefits of driving automation to mobility and productivity. Driving automation technologies can enable new ways for those with visible and non-visible disabilities to get around. We make tentative proposals for reform and ask questions.

The early work of the Commission has defined four concepts (reproduced verbatim below) which are likely to become the cornerstones of any future legislation.

> **A vehicle which "drives itself"**
> The Automated and Electric Vehicles (AEV) Act 2018 distinguishes vehicles which "drive themselves" from those which do not. Section 1 requires the Secretary of State to keep a list of all motor vehicles that are (in his or her opinion) capable of safely driving themselves, "at least in some circumstances". Once a vehicle is on the list, it is said to be "driving itself" if it is operating in a mode in which it is not being controlled, and does not need to be monitored, by an individual. The Government has indicated that vehicles must be able to achieve a minimal risk condition to be listed. In other words, they must operate at SAE Level 4 or above. While the AEV Act relates only to civil liability, we provisionally propose that the same definition of "driving itself" should be used in criminal law.

User-in-charge
Where a vehicle is listed as capable of safely driving itself, and the automated driving system is correctly engaged, the human user would not be a driver. They would no longer be responsible for the immediate driving task. However, a human may still be called on to drive in certain circumstances. We therefore tentatively propose that an automated vehicle hould have a person who is qualified and fit to drive, unless the vehicle is specifically authorised as able to operate without one. We refer to this person as the “user-in-charge”.

Automated driving system entity (ADSE)
We tentatively propose that automated driving systems should only be allowed if they are authorised, either at an international level or domestically. We refer to the entity putting the system forward for authorisation as the ADSE. This will normally be the vehicle manufacturer or the developer of the automated driving system. We suggest that the ADSE should have ongoing legal responsibilities to ensure that the systems are safe. The ADSE should also be subject to regulatory sanctions if the vehicle acts in a way that would amount to a criminal offence if done by a human driver.

Safety assurance agency
We tentatively propose a new agency to regulate the safety of the automated driving systems before they are permitted on the road. This might be a new Government body or a dedicated unit within an existing organisation (such as the Vehicle Certification Agency or the Driver and Vehicle Standards Agency).

4.2.2 The Code of Practice for trialling self-driving vehicles on public roads.
(https://www.gov.uk/government/news/government-moves-forward-on-advanced-trials-for-self-driving-vehicles)

The Code states that trialling any level of automated vehicle technology is possible on any UK road if carried out in line with UK law. Trialling organisations do not need to obtain permits or pay surety bonds when conducting trials in the UK. The Code notes, however, that those planning tests should speak with the road and enforcement authorities, develop engagement plans, and have data recorders fitted. Those planning to conduct advanced trials should contact the Centre for Connected and Autonomous Vehicles in advance. It should be noted that failure to follow the Code may be relevant to liability in any legal proceedings, but compliance with the expectations set by the Code does not guarantee immunity from liability.

The Code goes on to set out several important areas for consideration by those planning tests. These are summarised via the text extracts below.

Legal requirements

Conducting public trials of automated vehicle technology is possible in the UK at any level, provided the following legal requirements are met:

- A driver is present, *in or out of the vehicle*, who is ready, able, and willing to resume control of the vehicle;
- The vehicle is roadworthy; and
- Appropriate insurance in place.

It is the responsibility of those carrying out trials to ensure that their trials comply with all relevant legal requirements.

Deploying a service may require appropriate licensing.

Insurance

UK law requires the use of all motor vehicles to be insured. Therefore, any trialling organisation conducting activities on public roads and / or other public places must make sure that they have appropriate insurance, or otherwise comply with the statutory requirements. Failure to do so is an offence.

Minimum Engagement

Trialling organisations should inform the Centre for Connected and Autonomous Vehicles before conducting any public trials. Those planning a trial should also engage with all relevant organisations with responsibility for the trial area(s) at the earliest opportunity (list provided in the main document).

Trialling organisations should engage with the relevant highways authorities before conducting any trials. Specific infrastructure requirements that are considered necessary to support a trial, for example traffic signing or parking adjustments, will need to be agreed with the appropriate authorities responsible for the roads.

Any reportable incidents are expected to be communicated to the police. Depending on the specific incident, police and any other organisation relevant to an investigation may require access to relevant vehicle data. For guidance on data access, see section 2.10. of the main document).

Trialling organisations should maintain engagement throughout the duration of trial activity and beyond where necessary. It is recommended that trialling organisations establish a single point of contact to facilitate this engagement, which is publicly and easily accessible for those looking to engage with those responsible for the trial.

Safety Cases

Trialling organisations should develop a detailed safety case before conducting trials, and make an abridged, public version freely available. Any published safety case should also be sent to CCAV. Safety cases should be regularly updated where possible.

Safety Driver and Operator Requirements

During automated vehicle trials on public roads or in other public places, a suitably licensed and trained safety driver or safety operator should supervise the vehicle at all times, and should be ready and able to over-ride automated operation if necessary. For trials not conducted on the public road, it is strongly recommended that the safety driver or safety operator still holds the appropriate category of licence for the vehicle, even though this is not a legal requirement.

NOTE: ***The safety driver or operator may be outside the vehicle***, as long as they have the necessary capability to be able to resume control of the vehicle.

The safety driver or operator must hold the appropriate category of driving licence for the vehicle under trial if on a public road. It is strongly recommended that the licence holder also has several years' experience of driving the relevant category of vehicle. In the case of a prototype vehicle which cannot easily be categorised, the nearest equivalent conventional category of licence is expected to be held.

In locations other than public roads, and where the vehicle's maximum speed is limited to a maximum of 15 mph, trials should be overseen by a safety driver or operator who can, as a minimum, apply an emergency stop control.

Remote-Controlled Operation

Remote-controlled operation of a vehicle is possible if carried out in line with the legal requirements and the guidance set out in the Code of Practice. A full risk assessment should be undertaken to determine whether remote control operation is appropriate. Those conducting remote-controlled vehicle tests should mitigate, and safely respond to, risks associated with network access.

Those looking to undertake a remote-controlled trial of an automated vehicle on public roads or other public places will need to assure themselves that the remote-control system is able to deliver the same level of safety as having a driver inside the vehicle.

Remote-controlled trials should have appropriate redundancies in place to handle any failures or disengagements, including warning systems and the ability to allow the safety operator to take control of the vehicle at all times.

Remote-controlled operation may fail if there is wider communication network failure, or if access to the communication network is throttled. Trialling organisations should have a full understanding of connectivity in chosen operational domains.

Data recording

Automated vehicles under trial or deployment should be fitted with a data recording device or series of devices capable of capturing data from sensors and control systems associated with the automated features of the vehicle, as well as other information concerning vehicle movement. This is a minimum expectation for trials on public roads to provide safety and assurance to other road users. This data should, at a minimum, be able to determine who or what was controlling the vehicle.

The data should be securely stored. In the event of an incident, such data should be preserved in full.

4.3 The British Standards Institute (BSI) & the Zenzic Safety Framework

The BSI has a CAV standards programme which is sponsored by UK Government's Centre for Connected and Autonomous Vehicles (CCAV) in conjunction with the Department for Transport, Innovate UK, and Zenzic. The purpose of this programme is to support the development of CAVs in the UK and help shape the future of international standards in this area.

Recent and imminent publications that are relevant to the development of Autonomous Vehicles include PAS 1880, PAS 1881, PAS 1885/PAS 11281. All of these documents cross-reference other related standards and practices and the reader is encouraged to read the source material for more details.

One of the contributing organisations to the BSI programme (Zenzic) has also produced a set of safety guidelines referred to as ‘ Zenzic Safety Framework 2.0’. This guidance was produced specifically for use within the Zenzic ‘Test Bed’ sites in the UK. It is very similar to BSI PAS 1881, but has some rather more specific guidance in certain detailed cases.

4.3.1 A Standard Approach to the Development of Safety Cases

A ***safety case*** is a structured argument supported by a body of evidence that demonstrates that the safety risks have been identified, managed and reduced to as low as reasonably practicable (ALARP). The safety case includes (but is not limited to) risks associated with the vehicle, the operating platform, control of the vehicle, and all interactions with the operating environment. It must consider risks to all affected parties, including other vehicles, vulnerable road users, the safety driver or operator, passengers, road workers and third parties. The safety case needs to provide assurance to all stakeholders that might be involved in the trial or demonstration, including highway authorities, road operators, landowners, leaseholders, insurers and members of the public. The safety case is a live document that, when updated to reflect changes and learning throughout a trial, promotes continuous improvement and safety assurance.

Safety assurance for automated vehicles can be categorized into two interdependent areas: system safety and operational safety.

System safety is achieved through ensuring adequate functional safety, safety of the intended functionality (SOTIF) and cybersecurity. PAS 1880 (see Section 4.3.2 below) provides a guide for developing and assessing automated control systems. This process forms an integral part of the vehicle development activity and includes the vehicle specification, design, implementation, verification, and validation of the automated vehicle’s functions. System safety assessments can be risk-based assessments that identify the vehicle’s minimum safety and security requirements for achieving an acceptable level of risk and ensuring that this level of risk has been achieved.

Operational safety assurance considers the interaction of an automated vehicle with the operating environment, including the route, safety driver or operator, passengers and other road users and road workers. System safety and operational safety are intrinsically linked. PAS 1881 (see Section 4.3.3 below) focuses on the operational safety and references the required outputs from system safety assessments.

4.3.2 The PAS Library

The PAS series of publications (Publicly Available Specification) is a library of fast-track standardization documents which are prepared at user request by a steering group of stakeholders selected from relevant fields and led by BSI. They are not legally binding, nor are they enforcable Codes of Practice, but they are important because they define standards of good practice for industry-specific products, services and processes.

PAS 1880 (imminent publication) "Guidelines for developing and assessing control systems for automated vehicles"

PAS 1880 is expected in 2020, but has not been published at the time of writing. It will create guidelines for assessing the safety of control systems in automated vehicles and should be of interest to:

- Manufacturers and developers of automatic vehicles from driverless pods to large road-going vehicles
- Manufacturers and developers of automatic vehicle sub-assemblies and components
- Organizations involved in trials or other test/validation activities on AVs

PAS 1880 will help companies designing automated vehicles to assess with more confidence the safety-levels of their end-product, systems and components when operating in trials and on public roads. Specificlly, it will provide a set of initial guidelines for developers of control systems for the safe, secure and effective deployment of automated vehicles (AVs) that are capable of moving passengers and/or goods, without human intervention, within defined operational design domains.

PAS 1880 is not intended to cover general techniques for achieving functional safety in AVs; instead, reference will be made to related standards for information about such matters. Nor will it cover off-road machinery in any detail.

NOTE: For further information on general techniques for achieving functional safety in AVs see ISO 26262.

PAS 1881 (2020) "*Assuring the Safety of Automated Vehicle Trials and Testing*"

PAS 1881 was published very recently and is a flagship component of BSI's programme to develop a suite of standardization documents which promote the safe testing and deployment of automated vehicles in the UK. A coupled purpose is to inform wider international standardization activity.

PAS 1881 specifies minimum requirements for the safety cases which must be produced to support automated vehicle trials and development testing in the UK. This PAS is relevant to stakeholders including (but not limited to):

- trialling organizations,
- local authorities, highway authorities, road operators,
- landowners, leaseholders,
- insurers,
- test beds,
- licensing agencies.

The safety case framework detailed in PAS 1881 has been developed for automated vehicle trials but is based on existing safety standards and safety governance good practice including the DfT's *Code of Practice* referred to in Section 4.2.

PAS 11281 (2018) “*Connected automotive ecosystems – Impact of security on safety” and* PAS 1885 (2018) “*The fundamental principles of automotive cyber security”*

PAS 11281 complements PAS 1885 and the two documents should be considered together. The ‘ecosystem’ includes vehicles, road-side and other static infrastructure, communication channels between vehicles and infrastructure, servicing and repair facilities, digital services, data and information, and other services that support the proper operation of road transport. All levels of vehicle automation and autonomy are in scope.

PAS 11281 aims to help organizations in the CAV ecosystem ensure that security-related risks in their products, services or activities don’t pose an unacceptable safety risk in the physical world. The document is intended for manufacturers, operators and maintainers of products, systems and services used in the connected automotive ecosystem. This includes:

- Vehicle manufacturers
- Manufacturers of vehicle subsystems
- Maintenance organizations
- Infrastructure operators
- Owners of large vehicle fleets
- Digital service providers
- Regulators and other stakeholders in the connected automotive ecosystem
- Users/operators of vehicles.

PAS11281 applies to risks that can affect a single system or a collection of systems and covers the entire connected automotive ecosystem and its constituent systems throughout their lifetimes (including manufacturing, supply chain and maintenance activities).

4.4 Fixed Path (Segregated) Systems

Current projects being conducted in and around Cambridge mean that GCP should take a particular interest in the regulatory and legal requirements that apply to systems which run on segregated pathways. The C-CAV 4 project currently being carried out on the Cambridge Southern Busway, and the proposed CAM mass-transit system, are good examples of fixed-path applications.

Planning and Operational Safety requirements relevant to this context are summarized in Sections 4.4.1 and 4.4.2 below.

4.4.1 *Planning*

Building a new fixed-pathway for any transport system requires planning permission. The mechanisms which exist for gaining these permissions start with the regular Local Authority planning processes – but these are generally considered to be inappropriate for large infrastructure projects. More relevant are national provisions such as Direct Consent Orders (DCO’s) and the Transport Works Act (TWA). There is also the relatively new mechanism available to the Mayoral Combined Authorities known as ‘Mayoral Corporations’.

Direct Consent Orders (Planning Act 2008): The Planning Act 2008 set up a new process for dealing with proposals for “nationally significant infrastructure projects”. The process applies to major projects of certain types defined in that Act, including the construction or alteration of railway lines which are to form part of the national rail network in England, Highways Agency road schemes, major airport and harbour schemes, and larger offshore energy proposals.

Where a project needs development consent under the Planning Act 2008 it will not usually be possible for it to be included in a TWA order (see below). For further details of the Planning Act process, see:- http://infrastructure.planningportal.gov.uk/

It is unlikely that DCO's would be used for any autonomous vehicle project in Cambridge alone, but it is possible that a development proposal associated with the Oxford – MK – Cambridge Arc could be argued to be 'of national significance'.

The Transport Works Act (1992):

Orders under the TWA can relate to the construction and/or operation of the following kinds of transport system:

- railways and tramways;
- externally guided buses, monorails and certain other types of

  guided transport; and
- trolley vehicle systems.

N.B. It is important to note that the TWA applies only to 'externally guided buses, monorails, and certain other types of guided transport'. There is some debate amongst experts about whether this definition can be interpreted to include modern autonomous guidance systems (the term 'mechanically guided systems is used elsewhere in the Act). For the avoidance of future doubts, the GCP should be active in pressing DfT for a change to the Act which explicitly recognises and accepts the use of modern electronic guidance systems.

The TWA does not limit who can apply for an Order. This can be private companies and public authorities. Typical TWA Order applicants are passenger transport executives, London Underground, local authorities, private operators, and private companies wanting to develop guided transport schemes.

Matters that can be authorised by a TWA Order typically (but not exclusively) include:

● powers to construct, alter, maintain and operate a transport system or inland waterway;

● compulsory powers to buy land;

● the right to use land (for example, for access or for a work site);

● amendments to, or exclusion of, other legislation;

● the closure or alteration of roads and footpaths;

- provision of temporary alternative routes;

- safeguards for public service providers and others; and

- powers for making bylaws.

The powers applied for must be relevant to the scheme. They may relate to the scheme itself, or to matters that are necessary to support the scheme – for example, providing a park-and-ride site in connection with a new tramway or guided bus scheme.

The Rules specify the documents which must be sent with an application. These vary according to the type of order being applied for. The typical documents needed for a proposal involving works are:

- a draft order and an explanatory memorandum;
- a concise statement of the aims of the proposals;
- a report summarising the consultations carried out by the applicant;
- plans and cross sections;
- an environmental statement;
- a book of reference, including names of owners and occupiers of land to be bought compulsorily;
- the estimated costs of the proposed works; and
- the funding arrangements.

The organisation applying for an Order has to arrange for these documents to be available for inspection by the public, free of charge.

A TWA Order does not in itself grant planning permission. But the organisation applying for the Order can ask the Secretary of State to grant planning permission for any development described in the order. Alternatively, the organisation applying for a TWA Order may apply for planning permission, separately, to the local planning authority (usually the district or unitary council).

If there is no opposition to the application, the Secretary of State can proceed to give his or her decision directly. If an application has opposition, the Secretary of State must decide, within 28 days of the end of the objection period, whether to hold a public inquiry or a hearing, or whether to carry out 'exchanges of written representations' between everyone involved.

TWA Orders do not normally have to be presented to Parliament before they can come into force. Very occasionally, though, a 'special parliamentary procedure' has to take place before the TWA Order can come into force. This may arise because no replacement land is being provided for public open space which can be acquired compulsorily under the TWA Order. In that event, both Houses of Parliament have the opportunity to consider the TWA Order. If the special parliamentary procedure is successfully completed, the TWA Order comes into force, and is printed and published in the usual way.

Mayoral Development Corporations (MDC's – The Cities and Local Government Devolution Act, 2016):

The Localism Act (2011) permitted the Mayor of London to create mayoral development corporations in Greater London. The Cities and Local Government Devolution Act (2016) also permitted the creation of mayoral development corporations in combined authority areas, with the first being created in South Tees in 2017 by the Tees Valley Combined Authority.

The frame of reference for an MDC is set by the Mayor, and the powers of the MDC can be far reaching. Some of those powers which have most relevance to planning for a fixed-path autonomous system are summarised below.

MDC's may be defined by the Mayor to have functions in relation to Town and Country Planning. In particular, the Mayor may decide that the MDC for the designated area is to be the local planning authority, with powers to grant compulsory purchase orders, for the whole or any portion of the area.

An MDC may provide, or facilitate, infrastructure by acquisition, construction, conversion, improvement, or repair. In this context, "infrastructure" means, amongst other things,

(a) water, electricity, gas, telecommunications, sewerage or other services,

(b) roads or other transport facilities,

(c) retail or other business facilities,

An MDC may carry on any business and, with the consent of the Mayor, may form, or acquire interests in, bodies corporate. An MDC may also, with the consent of the Mayor, give financial assistance to any person. Financial assistance may be given in any form and may be given by way of:

(a)grants,

(b)loans,

(c)guarantee or indemnity,

(d)investment, or

(e)incurring expenditure for the benefit of the person assisted.

Financial assistance may be given on such terms and conditions as the MDC considers appropriate, including provision for repayment, with or without interest.

4.4.2 *Operational Safety*

Once built, the autonomous system must become operational and, for all public transport systems, some form of Operational Safety procedures must apply. The two principal instruments for governing Operational Safety are summarized below.

The body which has powers to grant a licence for the operation of rail systems is the Office of Road and Rail (ORR). The ORR is authorised to grant a licence to any person whom it is satisfied demonstrates:

a) good repute;

b) financial fitness;

c) professional competence; and

d) appropriate insurance cover for civil liabilities

The instrument which governs Operational Safety on rail systems is The Railways and Other Guided Transport Systems (Safety) Regulations (ROGS).

ROGS - The Railways and Other Guided Transport Systems (Safety) Regulations 2006 (as amended). The Railways and Other Guided Transport Systems (Safety Regulations) 2006 (ROGS) were introduced across the industry in April 2006. Changes were made in 2011 and 2013.

ROGS provides the regulatory regime for rail safety, including the mainline railway, metros, tramways, light rail and heritage railways. However, guided buses are excluded from the ROGS regime, and there is discretion to exclude from the mainline railway requirements certain other transport systems which fall within one or more of the following categories:

- metros and other light rail systems;
- networks that are functionally separate from the rest of the mainline railway and intended only for the operation of local, urban or suburban passenger services, as well as transport undertakings operating solely on these networks;
- heritage, museum or tourist railways that operate on their own networks; and
- heritage vehicles that operate on both the mainline railway and complies with national safety rules.

There is a long list of approved systems which are excluded from the mainline railway requirements. This includes 11 networks that are functionally separate from the rest of the main line railway and intended only for the operation of local, urban, or suburban passenger services. These ‘functionally separate networks’ include the Isle of Wight ‘Island Line’ (Ryde to Shanklin), the Glasgow Underground (Subway), the Tyne & Wear Metro, and the Docklands Light Railway.

Given the exemptions of the functionally separate networks, and the exclusion of guided bus networks, it seems reasonable to argue that any fixed-path autonomous vehicle system sponsored by GCP could, at minimum, be exempted from the mainline railway requirements. Arguably, it could be operated as a bus (see below) and operated totally outside the provisions of ROGS.

The body which has powers to grant a licence for the operation of buses is the Office of the National Transport Commissioner (working with a network of 8 regional traffic commissioners). The regulatory instruments which govern Operational Safety for buses are the Public Passenger Vehicles

Act 1981, The Transport Act 1985, The Public Service Vehicles (Operators' Licences) Regulations 1995, and The Road Transport Operator Regulations 2011.

Public Service Vehicle (PSV) Operator Licensing. The main purpose of public service vehicle operator licensing is to ensure the safe and proper use of PSVs. (PSV437, PSV operator licensing: a guide for operators).

Road-based autonomous transport systems providing public transport services will need a PSV operator's licence, in addition to a fleet of road legal vehicles, if the vehicle is designed or adapted to carry nine or more passengers and payment is taken for carrying passengers (this is termed 'hire or reward'). Smaller vehicles for hire or reward will usually be licensed by the Local Authority under a private hire or taxi regime. There is an exception for not-for-profit organisations who may be eligible for a section 19 or section 22 permit.

Applications for an operator's licence must be made to the national traffic commissioner and are processed through the Central Licensing Office. However, the country is divided into eight different traffic areas, and a local traffic commissioner is responsible for issuing these licences in each traffic area. Traffic commissioners are appointed by the Secretary of State for Transport and are independent from VOSA and other enforcement authorities. In Great Britain, the traffic commissioners are regulators of the road transport industry. Their function is to ensure that only safe and reliable operators of goods and passenger vehicles are permitted to be licensed. Traffic commissioners may take regulatory action against an operator - where they may revoke, suspend or curtail an operator's licence.

To be granted a licence, the applicant must satisfy the traffic commissioner that they:

- are of good repute;
- are of appropriate financial standing (i.e. have enough money to run the business);
- have good enough facilities (or arrangements) for maintaining the vehicles;
- are capable of ensuring that both the operator and staff obey all the rules.

The Vehicle and Operator Services Agency (VOSA) also has a role to play. The Agency ensures that the operators of heavy goods and passenger vehicles are compliant with legislation relating to matters including driver licensing, drivers' hours, roadworthiness, operator licensing and the safe loading of vehicles. VOSA also holds a National Register on behalf of the UK Government which includes certain operator licensing and transport manager data that is required by EU Regulations to be held centrally. The National Register combines the required information from the various authorities who control the operator licensing system in Great Britain, Northern Ireland and Gibraltar.

4.5 Is it a Bus, or is it a Train (or Metro)?

The development of 'segregated fixed path' autonomous systems raises a difficulty with regard to service definition and this, in turn, knocks on to create problems with regard to planning and licencing. The difficulty springs from a very simple dilemma: is the vehicle (or service) a bus or a train?

It would be logical to start by regarding the autonomous transport system as a bus, because it is a public transport vehicle with steerable, rubber-tyred, wheels. In terms of its construction and transport purpose, it could be operated on a normal road. However, the fact that these vehicles are guided by electronic systems raises a question about the need to designate them as a 'guided system'. This question is raised more sharply if the vehicles run on segregated pathways which are purpose-built for their exclusive use. At this point, the system could be described as a train.

This is not just a semantic argument. There are enormous differences between buses and trains in the approaches to system design and operational safety. Railways are much more heavily regulated than any road-based system and have a history and cost structure which reflects this fact. The cost and organisational overhead associated with building and operating a railway is far higher than the equivalent cost of building and operating a bus service. It therefore matters a lot whether the new autonomous systems envisaged here are designated as buses or trains (or metros).

Unfortunately, there is no clear guidance on how to make this decision. The planning guidance notes and service regulations need to be updated to reflect the advances in technology. The problem with the definition of 'guided systems' has already been raised in the context of the Transport and Works Act (Section 4.4.1), and the need to operate within ROGS was questioned in Section 4.4.2

This is, potentially, a big issue for GCP/CA. It is recommended that action be taken to resolve it as quickly as possible.

5. Technological Readiness & Commercial Potential

5.1 The Technological State of Readiness

There are many different types of autonomous vehicles/autonomous transport systems which are currently under development all round the world. A 'horizon scan' of activities was presented in Chapter 2 and, in this section, some estimates for times to practical implementation are presented.

A roadmap which shows the range of technology developments which might be anticipated between now and 2030 has been developed by Zenzic and is presented as an interactive tool on their web-site (https://zenzic.io/roadmap/). Fig 5.1 below presents an overview.

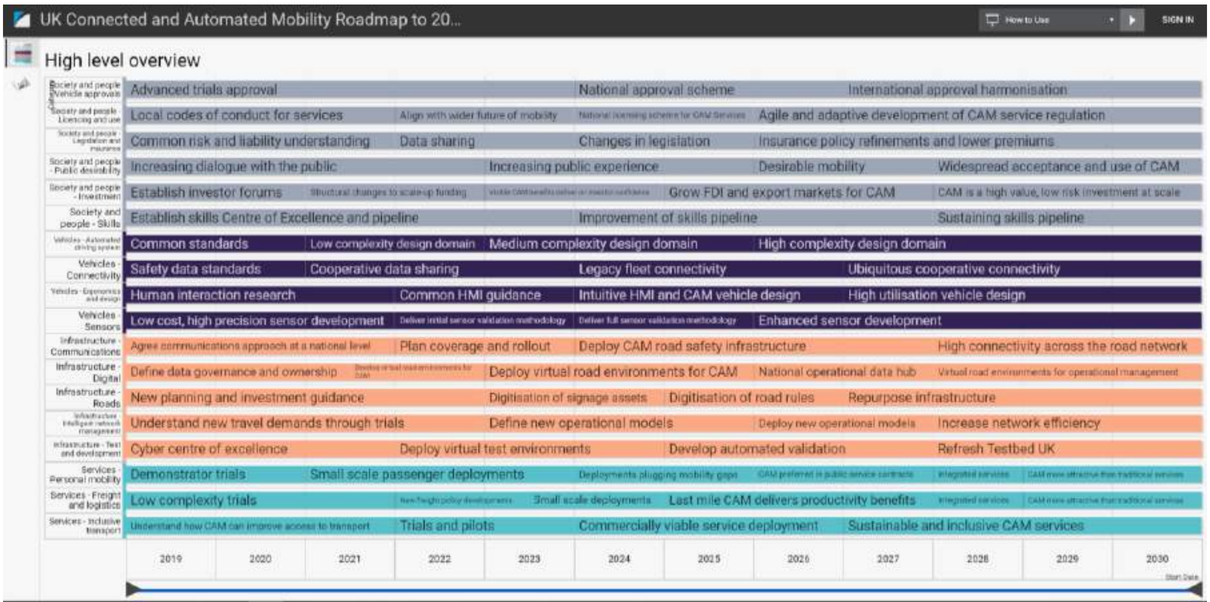


Fig 5.1 The Zenzic Connected and Automated Mobility Roadmap to 2030 (Zenzic, 2019)

The Zenzic work is very comprehensive and examines the elements of connected and automated mobility (CAM) in some detail. It defines the necessary technical and social building blocks and shows their inter-connections. Significantly, it suggests that transport services making use of CAM solutions will become more attractive than traditional transport services by 2030. However, it stops short of defining exactly what those services might be.

In an attempt to illustrate practicable transport opportunities for GCP/CA, an overview of the possible timescales for deploying working public transport solutions is presented in Fig 5.2 (a,b,c). These diagrams are based on the research experience of the author and are presented here in order to set a reasonable context for future service expectations.

Fig 5.2 uses axes of vehicle speed and the degree of vehicle segregation (from pedestrians, cyclists, and road-going traffic) to define a visual space within which time-lines can be drawn. In Fig 5.2(a), the diagram is segmented into six different vehicle categories sitting within three different operational zones (Fig 5.2(a).

Zone 1 (shaded blue, vertical, on the left side of the diagram): Low speed systems ***(L-SATS)***, in which the vehicles never exceed 20mph and operate primarily in pedestrianised spaces. The vehicles may be either segregated from, or fully integrated with, other users of the public realm (road traffic, cyclists, pedestrians, etc). These systems may be classed as SAE Level 4 or Level 5 autonomy depending on their degree of segregation/integration.

Zone 2 (shaded yellow, horizontal, running along the bottom of the diagram): Fast, segregated autonomous transport systems ***(F-SATS)*** in which the vehicles can move at much higher speeds, but are *always* physically segregated from other users of the public realm. These systems are classed as Level 4 autonomy because of their limited Operational Design Domain.

Zone 3: (un-shaded, covering the remainder of the diagram): In which the vehicles occupy normal road space and are either semi-integrated with normal traffic (meaning they have a designated Operational Design Domain) or are fully-integrated, without limitation. The former represents SAE Level 4 autonomy and the latter represents SAE Level 5 autonomy.

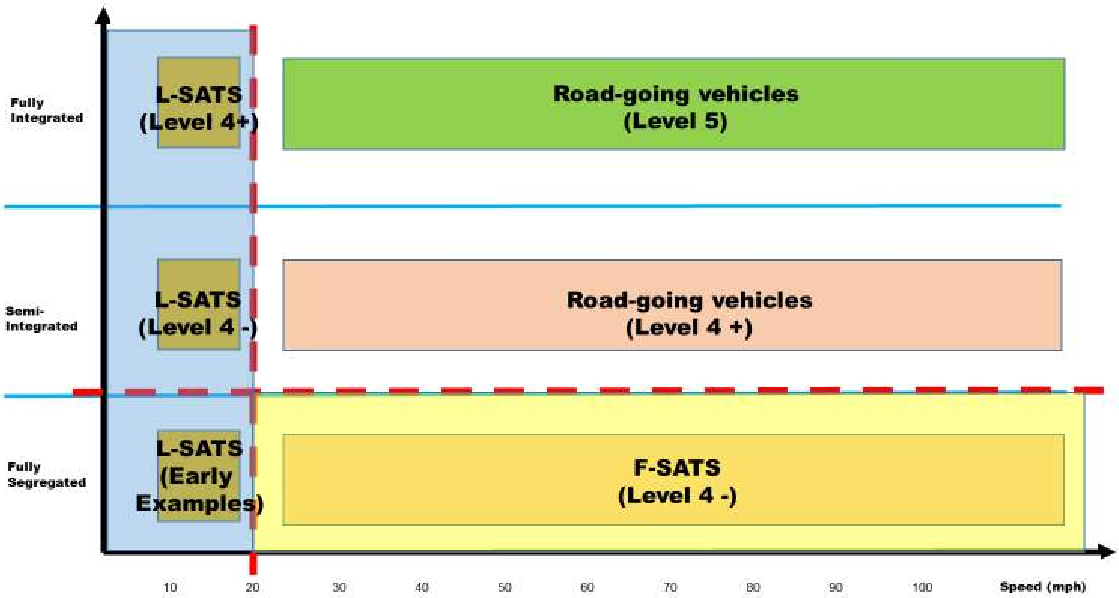


Fig 5.2 (a) The Implementation of Autonomous Vehicle Systems – background segmentation

The six vehicle categories are:

Category 1 (L-SATS, Early examples): These systems work at low speed on non-road, physically segregated pathways. Examples are the ULTRa System at Heathrow Terminal 5 and the ToGetThere system in Rotterdam, both of which have been operating for many years.

Category 2 (F-SATS, Level 4-): Like Category 1 vehicles, these vehicles are confined to run on non-road, physically segregated pathways. However, they can run at much higher speeds, thus making them suitable for urban and rural mass-transit applications. They are, strictly, SAE Level 4 systems, but they are categorised in the diagram as 'Level 4 minus' because of the simplification conferred by physical segregation.

Category 3 (L-SATS, Level 4-): These non-road systems are considerably more advanced than those of Category 1. They are capable of following a pre-defined (fixed) path through pedestrianised space but with no physical segregation from other users of that space (pedestrians, cyclist, service vehicles, etc). They are, strictly, SAE Level 4 systems, but they are categorised in the diagram as 'Level 4 minus' because of the simplification conferred by low speed.

Category 4 (L-SATS, Level 4+): These non-road systems represent the ultimate form of L-SATS. The vehicles can operate in mixed pedestrianised spaces without any form of pathway pre-definition or physical segregation. They are designed to provide on-demand public mobility services between random points of pick-up and drop-off, plotting journey-specific optimised paths through their designated spaces. They are categorised in the diagram as 'Level 4+' because of the complexities of inter-acting in close proximity to pedestrians and other users of typical pedestrianised spaces.

Category 5 (Road-going vehicles, Level 4+): These are road-going vehicles (cars, buses, commercial vehicles, etc) which operate within pre-defined Operational Demand Domains. They are categorised in the diagram as 'Level 4 plus' to emphasise that they lie at the more complex end of the Level 4 spectrum.

Category 6 (Road-going Vehicles, Level 5): These are the ultimate form of autonomous road-going vehicles. They can operate without driver engagement anywhere and at any time on the public road network.

The estimated timescales which might be associated with the practical implementation of these 6 vehicle categories are suggested by the 'year waves' which progress from left to right as shown in Fig 5.2 (b). In the diagram, each category becomes 'activated' when the Year Wave first contacts the representative block. At this point, the technology moves out of the laboratory and into the public realm. Initially, this will be in quite limited form/numbers and the technology can be expected to improve and reach full maturity as the Year Waves pass further through the block. By the time the Year Waves have flowed past the block, the technology can be considered to be 'mature' (meaning commonplace in terms of its presence and relatively stable in terms of its development cycles).

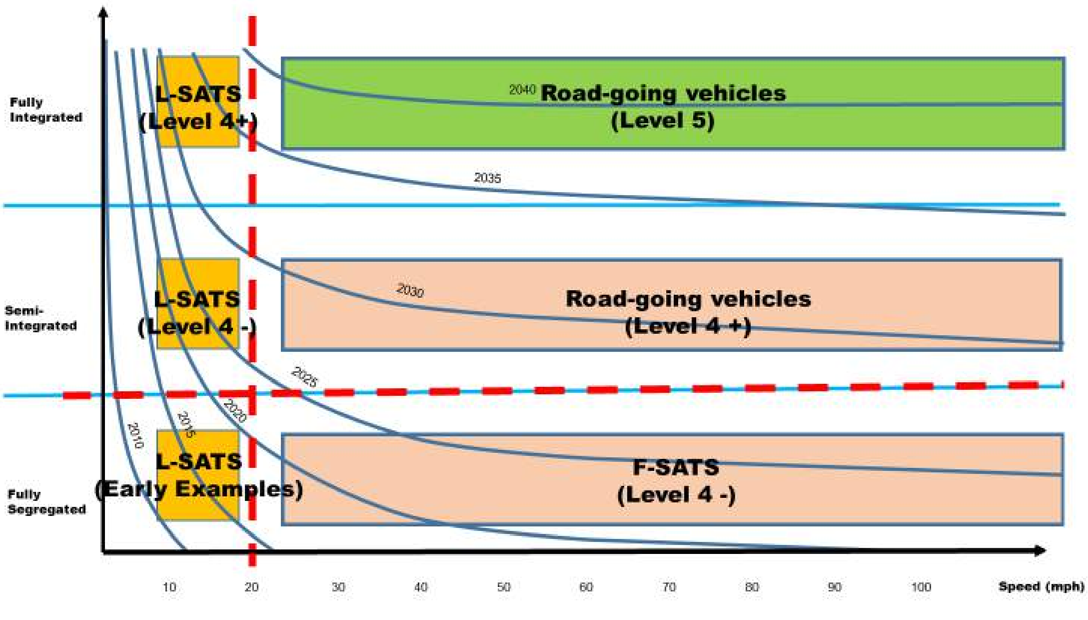


Fig 5.2 (b) The Implementation of Autonomous Vehicle Systems – timescales to maturity

The purpose of this report is to explore the near-term potential for autonomous and related vehicle technologies to have a meaningful impact on public transport systems. The period between 2020 – 2030 is therefore of primary interest and this period is shown in the shaded band in Fig 5.2(c) below. From this diagram, it can be seen that the vehicle Categories 2 and 3 have a good chance of reaching maturity by 2030 (Category 1 is considered to be mature already). Systems using these vehicle types should therefore be of greatest interest to GCP/CA over the next few years.

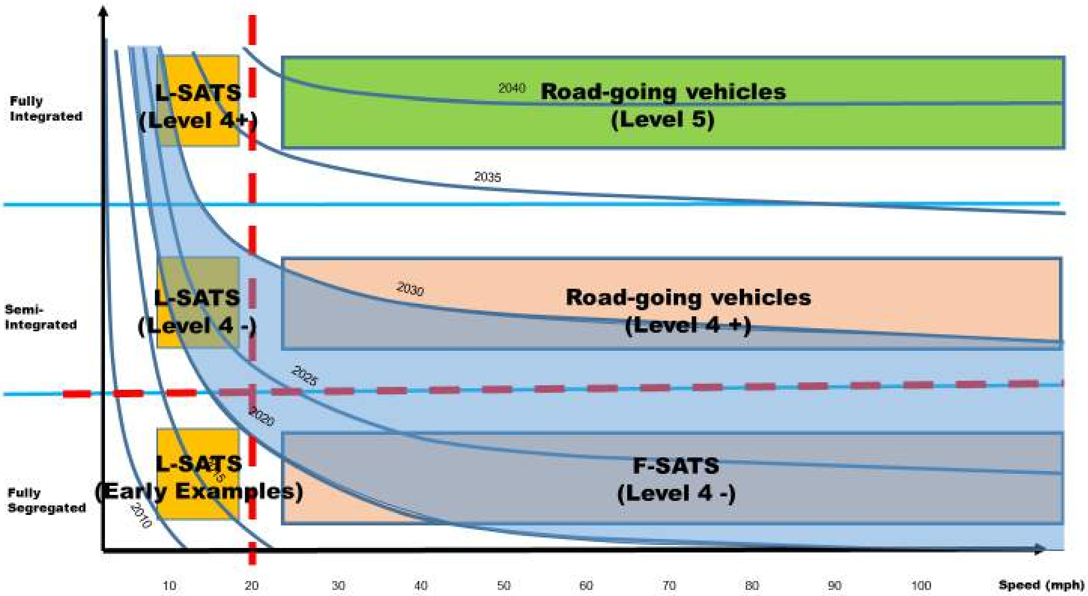


Fig 5.2 (c) The Implementation of Autonomous Vehicle Systems – likely developments within the next 10 years

5.2 <u>Commercial Potential</u>

The term 'commercial potential' used here refers to the potential for creating revenue-generating free-enterprise, or predominantly free-enterprise, transport services. Central to this aspiration is the cost of provision. Cost studies have therefore been conducted for a range of different transport categories and the results are described below in Sections 5.2.1. to 5.2.5

5.2.1 Urban Electric Transport Systems (Buses, Taxis, Home Delivery - no autonomous capabilities)

Pure electric transport solutions, without autonomous control, represent the 'low hanging fruit' for Local Authorities. Already, quite a large number of electric buses, cars, and vans can be found on the streets of cities across the UK. Provided they can be presented to the service operators as a cost-effective solution, all-electric vehicles provide an immediate starting point for GCP/CA in the progression towards the widespread provision of affordable, environmentally friendly, public transport services.

The primary benefits to the public derive from the big reductions in roadside pollution (carbon emissions, air quality, noise, and dirt) which stem from the zero tailpipe emissions associated with electric vehicles The resulting improvements in air quality and reductions in CO_2 and noise emissions are quantifiable and significant.

However, there is a resistance to immediate and widespread adoption which springs from the cost of implementation. When the cost of the vehicles and all the asociated charging infrastructure is calculated, the lifetime cost of operating an all-electric fleet is, at the time of writing, usually more expensive than the lifetime cost of running a conventional fleet. The cost calculations which lead to this assessment are presented in Appendix 1.

In summary, the environmental and social benefits of all-electric public transport are now easily deliverable from a technology perspective. However, the lack of a significant financial benefit, coupled with the perceived risks of adopting a new technology, leads most commercial transport operators to be very cautious when considering the transition to all-electric operations.

For all-electric transport systems to be deployed quickly and at scale in the GCP/CA area, the Local Authority must be prepared to give a 'nudge' to the commercial system. If the cost of the charging infrastructure is borne by the Local Authority, for example, the cost to the service operator of running an all-electric fleet of buses or taxis can be significantly reduced. (Indeed, under the right circumstances, it can even be made financially attractive for the operator to adopt electric vehicles). The question of 'nudging' is re-visited in more depth in Sections 6.1.1 and 6.1.2

5.2.2 Category 2 Systems (F-SATS)

The business case for a segregated fixed-path service, using purpose-designed vehicles with a capacity to carry 15 passengers at approximately 40mph on the Cambridge Southern Guided Busway, has been developed as part of the GCP's Trumpington-Cambridge Autonomous Bus Service Project (T-CABS). The results showed that, once the F-SATS technology becomes mature, the current conventional bus services could be replaced by an F-SATS service running 24-hours per day . The costs and revenues are summarised in the pair of tables below and it can be seen that the new system could make an excellent return on the initial investment. A fuller description of the T-CABS Business Case is presented in Appendix 2.

Number of 15-Seat Pods	28	31	33	36	39	41
Cost of Vehicle	£100,000	£100,000	£100,000	£100,000	£100,000	£100,000
Total Cost of Vehicles	£2,800,000	£3,100,000	£3,300,000	£3,600,000	£3,900,000	£4,100,000
Number of Pods at Station	8	8	8	12	12	12
Number of Pods at CBC	8	8	8	12	12	12
Number of Pods at P&R	12	12	12	12	12	12
Number of Pods at Junction Waiting Bays	0	3	5	0	3	5
Station and CBC Capacity per 10 minutes	120	120	120	180	180	180
P&R Capacity per 10 minutes	180	180	180	180	180	180
10 min Surge Capacity at Station and CBC	120	165	195	180	225	255
10 minute Surge Capacity at P&R	180	225	255	180	225	255
Infrastructure	£500,000	£500,000	£500,000	£500,000	£500,000	£500,000
Busway Modifications / Stabling etc	£1,000,000	£1,000,000	£1,000,000	£1,000,000	£1,000,000	£1,000,000
Capital and Interest Repayments (3% bond)	**£577,884**	**£618,202**	**£645,080**	**£685,397**	**£725,715**	**£752,593**
Fuel (Electricity) Costs	**£190,000**	**£190,000**	**£190,000**	**£190,000**	**£190,000**	**£190,000**
Staff Costs	**£1,450,000**	**£1,450,000**	**£1,450,000**	**£1,450,000**	**£1,450,000**	**£1,450,000**
Vehicle Maintainance (£2,0000 per pod)	**£56,000**	**£62,000**	**£66,000**	**£72,000**	**£78,000**	**£82,000**
Insurance (£1,500 per pod)	**£42,000**	**£46,500**	**£49,500**	**£54,000**	**£58,500**	**£61,500**
TOTAL COST p.a.	**£2,315,884**	**£2,366,702**	**£2,400,580**	**£2,451,397**	**£2,502,215**	**£2,536,093**

Cost Appraisal of a 24-Hour AV Service, for Different Pod Fleets and Levels of Service

Total Weekly 24-Hour Journeys:	60,509							
Single Fare per Trip	£1.00	£1.50	£2.00	£2.50	£3.00	£3.50	£4.50	£5.00
Weekly Income	£60,000	£90,000	£121,000	£151,000	£181,000	£211,000	£272,000	£302,000
Annual Income	**£3,120,000**	**£4,680,000**	**£6,292,000**	**£7,852,000**	**£9,412,000**	**£10,972,000**	**£14,144,000**	**£15,704,000**

Estimate of Annual Income from 24-hour Operation

A more ambitious form of the F-SATS category of vehicles is represented by autonomous mass transit systems. These were described in Section 2.3.2. These systems are suitable for urban commuter services and inter-urban connections between small towns. In these applications, the vehicle speed can be in excess of 60mph, the passenger-carrying capacity can be several hundred per despatch, and the connection distances can be tens of miles (20-30 miles is typical).

An analysis of the cost per passenger mile for Autonomous Mass Transit (AMT) systems is summarised in the table below. A similar analysis is presented for conventional rail systems for the purposes of direct comparison. Three different deployment scenarios have been examined.

- **A case study for re-opening the Wisbech – March branch line.** This is a single-track line which is in a reasonable state of repair. It is therefore represents a relatively low-cost exercise in branch-line re-opening. Details of the branch line, passenger demand, and the cost of rail operations, have been taken from the report on the March to Wisbech Rail Study (Stage 1) prepared by Atkins and issued in Dec 2012.
- **A more general case of rural branch line re-opening,** where the state of the track is in bad repair and needs re-laying. The capital cost of renewal is therefore very much higher than the previous case. The length of the line, operating costs, and the daily passenger numbers are modelled on the Wisbech – March data.
- **The proposed rail link between Bedford and Cambridge**. This will form the final link in the East-West rail project which will ultimately connect Oxford, Milton Keynes, and Cambridge. The rail costs are taken from the Bedford to Cambridge Preferred Route Options Report issued by East-West Rail Company in January 2020.

The ultra-light mass transit concept (MicroMetro) has been used as the cost base for Autonomous Mass Transit in all cases.

ITEM	TRAIN			AUTONOMOUS MASS TRANSIT		
	Wisbech – March	Rural	Bedford - Cambridge	Wisbech – March	Rural	Bedford - Cambridge
Length of Line (miles)	8	8	30	8	8	30
Infrastructure Capital Cost	£52,000,000	£330,000,000	£3,200,000,000 (at 2010 prices)	£64,000,000	£128,000,000	£500,000,000
Working Life	50	50	60	50	50	50
WACC (%)	4	4	4	4	4	4
Infrastructure Maintenance (p.a.)			£9,000,000			£1,000,000

Annualised Cost of Infrastructure	£3,120,000	£19,800,000	£210,000,000	£3,840,000	£7,680,000	£31,000,000
Vehicle Purchase Cost	N.A. (Leased)	N.A. (Leased)		£1,000,000 (2 vehicles)	£2,000,000 (4 vehicles)	£5,000,000 (10 vehicles)
Annualised Cost (Lease or Purchase over 10 years)	£124,000	£124,000		£140,000	£280,000	£800,000
Fuel	£141,000	£141,000		£31,000	£62,000	£1,000,000
Vehicle Maintenance	£90,000	£90,000		£17,000	£34,000	£90,000
Driver Costs p.a.	£70,000	£70,000		0	0	£0
Guard Costs p.a.	£40,000	£40,000		0	0	£0
Total Annual Staff Costs	£440,000	£440,000		£0	£0	£0
Total Annual Operating Costs			£12,000,000			£32,890,000
Annual Total Costs (Conventional)	£3,915,000	£20,595,000	£222,000,000	N.A.	N.A.	N.A.
Annual Total Costs (Autonomous)	£3,475,000	£20,155,000	£219,000000	£4,028,000	£8,056,000	£32,890,000
Passenger Journeys per year	300000	300000	3000000	300000	300000	3000000
Average journey length (miles)	8	8	30	8	8	30
Cost/passenger-mile (Conventional)	**£1.63**	**£8.58**	**£2.47**	**N.A.**	**N.A.**	**N.A.**
Cost/passenger-mile (Autonomous)	**£1.45**	**£8.40**	**£2.43**	**£1.68**	**£3.36**	**£0.37**

Comparison of Segregated, Fixed-Path, Transit Systems

The Autonomous Mass Transit solution offers substantially better costs per passenger mile in all cases except the first case, where there is minimal cost to re-instate the existing line. In all cases, the level of service provided by MicroMetro (with a typical departure frequency of once every 5-10 minutes) is far superior to that provided by conventional rail (once every half-hour, typically).

In the case where a relatively high level of daily demand exists (Bedford – Cambridge, with approximately 5,000 passengers per day per direction), Autonomous Mass Transit offers a cost per passenger mile delivered which approached that of a conventional bus service (see Section 5.2.4 below). This ability to deliver frequent departures at very low costs per passenger mile comes about because of the extremely light infrastructure requirements coupled with relatively small vehicles and driverless operation.

5.2.3 Categories 3 & 4 – Semi-Integrated and Free Roaming L-SATS

The UK Autodrive project in Milton Keynes which was completed in 2018 developed a general methodology for assessing the business case for un-segregated L-SATS operations. Exercising the UK Autodrive model in a generalised pedestrianised space of around 6 sq kms suggests that a good return can be made for the fleet operator over a range of different pod prices, operating regimes, and fare structures. The profitability of the case (in terms of Net Present Value over the life of the pod fleet) against variations in pod price, staffing levels, and fare prices is shown by the surfaces in Fig 5.1.

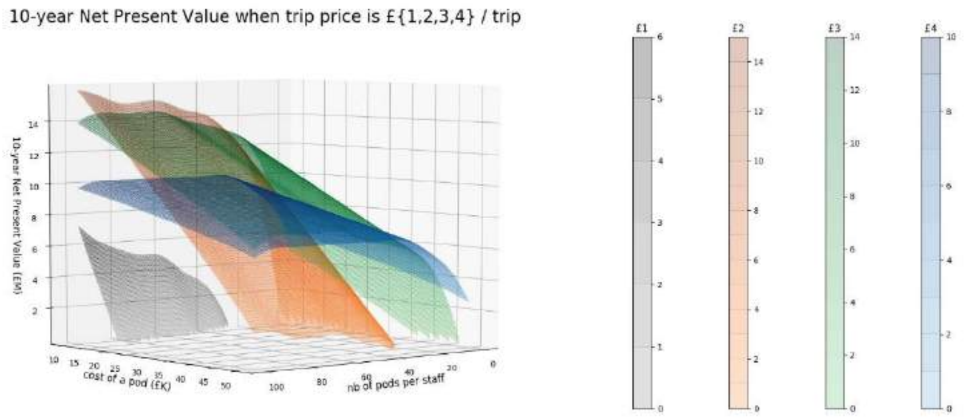


Fig 5.1 Net Present Value (10 years) for Un-segregated L-SATS Operations

5.2.4 Categories 5 & 6 – SAE Level 4/5 Road-Going Vehicles (Autonomous Buses, On-Demand Buses, and Taxis/PHV's)

Buses, taxis, and home delivery vehicles all operate within locally defined areas and, in the case of regular bus services, operate on specifically defined routes. This means these operations have a specified Operational Design Domain and vehicles equipped to SAE Level 4 standards of capability may be sufficient to deliver a safe driverless public transport service. In many cases, however, this will not be so and, in these cases, the delivery of a safe driverless public transport service will have to await the arrival of vehicles with full SAE Level 5 capabilities.

The Table below summarises the results of the commercial analysis for regular buses, flexible on-demand buses, and private-hire vehicles (PHV's). In each case, the analysis has been carried out for a conventional (non-electric) vehicle assuming the autonomous technology has reached 'maturity'. This implies that the 'on-cost' of the autonomoius control systems has become a relatively small part of the total cost of the vehicle. On this basis, the sensitivity of the cost per passenger mile to the introduction of autonomous operations has been tested.

ITEM	REGULAR BUS	SMALL ON-DEMAND BUS	PRIVATE-HIRE
Vehicle Purchase Cost	£180,000	24,000	£10,000
Working Life	15	4	4
WACC (%)	4	5	6
Annualised Cost	£19,200	£7,000	£3,100
Fuel	£21,000	£10,800	£6,648

Maintenance	£17,000	£1,000	£1,200
Annual Fuel & M'tce costs	£38,000	£11,800	£7,848
Driver Costs p.a.	£30,000	£30,000	£25,000
Driver shifts per day	2	1	1
Driver costs p.a.	£60,000	£30,000	£25,000
Insurances	£8,000	£8,000	£4,000
PHV Agency service fees	N.A.	(Assume the service is agency-operated	£6,000
Total Misc	£8,000	£8,000	£10,000
Annual Total Costs (Conventional)	£125,200	£56,800	£45,948
Annual Total Costs (Autonomous)	£65,200	£26,800	£20,948
Vehicle miles per year	50,000	45,000	40,000
Working miles per year (%)	100	80	75
Working miles/year	50,000	36,000	30,000
Cost/working vehicle mile (Conventional)	£2.24	£1.58	£1.53
Cost/working vehicle mile (Autonomous)	£1.30	£0.74	£0.67
Average passengers/working vehicle-mile	8	8	1
Cost/passenger-mile (Conventional)	**£0.28**	**£0.20**	**£1.53**
Cost/passenger-mile (Autonomous)	**£0.16**	**£0.09**	**£0.67**

Comparison of Unit Costs (GBP/Passenger-mile) for Bus and PHV Operations

The sensitivity of both bus and private hire vehicle (PHV) to the advent of autonomous operations is quite marked, but the cost per passenger mile is always higher for the PHV than it is for either type of bus. Despite this premium, however, experience shows that the flexibility and convenience of taxis over regular bus services is a significant traveller attraction. Door-to-door, on-demand, service is highly valued and a large number of today's travellers are willing to pay a higher price for this convenience. Some combination of door-to-door convenience with lower cost fares points towards flexible or 'On-Demand' bus services (sometime referred to as Demand Resposnsive Transport).

As the number of passengers in a shared-ride vehicle rises, the cost per passenger mile drops. For the on-demand bus service, the number of passengers required to drive the fare below that of a regular bus is around 5 per vehicle (average daily ridership per mile travelled). This is the case with, or without, autonomous operation. The result suggests that autonomous, on-demand, flexible route bus services could provide extremely attractive public transport services when the technoogy has reached a mature state.

5.2.5 Aerial Vehicles – Helicopters and Drones

Using small helicopters/drones as air-taxis for relatively short distance journeys between market towns, villages, and other dispersed rural communities holds some attraction in terms of speed of transfer and service flexibility. If combined with on-demand booking/billing capability, the service level offered to the traveller would become very similar to the conventional PHV. Journey times between origins and destinations typically 20-30 miles apart would be very short (flying times in the order of 10 -15 minutes). However, there are obvious difficulties with local noise and the provision of landing/take-off facilities (although agricultural land with sufficient surface access and aerial clearances is abundant in the rural areas).

Such services could be provided with conventional helicopters today, but the cost per passenger mile would be high (typically £3.00 – £4.00, as shown in the Table below). A 20-mile single journey would therefore cost upwards of £60.00!

ITEM	HELICOPTER/DRONE	
	Conventional Helicopter	Autonomous Electric Drone
Vehicle Purchase Cost	£250,000	£500,000
Working Life	10	10
Annualised Cost of Purchase	£40,000	£80,000
Fuel	£42,000	£19,000
Maintenance	£100,000	£70,000
Pilot Costs p.a.	£100,000	
Insurances & Misc	£10,000	£10,000
Annual Total Costs (Conventional)	£392,000	N.A.
Annual Total Costs (Autonomous)	£292,000	£179,000
Vehicle miles per year	120,000	120,000
Working miles per year (%)	50	50
Working miles/year	60,000	60,000
Cost/working vehicle mile (Conventional)	£6.53	N.A.
Cost/working vehicle mile (Autonomous)	£4.87	£3.00
Average Passengers/working vehicle mile	2	2
Cost/passenger-mile (Conventional)	**£3.27**	
Cost/passenger-mile (Autonomous)	**£2.43**	**£1.50**

Introducing autonomous electric helicopters or drones would help to solve two key problems. Noise levels would be substantially reduced and, assuming the cost of purchase reduces to within a level of two times the conventional aircraft costs at some point in the next 15 years, the cost per passenger km could be reduced to the order of £1.50. This is getting very close to today's PHV prices and, based on the demonstrable levels of current demand at that price point, a reasonable level of future demand could be expected. On this basis, the possibilities have to be rated as 'interesting'!

5.3 New Business Models

There are several interesting new business models which are raised by the CASE combination of technologies.

- **Joint Local Authority/private enterprise collaborations** in which the Local Authority works with a free-enterprise investor/provider and provides capital for some or all of the fixed infrastructure. Such arrangements are not uncommon in big transport infrastructure projects and they usually lead to an on-going franchise-like arrangement for the operation of the public transport services (either via the original free-enterprise investor, or via a suitable third-party).

  There is a compelling case for adopting this approach in connection with installing charging infrastructure for electric buses (particularly for 'Opportunity Charging' systems at Park & Ride sites). In scale terms, the financial and other risk exposure for the Local Authority would be quite small. This therefore presents an attractive opportunity for GCP/Combined Authority to precipitate short-term, meaningful, change.

- **Mobility-as-a-Service (MaaS).** This end-to-end, fully automated, approach to the provision of shared transport systems has a compelling underlying commercial case. The amount of money spent per household per year on private transport (cars) is substantial if the full costs of the vehicles are allowed for. If travellers could be persuaded to relinquish their cars and divert the majority of the savings to a 'Maas Pool', it is argued that equal or improved shared mobility could be provided at a lower cost to the traveller. For example, the typical car loses about half its price over 4 years, and consumes around £2,000 p.a. in fuel costs and servicing. This comes to around £5,000 per car per year (or, for a cheaper second-hand car, around £3,000 per year). This sum, spread over a range of bus, train, and PHV rides, would be ample to provide equivalent mobility at a lower societal cost, and the service could be made very convenient for the traveller if a commercial 'aggregator' took on the responsibility for organising daily vehicles,tickets for public transport, and other logistics. (The margins to the aggregator would also be improved, or prices to the consumer further reduced, through the power of bulk purchasing which would be available to the aggregator).

  The difficulty with this seemingly simple argument is that the aggregator requires scale in order to provide the levels of customer service required. Customer satisfaction depends on services arriving quickly and conveniently when called but, in the early days, scale does not exist. If under-resourced services fail to provide customer satisfaction, a lot of damage will be done to the reputation of the provider. It is doubtful that the company offering those services could recover from the reputational set-back, so early operations would have to be scaled-up despite a lack of market presence. The investor funds required to bridge this gap are enormous, and it remains to be seen whether any of the start-ups currently operating in this space will achieve success in the long run.

  MaaS is probably not a case where GCP/Combined Authority should take a lead, but the potential societal benefits are sufficient to make it worth offering 'suppport in kind' (e.g facilitation within the local community, etc).

- **'Free-riding'** in which rides are free to the traveller and the operator recoups the money via targeted advertising and local retail reinforcement. Short-distance services in city-centre locations are the most obvious opportunity for this type of revenue generation, which would be based on the ability to offer inducements to travellers to visit local shops and other attractions via in-vehicle screens during the course of their journey.

6. Scenario Definition

A series of possible future scenarios is described in this chapter. Each scenario is intended to define an area of future development/implementation that can contribute to the achievement of the GCP/Combined Authority's policy goals, as summarised in Table 6.1 at the end of this chapter. All the scenarios defined in the table depend on the successful take-up of new technologies. For this reason, each has a 'nudge' element which suggests a pro-active role which GCP/Combined Authority might play in bringing this scenario to fruition.

6.1 <u>Scenario 1: Low Emission Shared Transport Services</u>

In this scenario, it is postulated that GCP wish to press ahead aggressively with the delivery of publicly accessible low-emission shared transport services. This strategy does not mandate the use of autonomous vehicle technology and some material benefits can be delivered without it. This scenario therefore represents an achievable short-term goal which can be delivered through encouraging the co-ordinated deployment of electric buses, electric taxis, and electric bikes/scooters. The rate of public uptake of this multi-modal approach could be boosted by the introduction of end-to-end ticketing and tailored traveller information systems (Section 3.5).

6.1.1. Electric Buses

There are currently in excess of 100 conventional buses which operate the routes within and immediately around the City. Preliminary studies show that it is technically credible to operate electric vehicles on all these routes. The same studies show that the 5 main Park and Ride routes would be ideal 'flagship' routes with which to demonstrate and prove the credibility of all-electric buses, and that electrification of some of the longer distance routes on the Cambridge Guided Busway should also be considered as short-term objectives.

In the case of the initial routes, an attractive business model would be for GCP to install 'Opportunity Charging' infrastructure at key locations (e.g. on the bus stands at the Park and Ride sites) and then allow the bus operators to use this equipment as part of a route franchise arrangement. Under these circumstances, and with the confidence engendered by a 5 or 10-year franchise, it would be cheaper for the bus operators to operate electric buses than conventional diesel buses. This dynamic should create an enthusiasm to engage from the public transport providers – a condition which is an essential pre-requisite to proposing any joint activity between the Local Authority and private enterprise.

6.1.2 Electric Taxis (Private Hire)

There are over 700 Private Hire and Hackney Carriage vehicles operating in and around Cambridge. These services have become the *de facto* leader in the field of flexible public transport, providing well established on-demand, end-to-end journeys.

There are increasing numbers of hybrid and electric vehicles now coming to market which are suitable for use as Private Hire vehicles, but the confidence of the operators (largely owner-drivers) has yet to mature. Hybrid vehicles have become popular with PH drivers, but the uptake of pure battery-electric vehicles is currently very low. Range anxiety and fear of the unknown are big obstacles and the owner-drivers/operators need to be encouraged to cross these lines. Encouragement could be provided in a number of different ways, including (for example):

- GCP could provide a city-wide network of rapid chargers (minimum 50kW) which are prioritised for Private Hire vehicles. As was argued for electric buses, if the GCP funded this network of chargers, the cost of operation for the Private Hire drivers would become lower for electric vehicles than for conventional vehicles (see Appendix 2).
- The Local Authority could provide 'breaks' and incentives for EV drivers in the form of licencing constraints, fees, priority parking, EV taxi ranks, etc.

6.1.3 On-Demand Buses

The introduction of On-Demand small bus services could have the effect of bringing taxi-like levels of convenience and flexibility to the travelling public at a price that is comparable to conventional bus services (Section 5.2.4). On paper, there is a particularly attractive case for exploring the possibilities in connection with rural transport services, but no practical proof of this case yet exists and it requires a degree of scale to test the proposition robustly. GCP/CA should consider the possibility of putting on-demand styles of operation in place of one or more of the existing subsidised rural bus services. (i.e. swapping an existing subsidy to a new place).

6.1.4 Electric Bikes & Scooters

The arrival of 'dock-less' bikes has introduced the concept of spontaneous cycling, and this has proved popular with members of the public in many cities around the world. It is particularly attractive for travellers to have cycles readily available at interchanges with public transport (stations, bus stops, etc) which can be left at random destinations without recourse. The downside for other citizens is the potential for bikes to be discarded wantonly on the pavements and footpaths causing unsightliness and potential danger to the public.

A great improvement could be made if the process for collecting and re-distributing the bikes was better serviced and enforced. Recognising that the providers do not fulfil this function very effectively at the moment, the Local Authority should consider the possibility of providing this service itself. The cost of provision is (arguably) quite low compared to the benefits conferred by dock-less cycling and this could be borne either as a public service, or passed on to the provider via the licencing arrangement. (This would need to be enforced with some vigour, and it is possible that the cost of enforcement would be of similar magnitude to the cost of collection/re-distribution)

The value of dock-less cycling is geared-up when seen within the context of providing end-to-end journeys for the users of public transport. Having these services available to facilitate the first/last mile stages of a journey makes it much more attractive for travellers to use public transport services for the intermediate stages of the journey. Having a system-wide mechanism which allows simple, convenient, payment for bus/taxi/cycle journeys would further enhance the attractiveness to travellers. (Note: the arrival of contactless payment systems has almost fulfilled this need already; tap-in tap-out arrangements on transport are rapidly becoming commonplace).

6.1.5 Integrated Low-Emission Transport Services

The co-ordinated delivery of electric vehicles across bus, taxi, and cycle-hire services would provide access to low-emission public transport for a very large fraction of the travelling public. Given the precedents in other UK and overseas cities, this objective could be delivered with a high degree of confidence, within an affordable budget, over a reasonably short timeframe. This therefore represents one of the most achievable and affordable future transport options which are available to GCP/CA.

6.2 Fixed Path Autonomous Transport Systems

The provision of fixed path, autonomous transport systems (both segregated and semi-integrated) represents a particular opportunity for GCP and the Combined Authority. This is for several reasons:

- The presence of the Cambridge guided busway (both north and south sections) provides a natural and advantageous starting point for the development and demonstration of fast, segregated, autonomous transport systems (F-SATS). Proving the credibility of an autonomous mass-transit system could start here.
- The presence of many campus sites within the city and its surrounding regions makes it relatively easy to designate fixed path routes which can serve the majority of traveller needs. This applies both within their boundaries and to/from points of local access (e.g. remote Park and Ride facilities; railway stations; etc).
- There are several semi-used or abandoned 'Beeching Lines' across the Combined Authority area. These corridors provide an opportunity to re-connect rural communities and they lend themselves to being re-opened if an affordable mass transit solution can be made available.

The GCP should consider several specific scenarios/opportunities.

6.2.1 Category 2 Vehicles - Autonomous Mass Transit Systems (F-SATS)

These systems present a lesser challenge to the autonomous vehicle supplier than most other autonomous applications. This reflects the strictly limited Operational Design Domain within which the vehicles are required to operate.

Moving at relatively high speed (typically 50-60mph) presents some particular challenges, but several of the advanced driver-assist technologies which are now appearing on production cars are rated for operation at 100mph+. These devices prove the credibility of designing control systems which can operate safely at high speeds and gives confidence that the arrival of practicable F-SATS technologies is not far off.

The future of autonomous mass transit can be considered under three headings.

- *Urban Applications*

  This requires either the retro-fit of a mass transit system within existing urban fabric (e.g. within the city of Cambridge and its surrounding area), or the integration of a scheme within a new settlement at Master Plan stage. Whilst the former is usually the predominant requirement, there are several large new settlements being planned within the GCP/Combined Authority area and this opportunity should not be overlooked.

  Considerable work has already been done on urban retro-fit solutions for the City of Cambridge and this will not be repeated here except to note two critical points:

  - To become realistic options, the capital cost of installing and commissioning these new solutions needs to be around half that required to install and commission conventional tram/light rail systems. The same needs to be true of annual operating costs if sufficient annual surpluses are to be generated to repay the construction costs over a realistic period (30-50 years).

- Cambridge represents the near-ideal national case for introducing a new concept in affordable, low-emissions, mass transit.

- *Rural Applications*

'Trackless trams' represent an interesting alternative to conventional rail vehicles when it comes to re-opening dis-used rail corridors. Many such corridors exist within the area of the GCP/Combined Authority, and these present excellent opportunities to re-connect rural communities without incurring many of the costs which are normally associated with defining and creating the transit pathways. The passenger transfer rate requirements are generally quite low for these applications making conventional rail unattractive (see Chapter 3), but ultra-light autonomous mass transit has the potential to transform the case for re-opening rural rail connections.

- *'Strategic Connector' Applications*

This case is represented by the need to provide a high capacity, attractive, public mass transit service between strategic nodes in the GCP/Combined Authority Transport Plan. The clearest example is the East-West link between Bedford and Cambridge, for which the solution is currently being developed. Ultra-light autonomous mass transit offers a solution which is cheaper, faster, and more frequent than conventional rail at a fraction of the capital and operating costs (see Chapter 5.2.3)

6.2.2 Category 3 Vehicles (L-SATS)

Cambridge has already taken the initiative to explore segregated fixed-path systems via the T-CABS programme. However, running exclusively in segregated space is a great limitation for a low-speed public transport system. To become more attractive and useful to the traveller, L-SATS must develop the ability to operate in unsegregated space where pedestrians, cyclists, and others may stray randomly into the path of the vehicles.

Campus sites represent an ideal landscape for the development of unsegregated fixed-path L-SATS operations. Some of the best known L-SATS demonstration programmes in other countries have been located at this type of site for this reason (e.g. CityMobile 2 at the University of Lausanne).

Cambridge, with its heavy presence of campus sites, has good reason to be interested in this line of development. The technical and regulatory challenges are greater than is the case for F-SATS services running exclusively on segregated pathways (e.g. the Busway), but the ability to move around campus sites and take people to the door of their intended destinations adds greatly to the attraction of using an L-SATS system as the first/last mile part of the journey for a commuter, business traveller, or hospital visitor.

6.3 Free-Roaming Autonomous Transport Systems

6.3.1 L-SATS

Free-roaming L-SATS offer an attractive solution for application in pedestrianised spaces in cities, towns, and campus environments. These are exclusively short-range applications, serving journey needs which arise within spaces which may be between 1-10 square kms with passenger transfer requirements in the region of hundreds rather than thousands of passengers per hour. The attraction is the ‘anytime, any place’ characteristic of the connection service, but the downside is the temptation to replace walking and cycling as the default short-distance mobility choice.

The downside arguments reduce as the space to be served gets larger (because walking between the extremes becomes less practical and cycling through pedestrianised spaces presents its own difficulties). There are also a significant number of special case needs which need to be served (e.g. elderly and impaired travellers; inclement weather; carrying shopping bags; travelling with young children; etc). All of these considerations push for some sort of mobility solution to be provided as an adjunct to walking and cycling in urban mixed space.

GCP should consider the potential for introducing free-roaming L-SATS services, but this should be seen as a ‘horizon pushing’ activity with a focus on providing ‘adjunct’ mobility within spaces no smaller than 5 sq kms.

6.3.2 Autonomous Buses and Taxis

This is an area of application which receives a lot of attention, but the technology and regulatory barriers to delivering these on-road services are high. Some fixed-route bus services might be served by SAE Level 4 vehicles within strictly limited Operational Design Domains but, for the general case of on-road public transport, full Level 5 capabilities will probably be required.

The development of safe Level4/5 road-going vehicles which meet all the applicable UK standards and regulations is a formidable undertaking. This load is best left to the major vehicle manufacturers and their suppliers - it would not be cost-effective for any Local Authority to take a pro-active stance in this space. Despite this, the benefits conferred by the arrival of autonomous buses and taxis could be significant. The cost of public transport operations (and therefore the ticket prices) would reduce significantly, particularly for flexible, on-demand, shared services as shown in Section 5.2.4. This would make public transport simultaneously more attractive and affordable. For this reason, the GCP/CA should maintain an active interest in this space and be prepared to engage positively with any system developers/vehicle manufacturers/operators that show an interest in carrying out demonstration programmes in the GCP/CA region.

6.3.3 Drones

Autonomous or chauffeur-driven drones represent an eye-catching transport option which can be easily dismissed as fanciful. There are, however, two particular traveller user-groups within the GCP/Combined Authority remit who might benefit if the price of service provision could be brought within reasonable limits (e.g. within sight of the current pricing structures of Private Hire services as provided in the rural context)

- The Inhabitants of small market towns and villages, who may wish to travel distances of 15-25 miles on an occasional basis at random times of day and night. This might be for leisure or other reasons. Examples include trips between small towns/villages and larger towns/cities for business purposes, hospital visits, or an evening out. Typical origin/destination pairs might be St Neots to Cambridge, or King’s Lynn to Peterborough.
- Travellers wishing to make longer journeys in a hurry – for example going to London or Oxford from within the GCP/Combined Authority region, or travelling to Stansted (or any of the other London airports) for an international journey.

Because of the particular needs of a dispersed rural community (low passenger transfer volumes, medium distances, random origin/destination pairs), GCP should maintain a watching brief on the use of autonomous drones for carrying packages and passengers, and be prepared to become engaged when the conditions are right.

Scenario	Elements	Policy Driver	'Nudge' Required	Beneficial Impact				Comment
				Land Use	Congestion	Air Quality/CO2	Road Safety	
Low-Emission Shared Transport Services	Electrification of Conventional Buses On-Demand Buses Taxis (Hackney Carriage and P.H.V) Electric Bikes	Environmental improvement Public Health	Installation of charging infrastructure. Provision of cycle re-location services.	Low	Medium	High	Low	Near-term activity. Represents a short-term 'win' for environmental quality and public health. Presents opportunities to connect with adjacent technologies (e.g. wind and solar power generation; local micro-grids)
Fixed Path Autonomous Systems	L-SATS	Urban congestion reduction & environmental improvement. Re-connection of rural communities. Strategic connection between large towns.	Participation with end-users and funders to deliver the regulatory frameworks and fixed infrastructure required. (In the case of autonomous mass transit, may require revenue guarantees or co-ownership)	Medium	High	Medium	Medium	Medium-term activity, particularly attractive for the dispersed rural/urban demographic within the area of the GCP/Combined Authority
	F-SATS (Urban)			High	High	High	Medium	
	F-SATS (Rural)			High	Medium	Low	Low	
	F-SATS (Inter-Urban/Strategic Connector)			High	High	Medium	Medium	
Free-Roaming Autonomous Systems	L-SATS	Urban congestion Environmental improvement Improved public transport services Rural mobility	GCP to be pro-active in seeking opportunities to participate in technology demonstration programmes	Medium	High	Medium	Medium	A 'horizon pushing' activity. Shows considerable future potential for the City Centre zone and the Campus-heavy nature of Cambridge and its immediate surroundings
	Autonomous Buses & Taxis			Low	Medium	Low	Medium	Likely to have a big impact, but depends on technology developments from the major motor manufacturers. . Probably requires SAE Level 5 capabilities which will delay the earliest dates for practical deployment.
	Drones			Low	Low	Low	Low	Eye-catching 'horizon pushing' activity suited to the particular challenges of rural connection.

Table 6.1 A Summary of Policy-Driven Transport Technology Scenarios

7. Opportunities & Barriers for GCP

There are many opportunities for GCP/CA to take a leading position in the definition and implementation of C.A.S.E. public transport services. These opportunities come about because:

1) Cambridge is a city with a pressing need for new transport solutions. Current levels of traffic congestion are threatening the continued expansion of the city and its surrounding region, and conventional solutions seem unable to deliver anything beyond marginal improvements. A radical approach to reducing congestion and improving mobility is required.
2) Unconventional approaches have high risk profiles. This is sufficient to prevent most Local Authorities from truly embracing innovation. But Cambridge is endowed with a very strong entrepreneurial spirit and technical pedigree. This provides an excellent foundation from which to form risk-sharing alliances between the GCP/CA and local businesses (and other local stakeholders). Such alliances can make bold decisions.
3) The guided busway represents a rare infrastructure asset. It lends itself for use as a segregated pathway for autonomous vehicles and can therefore be used to demonstrate the potential of fixed-path systems (either L-SATS or F-SATS). It can also migrate, over time, to become a dedicated pathway for publicly operable transport services.
4) The plans to expand the network of guided busways around the city of Cambridge, and the presence of several ‘Beeching Lines’ throughout the wider Combined Authority area, increase the opportunity to deploy fast, segregated, autonomous transport systems within a realistic timeframe. (CAM is a particular example).
5) A very large fraction of south Cambridge regional employment is concentrated in a relatively small number of large Campuses which lie in and around the city of Cambridge. These sites, often categorised as Private Land, are ideal test-beds for the early deployment of both fixed-path and free-roaming autonomous transport services.
6) There is a strong desire at national government level to support the development of new C.A.S.E technologies in the UK. This particularly applies to autonomous technologies and it means that significant funds are available to support ambitious development and demonstration projects. These funds are distributed through regular competitions and are structured in such a way that Local Authorities are (essentially) fully paid for their participation.

There are also, however, some significant barriers to success.

1) The risk level is high. Autonomous technologies, while holding great promise, are not yet proven as reliable solutions to real public transport problems. This makes it a difficult ‘sell’ for advisors, executives, and politicians.
2) The lack of established practice in the field of autonomous vehicle design and system operation means there is a constant need to seek guidance on questions of standards and regulation. Protagonists must take the initiative when stock answers are unforthcoming from the authorities. The question of ‘bus or train’ (Section 4.5) is a good example of local initiative being required.
3) The general state of ‘unpreparedness’ within the legal and regulatory spheres means that advocates for autonomous transport schemes will need to engage with disparate parties in government and the national administration in order to get things done (e.g. government departments and agencies such as DfT, BEIS, DCMS, OLEV, C-CAV, Highways England, Civil Aviation Authority, etc). This requires determination and persistence, and it places a heavy burden on the protagonists.

4) Local responsibilities for political direction and transport planning fall to several different overlapping parties (e.g. the Office of the Mayor, the Greater Cambridge Partnership, the County Council, the sub-regional Local Authorities, etc). The potential for conflict is obvious and it is exacerbated by similar overlaps at national level in the field of regulation and operational safety (the DfT, the national and regional Transport Commissioners, the Office of Road and Rail; the Health and Safety Executive, etc).
5) Public opinion needs to be kept 'on side'. The UK Autodrive Project found a surprisingly high level of public support for the pursuit of autonomous vehicle technologies, but single adverse events can cause a dramatic swing in mood. Reaction to the recent busway fatality is a case in point. A concerted effort must be made to secure and maintain public confidence.

8. A 10-Year Vision for Cambridge and the Surrounding Region

Based on the findings of this study, a 10-Year vision for Cambridge and the Combined Authority has been developed. This is based on a combination of aspiration, pragmatism, and utility. The goals which define the vision, and the actions required to deliver the vision, are presented in timeframe order in Table 8.1. The aspirational objective may be articulated as follows:

"To provide a network of public transport options in and around Cambridge that is accessible by all and delivers a more attractive end-to-end journey than using the car"

8.1 Goals, Actions, and Timescales

Table 8.1 summarises the vision for Connected, Autonomous, Shared, Electric (CASE) transport services in and around Cambridge and its surrounding region.

Delivery Timeframe	Programme/Goal	Action Required	Comment
0-3 years	All bus and taxi services operating within and around the city of Cambridge to use vehicles with zero tail-pipe emissions.	GCP to be prepared to 'nudge' operators and be pro-active in developing pilot schemes and long-term co-operative frameworks for working with bus/taxi operators	Has relatively small cost implications for GCP but produces a massive public 'statement' on environmental action. This objective is readily extendable to other large centres of population (e.g. Peterborough)
	Exploration and demonstration of on-demand small bus services for the provision of short/medium distance urban and rural public transport.	GCP to be pro-active in developing and delivering pilot schemes and long-term co-operative frameworks for working with suitable providers	Probably the most attractive (but unproven) solution to the problem of using public transport for random urban and rural movements. Does not require autonomous operations; electric vehicles desirable but not mandatory.
	'Public' bike schemes available which enable random first/last mile traveller movements to become part of public transport provision	Facilitation of solutions to the problem of abandoned bikes (collection and re-location)	Fixing the first/last mile problem is an important step along the road to making public transport a convenient and attractive alternative to the private car.
2-5 years	Proliferation of on-demand small bus services in urban and rural areas	GCP prepared to 'nudge' operators to inaugurate public services	There are several tech start-ups operating in this area who might be

			encouraged to come to Cambridge.
	Prototype demonstrations of contender systems for Cambridge Autonomous Metro (CAM)	Identification of contender systems, definition of demonstration requirements, and support for demonstration programme implementation	A vital pre-cursor to the delivery of affordable urban and rural mass transit. It is in the interests of GCP/Combined Authority ensure that more than one option exists for the supply of vehicle technology.
	The appearance of 'first generation' fixed path autonomous public transport services, using pre-existing urban corridors (e.g. the busway) and well-defined campus pathways.	GCP to engage actively with major end-user beneficiaries (e.g. retailers and large employers occupying city-centre or campus sites) to align objectives and generate additional funding	These systems will be niche applications operating at relatively low passenger transfer rates and low/medium speeds (less than 40mph)
4 – 8 years	The wider appearance of 'second generation' fixed-path autonomous transport systems in and around the city centre zone, large employment campuses, new community developments, etc.	GCP to engage actively with major end-user beneficiaries (e.g. retailers and large employers occupying city-centre or campus sites) to maintain alignment and ensure a continuing joined-up approach to the resolution of urban congestion problems	Will include both low-speed, small vehicle systems (L-SATS) for local movements and higher speed, larger vehicle systems for longer distance, higher capacity movements (e.g providing connections to off-site locations such as stations and remote car-parks)
6-10 years	Launch of Cambridge Autonomous Metro as an urban public transport system.	GCP/Combined Authority to press government to deliver the regulatory and legal changes which are necessary pre-cursors to this event	Would represent a national (if not international) landmark event in urban mass-transit evolution
	Consolidation of 'second and third generation' fixed path autonomous transport systems with CAM to provide a comprehensive and integrated public transport offering.	Requires the development of an integrated plan for transport which has the enthusiastic support of a critical community of key stakeholders (Local Authorities; local and international businesses, education, healthcare, and others).	An essential adjunct to CAM, providing 'tactical movement' capabilities to supplement the strategic movement capability of mass transit.

	Introduction of first Autonomous Mass Transit system for re-establishing rural connections on former ‘Beeching Lines’.	GCP/Combined Authority to be active in looking for suitable ‘Beeching Line’ opportunities.	Could resolve the long-standing dilemma of how to provide the medium distance, medium volume, rural connections formerly provided by Beeching Line railway connections.

Table 8.1 Timescales, Goals, and Actions Required to Achieve the 10-Year Vision

9. Conclusions and Recommendations

Cambridge is a city with a pressing need for new transport solutions. Current levels of traffic congestion are threatening the continued expansion of the city and its surrounding region, and conventional solutions seem unable to keep pace with rising levels of demand. A radical approach to reducing congestion and improving mobility is urgently required.

The opportunities presented by recent developments in Connected, Autonomous, Shared, Electric (CASE) transport systems are exciting (Chapters 2,3). However, much preparatory work needs to be done by GCP/Combined Authority if these technologies, and new business models they bring with them, are to provide workable public transport solutions within reasonable timescales. In particular, the GCP/Combined Authority must to take steps to engage with the legal and regulatory processes which are beginning to produce a new framework for transport delivery. GCP/CA must be prepared to lobby for changes where current standards and definitions could impede the delivery of future systems (Section 4.5).

Scenarios in which CASE technologies play an important part in resolving the current problems have been described in Chapter 6, and a summary of the opportunities and barriers to progress have been presented in Chapter 7. A future vision with timescales, goals, and actions has been presented in Chapter 8.

The combination of need, opportunity, and entrepreneurial energy in the city provides a powerful foundation for taking imaginative strides. It is therefore recommended that:

- There is a significant volume of 'low-hanging fruit' which can be delivered at relatively low cost and in relatively short order. Opportunities include the electrification of the city's bus and taxi/private-hire networks, plus the introduction of flexible, on-demand, shared small-bus services. On-demand services could be particularly attractive as an alternative to conventional rural bus services wherever these are operated with a Local Authority subsidy.
- GCP/Combined Authority should play an active and enabling role in paving the way for further radical CASE-related transport improvements. GCP/CA should work pro-actively with suitable technology and business partners to explore and deliver CASE solutions wherever they have the potential to add value. The business 'roll call' in Cambridge provides an excellent starting point for the development of such collaborations.
- Using the unique assets of the city (particularly the guided busway and its proposed extensions, and the major employment campuses), GCP/CA should seek to attract government funding to the city to support CASE-related development and demonstration projects.
- GCP/CA should concentrate particularly on encouraging the development of *'fixed path'* autonomous electric systems. These should place an emphasis on light mass transit systems which are suitable not only for the city, but also for the re-development of:
    - rural connectivity along the old 'Beeching Lines',
    - the development of modern intra-regional connections (for example, along the Oxford-Milton Keynes-Cambridge corridor and the Cambridge-Stansted corridor).
- Whilst GCP/CA should focus on encouraging the development of fixed path systems, the major vehicle OEM's can be expected to make rapid progress with road-going SAE Level 4/5 systems for private cars. GCP/CA should therefore take steps to ensure that the city and its surrounding region is 'Autonomy Ready' by maintaining a watching brief and ensuring that essential infrastructure (e.g. communications systems, information systems, and traffic

control systems) are compatible with the emerging technical and operational standards for vehicles.

- GCP/CA should develop a budgeted plan within which a rational programme of activities can be developed. This plan should encompass:
    - **Immediate implementation (0 - 3 years)**: Low emission integrated public transport (buses, taxis/Private-Hires, micromobility solutions)
    - **Short-Term implementation (2 - 5 years):** On-demand, shared-ride, services for tactical transport provision
    - **Medium-term implementation (5 - 10 years):**
        - Integrated solution for Cambridge and its surrounding region, using Autonomous Mass Transit for strategic transport provision and a combination of on-demand shared ride and fixed-path light autonomous solutions for complementary 'tactical' transport provision.
        - Re-opening of selected 'Beeching Lines' in the wider Combined Authority area using Autonomous Mass Transit solutions.
    - **'Horizon pushing' activities (10 years +):** Level 5, free roaming L-SATS, and passenger carrying drones

- In light of the important position which traveller information systems occupy in the delivery of the vision outlined in Chapter 8, GCP/CA should consider taking a lead in promoting the formation of a Local Authority consortium to sponsor the development of an app (or apps) which provide real-time local travel planning information. This could be achieved by developing new, bespoke, products or, better, by creating a suitable mechanism for the development of localised versions of existing popular apps (e.g. CityMapper).

APPENDIX 1

The cost of running electric vehicles versus the cost of running conventional vehicles

Commercial operations such as bus, taxi, and home delivery services are driven primarily by considerations of cost and regulation. An outline cost analysis for each of these service types is presented in the following sections.

In the tables presented, costs which are identical between conventional and electric vehicles have been omitted since they make no difference to the balance of costs. (Examples include vehicle insurance, tyres, etc).

Buses

ITEM	**Annual Cost over 12 Year Life** Single-deck, 10.5m Fleet of 10 vehicles (PVR = 9 + 1 spare)	
	Diesel Fleet of 10	Electric Fleet of 10
Unit Vehicle price	£160,000	£300,000
Annual Fleet Depreciation Costs (10 vehicles)	**£145,000**	**£270,000**
Annual mileage	489,000	489,000
Diesel Fuel costs @ 8.0 MPG and £0.61/litre	£170,000	
Electricity Costs @ £0.11/kWh (with non-electric heating)		£125,000
Less LEG Grant (0.0965ppm)		(£49,000)
Annual Net Fuel Costs	**£170,000**	**£76,000**
Tyre costs	Not included	Not included
Major Units	£25,000	
Battery replacement (assumes battery life = 6 years)		£100,000
Parts and Materials	£16,000	£12,000
Other Engineering	£4,000	£3,000
Wages and salaries	£85,000	£75,000
Average Annual Maintenance & Engineering Costs	**£130,000**	**£190,000**
Total Annual Cost	**£445,000**	**£536,000**
Life Cost over 12 years	**£5,430,000**	**£6,432,000**

Private-Hire Operations

Private hire (PVH) is the most common form of 'taxi' service. Every city and town in the UK has a local PVH operator and many of the larger operators deliver more passenger-miles per day than the timetabled bus services. The advent of hand held devices and apps has made access to these services much more convenient and the cost per passenger-mile is constantly being pared down.

The PVH business model is almost universally based on owner-driver operations. This means the cost of the vehicle and its day to day running costs are borne entirely by the driver, and any attempt to introduce electric vehicles needs to win the hearts and minds of these individuals. This means that the costs must be positive and confidence in the range and reliability must be high.

PVH drivers favour the use of pre-owned mid-size family saloon or hatchback vehicles with four doors and good luggage space. Until recently, very few electric cars met this requirement and, even when they did, they did not have sufficient operational range (typically 120 miles per day). However, several new models now have a range of 150+ miles and represent genuine options. Because of their long range, these vehicles only require access to public realm charge points for 'comfort' purposes.

Cost comparisons for various different options are summarized below.

Cost of Running a Conventional (Used) Vehicle

ITEM	CONVENTIONAL VEHICLE (Second-hand Toyota Avensis)	
Annual cost of loan for purchase (3 years)	£3,000 (approx.)	Assumes purchase price is £8,000(plus finance costs) and zero residual value for the vehicle
Annual fuel cost	£6,400	Assumes 40mpg and 40,000 miles per year @ £6.40 per gallon
Annual servicing and maintenance (excluding tyres)	£2,000	Assumes driver self-maintenance
Annual road tax	£200	
Total Annual Cost	**£11,600p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£11,600**	Adjusted cost = (annual cost - vehicle residual value)/3

Cost of Running a New Hybrid Vehicle

ITEM	NEW HYBRID VEHICLE (Toyota Prius)	COMMENT
Car Loan (brand new vehicle – loan agreement over 4 years)	£7,000	MRP when new = £23,500 Assume 4 year loan at £7K p.a. Residual value at end of 3 years/120,000 miles = £6,000 (approx)
Fuel	£4,000	Assume £16/day for 250 days (approx. 40,000 miles per year at 60mpg)
Annual servicing & maintenance	£1,000	Dealer serviced with new vehicle warranty – excludes tyres and other consumables
Annual road tax	Nil	
Total Annual Cost	**£12,000p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£10,500**	Adjusted cost = (annual cost - vehicle residual value)/4

Cost of Running a Used Hybrid Vehicle

ITEM	2nd Hand HYBRID VEHICLE (Toyota Prius)	COMMENT
Annual cost of loan for purchase (3 years)	£3,500	Assumes purchase price is £9,500 (plus finance costs) and zero residual value for the vehicle after 3 years
Fuel	£4,000	Assume £16/day for 250 days (approx. 40,000 miles per year at 60mpg)
Annual servicing & maintenance	£2,000	Dealer serviced with new vehicle warranty – excludes tyres and other consumables
Annual road tax	£Nil	
Total Annual Cost	**£9,500p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£9,500p.a.**	Adjusted cost = (annual cost - vehicle residual value)/3

Cost of Running an New Electric Vehicle

ITEM	NEW ELECTRIC VEHICLE	COMMENT
Car Loan (brand new vehicle – loan agreement over 4 years)	£8,500	Brand new Nissan Leaf or Kia e-Niro, net of gov't grant = £30,000 approx. Assume 4 year loan at £8.5K p.a. Residual value = £0
Fuel	£1,100	Assumes 40,000 miles per year @ 4 miles/kWh and 11p/kWh ('white meter' tarrif)
Annual servicing & maintenance	£1,000	Dealer servicing plus new vehicle warranty (excludes tyres and other consumables)
Annual road tax	Nil	
Total Annual Cost	**£10,600p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£10,600**	Adjusted cost = (annual cost - vehicle residual value)/4
Range	**150+ miles (e-Niro)**	Daily mileage approx. 120 - 150 miles. Will need occasional access to public realm charge points.

Hackney Carriage Operations

The best example of this service is the London 'Black Cab'. Whilst Hackney Carriage services are found in most towns, they are generally much smaller operations than the competing PHV services.

In all cities, HC services are closely overseen by the Local Authorities. In London, TfL is responsible for oversight and the London Mayor also has a strong hand. As a result, it is not possible in London to buy a new diesel cab; all new cabs have been mandated to be hybrid or pure electric since 2018. The new range-extended vehicle by London Electric Vehicle Company (LEVC) is fast becoming a common sight on London's roads. It remains to be seen whether other cities follow suit.

Cost of Running a Conventional Vehicle

ITEM	CONVENTIONAL DIESEL TX-4	COMMENT
Cab Loan	£5,720	Assume Manufacturer's Finance package at £110/week for a 2017 reg vehicle (vehicle price = £37,000)
Fuel	£9,000	Assumes 25,000 miles per year @ 18mpg
Annual servicing & maintenance	£2,500	Excludes tyres and other consumables
Annual road tax	£200	
Total Annual Cost	**£17,420p.a.**	

Cost of Running an Electric Vehicle

ITEM	NEW ELECTRIC VEHICLE (LEVC – TX)	COMMENT
Cab PCP Plan	£9,780	Assume LEVC Finance package at £188/week (New vehicle price = £57,000)
Fuel	£1,200	Assumes 25,000 miles per year @ 2.5 miles/kWh and 11p/kWh ('white meter' tarrif)
Annual servicing & maintenance	£1,000	Dealer servicing plus new vehicle warranty (excludes tyres and other consumables)
Annual road tax	Nil	
Total Annual Cost	**£11,980p.a.**	
Range	**70 miles**	Daily mileage approx. 100 miles. Will need regular access to public realm charge points (but can use range-extender engine if necessary).

On-Demand Bus Operations

On-Demand bus (ODB) is a new type of public transport service which has become popularised by high profile tech-sector companies like Via-Van and others. Typical vehicle types which are used are large MPV's or medium minibuses.

At present, very few ODB services are operating electric vehicles. However, suitable electric vehicles are beginning to appear in this segment and the options are summarised below. The medium minibus-style electric vehicles are severely compromised by their high price and restricted range, but the smaller MPV-style vehicles appear to be quite an attractive choice.

Cost of Running a 15-seater Conventional Vehicle

ITEM	CONVENTIONAL VEHICLE ANNUAL COSTS	COMMENT
Loan Costs	£7,000	Assume Ford Transit or Peugeot 17-seat Minibus @ £24,000. 4 year loan at £7,000p.a. Residual Value = £4,000
Fuel	£10,800	Assumes 45,000 miles per year @ 27mpg
Annual servicing & maintenance	£1,000	Assumes dealer servicing and new vehicle warranty. Excludes tyres and other consumables
Annual road tax	£150	
Total Annual Cost	**£18,950p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£17,950**	Adjusted cost = (annual cost - vehicle residual value)/4

Cost of Running a 15-seater Electric Vehicle

ITEM	NEW ELECTRIC VEHICLE ANNUAL COSTS	COMMENT
Loan Costs	£15,000	Assume electric version of Mercedes Sprinter or Renault Master mini-vans (or similar) @ £60,000 less gov't grant = £52,000. 4-year loan at £15,000 p.a. Residual value = 0
Fuel	£3,600	Assumes 45,000 miles per year @ 1.5 miles/kWh and 12p/kWh (industrial tarrif)
Annual servicing & maintenance	£1,000	Dealer servicing plus new vehicle warranty (excludes tyres and other consumables)
Annual road tax	Nil	
Total Annual Cost	**£19,600p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£19,600p.a.**	Adjusted cost = (annual cost - vehicle residual value)/4
Range	**90 -100 miles**	Daily mileage approx. 120 miles. Will need regular access to public realm charge points.

Cost of Running a 7-seater Conventional Vehicle

ITEM	CONVENTIONAL VEHICLE ANNUAL COSTS	COMMENT
Loan Costs	£6,500	Assume Nissan NV-200 Combi or similar @ £22,000. 4 year loan at £6,500p.a. Residual Value = £4,000
Fuel	£8,400	Assumes 45,000 miles per year @ 35mpg
Annual servicing & maintenance	£1,000	Assumes dealer servicing and new vehicle warranty. Excludes tyres and other consumables
Annual road tax	£150	
Total Annual Cost	**£16,050p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£15,050p.a.**	Adjusted cost = (annual cost - vehicle residual value)/4

Cost of Running a 7-seater Electric Vehicle

ITEM	NEW ELECTRIC VEHICLE ANNUAL COSTS	COMMENT
Loan Cost	£9,000	Assume Nissan eNV-200 @ £32,000 (net after gov't grant). 4 year loan at £9,000p.a. Residual Value = £0
Fuel	£2,700	Assumes 45,000 miles per year @ 2 miles/kWh and 12p/kWh (industrial tarrif)
Annual servicing & maintenance	£1,000	Dealer servicing plus new vehicle warranty (excludes tyres and other consumables)
Annual road tax	Nil	
Total Annual Cost	**£12,700p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£12,700p.a.**	Adjusted cost = (annual cost - vehicle residual value)/4
Range	**100 miles**	Daily mileage approx. 120 miles. Will need occasional access to public realm charge points.

Home Delivery Operations

Cost of Running a Conventional Home Delivery Vehicle

ITEM	CONVENTIONAL VEHICLE ANNUAL COSTS	COMMENT
Loan Costs	£7,500	Assume Ford Transit with box van refrigerated body or similar @ £25000. 4 year loan at £7,500p.a. Residual Value = £4,000
Fuel	£7,600	Assumes 35,000 miles per year @ 30mpg
Annual servicing & maintenance	£1,000	Assumes dealer servicing and new vehicle warranty. Excludes tyres and other consumables
Annual road tax	£150	
Total Annual Cost	**£16,250p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£15,250p.a.**	Adjusted cost = (annual cost - vehicle residual value)/4

Cost of Running an Electric Home Delivery Vehicle

ITEM	NEW ELECTRIC VEHICLE ANNUAL COSTS	COMMENT
Loan Cost	£15,000	Assume electric version of Mercedes Sprinter or Renault Master mini-vans (or similar) @ £60,000 less gov't grant = £52,000. 4-year loan at £15,000 p.a. Residual value = 0
Fuel	£2,800	Assumes 35,000 miles per year @ 1.5 miles/kWh and 12p/kWh (industrial tarrif)
Annual servicing & maintenance	£1,000	Dealer servicing plus new vehicle warranty (excludes tyres and other consumables)
Annual road tax	Nil	
Total Annual Cost	**£18,800p.a.**	
Annual Cost Adjusted for Vehicle Residual Value	**£18,800p.a.**	Adjusted cost = (annual cost - vehicle residual value)/4
Range	**90 - 100 miles**	Daily mileage approx. 100 miles, but re-charges exclusively in depot. Has no need of public charging infrastructure.

APPENDIX 2
Summary of the T-CABS Business Case

Route

A map showing the route of the proposed T-CABS service is shown in Fig 1 below. The service is intended to operate on the southern section of the Cambridge Guided Busway when regular bus services are not running (i.e. during out-of-hours periods overnight and on Sundays).

Fig 1 Southern Busway Route for T-CABS

Service Quality

The new opportunities for public transport which are opened-up by the advent of autonomous vehicles revolve around the ability to provide improved quality of service. Quick, frequent, services and affordable fares are fundamental to this proposition.

The Business Case previously developed for the Southern Busway operation is summarised in the following sections. The intention is to provide a combination of journey times, service frequencies, and fares which, taken together, are more attractive to travellers than the current bus services.

Journey Times and Service Frequencies

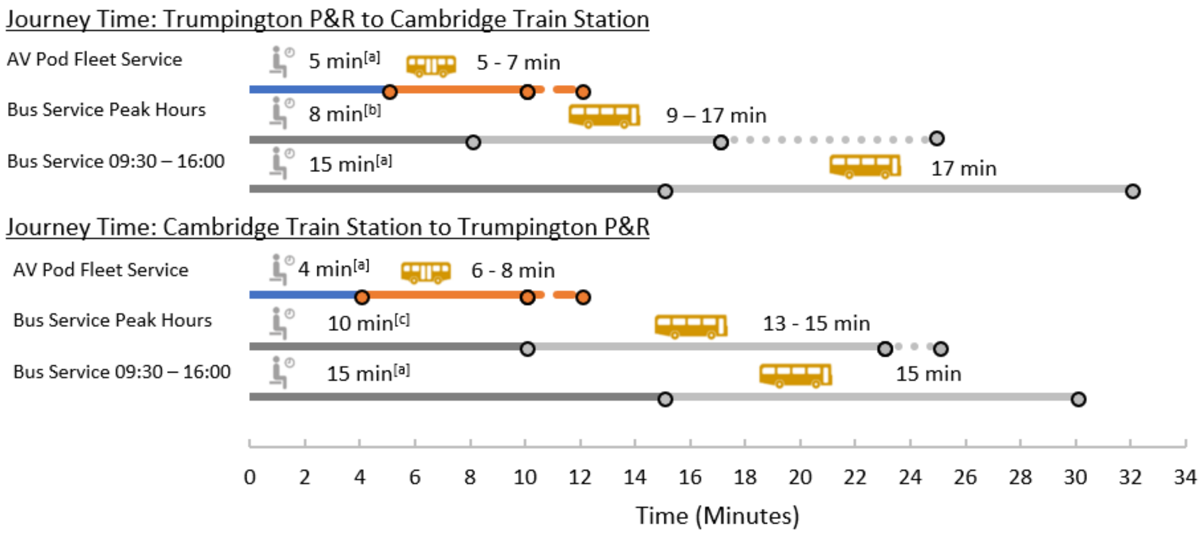
In order to deliver attractive journey times, the autonomous vehicles will need to travel at speeds in the region of 30-40mph. For a shuttle travelling at a maximum speed of 30mph, the journey transit times on the busway are shown in Fig 2 below. (Note, the current bus services run at a maximum speed of 50mph, but the shuttle speed deficit can be compensated for by more frequent departures as discussed in the following section - see also Fig 3).

Fig 2 Key Journey Times for an Autonomous Shuttle Service on the Southern Busway

With regard to departure frequencies, the business case was developed using a variety of different assumptions about passenger demand rates. The most difficult use case was found to be the ‘surge’ condition associated with the arrival of a train at the station, or a staff shift change at the CBC.

A 15-passenger vehicle was selected as the best compromise for balancing passenger transfer rates with fleet capital and operational costs. It was shown that a relatively small fleet of 15-passenger vehicles could ensure that passengers would have waiting times of no more than 5 minutes during the normal service period and no longer than 10 minutes during the occasional surge period. These figures easily improve upon the current bus departure frequencies of 10 minutes (during peak times), and 15 or 20 minutes (during off-peak times).

Based on the journey times shown in Fig 2, and the wait times outlined above, the overall level of service offered by the autonomous shuttle system would be far superior to that which is currently offered by the bus during daytime hours. This is illustrated in Fig 3 below.



[a] Maximum 'wait time' (the interval between consecutive vehicle departures). Vehicle departure is at regular intervals.
[b] Median wait time as bus departure times are at irregular intervals. Wait times are between 7 - 30 mins in this period.
[c] Median wait time as bus departure times are at irregular intervals. Wait times are between 2 - 30 mins in this period.

Fig 3 Journey Times Offered by Autonomous Shuttle System Compared to Current Bus Services

Ridership and Revenue Generation

Two business case assessments were produced. The first was for an out-of-hours service, in which the autonomous shuttle fleet was mobilised only when daytime bus services were not in operation. This represents a cautious starting point for autonomous operations, but it limits the number of travellers which can be served and impairs the overall business case. For this reason, a second business case was developed in which it was assumed the technical credibility of the service had been demonstrated and a good level of public acceptance had been created. Based on these assumptions, it was postulated that the autonomous shuttles would replace the daytime bus services, and the business case was re-calculated using the much higher levels of demand seen during daytime periods.

Out-of-hours Services

The passenger demand for out-of-hours services was estimated by considering journeys which arise from two principal sources:

1) People working shifts at the Cambridge Biomedical Campus (CBC)
2) Late-returning (or Sunday) commuters who return to Cambridge Station and live to the south-west of Cambridge (using the Trumpington Park & Ride).

A summary of the estimated levels of journey demand is presented in Table 1 below (single passenger journeys):

LOCATION	**Weekday Night** (9:00pm – 6:00am)	**Weekend Night** (9:00pm – 6:00am)	**Sunday** (6:00am – Midnight)
Addenbrooke's CBC	393	142	306
Cambridge Train Station	150	217	500
Trumpington P&R	553	380	858
TOTAL	1,096	739	1,664

Table 1 Overnight Journey Demand Estimates

The annual cost of operating a variety of different fleet sizes was assessed and the results are summarised in Table 2 below. There are some important assumptions which underpin the figures presented, the most significant of which are:

1) The purchase price of the vehicles assumes that reasonable maturity in the market has been achieved.
2) The service life of the vehicles has been set at 10-years. (Replacement with new vehicles is assumed at that stage).
3) Local Government rates of borrowing can be accessed for the purchase of vehicles, monitoring/communications equipment, and upgrades to infrastructure.
4) The vehicles can be operated without safety drivers/attendants in the vehicles.
5) The system can be supervised from a single control centre with a level of staff oversight that is independent of vehicle numbers.
6) The number and length of passenger journeys is unchanged with increasing fleet size. It is just the quality of service (wait time) which changes. The fuel costs are independent of fleet size.

Each of these key assumptions can be questioned and tested. The figures presented here are provided only for illustrative purposes.

Number of 15-Seat Pods	**12**	**15**	**17**	**24**	**27**	**29**	**36**	**39**	**41**
Cost of Vehicle	£100,000	£100,000	£100,000	£100,000	£100,000	£100,000	£100,000	£100,000	£100,000
Total Cost of Vehicles	£1,200,000	£1,500,000	£1,700,000	£2,400,000	£2,700,000	£2,900,000	£3,600,000	£3,900,000	£4,100,000
Station Capacity per 10 mins	60	60	60	120	120	120	180	180	180
10 min Surge Capacity at any departure point	60	105	135	120	165	195	180	225	255
Number of Pods at each departure point	4	4	4	8	8	8	12	12	12
Number of Junction waiting bays	0	3	5	0	3	5	0	3	5
Infrastructure	£500,000	£500,000	£500,000	£500,000	£500,000	£500,000	£500,000	£500,000	£500,000
Busway Modifications / Stabling etc	£1,000,000	£1,000,000	£1,000,000	£1,000,000	£1,000,000	£1,000,000	£1,000,000	£1,000,000	£1,000,000
Capital and Interest Repayments (10 year 3% bond) on vehicles, infrastrucutre and minor works	**£362,857**	**£403,175**	**£430,053**	**£524,127**	**£564,445**	**£591,323**	**£685,397**	**£725,715**	**£752,593**
Fuel (Electricity) Costs	**£55,000**	**£55,000**	**£55,000**	**£55,000**	**£55,000**	**£55,000**	**£55,000**	**£55,000**	**£55,000**
Staff Costs	**£460,000**	**£460,000**	**£460,000**	**£460,000**	**£460,000**	**£460,000**	**£460,000**	**£460,000**	**£460,000**
Vehicle Maintainance	**£12,000**	**£15,000**	**£17,000**	**£24,000**	**£27,000**	**£29,000**	**£36,000**	**£39,000**	**£41,000**
Insurance	**£18,000**	**£22,500**	**£25,500**	**£36,000**	**£40,500**	**£43,500**	**£54,000**	**£58,500**	**£61,500**
TOTAL COST p.a.	**£907,857**	**£955,675**	**£987,553**	**£1,099,127**	**£1,146,945**	**£1,178,823**	**£1,290,397**	**£1,338,215**	**£1,370,093**

Table 2 Fleet Size Versus Cost of Operations

The revenues generated by the estimated passenger numbers are directly related to the ticket-price and this dependency is summarised in the table below.

Total Weekly Out of Hours Journeys:	7883							
Single Fare per Trip	£1.00	£1.50	£2.00	£2.50	£3.00	£3.50	£4.50	£5.00
Weekly Income	£7,000	£11,000	£15,000	£19,000	£23,000	£27,000	£35,000	£39,000
Annual Income	**£364,000**	**£572,000**	**£780,000**	**£988,000**	**£1,196,000**	**£1,404,000**	**£1,820,000**	**£2,028,000**

Table 3 Annual Revenue as a Function of Fare Price

Based on these estimates, it can be seen that an out-of-hours service with a good level of 'surge capacity' (29 shuttles providing a peak capacity of 195 passengers during a 10 minute period) would require a single journey fare to be set at around £3.00. By way of reference, this compares with £2.80 for a single fare which is the current price of a single journey using the Stagecoach service.

NOTE: *The £2.50 fare shown above includes repayment of all capital sums associated with fleet purchase and infrastructure upgrade.*

Daytime and 24-hour Services

The business case was then extended to explore the characteristics of a future situation in which the autonomous shuttle service entirely replaces conventional bus services. The daytime levels of ridership are much higher and, as a consequence, the revenues are much higher. However, the capital costs associated with the infrastructure and fleet purchase are unchanged. As a result, it was calculated that a superior level of service could be provided, and an annual break-even condition could be generated, with fares as low as £0.75p per single journey.

Conclusions

For guided busway services of the type proposed for the T-CABS project:

1) Autonomous shuttles are capable of delivering a transport service which is far superior to that which can be offered by conventional buses.
2) Such services might be delivered at economic payback rates over a vehicle service life of 10 years.
3) Using a fleet of around 30 shuttles, passenger wait times would not exceed 5 minutes at any point on the system over a 24-hour period, except in the most arduous short-term surge conditions at the railway station.
4) In surge conditions, the fleet would have the capacity to move 195 passengers every 10 minutes (this matches a double-decker bus running every 4 minutes).
5) The flat-rate fares required to generate break-even financial performance whilst providing this level of service are around £3 per single journey in cases where operations are for overnight/weekend periods only, and around £0.75p per single journey where operations span a full 24 x 7 timetable.