smart CAMBRIDGE

Affordable Mass Transit for Cambridge and the Wider Region

GREATER CAMBRIDGE PARTNERSHIP
Growing and sharing prosperity
Delivering our City Deal

CAMBRIDGE AHEAD

“The sign of a developed society is not that even the poor have cars; it is that even the affluent use public transport”.

Enrique Penalosa – Mayor of Bogota (paraphrased)

Foreword

Cambridge is where the atom was split, the structure of DNA was discovered, the jet engine was created and where countless other world-changing ideas have and continue to be developed.

For 800 years the University, the City, and the wider Cambridge region have benefited from energetic collaboration between civic society, academia, and commerce. The last 50 years have seen a remarkable development of knowledge-intensive clusters that has made Cambridge a household name around the world, created the biggest entrepreneurial powerhouse in the world outside Silicon Valley, and made the area synonymous with science, technology, and creative thinking.

The result is a thriving, growing economy that is bringing jobs and opportunities for the whole region. But the rapid expansion means Cambridge and surrounding areas needs ever more, and better, housing and transport as well as a skilled workforce to sustain this success.
Increasing pressure on the transport network and the stifling effect of traffic congestion is a major challenge that needs transformative solutions to maintain growth and the quality of life for those who live and work in and around the city, and beyond.

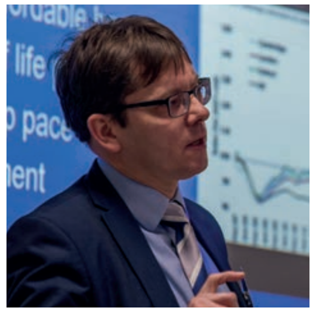
This report continues the tradition of collaboration, taking an idea that originated within the University and developing it into a concept which might serve Cambridge and the wider region. In future, it may also serve the needs of many other small, vibrant, cities across the UK and abroad.

The Greater Cambridge Partnership (formerly City Deal) and Cambridge Ahead co-funded the study with the University, and worked together to ensure that it looks at the options for the whole travel to work area.

The study represents a truly creative approach to a very real problem: how to use new and future technologies to transform our local transport system to make better connections between Cambridge and surrounding towns and villages, but within a capital and operating budget that is affordable and viable for a small but growing city region

The report illustrates the nature of what might be. It seeks to contribute to the debate, rather than proposing a definitive solution. It represents the continuing spirit of collaboration in Cambridge between civic, academic, and commercial minds and it will be one of the options to be considered as we develop our thinking on future transport for Cambridge and the wider region

Rachel Stopard
Interim CEO
Greater Cambridge Partnership



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VOLUME 2
System Architecture Options

1. Introduction

The City of Cambridge and its surrounding sub-region is one of the most vibrant, expanding, economic zones in the UK. In addition to a strong, home-based, industrial and commercial base, the international 'pull' of the University has brought many global tech companies to set up research centres and laboratories in, or near, the city. This, plus a large number of spin-outs and start-ups, has led to the description of the sub-region as 'Silicon Fen' – one of the world's most successful and dynamic technical/entrepreneurial centres outside Silicon Valley.

But the economic success of the city has come at a price. The ancient layout of the central part of the city was conceived in a previous age and whilst beautiful and precious, it is not well suited to addressing the needs of modern day housing and transport. The immediate surrounds of urban expansion were developed in the late 19th and early 20th centuries, with post-war developments tending to be in locations more remote from the city. These patterns of development pose different, but equally difficult, challenges from a housing and transport viewpoint. The consequence is that, whilst the city continues to attract an increasing population, housing has become very expensive and gridlock has occurred on the roads at peak travel hours.

There have been serial efforts over the years to relieve these problems using various different approaches, but the growth in demand continually outpaces the resulting benefits. Many observers are coming to the view that a transformative approach needs to be taken, one which can more fully meet the needs of the future city and its surrounding area, both in relation to congestion and as a means of easing the acute problems of housing affordability and availability. Bringing more of the surrounding area within easy commuting distance of key employment centres will be of enormous advantage in future years.

This report explores one such possibility: the introduction of a new, 21st Century, form of mass transit. The scheme proposed uses autonomous vehicles which are designed to work on segregated corridors running at surface level through extra-urban areas and through a network of small-bore tunnels within the city limits. The use of tunnels has big advantages with regard to limiting the intrusion of a new, segregated, public transport system within a city which has many ancient buildings, but it introduces cost disadvantages. The work completed to date suggests that, provided the tunnel bores can be kept below 3.7m internal diameter, the cost disadvantages can be contained within a system which, at the headline level, is about half the cost of a conventional mass-transit system of similar coverage.

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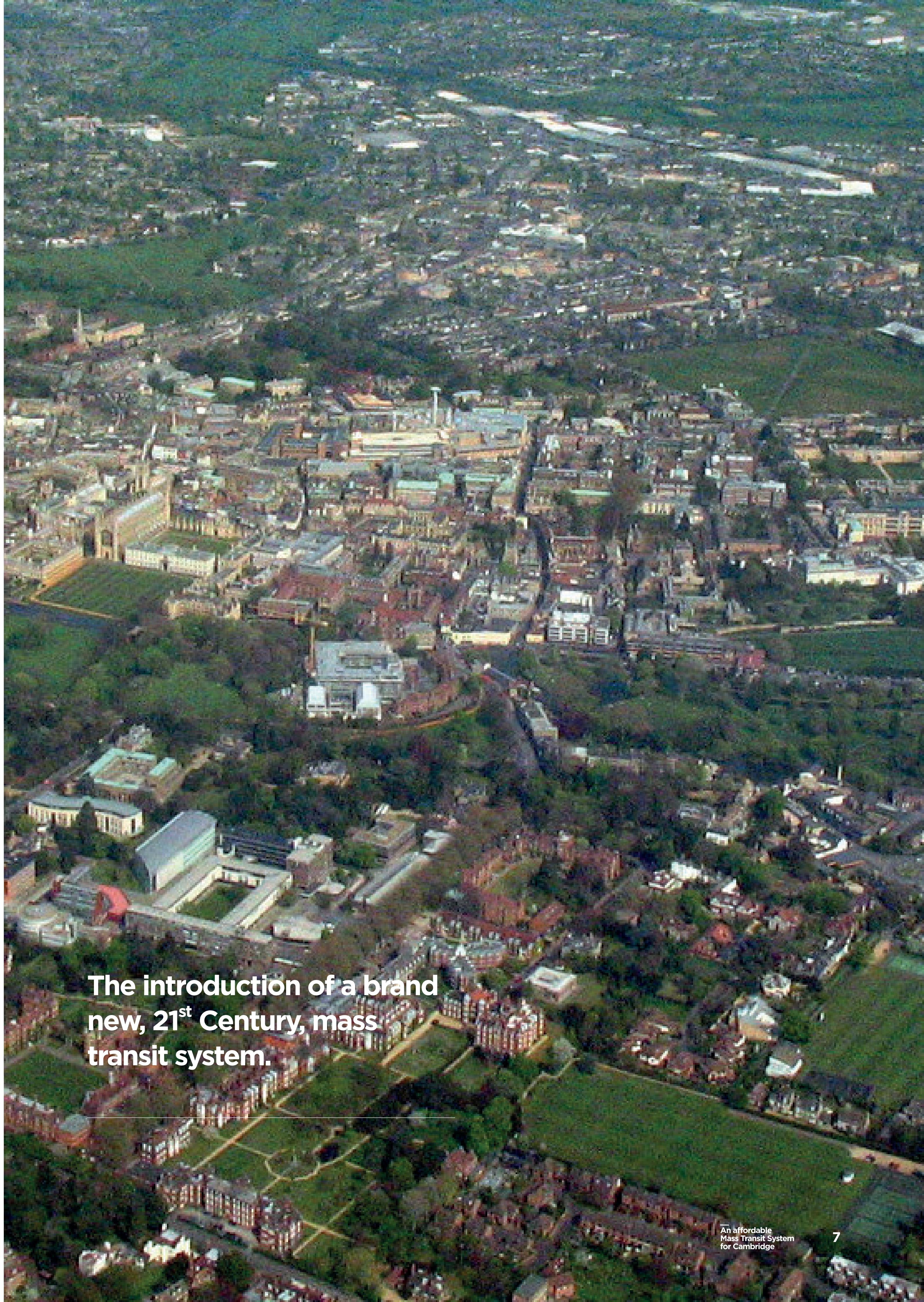

2. Mass Transit – the Background

Mass transit systems are an essential part of the infrastructure for all large cities around the world. London's Underground system is the original example, but its precedent has been followed all round the world and the recent examples of new metro systems in Moscow, Shanghai, and Singapore illustrate the great impact which such systems have on the effective working of their cities.

In the UK, there has been an explosion of interest in tram and light-rail systems in the UK over the past 35 years. As a result, there is plenty of historic data on which to base estimates for cost and other parameters when assessing new schemes – but this body of data leads to a number of disappointing conclusions:

1. **The cost-per-mile is high (typically in the range £16M-25M/km at 2016 prices). For a system of only modest length (50-60kms), capital expenditures in the order of £1BN+ are to be expected;**
2. **As a result, such systems can only be justified for very large passenger flows (typically 5,000-10,000 passengers per hour, each line, each direction). Only very large cities have such high and consistent levels of demand;**
3. **The surface traffic disruption caused during construction is massive. Worse, it frequently requires demolition of parts of the existing built environment – a course of action which is expensive and, often, culturally undesirable.**

These conclusions pose particular difficulties for a city like Cambridge. The city has a dense central zone layout and a multitude of ancient buildings which makes the insertion of a new fixed-infrastructure public transport system both contentious and technically very difficult. Worse, whilst Cambridge already suffers stifling traffic congestion (and this is universally expected to get worse), the levels of ridership which might be generated within the city over the next few decades are more likely to be in the realm of 2,000-3,000 passengers per hour than the 5,000+ passengers per hour which might be needed to make a light rail system viable.

What's needed, therefore, is a new form of mass-transit system that meets the needs of Cambridge and other small cities UK and world-wide. The solution must be evidence-based, attractive, and fit for purpose, taking advantage of modern technologies to side-step some of the inherent disadvantages of conventional mass-transit systems. The goal must be to provide levels of service that are so attractive that the use of mass transit becomes the decision of choice across all sectors of society whilst, simultaneously, the capital and operating costs are reduced to levels that are affordabe for a smaller city-region like cambridge.

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Modern tram/light-rail solutions provide an attractive form of public transport and a number of new systems have been built in the UK over the past 35 years. But, due to their needs for substantial rail and overhead power infrastructure, frequent stations/stops, and the massive surface disruption caused during construction, they come at a heavy installation price to the host city.

3. Patterns of Transport Demand

The definition of an appropriate form of mass-transit system for Cambridge must be built on evidence-based need. The first step in this process must be to examine the existing transport statistics and traffic flows and understand the nature and quantum of demand.

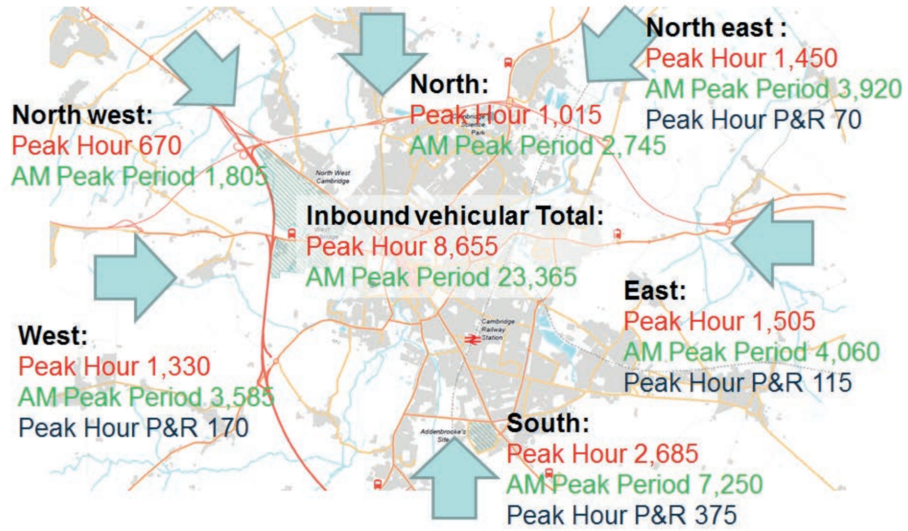
The current patterns of road use, based on data provided by the County Council and augmented by additional research within this project, are summarised on the opposite page.

Cambridge suffers a 'tidal-flow' problem at the morning and evening peak hours caused by commuters and visitors, many of whose journeys start well outside the city boundaries.

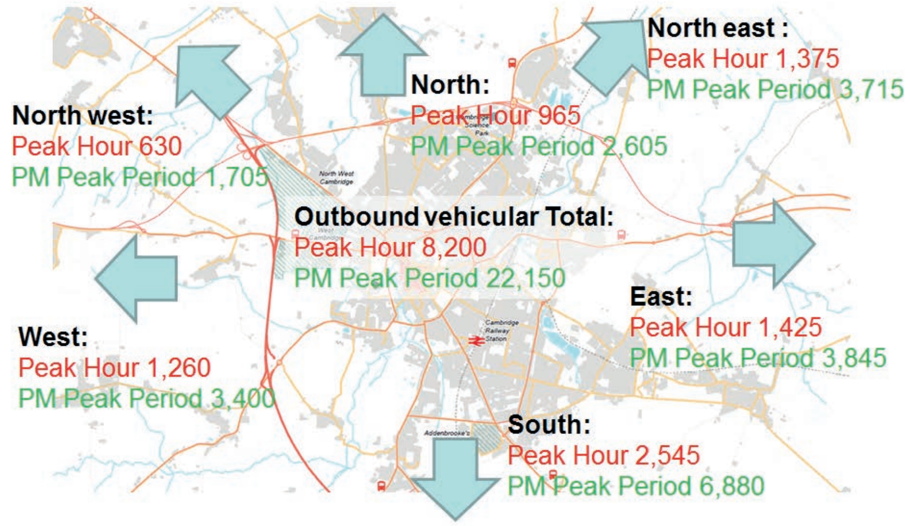
These flows, plus the plans for new housing and commercial developments which are currently being enacted within the sub-region, lead to the following observations:

- **Cambridge suffers a 'tidal flow' problem at the morning and evening peak times in which the major flows of traffic are caused by commuters and visitors, many of whose journeys start well outside the city boundaries;**
- **Given the constraints on building significant additional residential property within the city limits, future population growth will probably be largely met by residential developments which are built outside the city (e.g. Cambourne, Northstowe, Waterbeach, etc). In the absence of significant investment in public transport alternatives, this will aggravate the 'tidal flow' problems;**
- **The current peak movement levels lie in the region of 1,000-2,000 passengers per hour on each of the main arterial routes. Allowing for the growth in demand which will accompany the new residential developments outlined above, this figure might be expected to rise to the region of 2,000-3,000 passengers per hour within the next decade;**
- **Visitor movements form an important sub-set of the tidal-flow problem. Significant numbers of tourists arrive from London and other places in large touring coaches which have a disproportionate effect on busy traffic flows and parking accessibility within the city limits;**
- **In addition to all of the above is the regular movement of goods and freight into, and out of, the city. Most of the retail premises in the city centre area receive daily deliveries and many of the commercial premises in the surrounding urban areas have daily delivery and despatch activities;**
- **Superimposed on the main tidal flow pattern of demand is a 'random motion' element in which people and goods move relatively short distances at unpredictable times. These trips link origins to destinations which both lie within the city limits. (Shopping trips and business visits from one local location to another are good examples of this).**

AM Peak Inbound Flow Summary (Cars)



PM Peak Outbound Flow Summary (Cars)



4. Re-Defining Mass Transit

Conventional mass-transit systems (tram, light-rail, and heavy rail) have evolved over a long period of time from an original concept which came from the Victoian era. Today's very sophisticated systems are far different from their fore-runners, but they still represent refinements of the original idea – vehicles hauled in linked sets running on steel wheels guided by steel rails. This formula reduces rolling resistance to a minimum and is well tried and tested. The downside, however, is that the system infrastructure is very expensive and is highly disruptive during the construction period.

If mass transit is to be re-defined in the 21st Century, how can capital costs be reduced substantially whilst ensuring that fast and reliable services are maintained? The solution proposed in the remainder of this report sets out to answer this question. It is referred to as AVRT – Affordable Very Rapid Transit. It could, in future, be a means of providing low cost mass transit for many small cities.

4.1 Fast and Reliable Services

The most important characteristic of mass transit systems is that they deliver fast and reliable services for travellers. This is in marked contrast to road-going public transport systems like buses and coaches.

The ability to deliver fast and reliable journey times can only be conferred through the use of segregated pathways. Bus services attempt to achieve this through the use of bus-only lanes, but traffic congestion in cities is often so bad that even the best enforced systems fail to maintain the necessary freedom of movement. Service levels are therefore compromised.

It is considered that segregation is the only practical means of ensuring service quality, *so the emphasis in any new mass transit concept must be on minimizing the cost of the segregated infrastructure.*

4.2 Reducing Infrastructure Costs

The fixed infrastructure represents the biggest source of cost in the entire system. It follows that any cost savings achieved on this front will dwarf all other sources of cost reduction.

The core elements of infrastructure cost may be broken down under the following headings:

- **Permanent way (the rails and sleepers);**
- **Power distribution systems (usually overhead wires for tram and light-rail);**
- **Signalling systems;**
- **Stations;**
- **Marshalling Yards & stabling.**

The logical steps to reducing the cost of any new system therefore follow the steps shown in the sequence of illustrations below.

1. Remove the overhead power distribution system (Fig A and B below). This can be achieved by adopting battery-powered electric vehicles using technologies found on bus fleets which are currently operating in Milton Keynes, Nottingham, and London;
2. Remove the rails and sleepers (Fig C below). This can be replaced with a simple tarmac-surfaced roadway;
3. Replace the vehicle's fixed steel wheels with steerable rubber-tyred wheels that will run and steer on the tarmac surface (Fig D below);
4. Remove the complex switching and signalling systems. This can be achieved by introducing wheel-steered vehicles with autonomous control and simplified Concepts of Operations (ConOps – see section 4.4 below);
5. Reduce, as far as possible, the cross-section of the vehicle so that the size of the supporting infrastructure can be minimized (Fig E and F below);
6. Simplify the design of stations/tram stops, and reduce their number.

STEPS TO MASS TRANSIT COST REDUCTION

Figure A

Figure B

Figure C

Figure D

Figure E

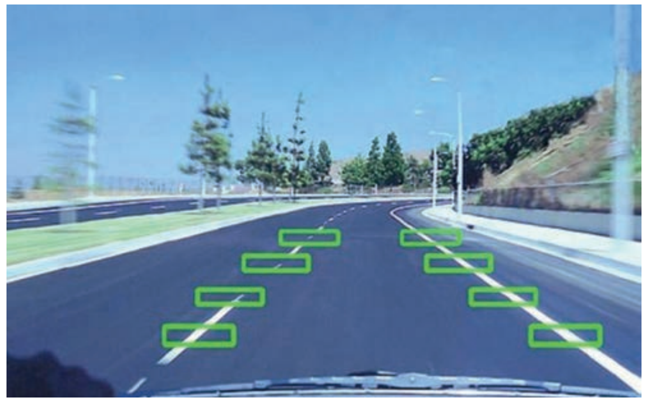
Figure F

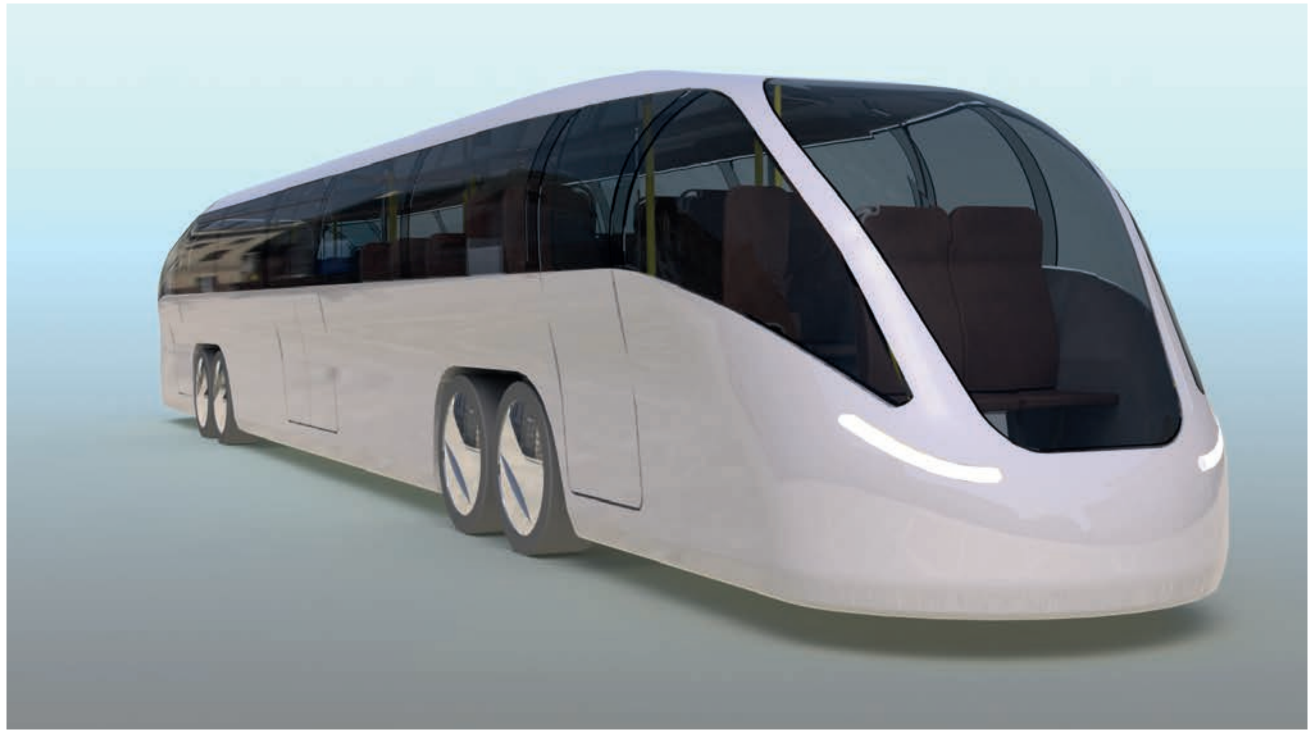
4. Re-Defining Mass Transit

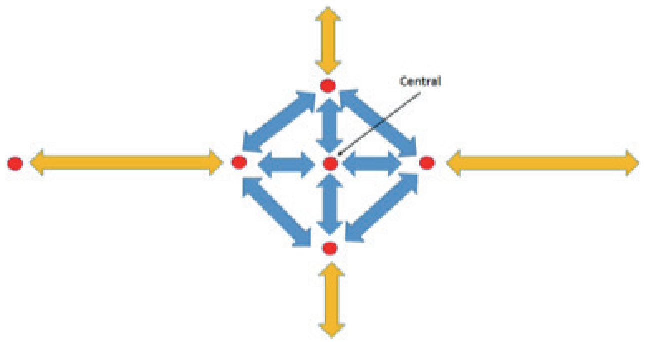
4.3 Vehicles

The technical specification for the vehicle is summarised in the table at the foot of the facing page. It is a vehicle which can run in either direction, so that it can reverse its travel without physically turning round. It has the smallest possible cross-section in order to minimize infrastructure cost and has wide, automatic, plug- doors arranged along its length to enable the swift entry and exit of passengers.

The vehicles are battery powered and designed to run on flat tarmac surfaces under autonomous control. This minimises both the capital costs and the operational costs. The result is a very simple, lightweight, vehicle which uses driverless technologies which are increasingly becoming available within the mainstream automotive industry. The vehicles can be electronically coupled to run in multiple sets during busy periods, and un-coupled to run efficiently with reduced passenger numbers in off-peak periods.

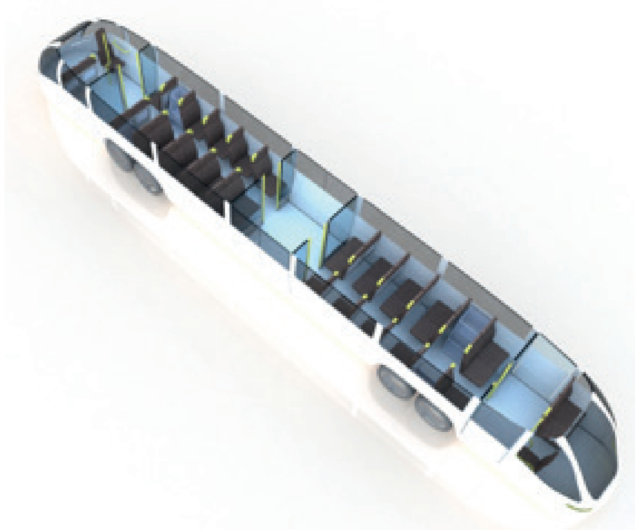






TECHNOLOGIES ADAPTED FROM SYSTEMS WHICH ARE BEGINNING TO APPEAR ON MAINSTREAM ROAD-GOING VEHICLES WILL ENABLE AVRT TO BE VERY COST-EFFECTIVE TO OPERATE. ELECTRONIC SENSORS WILL ALLOW VEHICLES TO FOLLOW SIMPLE LINES MARKED ON THE ROAD SURFACE, THUS ENABLING DRIVERLESS OPERATION.

INTER-VEHICLE COMMUNICATIONS SYSTEMS WILL ALLOW AVRT TO FORM 'ELECTRONIC CONVOYS' MUCH LIKE THOSE BEING DEVELOPED FOR FLEETS OF HEAVY GOODS VEHICLES. THIS WILL ALLOW THE CAPACITY OF EACH CONVOY TO BE VARIED IN RESPONSE TO DEMAND BY PICKING-UP, OR DROPPING OFF, ADDITIONAL VEHICLES.



4.4 Concept of Operations (ConOps)

A major part of the cost of building and commissioning any rail-based transport system lies in the cost of the signalling and movement control systems. Defining a style of operation which minimises these costs, without compromising the highest standards of safety, is a crucial element in defining the affordable mass-transit system. Adopting a 'shuttle' style of operation between the locations at which passengers board and alight would allow a very simple solution to be deployed.

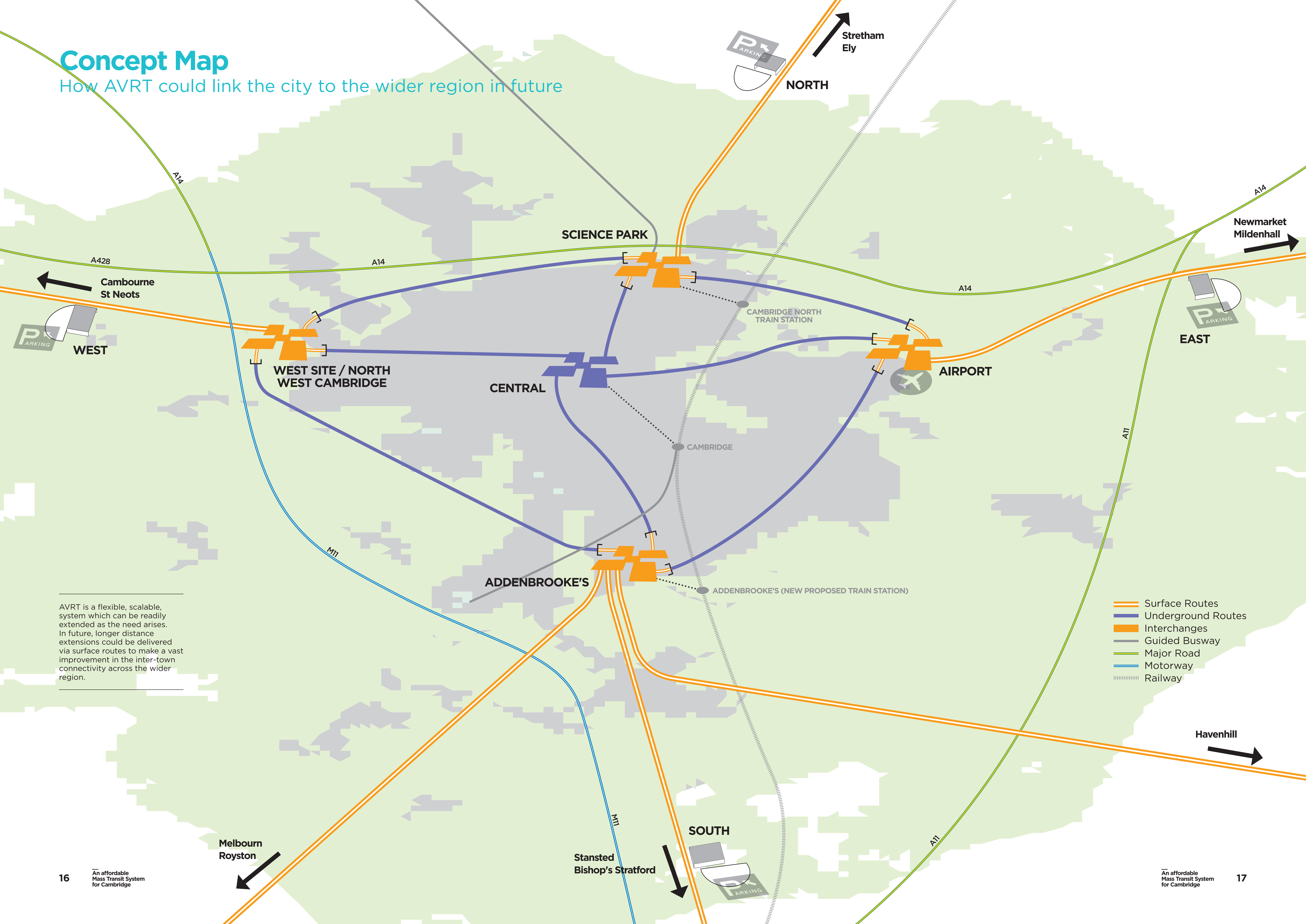
This concept is described in Appendix 1 which may be found at the end of this report. It is a very simple and attractive operational strategy, but it does have some important limitations. The most significant of these is that it precludes 'through journeys' (i.e. it requires passengers to change vehicles every time they pass through an interchange on the system). However, the overwhelming advantage is that it removes the need for complex signalling and movement controls. This enables safe two-way running on sections where single-track infrastructure has been built (thus reducing costs). It also allows the system to be deployed incrementally without disrupting services on previously completed legs.

For shuttling to be an acceptable operational concept, the process of transferring from one vehicle to another on a multi-leg journey becomes a critical element of the passenger experience. The design of the interchanges therefore becomes another critical design factor (see section 5.3.3 below).

Characteristic	Value
Dimensions	Length: 16m Width: 2.2m Height: 2.5m
Weight	16 tonnes
Propulsion System/Power	Electric motors (8x150kW)
Battery Capacity	200 kWh
Final Drive	8-wheel drive
Steering	8-wheel steer
Passenger Capacity	Approx. 40 passengers (all seated)

Concept Map

How AVRT could link the city to the wider region in future



AVRT is a flexible, scalable, system which can be readily extended as the need arises. In future, longer distance extensions could be delivered via surface routes to make a vast improvement in the inter-town connectivity across the wider region.

5. A System Architecture for Cambridge

To be successful, AVRT in Cambridge must offer a transport experience that is so attractive that travellers willingly relinquish their default use of the car for the majority of their visits to the city.
The system must also be affordable for a small but growing city like Cambridge, and flexible to changing patterns of transport demand, residential development, and employment. In construction terms, it must be scalable so that it can be deployed in stages without measurable disruption to the already functioning parts of the system. And, finally, it must avoid any prolonged surface disruption during construction either in the form of traffic disruption or building demolition. In short, it must be:

- **Attractive;**
- **Affordable;**
- **Scalable;**
- **Flexible;**
- **Non-intrusive.**

Within these parameters, AVRT must also meet the service requirements, and exhibit the system characteristics, which are outlined below.

5.1 Service Requirements

The service requirements for the system follow from the patterns of transport demand outlined in Section 3. They are:

- **Patterns of Demand:** The system must respond primarily to the 'tidal flow' aspects of the transport problem, but it must not be blind to the accompanying 'random motion' aspect. (Random, short-distance, journeys within the city boundaries are addressed in Section 7);
- **In-bound Origins:** The majority of the in-bound tidal flow problem comprises journeys in cars and touring coaches which originate well outside the city limits;
- **In-bound Destinations:** Tidal flow destinations are dominated by the major centres of attraction and employment (principally the city centre and the major campuses and business parks);
- **Outbound Movements:** The majority of the out-bound tidal flow movements are the reverse of the in-bound movements.

This statement of the problem suggests a solution which is designed to collect large numbers of in-bound commuters/visitors from locations outside the city and transfer them swiftly to their intended destinations inside the city (with the reverse requirement for out-bound commuters/visitors later in the day).

5.2 System Characteristics

A system topography which responds to these service requirements is presented in the illustration previous page. It has the following defining characteristics:

- **Park and Ride facilities, placed at a radius of approximately 10-12kms from the city centre, which facilitate access from all four points of the compass;**
- **Touring coaches from London and from other points to the south and west of cambridge;**
- **Interchange locations within the city limits that are defined by the major centres of visitor attraction and/or local employment.**

The new system must also have several further defining characteristics. For customers who have already travelled a significant distance in their cars (or coaches), the system must offer a service that is so attractive that they will make a willing decision to leave their vehicles at the Park & Ride – even though they are only 10-12kms from their intended destination. This means:

- **It must be quick and convenient to park the car/coach at the Park & Ride and transfer to the AVRT;**
- **The service must be so frequent and reliable that no timetable is necessary;**
- **The end-to-end journey from the point of embarkation to the intended destination must be substantially quicker than remaining in the car (where the car journey time includes the time required to find a suitable parking space);**

Parameter	Target	Commentary
CO_2 Emissions	Less than 30gms/passenger km	Must meet or beat the best standards of light-rail.
Flexibility	No significant operational restrictions when adding system extensions at a later date	Shuttle' style of operation is designed to facilitate this requirement (Appendix 1)
Maximum capacity at peak periods	2,000-3,000 passengers per hour	Represents the maximum transfer capacity in each direction on any one line. Should be sufficient to allow significant headroom for future expansion.
Efficient off-peak operating capacity	700-1,000 passengers per hour	Must be capable of operating efficiently for long periods of the day when ridership levels are well below peak.
Capital Cost (£/km)	£10M - £15 M per km	Represents approximately half the cost of a conventional light-rail system
Minimum Service Frequency	3 minutes	Defines the maximum wait during passenger transfer at an interchange
Maximum cross-city transit time	15 minutes	Represents the longest reasonable commuter journey from a remote Park & Ride to a major centre of attraction/employment at the far side of town (including transfers at interchanges).
Typical fare	£5 per day	Assumes a flat fare is payable by each passenger once per day. This fare would allow multiple journeys. (More complex fare structures could easily be devised, but simplicity is attractive)
Traffic disruption during construction	Minimal	No major city roads closed or inhibited during the construction period.
Buildings required to be demolished by the construction programme	Zero	No buildings demolished as a direct result of introducing the system

- **The all-in cost of using the system (i.e. the Park& Ride fee, plus the mass-transit fare, plus any bike-hire at the point of alighting – see Section 7) must be cheaper than the alternative of remaining within the car. The car comparator figure may, of course, be influenced by Local Authority policy in cases where it is deemed appropriate to introduce a congestion charge or parking levy;**
- **For commuters, the service must allow complete flexibility with regard to the time of their return journey (i.e. a late night at the office, or a visit to the theatre, will not cause them to miss the last service back to the Park & Ride to collect their vehicle).**

The final point above is very important in a social context. A vibrant, attractive, night-life requires public transport to run late-night, or even 24 hour, services

The table above summarises the performance requirements which have been used to develop proposals for an AVRT system for Cambridge.

5. A System Architecture for Cambridge

5.3 System Topography

The general topography proposed for Cambridge can be broken down into three distinct elements: extra-urban running legs, urban running legs, and interchanges. Each element has its own characteristics and design challenges.

5.3.1 Extra-Urban Running Legs

These running legs are typically some 10-12kms long but could be longer to link to key market towns. They are, characteristically, much longer than the urban running legs and there is, therefore, a need to minimise the cost per km for construction and maintenance. Because these legs run through open countryside, the simplest solution would be to run a simple tarmac-surfaced road at surface level with provision for either single, or two-way, running.

A preliminary assessment of the available route corridors suggests that roads running at surface level would be generally practicable, but there are numerous local features in the landscape which would require short sections of elevated running. As a general rule, the elevated sections will need to be minimised because of the significant increase in construction costs which accompany any requirement to build bridges and viaducts.

5.3.2 Urban Running Legs

Once the system enters the city limits, the landscape becomes much more difficult to negotiate. It is impractical to introduce a multi-line surface mass-transit system, which has the coverage required throughout the city, without running into near-impossible problems of traffic disruption and the need to demolish buildings. This violates two of the fundamental system performance requirements, not to mention the difficulties which would be associated with gaining the necessary public approvals and planning permissions.

The only practicable way of avoiding these difficulties would be to run the urban legs underground. This immediately introduces problems with the cost and complexity of tunnelling and any move in this direction could put the whole concept of low cost mass transit at risk. Careful consideration of this problem, however, has led to the conclusion that it might be possible to keep tunnelling costs within acceptable limits for the following reasons:

- **Cambridge sits on clay – this is an ideal medium for tunnelling and there is a huge body of technical experience in this field in the UK;**
- **The diameter of the tunnels can be kept relatively small (less than 4metres). The cost of tunnelling is highly dependent on the volume of material which has to be removed, so tunnel diameter is a highly important cost parameter;**
- **The length of the tunnelled legs can be kept relatively short (typically around 4-6kms).**

KEEPING THE COST OF THE INFRASTRUCTURE TO A MINIMUM IS ESSENTIAL. WHEREVER POSSIBLE SURFACE ROUTES SHOULD BE ADOPTED, WITH EACH ROUTE CONSTRUCTED USING THE SIMPLEST FORM OF TARMAC SURFACE. IN ZONES WHERE IT IS IMPRACTICAL TO RUN ON THE SURFACE, TUNNELLING COSTS MUST BE KEPT TO A MINIMUM BY ADOPTING TUNNELS OF THE TYPE USED FOR UNDERGROUND ELECTRIC CABLES (TYPICALLY LESS THAN 4M DIAMETER).

5.3.3 Interchanges

The concept of shuttling puts a great emphasis on the need for passengers to move swiftly and easily from one vehicle to another at each interchange. It is generally accepted that any need to transfer between vehicles within the span of a single journey significantly increases traveller resistance to using a public transport system. There is clear evidence, however, that travellers will make repeated changes in cases where there is certainty of fast and frequent onward travel – the London Underground is a perfect example. The interchanges for the Cambridge mass-transit system must therefore function with the smoothness and confidence levels which are commonly associated with a London underground interchange.

As for the segregated route construction, the cost of building the interchanges is an important consideration. For this reason, each interchange should be of the simplest possible form and be built at grade unless prevailing circumstances make this impossible. Preliminary studies suggest that building at surface level would be practicable in every case, except at the location of the Central Interchange where it might be preferable to keep the facilities underground at the level of the running tunnels (about 9-12 metres below the surface). Every interchange would need to be connected to the local high-voltage electricity distribution network to provide power for the battery re-charging equipment for the electric vehicles.

Three different types of interchange are required:

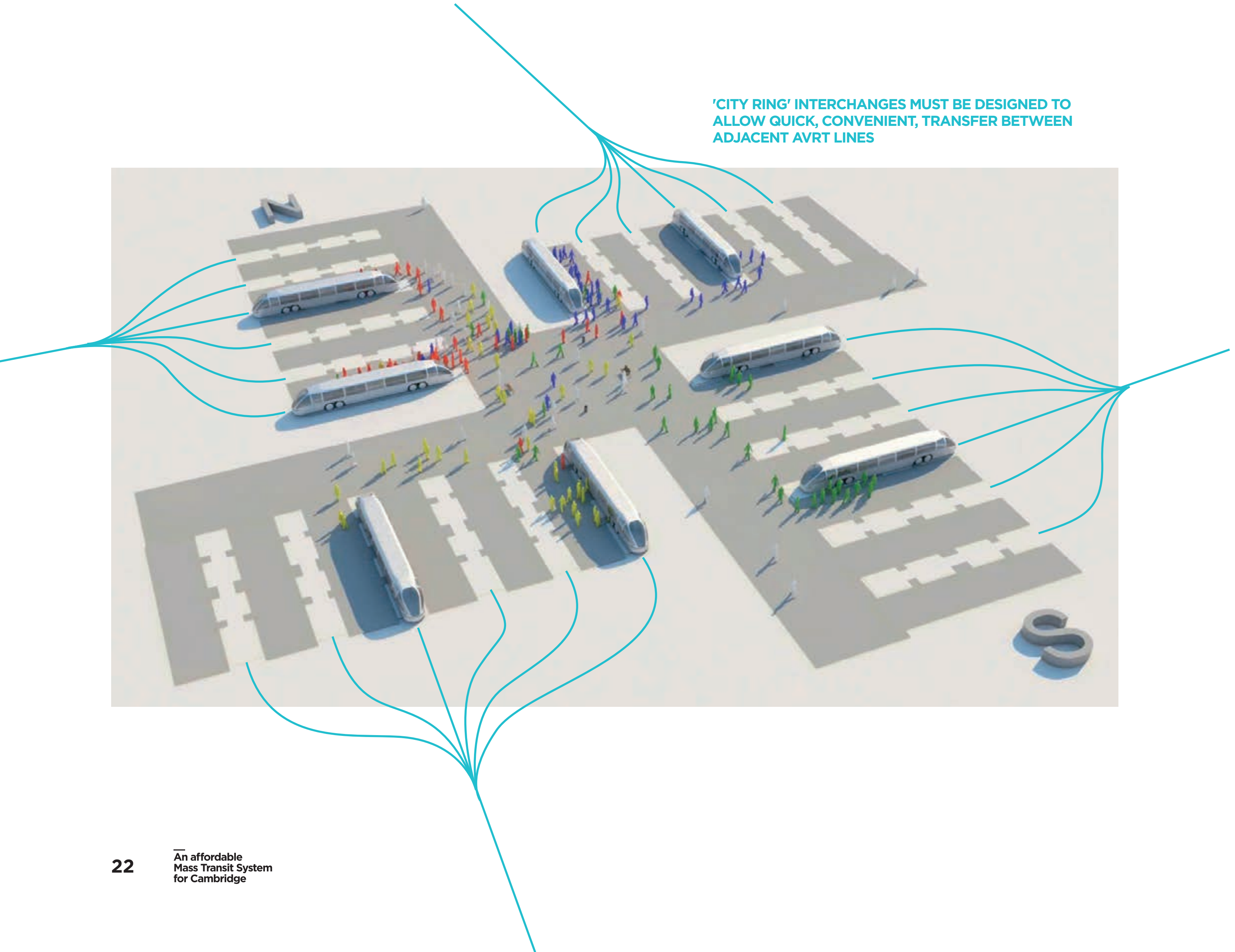
Peripheral 'collection point' interchanges which are well outside the city limits at Cambourne, Duxford, etc. The objective at these sites is to tempt travellers out of their cars (or tourist coaches) as they make their in-bound journeys. Frequent service departures, fast journey times to the centre of the city, and high levels of system reliability are probably the greatest factors in attracting users; the transfer experience at the interchange site must not detract from these benefits. The major performance requirement is to provide simple and efficient transfer between the in-coming vehicle and the mass transit system in a manner which is not unpleasant for the traveller. A simple, well laid out, Park & Ride facility will probably suffice.

PARK-AND-RIDE LAYOUTS FOR A PERIPHERAL INTERCHANGE LOCATION WOULD BE SIMILAR TO A CONVENTIONAL PARK-AND-RIDE FACILITY

5. A System Architecture for Cambridge

'City Ring' Interchanges which lie near the perimeter of the city at the major employment locations (Addenbrooke's, Science Park, Marshalls, etc). The objective at these sites is to enable swift and confident transfer from any in-coming vehicle to any out-going vehicle, and to enable those travellers arriving at, or departing from, the facility to enter and exit the interchange freely. If built at grade, these facilities would also be similar to a conventional Park and Ride site, with the addition of a vehicle transfer station designed to enable quick and easy transfer between vehicles which may arrive and depart from up to four different directions. A simple arrangement which could deliver this requirement is shown in the figure below.

The design and layout of these interchanges must be kept as simple as possible, but the key design requirement is to provide easy movement for travellers across the concourse area. This can be ensured by making the concourse sufficiently large that overcrowding never occurs even at peak travel times. Unfortunately, increasing the concourse area increase the land-take and pushes up the costs, so achieving the right balance between land-take and ease of transfer becomes the most important element of design for these interchanges. A computer simulation of the Addenbrooke's Interchange at peak travel time is shown below. It suggests that the chosen dimensions are adequate for current needs and provide some headroom for growth.



'CITY RING' INTERCHANGES MUST BE DESIGNED TO ALLOW QUICK, CONVENIENT, TRANSFER BETWEEN ADJACENT AVRT LINES

The Central Interchange needs to be close to the city centre which is a major location for employment and visitor attraction. Sites at appropriate locations are difficult to identify, but an underground interchange connected to a re-development of the Drummer Street bus station would create a very attractive proposition as a city-centre multi-modal transport interchange. Passenger transfer rates at peak times would be significant, but relatively small compared to a typical city centre underground interchange in London, so there is little doubt about the ability to provide high quality transfer rates.

5.4 Funding

If the system is to be 'affordable for smaller cities like Cambridge', the need for subsidy must be minimized. In an ideal world, the system would be privately fundable, with farebox revenues covering the annual costs of operation and construction loan repayment over a reasonable period of time (say 30 years). This would be an exceptional achievement, but AVRT could move a long way towards this ideal if the following can be delivered:

- **Capital costs in the region of £10-£15M/km;**
- **Operational costs minimized by the use of autonomous vehicles;**
- **Land value uplift at a small number of critical sites.**

This suggests a city-wide system construction cost in the region of £500-£800M. Our modelling to date, suggests that the system will be able to cover its ongoing operational costs from farebox revenues alone, without any need for public subsidy.

6. Options Studies

A range of different system configurations has been studied and cost/performance characteristics have been estimated for 9 different options. These studies are reported in detail in Volume 2 of this report, but two particular cases are presented in this section.

Option 1 represents a city- wide configuration with basic connectivity, and Option 2 represents a more highly developed system. The latter could be viewed as a future development option.

The journey times and service frequencies for the two options are shown on the illustrations on the facing page. Journey times between interchanges are typically less than 3 minutes and service frequencies are typically better than four minutes. It should be noted that a traveller approaching the Marshall's site (Cambridge Airport) from Cambourne would reach the intended destination within a maximum elapsed time of between 5 and 9 minutes (depending on the need to wait for vehicles at the West site and Central Interchanges).

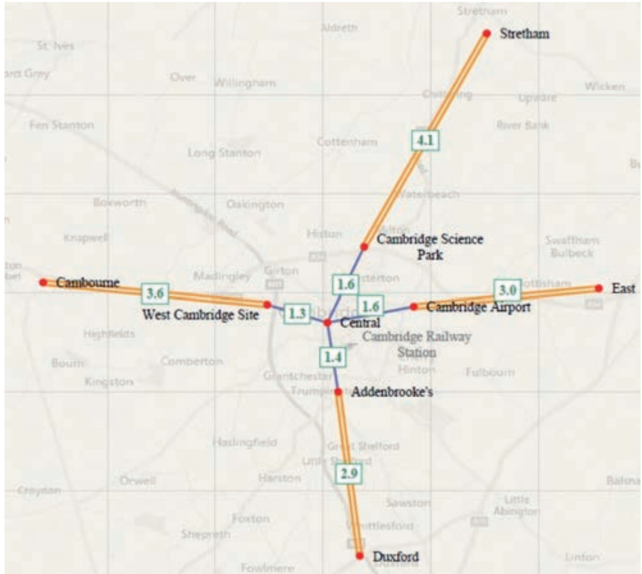
This is a transformational improvement over the time required to make the same journey by car at present. In terms of traveller inconvenience (changing between different vehicles at the interchanges), it is very little different to a typical commute on the London Underground.

For the options illustrated, the costs are estimated to be around £500M for Option 1 (total length approx 55kms) and £750M for Option 2 (total length approx 75kms). These are attractive figures (approximately £9-£10M/km) and they meet the stated target of 'approximately half the cost of conventional systems'.

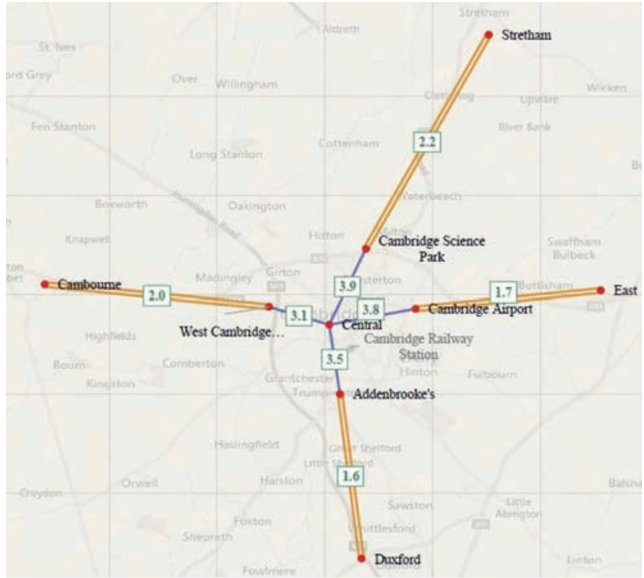
But, perhaps more importantly, AVRT also has the potential to provide a more desirable transport experience for the traveller.

The over-riding objective must be that whatever option is finally built, using the new mass transit system should always be more convenient/attractive than taking the car. If this can be achieved, travellers might adopt the system without any need for further inducement or penalty. Ridership levels (revenues) will therefore be maximised. A narrative which sets out to describe the quality of service which could be provided, and the wider social and economic benefits which might accrue to Cambridge, is presented in Appendix 2.

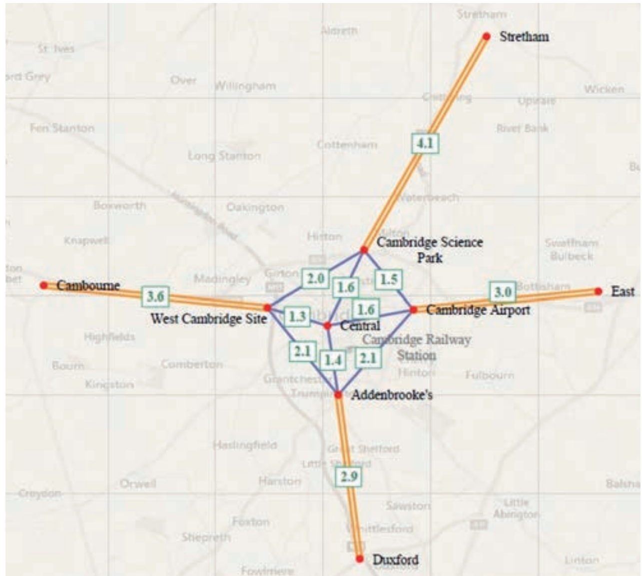
OPTION I: JOURNEY TIME ON LINE (MINUTES)



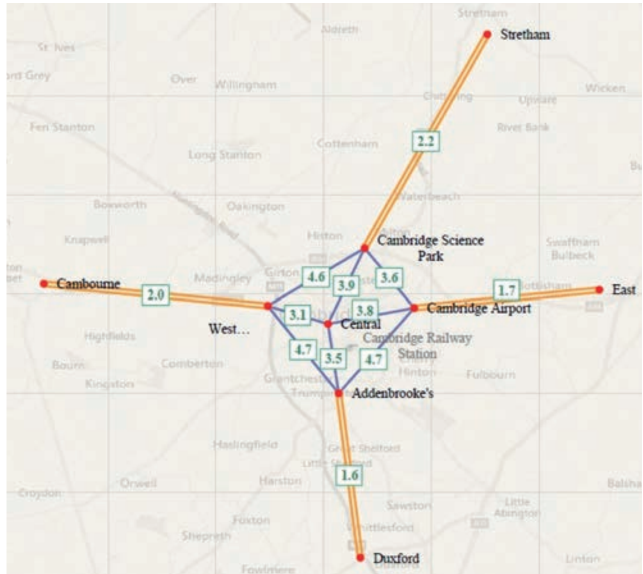
OPTION I: OPERATING FREQUENCY OF LINE (MINUTES)



OPTION 2: JOURNEY TIME ON LINE (MINUTES)



OPTION 2: OPERATING FREQUENCY OF LINE (MINUTES)



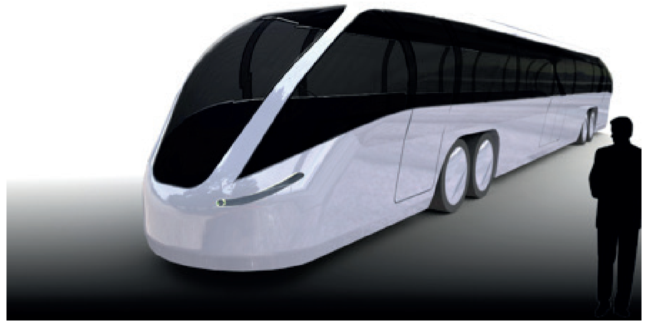
7. Last Mile Movements

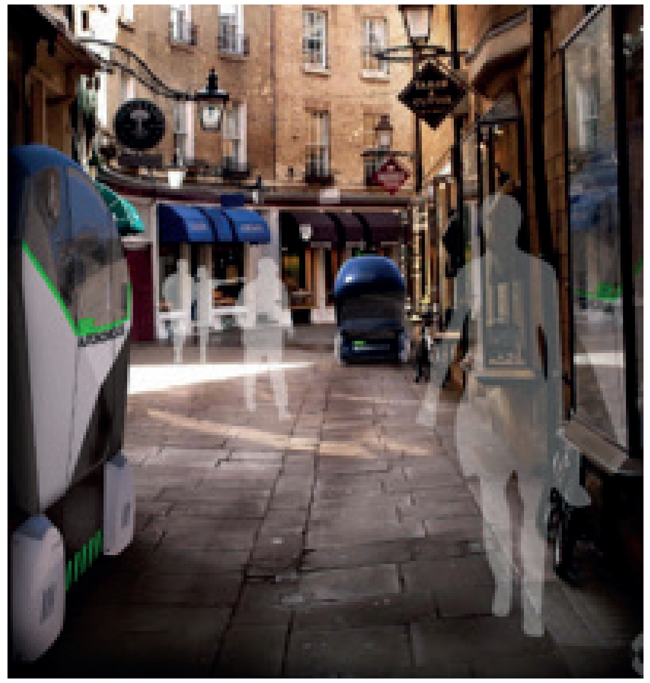
The options described in Section 6 provide a high degree of service coverage across the city and its immediate sub-region. However, one of the drawbacks of AVRT is the relative infrequency of the points of access; a typical distance between interchanges within the city limits is 3-5kms. This means that the origin or destination for any particular journey could be more than half this distance from the nearest interchange. It is particularly important, therefore, that some consideration is given to the provision of complementary public transport services within the zone bounded by the AVRT ring.

It would not be practicable to extend the AVRT to cover such short-distance needs, or to provide some different type of fixed-infrastructure system at grade (e.g. tram or guided bus). However, there is an opportunity to use the existing surface road network more effectively because the traffic flows within the AVRT 'ring' will have been reduced. As described in Section 3, some 23,000+ vehicles per weekday are currently entering the city in the morning and leaving again in the evening. The introduction of AVRT should remove a reasonable percentage of those vehicles and, if this is the case, an opportunity exists to introduce a range of new, more user-friendly, services. Examples include, walking, cycling, on-demand flexible bus services, traditional bus services and, even, autonomous pods. (The possible future use of autonomous vehicles within the city's central zone and major employment hubs has been examined elsewhere and the conclusions are very positive).

The ability to link all these services together and present options to the traveller via hand-held devices opens the door to the introduction of sophisticated 'Mobility as a Service' (MaaS) offerings. These range from the simple provision of cycle-hire at the point of alighting to the spontaneous booking and billing of on-demand bus or taxi.

Whatever the preferred solution(s), it is clear that a great deal more flexibility will be conferred on the transport authorities if the numbers of vehicles on the roads within the city-centre area are reduced – an outcome which is one of the principal objectives of AVRT.





Mobility-as-a-Service:
Integrated booking and billing systems will enable flexible 'last-mile' transport connections to be made anywhere within the AVRT belt

8. Conclusions

It is concluded that the AVRT system described in this report offers a modern version of mass transit which is:

- **Attractive;**
- **Affordable;**
- **Scalable;**
- **Flexible;**
- **Non-intrusive.**

The system proposed runs on segregated routes which are largely at surface level through the rural areas of operation, but run through small- bore tunnels within the historic city core. This strategy removes the traffic disruption and building demolitions which would accompany the construction of a new, segregated, fixed-route system through the central zone of the busy working city.

The capital and operational costs outlined in Volume 2 of this report suggest that AVRT could be less than half the cost of conventional systems with similar coverage, whilst the customer service levels delivered could be markedly superior. Assuming reasonable levels of uptake, it is realistic to suggest that the requirements for financial support could fit within the city's ability to raise capital. Importantly, the operating costs also suggest that the system would not require ongoing public subsidy, which is a problem for conventional systems in the context of smaller cities like Cambridge.

From a technology standpoint, the challenges are judged to be manageable, noting that:

- **The ground conditions in Cambridge lend themselves to tunneling, and the UK is a world leader in tunneling technology;**
- **The electric vehicle technology which is proposed is already being demonstrated on the road in Milton Keynes, Nottingham, and London;**
- **The level of autonomous capability required of the vehicles is very limited because AVRT will make simple, repeated, journeys on strictly segregated routes.**

Finally, the features which make AVRT a potential solution for Cambridge also make it a potential solution for other congested cities which are too small to entertain a conventional mass-transit solution. There are a large number of such cities in the UK and this represents an excellent opportunity for further exploitation of the concept. In particular, the cities of Oxford and Milton Keynes have expressed interest in making a joint promotion of AVRT to the National Infrastructure Commission (NIC) in connection with the Oxford-Cambridge 'Silicon Crescent' challenge.

With these thoughts in mind, the following steps are now recommended:

1. **That Cambridgeshire County Council and the Greater Cambridge Partnership team promote the idea of similar AVRT 'System Architecture' studies being undertaken for the cities of Oxford and Milton Keynes. This to be done with a view to developing a joint vision for transport in front of the NIC;**
2. **That in-depth scheme design and construction cost estimates are commissioned for the proposed AVRT infrastructure, using reputable civil/structural consultants;**
3. **That funds are raised to design and build a demonstration vehicle. This programme could (possibly) take advantage of the Cambridge Guided Busway for test and demonstration purposes. The activity would probably require a programme of 2-3 years duration for the development and prototype-build work. A budget of around £5M is anticipated. Private sector partners, willing to share a proportion of these costs, would need to be found, but initial discussions suggest this might be possible.**

Securing the active engagement of more cities could become an advantage in making progress towards the next stage of AVRT development – which must be to build and demonstrate a prototype AVRT vehicle.

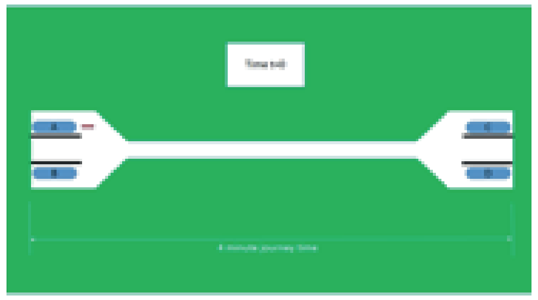
APPENDICES

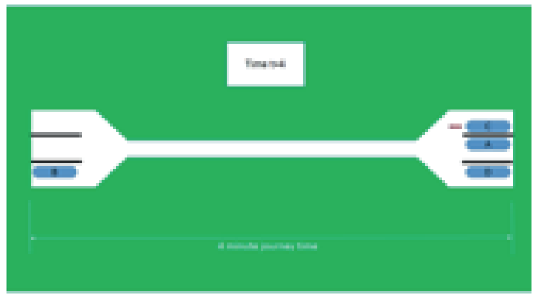
Appendix 1. Shuttle Operations

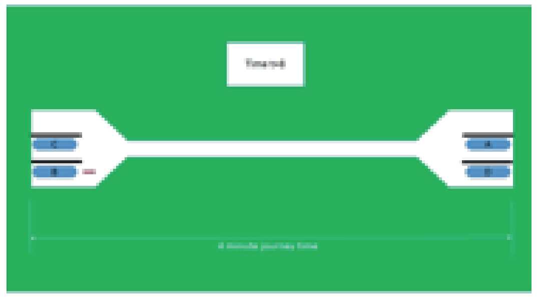
The concept of 'shuttling' is based on a very simple idea. The vehicles operating on any particular leg of the system are 'captive' to that leg, and never transfer to another leg at any time during normal operations. Rather, the vehicles simply run backwards and forwards along their respective legs all day, with stops at either end to enable passengers to board and alight.

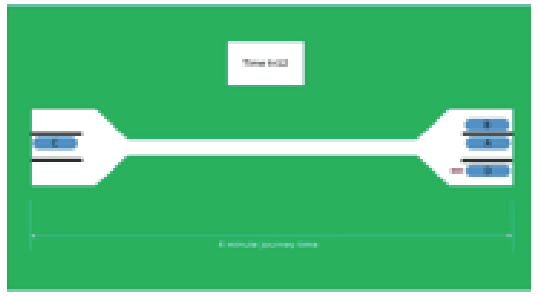
The process for a single-path connection between two locations is as follows::

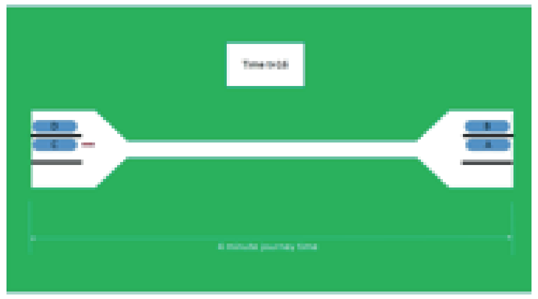
1. **Vehicles 'A' and 'B' are at interchange '1', and vehicles 'C' and 'D' are at interchange '2'. The journey time between locations 1 and 2 is 4 minutes;**
2. **For a single pathway connection, vehicle 'A' sets out at time 't' and arrives at interchange '2' 4 minutes later at time (t+4);**
3. **At time t+4, the pathway is clear and vehicle 'C' can depart. It arrives at interchange '1' at time (t+8);**
4. **At time t+8 the pathway is clear, and vehicle 'B' begins its journey from '1' to '2' (having had 8 minutes dwelling at interchange '1' to pick-up passengers). It arrives at time (t+12);**
5. **At time (t+12), the pathway is clear and vehicle 'D' begins its journey from '2' to '1'. It arrives at '1' at time (t+16);**
6. **At time (t+16), vehicle 'C' begins its journey from '1' to '2' .... Etc.**











Within this simple example, the journey time is 4 minutes and the departure frequency is 8 minutes. This difference occurs because there can only be one vehicle on the pathway at any time. If we link 'A' and 'B' with twin pathways, the departure frequency will improve to one departure every 4 minutes. Alternatively, we can achieve a 4 minute departure frequency using a single pathway by increasing the speed of the vehicle and reducing the journey time to 2 minutes.

The problem of ensuring that only one vehicle is on the pathway at any one time is very straightforward. It can be accomplished using the modern day electronic equivalent of a 'token ring' system (in which the driver of a locomotive leaving a section of railway must hand a physical token ring to the driver of the vehicle entering that section from the opposite direction).

The token ring control systems on each leg are entirely separate entities. By defining different topologies, and utilising different combinations of pathways, platforms, vehicle numbers, and vehicle speeds, we can arrange for a wide variety of system capacities, departure frequencies, and journey times to be operated on a city-wide network which needs almost no signalling or system-wide controls.

With the shuttle style of operation working on one leg of the system, additional legs are easily added provided no vehicle crosses from one leg to another. For example, a system in Cambridge could start with a limited pair of connections on the western side linking Cambourne to West Site/Northwest Cambridge and Addenbrooke's (Figure X). Thereafter, it could be expanded in further stages (Figure Y), to become a full city-wide system (Figure Z).

FIGURE X

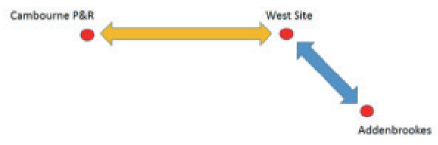


FIGURE Y

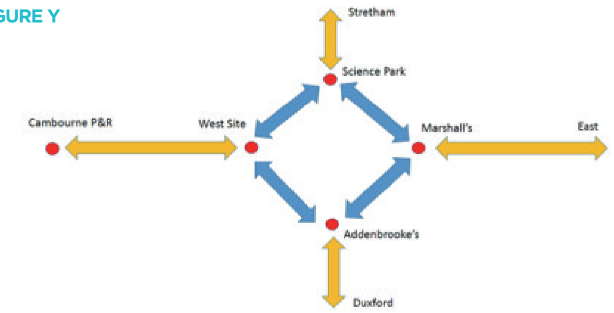
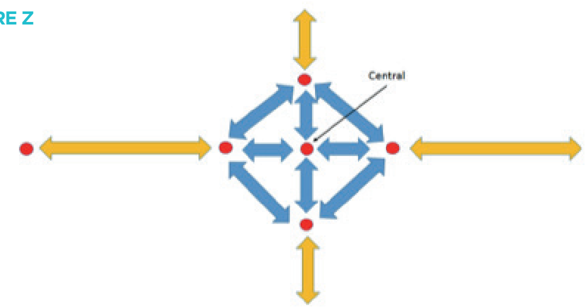


FIGURE Z



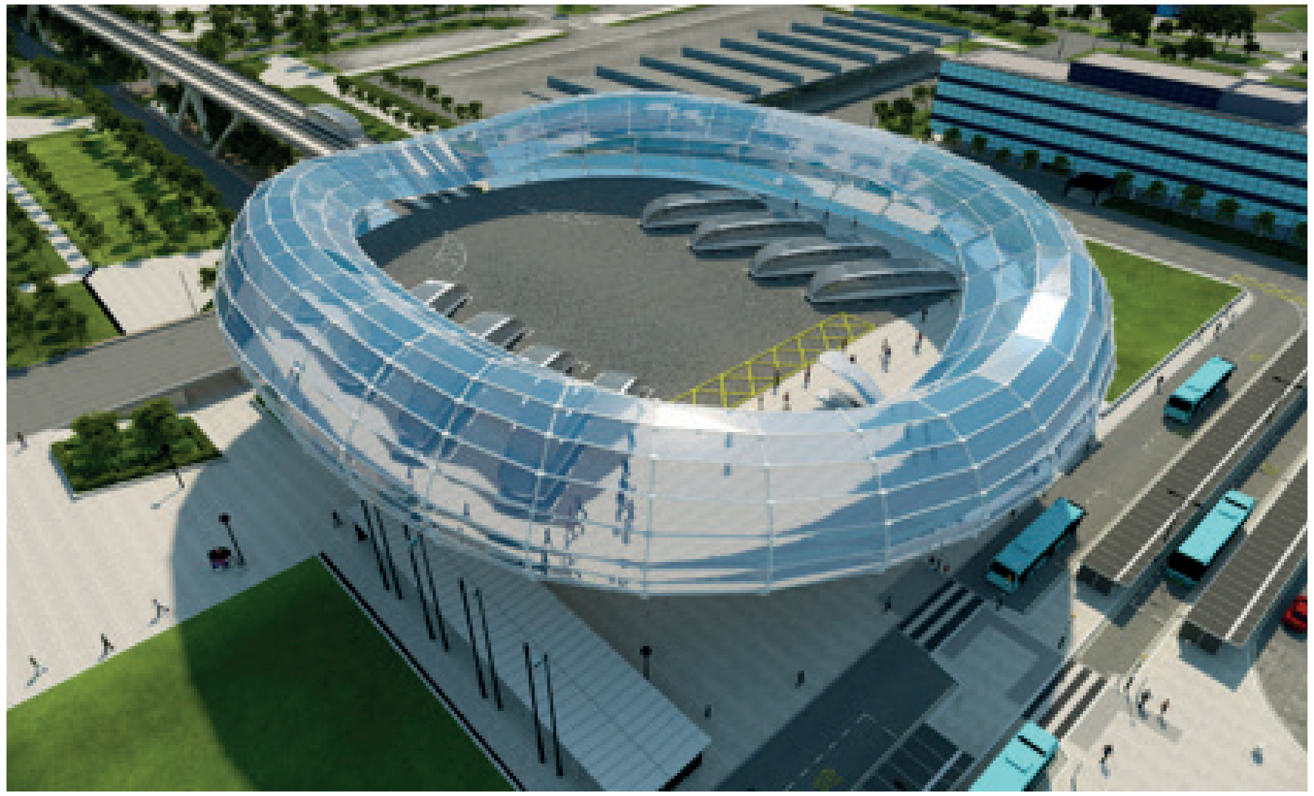
Appendix 2. The Future Travel Experience (2050)

It was barely light and slightly frosty as he crossed the short distance from his car to the cigar-shaped AVRT and stepped into the soft warm glow of the long thin cabin. It was already half full and he found his way quickly to an empty seat and sat down. As he buckled-up into the comfortable airline-style seat, a returning AVRT glided quietly into the adjacent bay; the other passengers coming up behind him from their cars made their way towards the newly arrived vehicle. At one departure every three minutes, no one ever had to worry about missing the service.

Although he had ridden the AVRT many times before, the powerful acceleration and the low hum of the electric motors still gave him a thrill as the vehicle rapidly picked up speed on the smooth, purpose-built, trackway. The journey from the park-and-ride on the A428 near Papworth Everard to the University's busy West Site on the Madingley Road took only three and a half minutes as the vehicle sped at 120mph along its path in the early morning half-light. As he travelled, he reflected on how easy it was now (pleasant, even) to make the commute from his home in one of the outlying villages to the west of the city. Years ago, if you approached from the west, the last few miles into the city centre had apparently taken 45 minutes or more as commuters queued on the Cambridge West slip road between 6:30 and 9:00 each morning and then crawled along the Madingley Road towards their final destination. And it had been the same going home in the evening – strangulation of the city and its aspirations had seemed inevitable in the pre-2020 period.

The AVRT cruised to a halt at the West Site interchange and he stepped out.

The big site spread out before him, with buildings stretching to all four corners. The high level of site development had been made possible by the massive improvements to transport access which had been brought about by the AVRT. He looked at his smartphone; it had automatically hailed his autopod and was showing the vehicle ID. He glanced around the wide open apron area and found the driverless, two-seater electric vehicle waiting nearby. He strolled towards it and waved his smartphone casually at the windscreen; the autopod recognised his booking and opened its door silently. He stepped in and sat back comfortably.



The pod was warm and it took off automatically in the direction of his office, effortlessly navigating the final mile of his journey at 12 mph alongside the early morning build-up of pedestrians and cyclists who also travelled to work along the wide landscaped pathways which criss-crossed the site. By the time he reached the main door of his building and stepped out of the autopod, he had checked his e-mails and caught the news headlines.

The AVRT and autopods had transformed Cambridge. Four high-speed AVRT links came in from well outside the city; his one from the west, plus three others from the north, east, and south, each of which connected to one of the four major employment areas at the Science/Business Parks, Marshall's, Addenbrooke's, and West Site. These radial links, plus the 'ring' which joined them all, meant that movements to, and between, the sites could be accomplished in a matter of minutes no matter which direction you approached from. Once on each site, travellers could use the local autopods to arrive at the door of their destination with ease, despite the vast size of each campus. These transport links meant that the enormous economic growth which had occurred in Cambridge between the early 2020's and the 2040's had been easily contained within the campuses and haphazard property developments had not been allowed to spoil the old city. This, plus the convenience of travel from the surrounding towns and villages, had meant that the catchment area of the city had expanded enormously and an economic explosion had taken place. Global giants in bio-sciences, software, pharmaceuticals, finance, and high-tech engineering had poured into The Fen, and a flood of new start-ups had spun out of the University. Together, they had created the world's largest and most successful techno-cluster outside The Valley, putting even London's Shoreditch, Hackney, and Olympic Park successes into the shade.

And, best of all, movements within the traditional city-centre area bounded loosely by the four campus sites had become startlingly easy. Thousands of commuter and visitor vehicles per day no longer entered the city, and the peak-time traffic crushes had been removed altogether. As a result, within central Cambridge, bicycles jostled with pedestrians, autopods, buses and cars in a manner that seemed to have been a Cambridge tradition for ever – except these days the traffic moved reasonably smoothly over the course of a day, rather than being caught in what felt like some perpetual grid-lock.

And all of this, he reflected, had been achieved without any draconian fines, car movement restrictions, or excessive usage charges imposed from above. Rather, it had all happened because the AVRT and autopods had simply made it more attractive for commuters, visitors, and residents to use public transport in preference to their cars.

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