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Roads for the Future

Dedicated Driverless Spaces

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EXECUTIVE SUMMARY

Dedicated Driverless Spaces offer a **bold but practical vision** for the future of the UK's road network. In this report we demonstrate that Dedicated Driverless Spaces are the **most feasible deployment pathway for Connected and Autonomous Vehicles (CAVs)**. By embracing Dedicated Driverless Spaces, policy-makers will enable significant progress and innovation today, secure wide-ranging immediate benefits while also maintaining the flexibility to accommodate future technology advances. We conclude that Dedicated Driverless Spaces provide an essential tool to help policy-makers successfully navigate the transition to CAVs, locking in the benefits while minimising risks.

This report combines recently published research, new spatial and financial modelling and real-world case studies covering **9 'typologies'** of Dedicated Driverless Spaces. Through these 9 typologies we present a clear holistic vision for CAVs and show how **this compelling vision will make our cities cleaner, safer and more efficient with optimised use of space and assets**. The key opportunities of this future world are set out below:

- **In our cities**, new autonomous mass transit provides low cost, convenient, high-speed travel serving commuting, leisure and education trips. Through cost engineering, autonomous and electric vehicles make high-quality mass transit a viable and attractive option for the majority of the UK's cities.
- The **first and last mile** of trips are seamlessly integrated with existing and emerging mass transport systems, maximising the use of the UK's assets, conferring frequent and reliable journeys and opening up new travel opportunities.
- **Urban freight** is delivered autonomously overnight, maximising the use of Dedicated Driverless Spaces and minimising day-time freight traffic and emissions. Urban Consolidation Centres, linked to autonomous inter-city platoons, create further delivery efficiencies.
- On our **motorways**, managed lanes adjust in real-time to maximise the throughput on the Strategic Road Network, optimising journey times and reliability for inter-city travel.
- In **residential areas**, CAV-only zones reprioritise community and open space, encouraging active modes while last-mile CAVs enable door-to-door journeys on GPS-guided routes. In these spaces our traditional concept of roads disappears entirely.
- And finally, all **new developments** are designed to minimise carbon and deliver the full benefits of CAVs – seamless integration with wider public transport networks, more open space and biodiversity and unlocking the potential to invest further in energy efficient infrastructure or affordable housing.

The challenges of congestion, carbon and capacity today are stark - rising levels of congestion, driven by population growth, urbanisation and new working and living demands, are clogging the UK's cities and its transport systems (NIC, 2017). The future world we envisage is not science fiction – the building blocks are deliverable today. Our current mobility paradigm - characterised by the fact that only private cars can provide individual and flexible mobility (Alessandrini, 2015) – now stands on the brink of unprecedented change.

However, a future based on shared mobility, the efficient use of vehicles, minimisation of congestion and optimal use of infrastructure is by no means a foregone conclusion. As the National Infrastructure Commission acknowledges, the full benefits of Connected and Autonomous Vehicles will not just happen (NIC, 2017). The literature goes further, warning that a do-nothing approach is unlikely to lead to the optimistic scenario arising (Papa, 2018). Some authors warn that CAVs could materialise a dystopian mobility future if the crucial decisions are not carefully approached (ibid). The decisions we make now are critical. Failure to address both the short and longer-term governance issues risks locking the mobility system into transition pathways which exacerbate rather than ameliorate the wider social and environmental problems that have challenged planners throughout the automobility transition (Docherty, 2017). Compounding this uncertainty is the fact that much of the current opinion around CAVs contains a great deal of speculation. We have conducted a fresh, even-handed analysis in order to holistically inform the trade-offs and decisions that need to be made.

WHAT WE DID

To evidence our conclusions, we:

- **Conducted a comprehensive literature review** covering safety, public acceptance, infrastructure need, CAV benefits and risks. In particular we reviewed extensively the literature on the network performance impacts of CAVs;
- **Interviewed manufacturers, operators and experts** to provide an up-to-date assessment of the technical and operational requirements across a range of technologies and the common themes with respect to CAV capability;
- **Developed a framework to understand the policy options available.** This framework enables us to assess the relative feasibility of the full range of deployment pathways for CAVs available to the UK;
- **Conducted a detailed analysis of the feasibility** of different deployment pathways. In particular we demonstrate the challenges for deployments in mixed traffic and ubiquitous CAVs;
- **Identified 9 'typologies'** of Dedicated Driverless Spaces to be investigated in detail;
- **Conducted site surveys and developed case studies** to demonstrate how infrastructure would be adapted to accommodate each Dedicated Driverless Space typology in practice;
- **Assessed the benefits and feasibility** of each of the 9 Dedicated Driverless Space 'typologies';

- **Conducted an expert 'challenge' workshop** to further shape and refine the case studies;
- **Developed a model and optimisation tool** to evidence the potential network benefits for CAVs focused on mass transit. The optimisation tool can also enable local authorities to identify the most beneficial opportunities for Last and First Mile CAVs.
- **Developed financial models and estimates** to explore the financial viability, incentives and benefits that could be unlocked through Dedicated Driverless Spaces.

CAV DEPLOYMENT OPTIONS & FEASIBILITY

In general, there is limited guidance as to how CAVs be rolled out onto public streets and how to protect the public if they fail (Reader, 2018). Little attention has yet been paid to what impact different CAV strategies will have on the condition of road infrastructure, its maintenance, renewal and configuration requirements. At the same time, technological change is outpacing the capacity of systems and governance structures to respond to the challenges already apparent (Docherty, 2017). It is therefore critical for policy-makers to understand the full range of possible deployment options, their costs and their impacts. In Part 1 of our report we show that the choice of deployment pathway has a considerable impact on the technical and financial feasibility of CAV infrastructure and the resulting benefits. Many deployment pathways are shown to be high cost and high risk. In contrast to these strategies we present Dedicated Driverless Spaces.

Dedicated Driverless Spaces are permanent or dynamic, certified sections of infrastructure upon which CAVs can operate, which minimise interactions with mixed traffic. The idea that driverless cars may need to be separated or segregated through infrastructure has been noted throughout the literature (Glancy, 2015; SDG, 2018; O'Sullivan, 2016). Our report, for the first time, explores and extends these concepts into a critical policy tool. We demonstrate that Dedicated Driverless Spaces are the most practical option and overcome the material challenges faced by alternative roll-out strategies. In particular, we find the following:

- **Safety in mixed traffic:** Based on the best data available, today's CAVs could be up to ten times more likely to be involved in a crash than conventional vehicles in mixed traffic. The most likely explanation for this is human drivers being unable to anticipate the behaviour of CAVs. As test miles grow, public acceptance risks becoming a major barrier to innovation and industry development. Dedicated Driverless Spaces enable simplified operating environments to be designed and delivered. Deployment pathways based on Dedicated Driverless Spaces can therefore happen faster and achieve much higher levels of public acceptance.
- **Regulatory environment:** There is currently no reliable safety approval process for CAVs. This is a highly complex area that could take years to resolve. Dedicated Driverless Spaces provide a system to separate CAVs, license operators and remove these concerns. As a result, they enable us to progress schemes and begin demonstrating the benefits of CAVs today.
- **Liability issues:** Mixed traffic is fraught with philosophical and legal debates about who is at fault or how machines should make decisions in critical situations. Dedicated Driverless Spaces provide the system to separate CAVs removing these concerns.
- **Congestion caused by human-CAV interactions:** Interactions between pedestrians and cyclists and CAVs in mixed traffic has significant potential to make congestion worse and not better. Dedicated Driverless Spaces simplify this issue by enabling fast and reliable journey times for the modes that make most sense.
- **Difficulty combining autonomous and human systems:** Systems that try to combine automated and manual driving introduce a completely new set of challenges and may even render humans worse drivers than they are today. Dedicated Driverless Spaces enable us to design safe systems that deliver the tangible benefits we're trying to achieve.
- **Infrastructure cost:** Deployment pathways that seek to achieve autonomy everywhere, while relying on intelligent (V2I) infrastructure could cost upwards of £700 billion pounds and deliver uncertain benefits. In part 2 we show that Dedicated Driverless Spaces are cost effective with many typologies offering strong commercial cases and Benefit Cost Ratios today.
- **Communications Infrastructure:** Most CAVs need uninterrupted communication networks to function. Roll-out of communication systems is time-consuming and costly - many rural locations still do not having full access to broadband or 4G. Dedicated Driverless Spaces make this simple - the operational theatre is a fixed zone and responsibility to ensure adequate and resilient communication infrastructure is in place can be allocated to the operator under license.
- **Maintenance costs:** These are likely to be high and common issues like mud and snow might make CAV operation difficult. With constrained budgets it is completely unclear where funding for higher levels of maintenance to enable CAVs would come from. Dedicated Driverless Spaces have a licensing model which pushes the requirements for higher levels of maintenance onto the operator. This enables the UK to get the infrastructure it needs with minimal impacts on public finances.
- **Cyber & software risks:** Coding and software errors and cyber security create completely new risks that have no simple solution. Cyber threat and software failure are critical concerns of the public. Dedicated Driverless Spaces enable the design of physical systems to mitigate these risks. They can be operated as closed systems, with their own dedicated communication networks and security systems.

In Part 2 we explore Dedicated Driverless Spaces in detail through 9 distinct typologies. Managed lanes on motorways, while offering significant benefits, are found to suffer from many of the safety and security issues that beset the alternative pathways and are therefore less feasible in the short-term. In contrast, we find that 3 of the 9 strategies - Last-mile solutions, solutions for Business Parks and New Developments - are nearing technical feasibility for deployment today. We also find strong near-term potential for First-mile systems, Autonomous BRT systems & Freight solutions and recommend that these strategies are supported further to demonstrate their benefits.

NETWORK PERFORMANCE & CAVS

In chapter 4 we focus on the literature concerning the network performance of CAVs in urban and intra-urban environments. Here we make the following key observations which inform our vision for CAVs:

- **Network efficiency benefits of CAVs are highly dependent on a complex set of variables.** Network efficiency benefits cannot be taken for granted and depend heavily on technical features of the vehicles themselves such as headway; features of the system design such as routing choices and integration with existing public transport; the delivery model such as the impacts of ride-hailing; and the overall impacts on travel demand and spatial distribution.
- **Critically, CAV delivery models based on shared-taxis risk increasing, not improving congestion.** Evidence from a number of papers shows that systems based on shared taxis reduce the number of vehicles required but are more likely to drive up vehicle miles travelled. Integration with public transport is essential to deliver network efficiency benefits. A range of further evidence suggests that taxi-based delivery models for CAVs could outcompete public transport and lead to overall higher levels of congestion.
- **Conversely, Shuttle services integrated with public transport could offer the most promise for reducing congestion** with previous studies revealing significant reductions in vehicle miles travelled (ITF, 2017).
- **The literature review demonstrates that public transport is essential to CAV strategies if network benefits are to result.** This leads us to develop our own model (STARR) to explore the potential for First and Last-mile CAV shuttles integrated with rail in Greater Exeter. Through this model we demonstrate that such a system has the potential to serve up to 48% of journeys and remove 54,000 car trips.
- **Further, we develop an optimisation tool to help local authorities identify these Last- and First-mile opportunities.** Using this tool, we estimate that for a commuter route in Greater Exeter, 20% of trips could be addressed by as few as 8 CAV shuttle hubs integrated with rail.

THE MOST CREDIBLE STRATEGY TO UNLOCK THE BENEFITS

Having shown that Dedicated Driverless Spaces are the most feasible option, in Part 2 we explore 9 potential ‘typologies’ to understand their benefits in detail. Here we evidence that CAVs could unlock considerable new finance for infrastructure while vastly enhancing the urban environment. The key findings are as follows:

We present detailed case studies for urban Dedicated Driverless Spaces, and through case-studies show how Dedicated Driverless Spaces could also support walking, cycling, green infrastructure and ambitious place-making. We present detailed case studies showing how a Last Mile solution could transform the entry experience to the City of Exeter, improve the public realm and reduce private cars. We show how an Affordable Very Rapid Transit system could be introduced on a major arterial route, supporting greater walking, cycling and biodiversity. And we provide a vision of the potential for scheme delivery across the ‘typologies’.

We find that Last Mile services could be particularly compelling where demand exists for 10 or greater trips per hour. Our financial modelling finds that in locations where a frequency of 8 “Fully Occupied Equivalent trips” (FOET) per hour can be achieved, these services can operate without subsidy. Further, in schemes which could support travel frequencies above 10 FOETs per hour, our model demonstrates that there is potential for the operation to provide significant contribution to, if not cover the investment in infrastructure.

We find that the removal of parking can create significant value uplift, offering significant potential for scheme viability in Business Parks and New Developments. Our estimates show that on business parks, the removal of parking could generate £16.5 million of land value uplift for every 100 acres and in residential sites, car-free developments could increase Gross Development Values by up to 65% compared to existing schemes.

We find that urban freight could operate autonomously on the “first mile network”, conducting deliveries overnight in order to radically reduce day-time traffic. Savings made through autonomy, combined with a new system of pricing, might provide compelling incentives to switch to overnight deliveries. Integration through Urban Consolidation Centres could enable even greater efficiencies.

We identify a compelling framework for the future optimisation of traffic flow on the highway network, through the use of Dynamic CAV Lanes. We explore in detail the potential use of Dynamic CAV-only lanes on the highways. These lanes are considered to be the most likely to be accepted by the public. Such a system is considered to have the potential to add capacity equivalent to 1.5 new lanes at only a third of existing costs.

Overall, we find that Dedicated Driverless Spaces make best use of the UK’s extensive and mature road network adapting existing infrastructure in a way that is practical and, in many cases, eminently affordable today and that our 9 typologies offer a set of advantageous interventions that will promote CAV uptake in a way that secures immediate benefits while minimising unwanted, negative outcomes.

RECOMMENDATIONS & NEXT STEPS

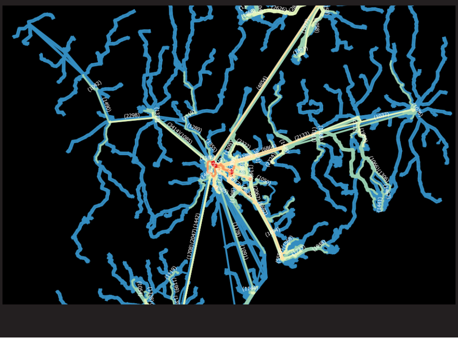
Our work leads to the following recommendations for next steps which are summarised below:

1. Recognise the benefits of Dedicated Driverless Spaces and their importance within CAV deployment strategies.
2. Further the development of the STARR model to assist local authorities in understanding the full impacts of CAV-shuttle interventions for all road users.
3. Identify a partner city or cities to fully develop an operational CAV last-mile scheme.
4. Encourage all new developments, in particular New Garden Towns, to consider CAVs and how these can support their sites.
5. Work collaboratively with developers to promote transport innovation in scheme development, in particular supporting the delivery of car-free business parks and new residential sites.
6. Direct innovation funding towards the development and testing of mass transit systems to underpin the technical feasibility for what are likely to be some of the most compelling CAV-opportunities for cities.
7. Commission or support detailed modelling exercises into the economics of a system of road pricing for CAV freight and detailed motorway simulation studies on the effects of heterogeneous vehicles and behaviours across a range of lane management strategies
8. Finally, identify opportunities such as the Commonwealth Games, which could be supported by CAV-based mobility strategies and offer a significant opportunity to showcase regional and national innovation.

RELEVANCE TO POLICY

In an examination of urban transport plans in 25 metropolitan areas in the United States researchers from University of Pennsylvania found that only one of these plans made mention of CAVs (Guerra, 2016). The OECD/ITF (2018) recommends that policy-makers become more aware of what different forms of automation imply for specific policy objectives. Although policy-makers are clearly aware of CAVs, the intense uncertainty surrounding these technologies has made it difficult to include them in urban plans—at least to date. Our project seeks to fill these gaps. As the Transport Systems Catapult (2016) has previously reported - “A starter kit for senior managers in authorities would be helpful”. We hope that this report fulfils such a role, accurately and impartially consolidating the evidence and providing the palette of ideas to build CAVs into local plans.

The NIC sets out the imperative for existing infrastructure to be used more efficiently and the need to invest more in alternatives to the private car to reduce congestion. The ‘Congestion Capacity and Carbon’ report sets out a vision for upgraded and expanded rail, bus and metro systems, alongside better facilities for cycling and walking (NIC, 2017). We show how Dedicated Driverless Spaces complement this vision – integrating with existing networks and transforming the customer experience. Local governments have a crucial role to play in preparing the legal, transport, and urban systems to accommodate CAVs (Papa, 2018). Connected and Autonomous Vehicles (CAVs) offer great potential to create disruptive influences that will shape our cities and their interconnections for better or worse for decades to come. Our work demonstrates that there is much potential for policy makers to embrace elements of this new technology and carve out a bold new future for their regions, maximising the benefits while minimising the risks. Dedicated Driverless Spaces offer control to policy-makers at this time of uncertainty; secure public trust during times of transition; and enhance wellbeing, establishing a positive pathway for society’s future use of CAVs. By embracing Dedicated Driverless Spaces, the UK can accelerate deployment of CAVs and begin capturing their benefits in a structured and fundable way.



PART 1 - ON THE STARTING GRID

CHAPTER 1 – CHANGING GEAR: THE TRANSITION TO DRIVERLESS CARS

The benefits that can be realised by CAVs are highly dependent on the deployment pathways we choose to adopt. The expert literature describes a complex set of trajectories that lead to a range of widely diverging outcomes. Wadud (2016) captures succinctly the range of outcomes on Green House Gases for example, remarking that "automation might plausibly reduce road transport GHG emissions and energy use by nearly half – or nearly double them – depending on which effects come to dominate". What benefits and risks ultimately come to dominate depends on a wide range of choices, compounded by – among other things – path dependence, (potential) lock-in, coincidence, and many other factors (Milakis, 2018).

The challenge is compounded by the fact that it is widely expected that the development of Connected and Autonomous Vehicles (CAVs) will involve a transition period where CAVs operate for some time alongside human drivers. How existing networks will function during this transition period, how safety will be guaranteed and how public trust and acceptance will develop are unknown. On the whole, there are two competing technology visions for how CAVs will interact with infrastructure and other traffic:

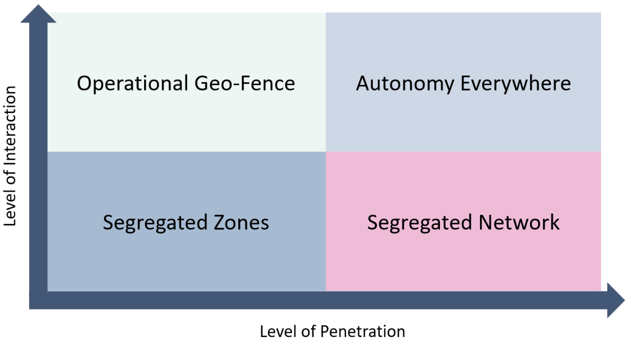
1. Fully autonomous, independent, self-driving vehicles that can work with the existing infrastructure, or a simplified version thereof; and
2. CAVs which are only fully autonomous where the road infrastructure permits, and switch between levels of autonomy (RAC, 2017).

These divergent technology aspirations also create uncertainty for policy-makers. While the first aspiration is beyond the capability of existing technology the fast-moving nature of technology creates a risk that deployment pathways focused on infrastructure will quickly become redundant (TSC, 2016). Even in the fully autonomous model, the operation of vehicles is not independent of communications infrastructure or on road markings and signage.

Against this backdrop of uncertainty, we present a simplified framework to help understand the range of infrastructure options available. This framework focuses on the dimensions most related to the transition period – the proportion of infrastructure covered by changes and the level of interaction allowed. Essentially in infrastructure terms, all transition pathways to CAVs can be viewed along these two axes:

- Level of Coverage – the overall percentage of the UK's road network infrastructure that is converted for use by CAVs; and
- Level of Interaction – the degree of mixing (for example between different types of CAVs and non-CAV traffic) that is allowed to take place on the road network.

Framing the problem with regards to these two dimensions allows us to categorise four broad classes of deployment from the perspective of infrastructure (see below).



The 4 classes of CAV deployment

"Autonomy Everywhere" (High Interaction, High Coverage): At the extreme we have the concept of autonomy everywhere. Under this scenario, infrastructure change will be widespread covering the majority of the UK's roads and vehicles will be allowed to interact largely as they do today. As a result, a CAV will be expected to be able to perform any trip in all contexts and all environments.

"Segregated Network" (Low Interaction, High Coverage): In a deployment pathway in which we aspire for CAVs to operate everywhere but also aim to restrict their interactions with other traffic (for example due to safety concerns), the resulting change would develop a separated network upon which CAVs would operate.

"Operational Geo-Fence" (High Interaction, Partial Coverage): Under this deployment pathway we would aim for high interaction with other road users but require certain pre-requisites for the operational theatre of the CAV (such as high definition mapping or higher levels of maintenance within the environment). CAVs would be limited in terms of where they could go in automated mode and would need to alert users to transition to manual driving when they exit the geo-fence.

"Dedicated Driverless Spaces" (Low Interaction, Partial Coverage): Dedicated Driverless Spaces are distinct zones where certain types of CAVs are able and allowed to operate. They can be static or dynamic – in some cases offering priority flow along critical demand channels and in others responding dynamically to changes to demand

and congestion. Critically they acknowledge the reality that high levels of coverage are unfeasible in the short-term and that mixing traffic presents a range of new challenges which increase complexity and risk. As a result, they enable accelerated deployment while providing the essential infrastructure and governance readiness to progress to more advanced deployment pathways once public confidence and benefits can be assured.

Framing the deployment pathways with regards to these two key dimensions enables us to assess clearly the relative levels of feasibility based on technology as it stands today and in the future. In this report we show that high levels of coverage and high levels of interaction are unfeasible in the short-term. While technology may eventually overcome these challenges it is difficult, if not impossible, to put a timeline on technology readiness. By understanding the feasibility issues of the alternative deployment pathways, we aim to shift the policy debate deeply in favour of Dedicated Driverless Spaces. In the following sections we discuss the feasibility challenges of these alternatives and demonstrate, in each case, how Dedicated Driverless Spaces can be employed to overcome them.

CHAPTER 2 – THE SAFETY CAR

> *“Because more than 90% of motor vehicle crashes are attributed to driver error, automation in cars offers significant potential to save tens of thousands of lives every year by eventually replacing the driver. However, introducing automation into such a complex and unstructured environment will be very challenging and must be pursued thoughtfully and with considerable caution”*
>
> - Member of the National Transport Safety Board

The first among the pre-requisites for CAV deployment is that authorities can guarantee that vehicles and the traffic system are safe. In aviation and for trains there is virtually no balancing between safety and efficiency - safety comes first (OECD / ITF, 2018). For CAVs there is fervent optimism regarding the potential for systems to remove human error. With few exceptions (Shoettle, 2015; Noy, 2018) the predicted safety benefits are accepted uncritically on the basis of the observed rate of human error-involved crashes. Clearly the potential for automated vehicles to remove common and pernicious human errors and misjudgements from the driving task is significant (Anderson, 2016; Fanant, 2015). Automated vehicles will not drive when impaired, will not drive while fatigued or face distractions such as texting (respectively factors in 41%, 2.5% and 10% of fatal crashes in the US) (OECD / ITF, 2018). It is clear that human drivers today make critical mistakes, however, for other types of incidents some researchers argue that wider system issues in road-safety such as poor roadway design, faulty vehicle, visual obstruction etc. are often attributed to human causes when they are, in fact, design-induced errors (Noy, 2018). The potential new risks introduced by CAVs – in particular edge cases and the interaction of human drivers with them, may reduce road safety in the short-term – unless the system is designed to limit interactions and restrain complexity. Ultimately, it is policy-makers who will need to independently verify that the road system is safe, that risks have been identified and managed. Our review suggests that where interaction is allowed it is currently very difficult to provide these assurances.

Mixed Traffic

One of the most important requirements for creating CAV-friendly road systems is achieving maximum predictability in the traffic environment (Ng & Lin, 2016). Complex urban environments mixing a diverse range of conventional driving styles with pedestrians, cyclists and other road uses do not provide the simplest environments for emerging CAVs.

Increased complexity leads to higher risk for autonomous systems. AI systems can be challenged when situations present themselves that are out of the range of what the AI is capable of handling (Le Lann, 2017). Complexity – in particular the complexity of mixed user environments – has been cited by many as a clear barrier to automation (TSC, 2016; Vardi, 2017) and, as a result, the majority of trials of CAVs are being carried out in constrained scenarios (RAC, 2017). It is expected that interactions between vehicles at different levels of autonomy (i.e. fully autonomous vehicles sharing roads with vehicles with partial or no automation) will also put even greater strain on road infrastructure (ibid). Reducing this complexity has been seen as a mechanism to assist with public acceptance (TSC, 2016).

73% of all respondents to a survey by ITS start-up Valerann mentioned two specific safety issues as their top concern; system malfunctions / cyberattacks, and integration between CAVs and today’s traffic (Vardi, 2017). The complexity of mixed fleets stems from the current reliability of categorisation systems used to interpret data from sensors and the wider challenge of getting an AI system to understand context. Common traffic scenarios still confound automated driving system capabilities including crossing paths and turns across traffic (Shoettle, 2017). Even features such as traffic lights can be difficult to categorise reliably in all circumstances. A number of examples are provided in the Transport System Catapult's report on the preparation for CAVs (TSC, 2016). In a recent high-profile example, Mobileye's demonstration car ran through a red light during a demonstration with Israeli television journalists (Reader, 2018b). Classification risks could be reduced through the pre-mapping of permanent road features, but no such solution can be offered for moving objects such as pedestrians and cyclists. As a result, some of the industry leaders see deployment of CAVs being much more incremental, limited to lower risk contexts and environments first (Gomes, 2016).

Safety in mixed traffic

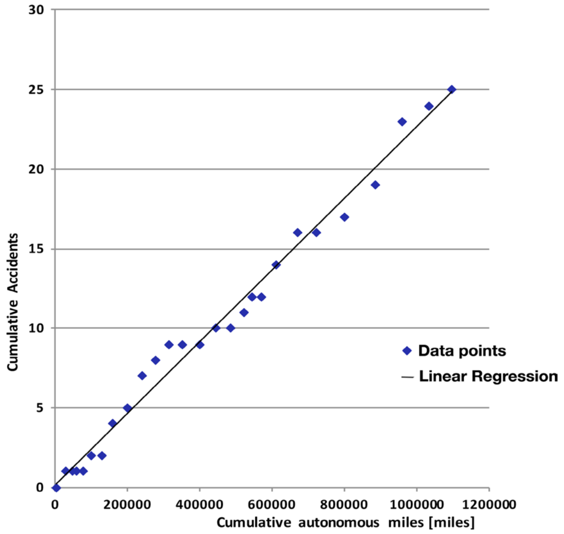
On Sunday, March 21st, 2018, Elaine Herzberg was wheeling a bicycle across a two-lane road in Tempe, Arizona, when she was struck by one of Uber's self-driving cars (Reader, 2018). When considering safety in mixed traffic in the absence of hard data, every incident involving a CAV is likely to be highly scrutinised. As deployments grow, negative headlines, in particular those caused by accidents could significantly slow deployment and industry progress. Uber's dramatic scaling back of testing of autonomous vehicles four months after the Arizona crash (Small, 2018) demonstrates the critical safety challenge faced by OEMs, technology firms and policy-makers alike.

As the ITF describes - fundamentally a lack of experience and data complicates an assessment of how safe automated driving really is (OECD/ITF, 2018). This is compounded by difficulties around data sharing. As described in research for the DfT "in all the trials the technology is proprietary, and given the competitive nature of the industry, automotive manufacturers are understandably restrictive concerning published technical information" (DfT/Atkins, 2016). One dataset that does exist offers further insights into the challenges that mixed environments are likely to present. In California, accident reports must be filed for any accident involving autonomous vehicles undergoing testing on the state's public roads (Favaro, 2017). Researchers have begun investigating this data to identify trends and accident rates. Studies in both 2015 and 2017 both concluded that the current best estimate is that self-driving vehicles have a higher crash rate per million miles travelled than conventional vehicles (Schoettle, 2015). Favaro's study in 2017 concluded that overall, accident frequencies computed for all manufacturers showed that conventional vehicles drive one order of magnitude more miles compared to AVs before encountering an accident, with a mean mileage before a crash for conventional vehicles of about 500,000 miles, compared to 42,017 miles for AVs (Favaro, 2017). There are important nuances to note behind these findings regarding how to account for unreported crash rates in the US data, and how to account for fault - Schoettle found that in each of the incidents the CAV was not at fault, for example. This raises an interesting question as to the underlying causes of this higher crash rate.

The data shows that the majority of self-driving vehicle crashes (73%) occurred while the vehicle was stopped or slow (<5 mph) in traffic with rear-end crashes the most common collision (Schoettle, 2015) i.e the data suggests that human drivers crashing into the back of CAVs is the most common cause of collision. Others have noted that unexpected behaviour by CAVs may create new risks – for example, EuroRAP cited the actions of CAVs to avoid birds, other small animals or indeed large plastic bags, as creating much confusion for human drivers (EuroRAP, 2018). In response to these issues, some have suggested the need to define acceptable behaviours of CAVs in relation to other road users (Habibovic et al., 2014) while others have suggested, in the absence of segregated lanes, programmes of education and adaptation for human drivers (RAC, 2017).

This is not a simple problem to address. California's data also provides insight into the trajectory of improvement of accident rates. One of the main conclusions drawn in other studies was that the number of accidents observed had a significant high correlation with the autonomous miles travelled (Dixit, 2016). While this conclusion may seem obvious, many would expect miles driven to drive down accident rates, indicating that AV technology is learning and approaching an "accident-free" plateau (Favaro, 2017). While technology is very likely to improve over time it is difficult to identify, based on current trends a future year when policy-makers might be able to conclude that CAVs in mixed traffic are safe.

> Dedicated Driverless Spaces overcome the safety challenges of mixed traffic by vastly simplifying the operating environment. Also, by removing human drivers, they prevent the current observed patterns of manual vehicles not anticipating CAV behaviour.



Cumulative miles & accidents. Favaro (2017).

Safety Approval Process

The assessment of vehicle safety and traffic system safety are at the heart of the regulatory function in the field of transport (OECD / ITF, 2018). It is clear that a robust safety approval and certification regime needs to be in place before vehicles are allowed on the road. The safety issues discussed above raise persistent and pertinent questions regarding the approval process for CAVs and their operating environments. Many have tried to estimate the number of miles of testing that would be required to prove the safety of CAVs. According to Klara and Paddock (2016) automated driving systems would have to log hundreds of millions – perhaps hundreds of billions – of miles in order to demonstrate their ability to improve safety. Under even aggressive assumptions, this level of testing would take tens – possibly hundreds – of years to complete. According to Shai Shalev-Shwartz (2017) of Mobileye attempts to guarantee safety using a data-driven statistical approach are naive at best. As the TSC exclaim - what process would policy makers follow to verify that an automated system will be able to go 3 million hours without a fatality? If not a statistical approach, then what? There is currently no verified simulation that can prove such levels of safety (TSC, 2016). Another challenge lies in the fact that kilometres driven are not representative of "average" driving kilometres in any other conditions than those faced in the testing environment. As a result, if the majority of test kilometres are driven in generally sunny, clear, dry conditions on wide and relatively uncomplicated road networks with few complex interactions then the resulting safety performance should not be compared to average conventional driving. A further complication arises from the fact that a simple software update could propagate a material change to the vehicle's operational framework. A self-driving car is, in stark contrast to a conventional vehicle, a combined hardware and software system. The critical performance characteristics of such a system can change radically with a software upgrade (OECD / ITF, 2018). *How will regulators approve the safety of every new software release?*

There is also the potential that safety requires communication with infrastructure – a subject we consider later in this report. A significant question is whether safe performance of vehicles is conditional on connectivity to external networks or whether functional safety can be guaranteed within an isolated core. Some argue that for SAE level 4 and 5 automation, communication is not just an enabling feature but a necessary condition for vehicle control and safety, particularly in highly complex urban traffic situations. Others argue that in no case should the avoidance of unwanted outcomes rely on access to shared external communications channels. This raises a further question as to how to validate any dependency between vehicle and infrastructure. This leads to the conclusion that actually policy-makers are approving a complete system, and not just a vehicle. Our view is that having an appropriately designed system that separates modes would vastly simplify the verification process. Similar systems such as existing PRT solutions have a proven safety, environmental and passenger service record on segregated tracks (TSC, 2016). Dedicated Driverless Spaces could therefore provide a process to assure trusted CAV deployments and accelerate uptake.

Dedicated Driverless Spaces vastly simplify the safety approval process. A complete system, segregated from other traffic, could be licensed for operation based on a robust set of plans and technical checks. Policy-makers could have full confidence in these systems due to extensive experience with similar systems in business parks and airports.

Public Acceptance and Machine Ethics

A survey by the BSI found that public acceptance was perceived to be a critical challenge for CAV deployment and adoption (BSI, 2017). Many public acceptance concerns were risks to safety, such as security threats or the negative impact from crashes or incidents. As a response to the risks of mixing pedestrians, cyclists and CAVs, some have suggested that cyclists are encouraged to wear beacons to identify themselves (Marsilio, 2018). Others have suggested that pedestrians may need to be restricted to designated crossing areas via a Jaywalking law, similar to the US (TSC, 2017). Others have suggested that 'a drop in absolute safety may have to be conceded' in order to allow mixed fleets (ibid). Some authors have suggested the possible emergence of a tiered system of safety if left fully to market forces with the relative safety of algorithms being used as a competitive advantage. A precedent of this has already been reported in the US – the 'arms race on roads' - where SUV and pickup trucks are being bought to protect their passengers while putting other road users at more significant risk (Papa, 2018). Our view is that none of these solutions to safety challenges would meet simple public acceptance tests. As a result, these types of approaches will likely delay deployments in mixed traffic.

The complexities of mixed traffic raise a range of questions regarding the interactions that will be programmed into vehicles and the legal issues that could take years to resolve. One such area is that of machine ethics. Many have questioned how CAVs would make decisions in mixed traffic situations with limited agreement to date. For example, what happens in a situation where the CAV is certain to crash if it does not change lane, but cannot change lane because this will endanger other vehicles or road users? Teaching vehicles to make choices is a highly charged issue – as an interviewee in the TSC (2016) preparation report stated: "This is not acceptable. You cannot teach a machine to choose which human to kill". These issues will be very difficult to conclude, therefore segregated schemes that can be demonstrated to be in the public interest will be far more feasible to deliver.

> Dedicated Driverless Spaces avoid challenging philosophical and legal debates. As a result, they will accelerate CAV deployment and most importantly provide confidence to the public about how CAVs will act and interact with them.

Capacity

The congestion impacts of CAVs are considered in detail in chapter 4. However, in this section we note how certain capacity issues that have been identified could impede flows in mixed traffic situations. Briefly, the role of headway and user preference has a significant impact on the capacity benefits of CAVs. Different characteristics of headways in mixed traffic ultimately affect a range of traffic dynamics (Hussain, 2016). In particular, programmed cautious behaviour when mixing with the existing vehicle fleet could impede flows rather than improve them (DfT/ Atkins, 2016). There is also some evidence that current CAVs (when mixed with the non-CAV fleet) perform less well than human drivers in terms of junction delay (Ibid).

A further issue from the perspective of existing traffic flows is the potential behaviour of pedestrians and cyclists when they begin to interact with CAVs programmed to take a safety-first approach. If pedestrians and cyclists know vehicles (ADAS or driverless) will not hit them, they could walk or cycle across roads at will. Some authors have suggested this type of behaviour could bring city-centre traffic to a near standstill (Sowman, 2016). A key reason to support Dedicated Driverless Spaces is to ensure service reliability and frequency and achieve the benefits of reduced headway in a safe, 100% CAV operating environment.

> Dedicated Driverless Spaces eliminate the potentially detrimental impacts on capacity of mixed traffic operation. Operating models and a simplified operating environment can support reduced headways and avoid interactions that reduce service and journey time reliability.

Operational Geo-Fence

Before moving on from the complexities of mixed traffic, it is worth considering one final variation of deployment possibility – a system where drivers formally switch between autonomous and manual modes (Shladover & Bishop, 2015). Testing of highly automated driving in densely mapped environments relies on human back-up or safety drivers who will take over control when the computer reaches the limits of its capabilities. Waymo (Google's autonomous car subsidiary) has developed its capabilities like this through a process of extreme gradualism. The company began testing in a few carefully selected areas with excellent weather and well-marked roads. Over time, Waymo has gradually upgraded its vehicles' software and sensors, collected more and more map data, and gradually expanded to new, more challenging operating environments. Having been testing its cars for the best part of a decade it has only recently begun serious work on operating in snow for example (Lee, 2018). Certainly, until CAVs can perform in all travel conditions there is an expectation that the human driver will need to take over in certain circumstances (RAC, 2017). This raises the question of whether hybrid Human / Automated systems could be deployed in mixed traffic or move between operational geo-fences switching between automated and manual driving, collecting much more data and progressing CAVs without dedicated zones. Such a system might be able to overcome the challenges of mixed traffic allowing self-driving vehicles to operate in their automated mode only on certain roads, separated from traffic on others or partially integrated and returned to level 0-2 driving when not on dedicated roads or in dedicated lanes. This would entail having effective and reliable infrastructure cues or communications to alert drivers and vehicles to the need to switch (RAC, 2017).

It is important to note the challenges and unintended consequences of such an approach and the subsequent impact on the feasibility of this deployment pathway. Much has been written about the difficulties making a human the back-up to a car that drives itself or seamlessly switching between levels of autonomy (Reader, 2018; OECD / ITF, 2018). A human back-up has so far not proved to provide a fail-safe - in the case of Uber's accident in Tempe, there was a safety driver monitoring the car as it drove (Reader, 2018). The fatal Tesla crash under autopilot also had a driver at the helm (Guardian, 2018). So far automated vehicles designed to share driving tasks between humans and machines have confounded efforts to ensure safety. A shared responsibility for driving among both automated systems and humans may not render decision making simpler, but more complex. Thus, hybrid systems risk the unintended consequence that driving becomes less safe, not more (OECD / ITF, 2018).

> *Hybrid systems risk the unintended consequence that driving becomes less safe, not more.*

To enable seamless transitions between automated and human driving not only are appropriate behavioural responses and communications required, but also systems that ensure the system knows when it has failed, is failing or is about to fail. A range of behavioural issues have been identified related to the human-machine interface – these include: the types of task that are allocated to the automated system versus the human driver; loss of skill; lack of situational awareness; longer reaction times due to distractions; and loss of control. If people can perform a task relatively well but do not perform the task for a long time, they lose the skill to perform that task. In aviation, flight crews are known to disengage automated systems on a regular basis to refresh their training (Barley, 1990). Driving is a 'learned' skill – in taking back control, drivers may overcompensate, creating new risks. The need to resume control when attention is directed towards another (non-driving related) task leads to dangerous and sudden changes in workload which can be detrimental to driving safety (Merat, 2014; Rudin-Brown & Parker, 2004).

Humans are easily distracted behind the wheel as we know from experience with the introduction of mobile phones. Engagement in other tasks is directly linked to the removal of drivers' attention from the road and may lead to reduced driving performance (Merat, 2014). Results from the CitiMobil project showed that driver response to unexpected or critical traffic situations was significantly later under highly automated conditions, implying both reduced situational awareness and excessive trust in the automated system (Toffetti, 2009). Vogelpohl (2018) found visual delays of up to 5 seconds when taking back control from the automated system, while Merat (2014) found that it took drivers around 35-40 seconds to stabilise lateral movement.

> *"We believe that an automated driving system should be safe for all drivers, even the slow ones"*

Vogelpohl (2018) rightly asks "What minimum time of preview before a deactivation of the system has to be guaranteed in order to ensure a safe take-over? We believe that an automated driving system should be safe for all drivers, even the slow ones". Try to envisage all the possible scenarios in which a CAV may require a driver to retake control. Is it really possible to suppose that in these situations there will be sufficient time for the driver to fully react or that the CAV would retain sufficient functionality to navigate to a 'safe harbour area'? As one respondent to the TSC's survey commented: "You are providing the driver who holds the steering wheel a false sense of security because he will think he can look around, do other things because he will think that the car will take care of itself", (TSC, 2016). It is unclear to what extent workarounds in system design can effectively address poor task allocation, de-skilling or cognition and control issues. It is possible that these are intractable vulnerabilities that cannot be "designed away". These issues have led some to suggest that SAE Level 3 automated driving is simply inherently unsafe and perhaps Level 4 as well (OECD / ITF, 2018).

While requiring a driver, systems like Tesla's autopilot are available on the roads today. It is likely that we will see more of these in the future and many will improve the safety performance of drivers. However, driver distraction is a complex area that can also impede safety and should be monitored closely. The process of designing a system of operational geo-fences for CAVs where drivers shift between interaction and none is likely to be a challenging and higher risk undertaking than the development of Dedicated Driverless Spaces. These types of systems could also take longer to fully test and refine than systems designed for a single simplified context. Dedicated Driverless Spaces offer flexibility here – they could be safely implemented today and in future retro-fitted for use as an operational geo-fence at such time that the more complex issues are demonstrably resolved.

Overall, we conclude that the mixed traffic deployment pathway has a number of feasibility challenges that will take considerable time to overcome. Dedicated Driverless Spaces solve these problems today by:

- offering a safer deployment pathway than the alternatives;
- enabling a simplified system of testing and approval, ultimately making deployment faster and more feasible;
- avoiding complex legal issues and providing confidence to the public about how CAVs will act and interact with them;
- eliminating the potential negative issues associated with capacity;
- and finally, by offering a flexible infrastructure that could be retrofitted into operational geo-fences once technology and behavioural issues are resolved.

By embracing Dedicated Driverless Spaces, authorities can accelerate the commercial operation of CAVs, provide confidence to the public and ensure the highest levels of safety during the transition period.

V2I and Smart Infrastructure

A range of edge cases and challenges exist both in terms of what sensors can do, and how reliably patterns can be recognised by AI systems. In simple sensing ability, researchers at the University of Michigan found mixed results regarding the ability for hardware / software systems to replicate and improve on human senses in all situations (Shoettle, 2017). One of the problems already encountered is that poor weather conditions interfere with many sensors that require line of sight (Glancy, 2015). For example, strong sunlight at low angles can severely disrupt the ability of CAVs to perceive traffic signal information (Ng & Lin, 2016). In response to the fatal Model S autopilot crash on 7th May 2016, Tesla commented: "Neither Autopilot nor the driver noticed the white side of the tractor trailer against a brightly lit sky, so the brake was not applied" (Lambert, 2016). Analysing the accident, the NTSB (2016) reiterated its recommendation for minimum performance standards for connected vehicle technology and for this technology to be installed on all newly manufactured vehicles. Based on these challenges, and those explored in the previous chapter, many authors have come to similar conclusions proposing infrastructure- and beacon- based solutions for traffic lights, traffic management or other road users. The Transport Systems Catapult (2017) summarise this as follows: "Unless vehicle sensors and systems have the ability to detect and interpret traffic management measures with an extremely high degree of reliability and in a wide range of environmental conditions then there will be a need to communicate details of temporary traffic management measures to CAVs.

Many fully expect driverless car technology to emerge that can operate in all environments independently of infrastructure. Certainly, our interviews with manufacturers indicate a reluctance to create any dependence on infrastructure – this, in the view of many respondents, could slow progress. However, as we have seen in the previous chapter, no vehicle currently exists that offers this level of performance. While technology may advance quickly, we should also be prepared for a scenario in which it progresses much more slowly. Policy-makers should promote schemes which could deliver substantial benefits today while ensuring their design is sufficiently flexible for the possibility that full autonomy does not require infrastructure change.

It would certainly vastly enhance safety today if vehicles are connected to infrastructure, signals and the positioning of other vehicles on the road. As has been shown, connectivity can help improve the situational awareness of automated vehicles and provide input that enhances their safety (OECD / ITF, 2018). However, this raises another challenge - if CAVs are to have widespread benefits that support the whole of society and not just a privileged few, they must have a reach that covers the full extent of the UK's road network. This is an extensive undertaking if infrastructure changes are required. This infrastructure, or the standards upon which this infrastructure should run do not exist today - only ~4% of UK roads currently have any type of active monitoring and management technology in use (Vardi 2017). It is therefore unsurprising that a survey by Valerann found that 88% of participants indicated they do not have the ITS systems in place required to safely and effectively manage traffic that includes CAVs (ibid).

ITS installations can cost upwards of £1.6 million per km (ibid) and assuming a similar cost for the basic levels of smart infrastructure, any roll-out across the whole of the UK would likely cost in excess of £675bn. To put this in context the total expenditure of the UK government is expected to be £828.6bn in 18/19, including £149.7bn on the NHS. To put this figure in a roads context, Highways England's total capital program in 2018/19 is £2.7bn (Highways England, 2018).

Based on current budgets, even if we assume the entire annual budget is allocated to ITS systems, the prospect of ITS everywhere would take in excess of 100 years.

This raises obvious questions of where the money would be found to fund infrastructure changes to enable the use of CAVs on urban and rural roads (RAC, 2017). As concluded by Gill et al (2015) given the huge costs involved in altering all infrastructure, it is more plausible to focus on sections of roadways rather than attempting a wholesale transformation.

Many have come to a similar conclusion – Huggins (2017) concluded it will be prohibitively expensive to modify all existing road infrastructure in the short to medium term; the RAC (2017) concluded that any new system requiring extensive roadside communications technology could prove prohibitively expensive, as well as raising issues of international interoperability and more recently, the European Commission has said that infrastructure deficiencies lead to the realisation that true (ubiquitous) SAE level 5 vehicles may never be possible since comprehensive infrastructure support will likely never cover the entire road network (EuroRAP, 2018).

Dedicated Driverless Spaces offer a deliverable vision for CAVs focused on individual schemes where maximum benefits can be evidenced. With a simplified operating environment, the costs of V2I and Smart Infrastructure are much lower. And most importantly, as we demonstrate later, funding contributions from the private sector for infrastructure change are plausible in a range of cases.

Communication Infrastructure

The roll-out of digital connectivity along roads, recommended in the NIC's Connected Future report, is seen as crucial for realising the benefits of CAVs, in particular the benefits of connectivity between vehicles (NIC, 2017). However, the precise connectivity infrastructure required by autonomous vehicles is unclear. The Transport Systems Catapult, for example, envisages a future where multiple communication protocols are used, however recognises the current uncertainty in knowing the precise role each protocol will play (TSC, 2017). Certainly, based on our interviews, at full autonomy there is a consistent requirement across the technologies for very high definition and constantly updated digital maps (Sowman, 2016). Downloading these maps requires high-resilience communications infrastructure. One respondent stated they were considering 5G but 5G alone may not be sufficient in all circumstances - for example there is a requirement for communications to continue to be available during all circumstances, including during large scale events. Every manufacturer we interviewed confirmed that outside of connectivity, the vehicle would require the human to regain control or enter its fail-safe mode.

There are further complexities if vehicles are required to communicate with each other. Because vehicles are in movement, low-latency in mission-critical communication is necessary but it is uncertain that transmission can be guaranteed using existing approaches as the number of connected vehicles scales (Le Lann, 2017; Le Lann, 2018). Whether the UK has the capacity and bandwidth to collect and send the vast amounts of data required, for example from many millions of vehicles is an open question (TSC, 2016). The requirements for communications infrastructure at scale and the cost needed to achieve penetration of CAVs at scale therefore requires further investigation.

To understand what the challenge might look like once a technology consensus has been agreed, we can look at previous roll-outs of major communications infrastructure as a guide. Certainly, there are many areas of the UK, in particular rural roads, that still have poor coverage from 3G and 4G networks, let alone the 5G likely required for CAVs. Any roll-out of communications networks of this scale would take many years and may require public subsidy in rural areas. The UK's history of broadband deployment described in Mercer (2018) provides a parallel with multiple missed targets and rural roll-out issues.

Dedicated Driverless Spaces place the requirement on the zone operator to ensure that the zone has the requisite communication infrastructure for full vehicle functionality. In this way, the system operation can be designed, planned and delivered with back-up systems installed to ensure required connectivity at all times. Eventually, communications standardisation between zones can be introduced based on successful operations and the emerging technology consensus.

Road Maintenance

A number of authors have pointed to the issue of road maintenance practice. The NIC (2017) acknowledges, for example the need to enhance road signage and traffic signals. The state of the art encounters a range of challenges with infrastructure that is standard on many of today's roads in the UK. While human drivers can cope with situations such as broken or temporary traffic lights, pot holes, obstacles, flooding, poor road markings, obscured signs and many others, automated systems currently struggle (Sowman, 2016). Not all of these challenges can be solved by connectivity but will simply require a higher level of maintenance. Road markings are critically important since they are relied upon by a number of systems for latitudinal positioning and lane-keeping.

In the USA there are documented examples of CAV trials coming to a standstill because of poor road markings (Louw, 2016). Tesla's CEO, Elon Musk, and Volvo's North American CEO, Lex Kerssemakers, have both complained about the poor state of lane markings hindering the deployment of CAVs (TSC, 2017). This implies that these markings need to be maintained to a higher standard if autonomous systems are to function correctly everywhere (RAC, 2017). This may not just include routine maintenance, but maintenance to ensure safe operation in all conditions including to enable seamless function in mud, heavy rain, fog and snow (TSC, 2017). Finally, there is the further problematic situation of how to deal with roadworks in which lane markings may disappear, be replaced by cones, or where traffic is guided through the roadworks by staff using hand signals (Ng & Lin, 2016).

Beyond lane markings, other specific UK issues such as potholes and roundabouts have been noted as particular challenges (Archer, 2018). For example, a pothole in a traffic lane carrying vehicles in a platoon, where vehicles follow each other very closely, could be extremely hazardous, especially at high speed (RAC, 2017). Our detailed interviews with manufacturers indicate different approaches to identification of potholes - some vehicles can't currently identify them while others would treat them as a stationary object, slow down and require a human driver to resume control. Similar complexities and problems could be caused by road signs. Road signs are currently inspected every 12 months, meaning they could spend a significant period in a state that is unreadable to CAVs (TSC, 2017). How vehicles would account for differences in signage (for example across borders) is also unclear. Vock (2016) found that in the US there was little standardisation of signals and signs which the researchers had supposed were common across states.

It is clear that to accommodate CAVs across the whole infrastructure a major change in the approach to road maintenance would be required so that signage, markings and integrity of main roads could be quality assured in a manner equivalent to air and rail transport (EuroRAP, 2018). As a result of these issues, the European Road

Assessment and Car Assessment Programmes (ERAP and ECAP) have called for the establishment of an intervention and maintenance policy to ensure that road markings on Europe's roads remain visible to CAVs and human drivers at all times, irrespective of weather conditions (TSC, 2017). In a UK context, prioritisation methods used by Highways England and by county councils to schedule maintenance, repair, renewal and enhancement would need to align with the national policy on CAVs (RAC, 2017) – this would likely require additional funding.

As the RAC (2017) describe "These conclusions about the requirements for the state of roads sits awkwardly with the current state of condition". Experience in other sectors – for example aviation and rail – suggests that as greater use is made of sophisticated technology, maintenance costs increase significantly. 98% of the UK's road network - carrying two thirds of all traffic and including many important rural and urban 'A' roads - is managed by local authorities. Funding is increasingly being constrained with local authorities having faced average budget cuts of 26% in real terms since 2009/10 (IFS, 2016). These cuts have impacted on maintenance programmes and local roads are increasingly in poor condition. The Asphalt Industry Alliance (2016) Annual Local Authority Road Maintenance survey reports that local roads in the UK are deteriorating at a faster rate than they can be repaired, and that the one-off cost of getting the local road network in England and Wales back into reasonable condition would be £11.8bn. This is similar to the Government's total spending on all roads each year (NIC, 2017). Moreover, and perhaps even more challenging, is that the time estimated to clear the backlog of repairs in England is 14 years. These conclusions about the potential costs also sit uncomfortably with the 'Congestion, Capacity and Carbon' report. Here, the NIC notes that if the UK electrifies the vehicle fleet without changing the tax system, Fuel Duty and Vehicle Excise Duty would fall towards zero by 2050 and that under such a trajectory, taxes on road users would no longer be sufficient to cover the costs of enhancing and maintaining the roads (NIC, 2017).

With higher levels of maintenance required, reduced revenue budgets for local authority-maintained roads and potential risks to road taxes through electrification, critical decisions will need to be made about who pays. As with many technologies, fully operational CAVs are likely to initially be premium vehicles (e.g. Tesla) available only to the those who can afford them. If this is the case, there will certainly be many difficult political questions if the costs of maintenance that ensure their safe operation are socialised to non-CAV drivers. One idea that is commonly proposed is that road sections could be "certified" as able to support certain AV use cases. Certification would work by evaluating and defining roads that are suitable for specific vehicles and use cases (Huggins, 2017). Requirements for road markings, signage, surfaces and communication infrastructure could then be clearly specified and evaluated. Dedicated Driverless Spaces provide this precise function, shifting the maintenance responsibility to the licensee.

> Dedicated Driverless Spaces provide the opportunity to license dedicated zones to operators. Within these zones, the operator will be responsible for maintenance of the roadway and operational theatre factoring this into their service costs. They will need to demonstrate plans and systems for all weather conditions (e.g. snow) to ensure a resilient operation.

New Risks

While CAVs may reduce driver error, they may also introduce a new spectrum of risks – none of which are currently regulated. Regulatory oversight is present for the analogue systems present in a vehicle (chassis, steering and acceleration/braking control, protective functions etc.) but has not been developed for the lines of code that control the operation of autonomous vehicles (OECD / ITF, 2018). In perception surveys, fears about software failure and security have been found to be commonplace (Sanbonmatsu, 2018). Each CAV system uses extensive software - for example, melding together lidar and camera data – a process known as sensor fusion – requires significant code in its own right increasing complexity and the opportunity for software errors (Lee, 2018). One complication related to coding for uncertainty is that there is no single algorithm that covers the full range of pre-crash and crash situations. Multiple algorithms are therefore combined to address a wide range of potential safety-critical situations. As the volume of mission-critical code grows, so does the potential for error and unexpected interaction effects. Code embedded in automotive systems are prone to errors (20-50 errors for every 1000 lines of code, 15% of which are missed by industry standard quality assessment techniques (Reader, 2018; Lonsdale Systems, 2016; OECD / ITF, 2018). This code complexity raises the potential that errors or software updates contribute to unsafe outcomes.

While human drivers may be responsible for many risks, the introduction of CAVs introduces new risks to the system. Overall, our research has identified the following broad potential crash causation scenarios for automated vehicles:

1. When sensors do not detect a critical part of the vehicle environment or incorrectly identify it;
2. Where the automated system makes the wrong manoeuvre for a particular situation either through programming or through mis-categorisation of the situation;
3. Where human drivers mis-interpret the behaviour of autonomous vehicles;

4. Situations where faulty human-machine interactions contribute to a crash;
5. Edge cases – situations where the system encounters a context unforeseen or anticipated by its software
6. System or software failure – where the system itself fails
7. Cyber breach – where the system has been compromised

One of the chief concerns from the public is that of cyber risk. The ITF have described a reliance on connectivity for safety as "fraught with risks, especially with regard to cybersecurity" (OECD / ITF, 2018). Connectivity raises critical questions about the ability of networked automated driving systems to withstand cyberattacks that could compromise safety. Cyber threats within CAVs exist on two levels: the operation of AVs themselves as individual vehicles and their communication capabilities as connected and automated vehicles (Bagloee, 2016). On board Wi-Fi, Bluetooth to connect mobile devices, SD card readers, GPS sensors, radar / lidar sensors, ultrasonic sensors, 3G / LTE connectivity and even CD / DVD players all offer possible methods to tamper with the security and integrity of modern vehicles (OECD / ITF, 2018). Risks such as manipulating GNSS data, providing fake messages and spoofing cars are also new emerging concerns. Researchers from the Michigan Traffic Labatory found that ITS systems are "relatively easy to trick" with the research finding weakness not just in the communication technology, but also in the algorithms used to manage traffic flow (Chen, 2018). As Ratti (2017) describes, "Malicious hacking is difficult to combat with traditional government and industry tools, and it is particularly dangerous in the case of systems, such as self-driving cars, that combine the digital and physical".

Various methods have been proposed to digitally manage trust within the system. As a starting point the use of a verifiable digital identify and authentication protocol could enable trustworthy interoperability and secure connectivity (OECD / ITF, 2018). However, it is unclear how such a system would fully eliminate vulnerabilities. It is important to understand that the processing of digital certificates is "computationally expensive", which means that it introduces a time delay even when using the most state-of-the-art computers. This additional delay to validate a message simply might not be practical, in particular at high speeds i.e. **attempts to guarantee trustworthiness digitally may eliminate the very benefits of connectivity in situations where it is most needed.** Many have called for systems that are designed to fail smoothly (Bagloee, 2016). But the process for doing this is also not known. Christopher A. Hart, Board Member for the NTSB, sums this up in his statement accompanying the Tesla crash: "In aviation, although automation has generated substantial safety, efficiency, and other benefits, we will not see airliners without pilots any time soon because no graceful exit has yet been developed."

The ITF conclude that until these technologies are demonstrably ready to reliably handle high-volume and high-speed interactions in line with safety objectives, a Safe System approach should be progressed based on proven approaches to ensure that essential safety performance is not predicated on connectivity – for example, managing differences in speeds between potential crash opponents, adapting the material properties of surfaces and utilising robust separation techniques to minimise harmful interactions (see OECD / ITF 2018). Dedicated Driverless Spaces enable such Safe System approaches to design – they can operate with a known registered fleet of vehicles, have dedicated firewalls and networks, place security restrictions on operating personnel, manage speed so that any incidents result in minimal damage and design physical infrastructure to avoid major risks.

Dedicated Driverless Spaces enable operators and policy makers to gain appropriate confidence through the specific design of the scheme and operational plan. Code can be simplified based on the reduced complexity of the operating environment. The vehicle fleet and infrastructure can be pre-registered, and so open communication channels will not be necessary. Connectivity can be closed, firewalled and the operating theatre physically secured. Finally, physical infrastructure and managed speeds can reduce or prevent damage in high risk situations.

Overall, we conclude that development of CAV infrastructure and maintenance processes to support ubiquitous CAV operation is not feasible based on existing technology and improvement trajectories. Dedicated Driverless Spaces overcome these challenges by:

- offering a deliverable vision for CAV deployment based on specific schemes where individual benefits and costs can be managed;
- confering certain responsibilities, such as maintenance and connectivity, to an operator under a license. This prevents these becoming significant public costs;
- supporting funding contributions from the private sector making them a much more viable proposition for wide-spread adoption;
- and finally, providing the framework in which a Safe System can be designed, critically using a range of techniques to mitigate against Cyber and other risks.

By embracing Dedicated Driverless Spaces, authorities can accelerate the benefits of CAVs while avoiding high cost and high-risk alternatives that could otherwise undermine the UK's CAV progress.

In order to identify the key influences that CAVs could have on network congestion, we first review the extensive modelling activity that has taken place to date. Our focus here is on both general roads and city-based strategies. Many of the insights that can be gleaned from the literature are based on strategies that have been applied to cities. Of our 9 typologies for Dedicated Driverless Spaces, 7-8 have potential applications within Urban environments. Therefore, this section provides a focus on cities and the network performance benefits CAVs could generate.

As drivers of economic growth, cities are essential to the UK's industrial future but also the jobs and livelihoods of their residents. Cities are the predominant spatial structure in which people choose to live - synergistic hubs of innovation and enterprise, as well as critical centres of government, trade and knowledge. Representing 60% of jobs (Centre for Cities, 2017) cities drive the economy, create efficiencies of scale and demonstrate super-linear scaling for positive outcomes such as income, productivity and innovation (Arbesman, 2008). Large populations and business density in cities create agglomeration effects (Krugman, 1991) enabling people to interact rapidly and share knowledge (NIC, 2017). It is no wonder that 71% of jobs in knowledge-intensive service industries are in cities, and 74% of the UK's service exports come from them (Centre for Cities, 2017). Higher concentrations of employment result in higher productivity and wages (NIC, 2016). "Enabling these concentrations to develop and thrive is one of the key ways in which infrastructure can support the economy" (NIC 2017).

Many of the UK's cities have been shaped by history – a consequence of geographic, social, economic and political factors over centuries. Place-names like -ford, -bridge, -mouth, -port and -pool result from the legacy of the development of many of our towns and cities around water – historic confluences of trade, production and industry. In many of our cities, the combination of historic streetscapes, river crossings, geographic and organic layers of development, create multiple bottlenecks for intra-city movement. As a result, capacity on city networks cannot be easily or sustainably expanded. The impact of traffic flow in cities is therefore seen by many as "increasingly unbearable" (NIC, 2017). Rising demand for travel will risk creating high levels of transport congestion and delay, unless action is taken to address this (ibid).

In congested city centres competition for road space is high and only set to get fiercer. Against this backdrop, policy-makers must find new ways to enhance urban capacity and make critical choices about the priorities for road space.

Private cars are an underused asset - mainly active during peak hours and rarely for more than 10% of the day. Much of their capacity is also underused since cars typically display low levels of occupancy in each trip – often with only one occupant. Despite this, they are "highly valued assets" – with households putting up with these levels of inefficiency in order to derive specific benefits relating to comfort, door-to-door service and schedule-less travel (OECD / ITF, 2015). But what is the alternative? Cycling and walking are becoming ever more popular options where the infrastructure is supportive, but despite the growth in these modes, are not feasible for many longer distance commuting 'tidal flows' or leisure trips. Conventional buses remain an unattractive option to many in the UK – with service levels constrained by congestion, buses have become 10% slower every decade (Begg, 2016) and route designs often do not offer direct trips between high-demand zones. Urban rail has many benefits but is a high-cost intervention that requires sufficient density and usage to be viable – often not available to many smaller cities. Against this backdrop there is much hope that CAVs could provide efficient door-to-door, shared services combining optimal route design with the user-benefits of the private car. However, the capacity and congestion benefits of CAVs are complex. In the next section we review the literature and modelling in detail to understand what critical decisions we need to get right to truly deliver urban congestion and network efficiency benefits.

Urban Capacity and CAVs

One of the major anticipated benefits of CAVs is the promise of improved capacity and reduced congestion. However, as DfT/Aktins (2016) notes, there are still many unsupported and unsubstantiated claims regarding these benefits. Many academic models have been developed through the literature, each based on a different system design and assumption set. Much work to date concerns passenger cars, and taxi-based, on-demand solutions. Far less modelling has been conducted considering public transport – in particular buses, shuttles and other mass transit solutions (Ibid).

Despite this gap, the following key factors can be identified within the literature through which CAVs are expected to influence capacity and congestion. **The evidence related to each key factor is discussed below:**

Headway

Headway measures the longitudinal spacing between vehicles. It is often suggested that CAVs will be able to travel together more tightly, in "platoons", due to a presumed ability to communicate precise positional information across the fleet. The logic follows that by reducing the spacing between the fleet, more vehicles will be able to occupy existing road space, hence increasing its capacity. In addition, some have speculated that, with a fully connected and autonomous fleet, traffic light systems could be replaced with a 'slot intersection' system further reducing headway at existing urban bottlenecks. Modelling of slot intersections suggests they could double junction capacity compared to conventional traffic lights (Ratti, 2017). However, depending on the configuration and demands for safety, reduced headways may not be deliverable in practice (DfT / Atkins, 2016b).

In general, while potentially being desirable from a policy perspective, reduced headway is not a major consideration in the design process for CAV manufacturers. Safety and user preference represent a much higher priority and as a result conservatism and larger headway often prevail. Studies show that most users prefer low jerk and slow acceleration - driving styles that do not necessarily correspond to how humans would drive manually. This may be because a slower acceleration seems more controlled. It may be impossible to separate driving style and the perception of risk in the user's preferences (Bellem, 2018).

This trade-off between reduced headway and user perceptions will have a major impact on whether higher capacity is actually achievable through CAVs. Le Vine et al (2015) specifically examined the tension between occupant experience and capacity by looking at the impact at a signalised junction. Their work showed that if the level of comfort required was assumed to be the same as high speed rail (in terms of acceleration and deceleration on all three travel axes), capacity would significantly worsen (by between 21% and 54%) (ibid). This conclusion is echoed in a publication from Princeton University (Bierstedt et al, 2014), which found that CAVs "will either have no impact or at worst could degrade capacity as safety conscious programming of vehicle speeds and headways reduce vehicle densities".

Headway is also greatly influenced by the levels of mixing allowed within the fleet and how humans are likely to behave around CAVs. Certainly, it is clear that even if CAVs can be incentivised to provide improved headway then the benefits will be limited if CAVs are unable to operate together within a Dedicated Driverless Space.

Demand

It is a widely acknowledged phenomenon that new roads lead to new journeys which in turn can quickly undo the effects of the increased capacity. Post-opening evaluations of major road schemes suggest that journey time savings, especially at peak times, tend to be lower than forecast. Particularly in urban areas, increases in capacity lead to changes in behaviour with congestion generally returning to a similar level experienced prior to scheme opening (NIC, 2017). The so called "fundamental rule" of road congestion (Duranton, 2011), also known as "Induced Demand", prompts many to believe that it is simply impossible for the UK to build its way out of congestion (NIC, 2017). That the capacity benefits of CAVs could also be eroded through induced trip making has also been widely speculated (DfT / Atkins, 2016; Childress et al, 2014). Childress et al (2014) explored possible impacts of CAVs showing that if capacity was increased by 30%, vehicle miles travel would increase to take up the extra capacity and vehicle hours would reduce by around 4%. Further, many have suggested that if driving is cheaper and more attractive in a predominantly CAV-based future, congestion could get much worse (NIC, 2017; Wadud, 2016).

Cost of travel is a key driver of demand – as cost falls, demand is expected to rise. The National Infrastructure Commission's National Infrastructure Assessment sees the cost of travel falling simply by means of electrification (NIC, 2018). A study by Wadud (2016) estimates that autonomous cars can cut the cost of travel by as much as 80%, and that this could be expected to drive up kilometres travelled by 60%. Puylaert (2018) applied a Systems Dynamic Approach to model the effects of CAVs. Here, the private car was expected to become more attractive due to lower costs and a reduction in the value of time. In general, this resulted in an increase of car trips. This led Puylaert (2018) to conclude that if autonomous vehicles do not exhibit capacity benefits the average speed will be lower than without the technology and delays may very well increase.

Hensher (2018) speculates that the sharing of private cars could also lead to increased trips overall through a higher number of trips per vehicle, and to greater congestion if the number of trips overall goes up. Others note that CAVs will fulfil previously unmet demand and potentially create new demand (Truong, 2017; Wadud, 2016). Survey-based research confirms the potential upward bias in travel demand. A survey of the Danish population revealed indications of increased travel including for holidays and long-distance travel resembling similar findings from US studies (Nielsen, 2017). Hensher (2017) and Karlsson (2016) note the changing incentives and that, under a mobility model, the incentive for a mobility service provider will be to generate as much mobility as possible (i.e. trips and kilometres) to maximise returns on capital.

Overall, demand effects lead to considerable uncertainty in model outputs, often overwhelming capacity benefits emerging through other mechanisms (e.g. reduced headway, sharing or routing efficiency). To demonstrate the uncertainty this creates, Wadud (2016) concluded that automation might plausibly "reduce road transport Green House Gas emissions and energy use by nearly half – or nearly double them – depending on which effects come to dominate". Maciejewski and Bischoff's (2017) conclusion was even more stark, stating – "if CAVs, through their performance, do not result in higher road capacity, Autonomous Taxi services cannot be introduced on a large scale, as it would lead to even heavier congestion in urban areas".

Routing

There has been little research on the impact of routing choice within CAVs. Bagloee (2016) suggested that a major knowledge gap exists regarding CAV technology in terms of the impacts of their routing behaviours. Bagloee went on to show that the effects of "System Optimal" routing behaviour would be considerably different to "User Equilibrium"-based routing choices. In terms of the total travel time spent on the network, the gap between User Equilibrium and System Optimal routing was found to be as high as 2.15. In other words, congestion could be significantly improved by enforcing a system optimal traffic patterns within a connected and collaborative fleet (Bagloee, 2016). The corresponding impacts on the user's journey experiences under System Optimal routing were not assessed.

In contrast some authors have indicated that the nature of CAVs may result in unexpected trips. For example Robin Chase, co-founder of the car-sharing service Zipcar, has written of "zombie cars – those with no one in them – clogging our cities and our roads" (Ratti, 2017). Adams (2016) questioned whether hire vehicles would be parked or whether CAVs would cruise around towns and cities waiting to be hired? Adams refers to this latter possibility as performing the "infinite-Uber-loop". These are important questions. The travel cost from optimal repositioning of fleets is captured in much of the modelling work to date, but in most cases, additional miles due to induced idle time are not.

Ride-sharing

New models for car ownership, in particular, ride-sharing based on Mobility as a Service are widely expected to drive greater asset utilisation and improve the efficiency of transport. As a result, the concept of ride-sharing is deeply interwoven with expectations about CAVs. A range of authors have looked at the potential benefits that could be derived from this new mobility paradigm. For example, based on combined car sharing and ride sharing, and a city could be expected to require only 20 percent the number of cars now in use, with its residents traveling on-demand (Ratti, 2017). Other studies have arrived at similar conclusions. For example, a study by Spieser et al. (2014) explores the effect of a complete removal of the entire private vehicle fleet in Singapore, and its replacement by a shared self-driving fleet. The findings suggest that such a fleet could remove two thirds of the vehicles currently operating while still delivering all of the trips currently made. A model of Ann Arbor and Babcock Ranch by Columbia University find that near instantaneous access to a vehicle could be provided with only 15% of the vehicles currently needed to carry those trips (Burns, 2013). And finally the International Transport Forum (ITF) modelled a system of "TaxiBots" (shared passenger taxis) finding that when combined with high-capacity public transport they could provide the same level of mobility with only 10% of the cars (OECD / ITF, 2015). The evidence is therefore clear that shared vehicle fleets could free up significant amounts of space in a city, with the caveat that space management policies are in place to ensure these benefits are fully reaped (Ibid).

These findings, however, mask important information about how a smaller operational fleet would be used. While the reduction in vehicle numbers can unlock meaningful benefits in terms of parking space requirements and the potential for public realm enhancements, it is ultimately vehicle miles travelled which has the greatest potential impact on network congestion. These models show that fewer vehicles are needed to provide the same mobility, but in each case the overall distance travelled by the fleet modelled goes up. Spieser (2014) found that the overall distance travelled as well as the vehicle-use intensity would increase, concluding that this may erode the benefits linked to travel times and congestion. The ITF study modelled a number of scenarios to further understand the increase in vehicle kilometres. This study demonstrated that in the shared service solution with public transport, the increase is fairly modest (9%), however a single passenger solution without high capacity public transport would prompt a significant (103%) increase in vehicle miles (OECD / ITF, 2015). This study also assessed the impact on the transition, concluding that this period would be "challenging" finding that if only 50% of car travel is carried out by shared self-driving vehicles then total vehicle travel will increase between 30% and 90% (Ibid). The MERGE (2018) Greenwich consortium found that the introduction of a low-cost, convenient service alongside existing modes could lead to switching from Buses and increase vehicle miles travelled by up to 57%.

It is also important to note that a shared-mobility scenario is by no means a foregone conclusion. In survey-based research, sharing is not, by default, preferred by consumers – for example in a survey of attitudes towards CAVs in the Danish population the authors found that all categories of potential users saw themselves as being more interested in ownership rather than shared use, and the shared use-case overall was among the least preferred! This conclusion is interesting, in light of the widespread view that a shift away from private vehicles towards shared fleets is a likely outcome of the development towards increased automation (Nielsen, 2017). MERGE (2018) also found that only 46% of people would be willing to use a ride-sharing service regularly. This relative reluctance to share was due to concerns about privacy, personal security and unwanted social interactions with strangers.

Ride-hailing

It is important not to confuse ride-hailing with ride-sharing – ride-hailing being the act of digitally calling a taxi trip. The rapid adoption of ride-hailing poses a significant challenge for transportation researchers, policymakers, and planners, as there is limited information and data about how these services affect transportation decision-making and travel patterns (Clewlow, 2017). Globally ride-hailing platforms have seen significant investment (the top 4 ride-hailing platforms globally have received $44.4bn in venture investment), ride-hailing adoption is occurring now, and it is expected to be a key delivery model for CAVs – for example Google's Waymo and GM's Cruise brands both aim to bring CAVs to market via a ride-hailing taxi model. Understanding the full effects of ride-hailing is critically important if we are to fully understand the likely impacts of CAVs. In this area, the literature is inconclusive.

Li et al. (2016) assessed the impact of Uber's entry into transportation markets and found evidence that ride-sharing services significantly decrease traffic congestion time, congestion costs, and excessive fuel consumption.

However, Clewlow et al (2017) concluded that based on mode substitution and ride-hailing frequency-of-use data, ride-hailing was contributing to growth in vehicle miles travelled in the major cities studied. Most notably they found a demand inducing and substitutive effect stating that 49% to 61% of ride-hailing trips would have not been made at all, or by alternative modes such as walking, biking, or transit (ibid). They also found that ride-hailing may have negative impacts on car-sharing and transit use. Among adopters of prior carsharing services, 65% have also used ride-hailing with more than half dropped their membership, and 23% citing their use of ride-hailing services as the top reason they no longer car share. The authors also found ride-hailing attracting Americans away from bus services (a 6% reduction) and light rail services (a 3% reduction). Finally, Babar et al (2017) found a broad mix in the impacts – finding significant reductions in the utilisation of road-based, public transit services - namely city buses - while increasing utilisation of rail-based and long-haul transit services, such as subway and commuter rail. This study also noted the competitive advantage of ride-hailing over public transport concluding that 66% of ride-hailing trips would have taken twice as long by public transport (Ibid). Overall, given the limited consensus, we feel this is a key area for further study.

Integration

Integration describes the degree to which CAV-based systems are designed to operate alongside existing public transport. As previously suggested CAVs could be highly competitive with public transport due to cost or journey time benefits (Puylaert, 2018; Babar, 2017). The ITF study above demonstrates that TaxiBots without high capacity public transport could result in a significant increase in vehicle miles (103%) (OECD / ITF, 2015). In contrast, Zachariah et al. (2013) modelled the implementation of a fleet of autonomous taxis (ATaxis) in New Jersey, based on origin-destination trips derived from travel surveys. ATaxis were modelled based on pick up locations (“stations”) near their origin and dropped off at stations near their destination with ride-sharing built into the system. The results of the simulation demonstrated that such a system could contribute to significant reductions of congestion in heavy-traffic areas. The authors concluded that such an autonomous taxi system would be especially valuable in areas of high demand such as train stations (ibid).

In an extension to their 2015 study the ITF modelled the impact of replacing all car and bus trips with shared mobility operating around rail and subway services. The study again focuses on Lisbon and simulates shared mobility delivered by a fleet of six-seat vehicles (“Shared Taxis”) that offer on-demand, door-to-door shared rides in conjunction with a fleet of eight-person and 16-person mini-buses (“Taxi-Buses”) that serve pop-up stops on demand and provide transfer-free rides. Under this model, congestion disappeared, traffic emissions were reduced by one third, and 95% less space was required for public parking but most importantly, vehicle-kilometres were 37% lower even during peak hours (ITF / OECD, 2017). In the simulation, inequalities in access to jobs, schools or health services across the city virtually disappeared (Ibid). However, this work noted the challenge during the transition period finding that if 60% of the private cars were to remain, no reduction in congestion or CO2 emissions would be achieved (Ibid). This raises the question as to what policies need to be in place alongside CAVs to maximise the benefits. This question was echoed by the MERGE (2018) Greenwich consortium who conclude that CAV ride-sharing services will need to be supported by external policies which increase the cost of motoring in order to encourage more switching from private cars – unless this is achieved, the new fleet will increase the total kms and will naturally contribute to congestion. NIC (2017) notes that in European cities which have driven shifts to public transport, better infrastructure is also associated with restrictions on driving – Vienna limited parking and driving to further encourage the up-take of public transport modes.

Understanding competition with other modes will be critically important to ensure successful schemes, In a final example, researchers at Delft University investigated a system of Automated Last-Mile Transit comprising a fleet of small, automated single passenger vehicles. The location chosen for the analysis linked a campus to a railway station in a region that offered a high proportion of onward travel by foot or bike. The system was found to be competitive with the walking mode but that additional measures were deemed necessary to increase competitiveness against cycling (Scheltes, 2017). In cases where the last mile is already well-served by walking and cycling, CAVs may not be the most appropriate solution.

Dispersion Effects

The final effect is “dispersion” – the propensity of CAVs to induce a spreading out of a city’s suburbs. A survey of the Danish population showed that enthusiasts towards self-driving cars expected to travel more with many seeking to use CAVs to live further from urban areas or their place of work with obvious consequences on vehicle miles travelled (Nielsen, 2017). Explorations of the land use impacts of automated driving reveal two main land use dynamics in the city - reduced transport costs causing cities to further expand, while reduced parking requirements potentially leading to densification of economic activity in the centre (Zakharenko, 2016). Similarly, Gelauff et al. (2017) concluded that automated vehicles could induce both urban dispersion and concentration effects with dispersion occuring when more productive uses of time during travel were assumed. Puylaert (2018) found that when dispersion effects were considered, automated vehicles would cause an overall increase in trip lengths and as a result vehicle kilometres travelled. Therefore, the wider long-term land-use implications for CAVs must also be considered and policies adopted to ensure these effects do not create exacerbate existing “tidal flow” effects across our city’s road networks.

SUMMARY OF KEY CONGESTION DRIVERS

This section demonstrates that there can be multiple benefits from the adoption of CAVs into the fleet. However, there are detailed design issues that must be taken into account if the benefits are to be maximised and secured. These considerations include system operation, the make-up of the fleet, the role of public transport, integration with other modes and wider policies to encourage behaviours that secure a lower congestion future. To summarise, a deployment pathway that considers the following key points is essential if the benefits of CAVs are to be achieved. In each case we believe that Dedicated Driverless Spaces provide the appropriate infrastructure and policy tool to do this.

Headway	Consideration should be given to how to encourage headway improvements while retaining safety. Beneficial headway characteristics could be encouraged through support for certain vehicle specifications and through Dedicated Driverless Spaces, giving priority to safe operation.
Demand	The potential demand effects and competition with other modes should be considered over the long-term. As well as support for CAVs, a package of measures supporting home working, public transit and active travel should be promoted. Dedicated Driverless Spaces support the role of public transit and through the case studies we demonstrate how they can be linked to active travel interventions.
Routing	Systems that incentivise collaborative routing and eliminate wasteful idling will be essential to maximise the benefits of CAVs and ensure that system-optimal choices are made. A network of Dedicated Driverless Spaces can be designed holistically with the routing trade-offs explicitly explored within strategic models.
Ride-sharing	Sharing clearly has benefits and can deliver the same mobility with fewer vehicles. However, in every model we have reviewed, taxi-based systems show an increase in overall vehicle miles travelled under the new system. Survey evidence suggests that the majority of the public will resist sharing and therefore the current evidence lead us to conclude that taxi-based models may be sub-optimal for urban mobility. Dedicated Driverless Spaces are used by shuttles, mass transit technologies and to serve the last-mile. The modelling we develop in the next Part shows that significant benefits can result.
Ride-hailing	The evidence is inconclusive as to the effects of ride-hailing on urban transport. Given the growth in these services, this is a critical research gap that should be addressed.
Integration	In modelling activities, when public transport has been replaced by CAVs, detrimental impacts have resulted. It is therefore essential to maintain and enhance public transport, integrating CAVs into this network. The system design of the 2017 ITF model, utilising a system of larger shuttles, taxis and public transport offers the greatest promise from the perspective of reducing vehicle miles travelled. The Dedicated Driverless Spaces we promote utilise these key features within their design but also allow for specific schemes to be developed providing the delivery mechanism for this future model.
Dispersion Impacts	Over the long-term, land-use changes may lock in adverse consequences of CAVs. Therefore policies should be considered that minimise sprawl, instead incentivising and prioritising development and densification around strategically located high-quality public transport hubs. This could be achieved through the CiL regime or through future pricing policies. The Dedicated Driverless Space concepts we explore are built around transport hubs

The ‘Congestion, Capacity and Carbon’ report sees connected and autonomous vehicles providing a valuable link from suburban homes to high density transport hubs, “but not replacing public transport in city centres, where lack of space will remain the main constraint” (NIC, 2017). Ultimately, in order to maximise network performance benefits, policy-makers need to take a leadership role in the design of the system in which CAVs will operate. This means there need to be clear priorities as to the characteristics of infrastructure systems that will be most beneficial to our cities. Dedicated Driverless Spaces offer the key planning tool that can be used to design a system that will maximise the benefits.

In part 2 we explore how we can begin to deliver these benefits today and into the future through 9 key typologies.

PART 2 - TYPOLOGIES AND CASE STUDIES

> *"For all their benefits, neither electric nor connected and autonomous vehicles will solve the problems of urban transport; rather they are likely to increase the number of drivers on the roads. Government and cities need to act now to ensure that space in cities is used effectively, with room allocated for fast, frequent public transport systems, well-connected and affordable housing, and pleasant public spaces."*
>
> \- National Infrastructure Assessment, July 2018.

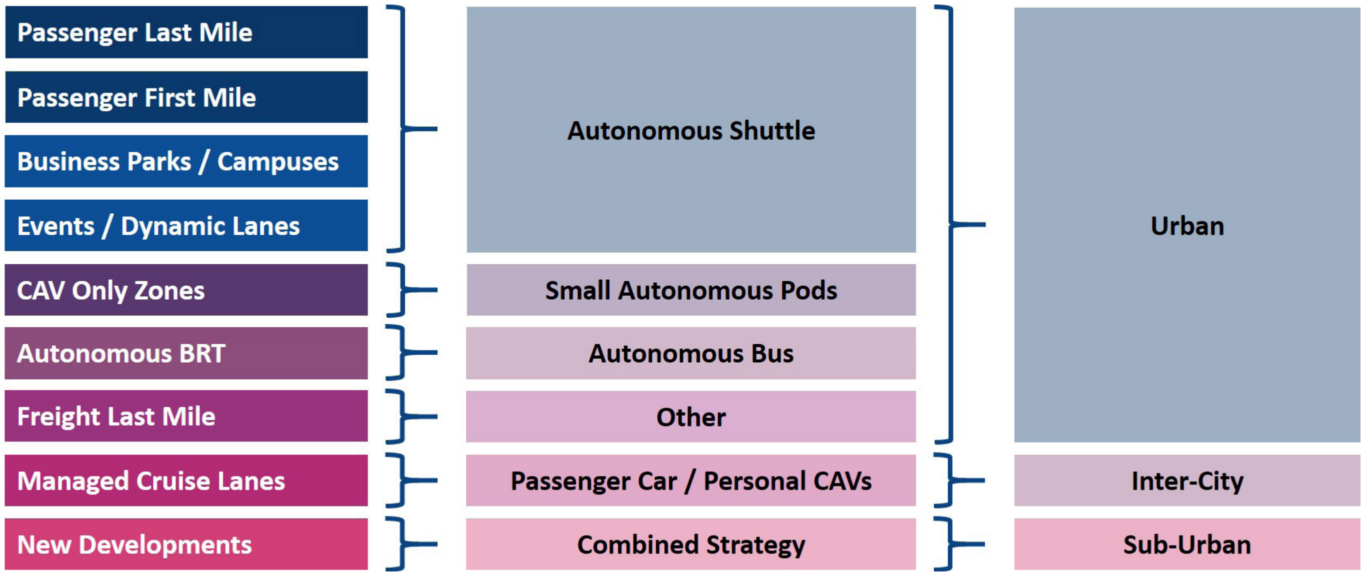
THE VISION

Our vision for CAVs is one that puts place-making and sustainable and active modes at its core while capturing their benefits in our cities and for longer distance trips. Our research in part 1 demonstrates that Dedicated Driverless Spaces are the only feasible deployment pathway for CAVs and that a focus on public transit and sustainable modes is essential if we are to secure the benefits of enhanced network performance. This vision is aligned to that of the NIC as expressed in the 'Congestion, Capacity and Carbon' report and the National Infrastructure Assessment. Here the NIC (2017) supports new public transport and cycling and walking infrastructure as the preferred strategy for tackling urban congestion and promoting healthy growth. The recurring theme is that road space is used better - reallocated for fast, frequent bus and tram services and more car-free areas for leisure, shopping and socialising combined with measures to counter congestion on roads such as road pricing.

We define a Dedicated Driverless Space as a zone or lane which is certified from an infrastructure and maintenance perspective to accommodate CAVs.

In our conception of Dedicated Driverless Spaces, they are designed to employ a range of permanent or dynamic techniques to achieve the benefits of CAVs on the road, in particular with regards to overall network performance. For simplicity of operation, safety and to improve journey time reliability, Dedicated Driverless Spaces also aim to create separation between CAVs and other modes. Where it is not desirable for modes to be separated, Dedicated Driverless Spaces impose adequate speed differentials to ensure the safety of all roads users. We have identified 9 different Dedicated Driverless Space typologies of potential infrastructure interventions which serve different purposes within Urban, Sub-Urban and Inter-Urban transport.

We have shown in Chapter 4 that the precise configuration of CAV services is important if vehicle miles travelled are to be managed. In particular the evidence suggests that shared taxi-based solutions, even when integrated with public transport, are likely to lead to higher vehicle miles travelled and thus might increase congestion. This is an incredibly important conclusion and has shaped the development of our infrastructure interventions which focus on shuttles and buses. The nine typologies, the relevant CAV technologies and contexts of application are outlined below.



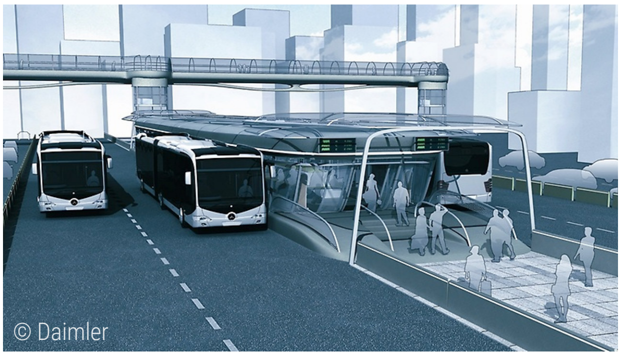
The 9 CAV typologies

THE CASE STUDIES

In the sections that follow, we explore each typology in detail and present a case study of its use as a real-world prototype. The case studies we have selected have emerged from detailed local studies within Exeter but relate to common contexts across the UK where they could be applied more widely. Exeter's pressures are characteristic of those of other regions - challenged by the confluence of greater growth and historic constraints leading to a fierce competition for space. The benefits we demonstrate in each typology could be easily transferred to other places. A range of examples of where the relevant typology could apply can be seen below.

Passenger Last Mile	Exeter St. David's Station; Cambridge Station; Bath University – City Centre
Passenger First Mile	Exmouth, any other commuter town
Business Parks / Campuses	NEC; University of Birmingham; Warwick University; Reading Business Park
Events / Dynamic Lanes	Exeter Chief's Rugby; Villa Park (2022 Commonwealth Games)
CAV Only Zones	Shoreditch (as examined by SDG)
BRT / Tram-Like	Cambridge AVRT; Coventry ULR
Freight Last Mile	Exmouth, any other commuter town
Managed Cruise Lanes	Regularly congested motorway section e.g. M5; M25 (approach to Junc. 15)
New Developments	Taunton New Garden Town

Areas were Dedicated Driverless Spaces could be applied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TYPOLOGY DESIGN PRINCIPLES & PLACEMAKING

Our vision for the deployment of CAVs is that technology is seamlessly integrated with good design that enhances the quality of life of people living and working in cities.

The goal in each case below is to combine a positive effect on network performance and function with wider benefits such place-making that can be achieved through well-designed schemes.

We have developed a palette of interventions designed to show how changes could transform existing places. The aim is that Dedicated Driverless Spaces, while designed strategically at a city scale, offer interventions which are human-scale and user-friendly. Cultural, leisure and social activities, increased walking and cycling and green spaces must be supported by these interventions. By considering infrastructure and the built environment in parallel towns and cities are more likely to be attractive places to live and work. We also aim to ensure that green infrastructure and public realm improvements are a common thread but with design that responds to the individual character of local streets and buildings. At the strategic level we want to ensure that Dedicated Driverless Spaces can develop into a holistic green network that creates widespread benefits for the whole city combining improvements in ecology, drainage, air quality, amenity and biodiversity.

AUTONOMOUS SHUTTLES: TECHNOLOGY REVIEW

Autonomous systems technology, once available, could in theory be applied to any vehicle type. Our detailed interviews with manufacturers sought to identify converging trends in technology and specifications that should feed into our case studies for road design. One clear area of convergence is that of autonomous shuttles.

A wide range of autonomous shuttles and manufacturers already exist in trial, testing or development, usually accommodating 15-25 people per trip. It has been noted previously that these small automated buses operating along dedicated routes, could have significant technical advantages enabling them to be deployed far more quickly (TSC, 2017). Routes could be mapped in detail and special, certification arrangements be established to manage the issues identified in Part 1.

Similar PRT solutions have a proven safety, and passenger service record which provide confidence in the ability of shuttles to work effectively. For example, the Heathrow PRT operated by UltraPRT, offers a pod system providing capacity of 656 passengers per hour per direction. Pods are deployed on a slot-based system and run at a maximum speed of 25 miles per hour. In this operation, specialist detection systems are built into the track to ensure a safe headway between vehicles is maintained. Specific edge cases are catered for in the operational plan – for example, a “snow and ice” vehicle is available to keep the guideway clear in extreme conditions (Smart Cambridge, 2015b). 2GetThere has been operating shuttles since 1997 at Schiphol Airport. Deployments at Business Park Rivium in the Netherlands followed in 1999 with Masdar City coming online in 2010. These initial deployments operate on a flat track on virtual routes with the vehicle position verified relative to magnets embedded in the road surface. There are a number of other examples of early PRT deployments within private campus settings.

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© 2getthere

© Ultra Global PRT

Now, new shuttle vehicles such as the Navya Autonom, the Easymile EZ10 and others are rapidly expanding trials and deployments across the globe including MCity Ann Arbour, Paris and Las Vegas. Deployments and tests include private campuses, pedestrian & cycling zone and in mixed traffic environments. Tests are also taking place across a range of conditions including rain, snow, excess heat and cold. Below we outline some of the design characteristics of the shuttle manufacturers surveyed during this study.

2GETTHERE – GROUP RAPID TRANSIT	
W,H,L (m)	2.1, 2.8, 6
Weight (kg)	3500 empty
Clearance (m)	0.4
No of passengers	24
Max Speed	60km/h
Fuel type	Electric


© 2getthere

NAVYA – AUTONOM SHUTTLE	
W,H,L (m)	2.11/4.75/2.65
Weight (kg)	2400 empty
Clearance (m)	0.2
No of passengers	15
Max Speed	45km/h
Fuel type	Electric


© NAVYA

EASYMILE – EZ10 DRIVERLESS SHUTTLE	
W,H,L (m)	1.998/4.02/2.87
Weight (kg)	2030 empty
Clearance (m)	0.17
No of passengers	15
Max Speed	45km/h
Fuel type	Electric


© EASYMILE

Where space saving is imperative in city centres, working with vehicle manufacturers to understand what could ultimately be achieved (in terms of potential further narrowing of vehicles or lane-keeping accuracy) would also help design the most efficient system. Narrower lanes might be achievable if lateral accuracy of the autonomous system was a priority for the system design. For single carriageway roads in the UK with two-way traffic today, an unobstructed width of carriageway of 5.5m is normally required. Where buses are present (which will often be the case in urban environments) the minimum requirement for lane width is 3m, with some bus lanes being as wide as 4.5m. Based on the specifications above autonomous shuttles could potentially operate within lanes of width 2.3-2.6 meters. It should be noted that the vehicles reviewed have gradient restrictions within the existing design configuration. These could also be technically overcome with suitable drive train for specific regional contexts. All vehicles are 100% electric with zero emissions where deployed. Overall, autonomous shuttles are seen as a flexible technology which can provide integration between transport hubs and ultimate passenger origins and destinations.

AUTONOMOUS SHUTTLES: PASSENGER LAST MILE

Concept

In this section we focus on the provision of shuttle services between transport hubs, expected to largely be railway stations, to onward destination zones of high demand. These last mile services are expected to support frequent commuter services in cities. The NIC (2017) note that urban transport is too often not joined up or integrated. The NIC also concluded that road transport is unlikely to supplant rail in its core markets: commuting into city centres (where physical road space is a key limitation). "The priority should be to maximise the benefits of rail in its core markets, where it is cost-effective, and to integrate it effectively with technology developments on the road to deliver more intermodal travel options" (ibid).

Integration of last mile services is a key enabler of public transport. The last mile is one of the main deterrents to public transport compared with the car (Wang, 2012). Some see last-mile solutions as the most promising short-term application of CAVs for public transport purposes to improve door-to-door performance (Van Arem, 2015). Mueller and Sgouridis (2011) concluded that a PRT system could be made more viable if it was integrated with light rail or metro lines, such that it encourages multimodal transport, and decreases the disutility of the last mile by providing fast transport from or to a transit hub (Mueller, 2011). Last mile around railways can also benefit Train Operators – in announcing their 'last mile' partnership with Uber, Virgin Trains stated, "we know that tackling the first and final mile is critical to opening up rail travel to new customers" (Railway Gazette, 2018). We therefore see last mile shuttle services as a potential "win-win-win" – better journey experience for customers; enhanced network operation supporting public transport; and greater revenue for operators.

How it works

- The Dedicated Driverless Space in this case would be a permanent, segregated, or separated lane upon which the autonomous shuttle would operate in simple loops connecting the main sites.
- The Dedicated Driverless Space will minimise interaction with other road users to:
  - Provide clear priority for shared mass transit services & deliver a frequent & reliable service
  - Ensure safety and reduce risk
  - Provide defined zone for operation (comms infrastructure, mapping etc.)
- The new infrastructure intervention would be designed to connect the business park or campus to surrounding transport networks, car clubs, cycling facilities, park and rides or transport hubs.
- Infrastructure changes would be designed to also enhance cycling, walking and public realm making sites more attractive for employees, businesses and customers.
- Scheme interventions should be consistent with and integrate with the local long-term network plan.
- Interventions need to be as low cost as possible – no more expensive than provision of cycling infrastructure of similar length. It is anticipated that these types of intervention could be fully funded by the business park as part of a strategy to unlock further development land.
- As other systems of segregated lanes, the lanes should be 'certified' to the national standard (see chapter 3) and operators offered licenses for use. In some cases, it may be desirable to ensure operators can offer routes which utilise both the public and private elements of the certified network. Signage, ANPR/Cameras and street furniture will provide physical and non-physical deterrents against other road users entering the space.

FEATURE	
Level of Segregation	Some sections may be segregated via low lying strips, kerbs, planting or street furniture. Dedicated spaces will be differentiated through the use of different materials, colours or light.
Speed Limit	30-35 mph. Higher speeds could be delivered with more robust infrastructure.
Road Rules and Regulations	Signage, CCTV and street furniture provide physical and non-physical deterrents against unauthorized entry. It would be an offence to utilise a portion of the DDS.
Traffic Management	Business access should give way to CAVs. Traffic management at crossing points should be assessed on a scheme by scheme basis.
Target Cost / km	£0.74m/km - £1.45m/km (equivalent to Cycle Superhighway)
Operating Model	Licensed operators only, certified lane

Feasibility component	RAG RATING
Technical Readiness	Operational
Technical Feasibility	High
Public Acceptance	Challenging
Commercial viability	High
Overall concept readiness	Deployment

BENEFIT COMPONENT	RAG RATING
Congestion reduction	Localised
Efficient use of vehicles	Shared
Improved journey quality	High
New travel opportunities	Scheme specific
Land use enhancements	High

CASE STUDY: PASSENGER LAST MILE

EXETER ST DAVID'S LAST MILE OPERATION

Exeter St David's is remote from the core of the city. The Station to the High Street is a hilly 1 mile walk that takes roughly 15-20 minutes. Exeter St David's is the main station linking the city to national rail services. It's located next to the University and River and could offer considerable opportunity for redevelopment and growth.

AUTONOMOUS SHUTTLES: PASSENGER FIRST MILE

Concept

To address the passenger first mile problem, we propose the development of a priority network of Dedicated Driverless Spaces for suburban areas. As with last mile passenger journeys, the first mile can act as a significant deterrent to the use of public transport such as rail. As the literature suggests, a system of individually owned CAVs (in contrast to a shared collaborative model) could lead to further urban sprawl outside of city centres (Zakharenko, 2016; Gelauff, 2017) and increased congestion. Better connectivity within and to commuter towns could encourage better utilisation of existing networks. Commuter towns in regions outside London often have low density and are dispersed across a relatively wide area. These towns provide a different set of transport challenges to the last-mile of the journey. Historic patterns of development within these towns, often beyond walking distance from existing transport hubs, have tended to expand the town footprint and promote further use of the private car. To work effectively, a network of Dedicated Driverless Spaces within a suburban setting will need to fulfil a range of objectives. Ideally, every household will be within 500m of a shuttle service. Frequency of service will need to be much higher than existing buses, and seamless integration with longer distance travel needs to be ensured to promote maximum usage. Reliability and user-experience require carefully designed routes afforded priority over other traffic, in particular private cars. Physical segregation would need to be minimal to keep costs extremely low. Changes to infrastructure would also need to overcome a range of challenges such as on-street residential parking (TSC, 2017); access to residential properties; traffic calming measures such as speed humps (Begg, 2014), roadworks and utilities; and the impact on other road users. Infrastructure changes should also seek to encourage cycling and walking.

How it works

- The Dedicated Driverless Space in this case would be a network of permanent or dynamic (e.g. priority at peak hour), marked lanes upon which autonomous shuttles would operate in a system designed to optimally connect residents to key services. In particular, the network would link residents to transport hubs for longer distance onward travel via rail or other automated services (e.g. Affordable Very Rapid Transit – see page 39 onwards).
- The Dedicated Driverless Space will minimise interaction with other road users to:
    - Provide clear priority for shared mass transit services
    - Improve safety and reduce risk
    - Provide a well-defined zone for operation (comms infrastructure, mapping etc.)
    - Enhance service frequency and reliability
- The aim is to provide a flexible, extensible and/or modular approach to network development that could ultimately be used by multiple operators of shared CAVs. In order to achieve this, it is proposed that alongside individual scheme proposals, a long-term network plan be developed to ensure that the scheme could form part of a wider series of integrated interventions.
- Interventions need to be as low cost as possible – based on a mix of signage, road markings and initial capital budget to address specific maintenance backlog issues (e.g. potholes).
- As a system of marked lanes, the lanes will be 'certified' (see chapter 3). Operators will be licensed prior to use as taxi services or bus franchises are today. Signage and control via ANPR/Cameras will provide non-physical deterrents against other users entering the space.
- Services will combine frequent operation with on-demand offerings based on time-of-day and overall demand.

FEATURE	
Level of Segregation	Dedicated spaces will be differentiated through the use of materials, road markings, colours or light, while keeping cost to a minimum.
Speed limit	20-30 mph.
Road Rules and regulations	Signage, ANPR and road markings will provide non-physical deterrents against unauthorized DDS use. Priority would be given to shuttle services.
Traffic Management	Residents should give way to CAVs as they do today
Target Cost / km	<£0.5m/km
Operating Model	Licensed operators in certified lane initially. A future model could be for shared ownership CAVs coordinated through ITS.

FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	Operational
Technical Feasibility	Medium
Public Acceptance	Challenging
Commercial viability	Potential
Overall concept readiness	Pilot

BENEFIT COMPONENT	RAG RATING
Congestion reduction	Localised
Efficient use of vehicles	Shared
Improved journey quality	High
New travel opportunities	Minimal
Land use enhancements	High

CASE STUDY: PASSENGER FIRST MILE

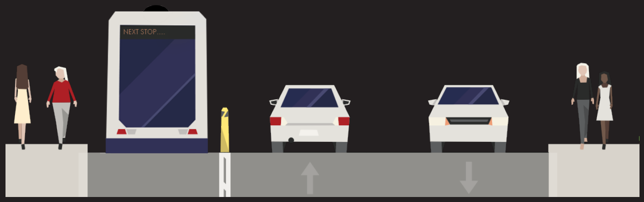
SUBURBAN COMMUTER TOWN, EXETER

Exmouth is a seaside town with a population of 35,000, many of whom commute into Exeter. It is the biggest town in Devon. The A376, a key commuter route, is highly constrained during the morning and evening peak and suffers from resilience issues.

TYPICAL ROAD IN EXMOUTH

BEFORE

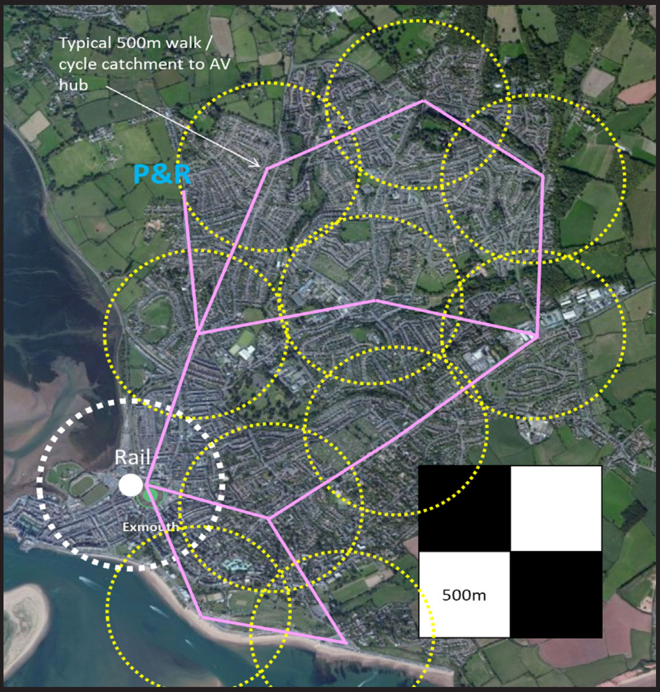
AFTER



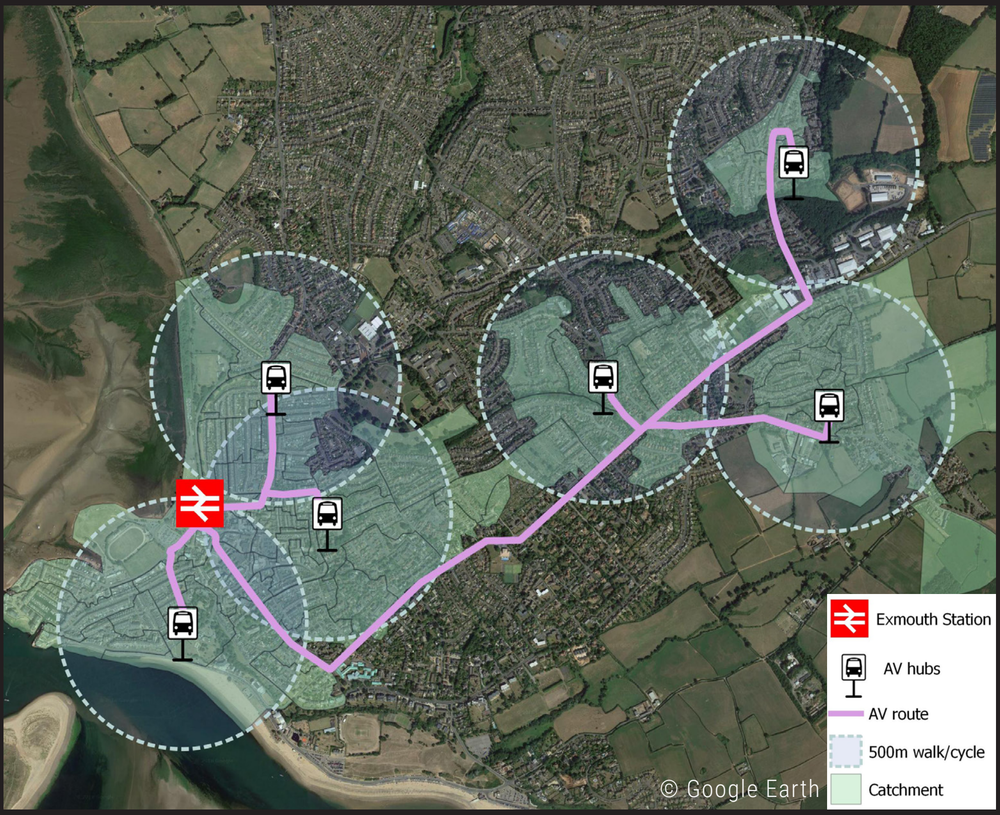
When designing the first mile network one option is to fully cover the town. This is likely to be a more *risky* initial option.

The STARR model enables us to design an optimised network based on a theoretical resource constraint. The transport hub locations are designed to maximise the attractiveness of the mode to as many people as possible within the constraint.

Option 1 - Full Coverage Network



Option 2 - Optimised First-mile Network



© Google Earth

The STARR model shows we could serve **20%** of all commuting trips with only **5** travel hubs. An example optimised network derived from the model is shown here.

Residents have a short walk to neighbourhood AV hubs where shuttles can be hailed on demand.

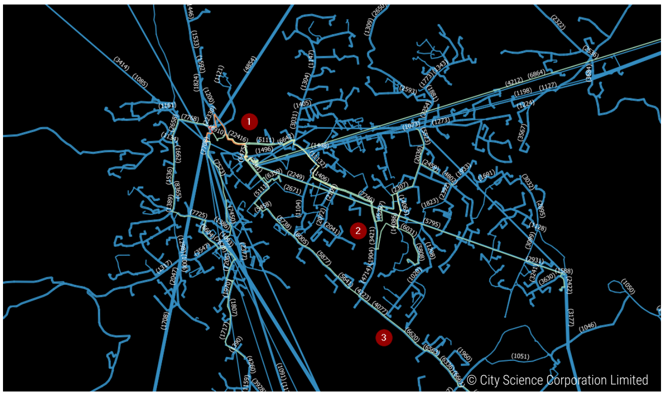
Neighbourhood AV hub with cycle parking & delivery storage

BENEFITS

Better Road Network Performance

The National Infrastructure Assessment states that more investment in public transport, alongside the promotion of safe cycling and walking, is the only way that cities can increase their infrastructure capacity to support growth (NIC, 2018). In Chapter 4 we identified gaps in the research related to the network impacts of CAVs. As a result there is limited information on how a system of Dedicated Driverless Spaces would work at a strategic level. To fill this gap we worked in collaboration with the University of Exeter to develop a model ("STARR – Strategic Transport model for Autonomous Road and Rail") for a network of first and last-mile shuttle buses integrated with existing rail networks. While there are some differences in other aspects of feasibility of Dedicated Driverless Spaces our model and the following discussion, covers both Last Mile and First Mile operating together to provide an analysis at the city level.

The model was developed on the Exeter rail and road network but could readily be applied to any system of transport hubs and onward connections in any city or region in the UK. The model includes a flexible mode-choice component to test a range of assumptions about CAV uptake and an optimisation tool to enable local authorities to strategically prioritise where to site the most effective schemes. The preliminary model development first sets aside some of the existing constraints (such as rail frequencies) to understand the maximum potential for such a system. Under an unconstrained scenario, the model demonstrates that a first and last-mile system of autonomous shuttles, integrated with rail could accommodate 48% of all trips daily and remove up to 52,000 passenger car trips from Greater Exeter's road network at peak hours while maintaining or improving citizen travel times from those they experience today. Given the rural nature of many of the wards in Greater Exeter, we would expect even higher potential in denser urban agglomerations.



STARR model developed in collaboration with the University of Exeter

More efficient use of vehicles

Using the STARR model we can optimise the location of the hubs based on an assumed investment constraint for the city. We find that many benefits can be delivered through a limited number of hubs. Since the autonomous pods are shared, overall there will be more efficient use of vehicles. The system would however need to be designed to be so seamless, frequent and efficient that citizens could be willing to give up their cars. Optimisation processes, like those already built into the model, could be used to inform the system design and ensure maximum efficiency. The integration with existing rail services would also support higher levels of patronage and investment in the railway. In many cases this would lead to more efficient use of these assets and mitigate the risk that CAVs have a negative impact on rail through competition.

Improved journey quality

The STARR model also demonstrates the importance of seamless interchange in ensuring that the CAV-based system is competitive with traditional driving. Our initial model runs assumed WebTAG interchange penalties and resulted in CAVs avoiding the railway system and routing straight to the desired destination. Seamless and fast interchange is essential to route choices making sense for customers. Therefore, these elements of journey design are an integral feature of the system. Essential to this is integrated ticketing, booking, real-time traffic information and consideration of the end-to-end journey experience from the perspective of the customer. In operating models that include multiple operators this will require significant collaborative effort, contractual incentives and penalties (in particular higher customer compensation than is currently offered for delays on the railway) to ensure that users are provided with a highly competitive transport experience. Data on arrival times from ride-hailing systems indicates that for a system to be competitive with ride-hailing, the service would need a frequency of between 3-5 minutes with consistent levels of reliability at peak hour. These levels of service would need to be designed into the operational plan. Implementation of such a system and delivery of the required integration between modes will likely require new forms of governance and powers. Our view is that this is an overhaul that must take place if public transport is to keep pace with changes in technology and customer expectations.

Specific areas that need to be addressed which relate to all operating models involving shared mobility is how to address perceptions of safety without a driver, in particular late at night. Evidence from previous passenger shuttle trials have found the need to enhance perceptions of on-board security, especially among female passengers (Salonen, 2017). Well-lit roadways and cabs, CCTV in cabs, meeting points for vulnerable groups and clear systems to contact operators are some of the means through which this issue may be addressed.

Improved Road Safety

A network of First and Last Mile CAVs is expected to have positive impacts on road safety through the following mechanism. First, the simplified operating environment and clear priority will ensure that the current safety issues associated with CAVs are overcome. The road surface and operating environment will be certified and the operator will be responsible for providing detailed security, safety and emergency plans for the zones. Second, the network will remove vehicles from the road, in particular in dense city centres. This is expected to have a great impact on the existing fatalities of which pedestrians and cyclists represent 31% and of which 51% occur on built-up roads (DfT, 2016b). And finally, the system is expected to remove many of the human fallibilities which lead to traffic incidents – for example, by providing greater accessibility to the city centre and night-time economy, the system could reduce occurrences of drink driving.

Land Use Enhancements

Accessibility has a clear impact on land values. Values of homes within 500m of rail and tube stations within London have been shown to have a 'transport premium' of up to 10.5% (NIC, 2017). Last Mile and First Mile services as part of a high-frequency transit system widen the reach of existing infrastructure and could create much greater equity of access across the city. In addition, Last Mile and First Mile shuttles could facilitate numerous possibilities for redevelopment that are currently not possible. It is estimated that up to one third of the land in cities is devoted to parking (Rodoulis, 2014). Through an optimised fleet, an autonomous shuttle-based system would have similar effects on parking reduction effects as a system of shared autonomous taxis – enabling the removal of parking spaces. Based on the typical layout of cities like Exeter with radial commuter towns, it is likely that scheme designs could be accompanied with a review of the parking requirements. The NIC (2017) notes that densification around urban infrastructure hubs, notably bus or railway interchanges or near city centres, could help to provide much needed homes in high demand and desirable locations. The removal of parking spaces in these key locations would provide much more land for high-quality redevelopment. In our Last Mile case study (Exeter St David's station) possible redevelopment of the station is currently in the early stages of discussion. One of the key issues to overcome is parking provision. Options in this location could include continued street level parking or the development of a multi-story car park. The accessibility afforded by the shuttle service in our case study (or alternative shuttle services linking off-site parking provision) could reduce or eliminate the need for the existing 435 parking spaces. This would directly enable more aspirational redevelopment opportunities to become available, creating significant enhancements to land value and use in this area of the city. This opportunity could also be used to achieve a dramatic improvement of the site's credentials in terms of sustainability, links to the river, biodiversity and liveability.

The potential environmental benefits of a CAV-based shuttle system are also clear. Particulates arising from diesel fuel, tyre wear and road abrasion are critical causes of air pollution (Defra, 2017). Fuel change could immediately facilitate enhanced air quality and road use would also be reduced, minimising abrasion. Infrastructure changes such as those set out in our case study demonstrate how Last and First mile infrastructure can be provided alongside enhanced walking and cycling, green infrastructure and greater opportunities for place.

New Travel Opportunities

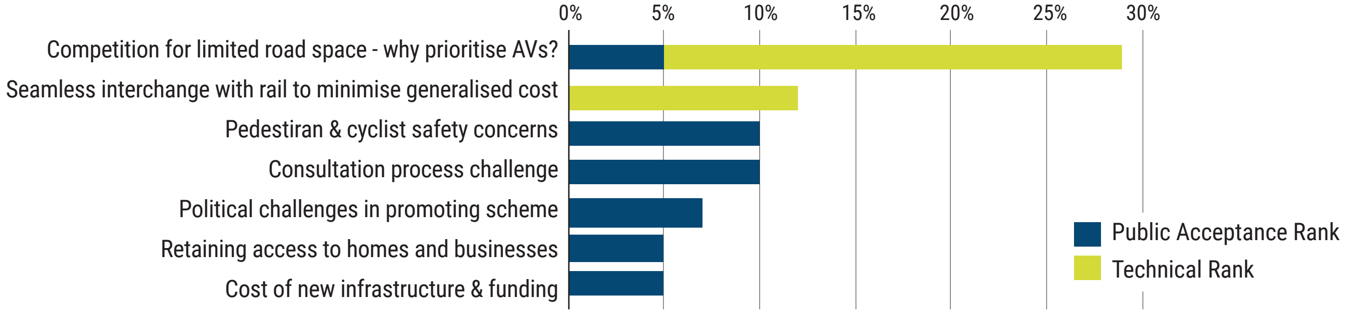
The STARR network does not open up new travel opportunities geographically but instead seeks to optimise the flows between existing trip production and attraction zones. However, in some contexts, shuttle services could create new links between communities.

FEASIBILITY

Public Acceptability

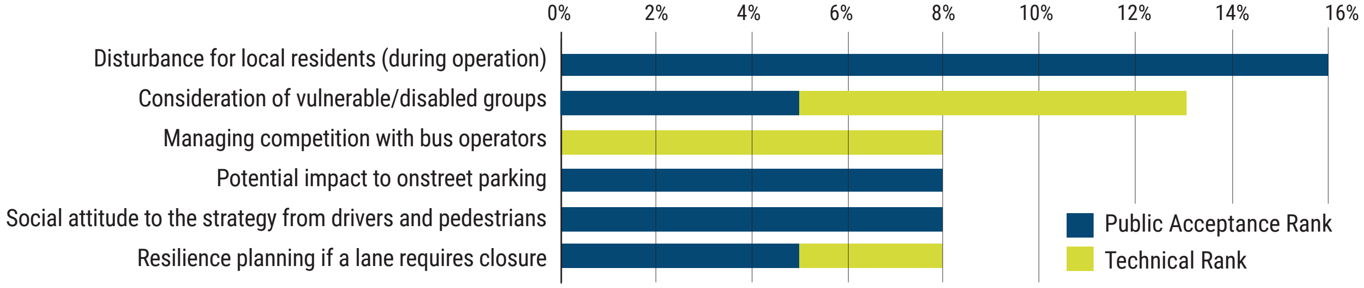
In perception surveys of autonomous vehicles participants' have been found to have strong confidence in negative beliefs about fully automated vehicles suggesting that their opinions will not be easily influenced (Sanbonmatsu, 2018). At the same time, public acceptance is critical to the future take-up of CAVs. It has certainly been suggested previously that segregation of AVs would aid deployment, at least in the early years (TSC, 2016). We therefore believe that the concept of Dedicated Driverless Spaces, when compared against alternative deployment pathways, provides a clear mechanism to maximise public confidence. However, there are still a range of public acceptance issues that need to be identified and overcome. We held a workshop where we brought together experts from the Public Sector, Industry and Academia to explore these issues. The results below demonstrate the key public acceptance and technical challenges that were identified for Last and First Mile Passenger services. Participants were also asked to develop potential ways to overcome the challenges identified. These solutions are summarised in the tables below. In particular the allocation of road space is seen as a controversial issue with highly polarised views. These are challenges faced by public transport and active travel schemes generally and are not necessary purely a feature of CAVs. Many have asked however why CAVs should take priority. In our view, CAVs represent a unique opportunity to redesign the transport system in a data-driven, optimised way and provide multiple benefits however these will need to be clearly communicated to the public. Workshop participants developed a number of ways in which the consultation process could be enhanced. We note however that deploying an integrated system such as this will also ultimately require considerable vision, strong leadership and clear governance.

Passenger Last Mile: Key Challenge Areas Identified by Expert Workshop



Challenge Area	Possible Solutions Identified by Expert Workshop
Competition for road space	Clear commitment to prioritise most efficient modes (mass transit and active travel) above single occupancy vehicles. Encourage longer, narrower vehicles to utilise less road width. Dynamic traffic light prioritisation.
Seamless Interchange	Real-time data. MaaS / smart ticketing / unified pricing (charged by distance). Overall system design. Systems to assist with transfer of luggage/shopping.
Pedestrian & Cyclist Safety	Segregated routes with clear separation marked. Expand trials in transitional environments e.g. airports to raise confidence. Regulate speeds. Provide clear statistical evidence of safety
Consultation process	Provide clear compelling evidence regarding the 'Do-Nothing' scenario, engage a wider demographic, in particular the voice of the young. Gamification of the process could attract different people and clearly highlight the trade-offs.
Political challenges	Changes to the decision-making process has occurred to promote new house building. Engagement of different demographics in the process. Overcome effect of political cycles through long-term infrastructure plans and funding.
Retaining access to properties	Scheme design such as placing shuttle lane in the centre of the highway. Management of speeds and turning priorities. Clear markings and priority signage.

Passenger First Mile: Key Challenge Areas Identified by Expert Workshop

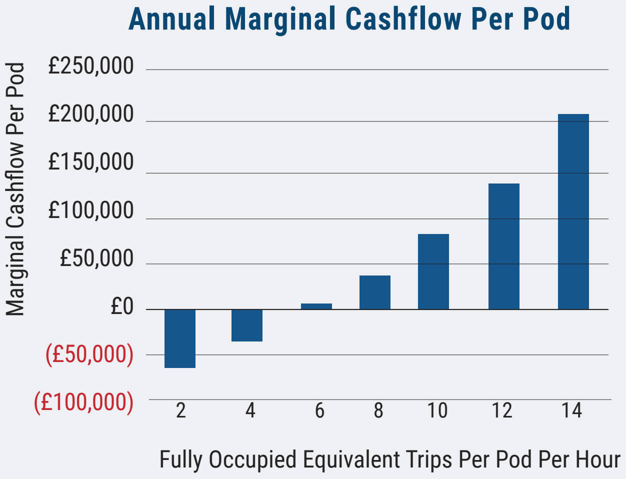


Challenge Area	Possible Solutions Identified by Expert Workshop
Disturbance for residents	Clear consultation with an incremental approach. High quality design and non-intrusive infrastructure. Manage using incentives & regulations to avoid unintended consequences.
Consideration of vulnerable groups	Ensuring access to properties. Door-to-door service for some groups could be offered once infrastructure is in place. Provision for diverse needs.
Competition with bus services	Range of operational models e.g. the bus operator manages the system. Early consultation with operators during trials and planning. Develop interactive model to evaluate the profitability, social benefits and trade-offs.
On-street parking	Co-ordinate gradual reduction in on-street parking supply or increase pricing over time to make it less attractive. Provide alternative parking e.g. brownfield sites at the edge of developments.
Social attitudes	Arrange 'demo' days like Paris car free streets days to showcase how the system could operate. Enable co-design through the consultation process. Lower risk demonstrations to build confidence. Co-ordinate changes alongside wider incentives to reduce car use e.g. scrappage scheme, increase generalised cost.
Resilience	Better and more coordinated forward impact and mitigation planning for known events. System-wide operational incident and re-routing plan to ensure resilience built into system design. High-quality real-time communication with customers.

One further challenge that wasn't captured by the workshops was the fear that dedicated infrastructure in urban environments would be perceived as creating new barriers to the use of urban space or assigning more space to vehicles at the expense of pedestrians, cyclists and non-transport purposes. Our case studies demonstrate that this is not the case and that schemes can be implemented to maximise benefits holistically. It is recognised that good design and consideration of wider user groups will be essential for scheme success.

Affordability / Utilisation of Existing Network

Infrastructure to support public transport in growing and congested cities is considered to offer some of the highest returns for transport investment (NIC, 2018). Several commercial models could be explored. A system provider could own and operate the system, recouping their costs through fare income; a systems provider could partner with a local public transport company who would operate the vehicles; the system could be owned and operated by a public transport operator; and finally, the system could be owned and operated by the transport authority (Smart Cambridge, 2015b). Advertising can provide an additional source of revenue. We have modelled the potential financial viability of a CAV shuttle operation based on a modest fare assumption of £0.75 per trip. We find that such a model is likely to be viable without subsidy in locations where a frequency of 8 "Fully Occupied Equivalent trips" (FOET) can be achieved per hour. In schemes which could support travel frequencies above 10 FOETs per hour, our model demonstrates that there is potential for the operation to provide significant contribution to, if not cover the investment in infrastructure.



Future-Proofing / Flexibility

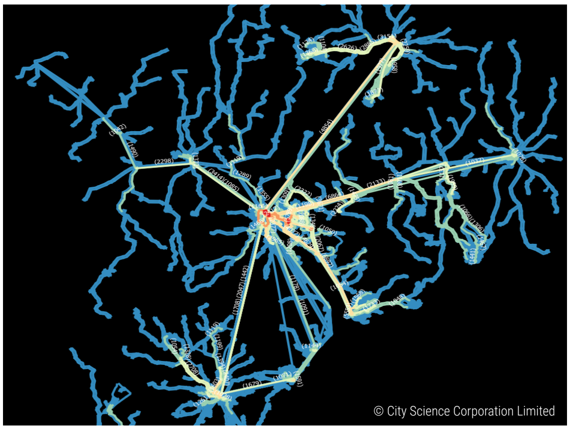
In the case of the Exeter St. David's case study, the scheme would provide a system that is highly flexible and responsive to demand growth. Initially, a two-pod system might be implemented to carry 450 passengers per hour. This could be easily extended to more pods or pod-trains of 2, 3 or greater units operating together. Such configurations could ferry more than 2,000 seated passengers per hour. Initially, a single-lane system with passing points could be designed, minimising the impact on existing traffic. Over time, traffic could be phased out and replaced by cycling, walking or additional Pod lanes depending on demand.

Resilience Impact

Resilience impacts were noted at our expert workshop as a potential challenge, in particular in First Mile deployments where there were questions about what would need to happen in the case of road works or road closure. Across all contexts it was felt essential that advanced warning and planning be made to minimise service interruptions. Real-time information was also felt to be critical to ensuring that citizens could make informed choices about travel and that demand could be managed during network impacts. Links to the rail network may also require rail network resilience to be enhanced for end-to-end journeys to be acceptable to users. The City Science Network Resilience Analysis tool (developed using an innovation grant from the DfT) could also be used to assess areas of network vulnerability and the link-by-link impact of issues – this would enable resilience to be enhanced across the network.

OUTCOMES AND NEXT STEPS

The STARR model provides a tool for Local Authorities to systematically identify potential locations for Last Mile and First Mile interventions. City Science aims to productionise this into a web-based tool, which would make it readily available to city-regions for use as part of their Strategic Planning processes. This could widen the consideration of CAVs within local plans. Given the potential financial viability of the Exeter St. David's case study and existing redevelopment of the station, we have held early discussions with the project board about the role of CAVs in their plans for this site. We are encouraged by the response and aim to move these conversations forward.


© City Science Corporation Limited

The rail and road network upon which the STARR model assesses optimal locations for transport hubs. The model selects transport hubs to enable as many people as possible to improve their journey times using the CAV + Rail mode.

AUTONOMOUS SHUTTLES: BUSINESS PARKS & CAMPUSES

Concept

Business Parks, University Campuses, Exhibition Centres, Airports or Shopping Centres are large drivers of demand, providing concentrated centres of employment space and economic activity. Many such developments are located next to the Strategic Road Network (SRN) for easy road access for customers and to onward markets. As a result, these developments often create additional demand for the SRN. Within cities, the continued growth of these types of developments can be constrained by wider congestion issues with a reliance on passenger cars hampering growth. Autonomous Shuttles offer the potential to release these constraints, enabling new productive development, if high quality routes can be appropriately integrated into demand corridors.

Autonomous Shuttles have been in operation for some time in airports or private campuses and many further trials are taking place and are planned within these contexts. This concept uses Dedicated Driverless Spaces to enhance connectivity between offices and wider transport hubs with a view to unlocking site potential – namely to reduce parking requirements and enable further development and densification. Dedicated Driverless Spaces could overcome the direct opportunity cost of parking provision, allowing business parks & universities to unlock additional valuable land for productive economic development.

How it works

- The Dedicated Driverless Space in this case would be a permanent, segregated, or separated lane upon which the autonomous shuttle would operate in simple loops connecting the main sites.
- The Dedicated Driverless Space will minimise interaction with other road users to:
    - Provide clear priority for shared mass transit services
    - Ensure safety and reduce risk
    - Provide a well-defined zone for operation (comms infrastructure, mapping etc.)
    - Deliver service frequency and reliability
- The new infrastructure intervention would be designed to connect the business park or campus to surrounding transport networks, car clubs, cycling facilities, park and rides or transport hubs.
- Infrastructure changes would be designed to also enhance cycling, walking and public realm, making sites more attractive for employees, businesses and customers.
- Scheme interventions should be consistent with and integrate with the local long-term network plan.
- Interventions need to be as low cost as possible – no more expensive than provision of cycling infrastructure of similar length. It is anticipated that these types of intervention could be fully funded by the business park as part of a strategy to unlock further development land.
- As other systems of segregated lanes, the lanes should be ‘certified’ to the national standard (see chapter 3) and operators offered licenses for use. In some cases, it may be desirable to ensure operators can offer routes which utilise both the public and private elements of the certified network. Signage, ANPR/Cameras and street furniture will provide physical and non-physical deterrents against other road users entering the space.

FEATURE	
Level of Segregation	Some sections may be segregated via low lying strips, kerbs, planting or street furniture. Dedicated spaces will be differentiated through the use of different materials, colours or light.
Speed Limit	30-35 mph. Higher speeds could be delivered with more robust infrastructure.
Road Rules and Regulations	Signage, CCTV and street furniture provide physical and non-physical deterrents against unauthorized entry. It would be an offence to utilise a portion of the DDS.
Traffic Management	Business access should give way to CAVs. Traffic management at crossing points should be assessed on a scheme by scheme basis.
Target Cost / km	£0.74m/km - £1.45m/km (equivalent to Cycle Superhighway)
Operating Model	Licensed operators only, certified lane

FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	Operational
Technical Feasibility	High
Public Acceptance	High
Commercial Viability	High
Overall Concept Readiness	Deployment

BENEFIT COMPONENT	RAG RATING
Congestion Reduction	Localised
Efficient use of Vehicles	Good
Improved Journey Quality	High
New Travel Opportunities	Minimal
Land Use Enhancements	High

BENEFITS

Land Use Enhancements

The key benefit for autonomous shuttle-based systems within business parks and campuses is to free up considerable land which is currently used for parking. Parking space represents a significant asset for the owners of land, but one that is currently 'trapped'. Using Exeter as an example, the value of commercial land ranges between £500k-£1m per acre, implying the value of a single parking space being between £3,000 and £7,000 (assuming between 150-180 parking spaces per acre). In denser cities these values are likely to be even higher. Traffic constraints also often prevent the development and extension of business parks due to the transport impact on access roads. Contributions under the Community Infrastructure Levy (CIL) are often negotiated between the developer and planners.

A system of autonomous shuttles providing ready access to the business park or campus could enable densification of these sites, enabling greater levels of access for employees and opening up new land for development through the removal of parking. Greater concentrations of knowledge workers can create localised agglomeration effects, supporting sector clusters or hubs to emerge. Wider, reliable access between out-of-town business parks and city centres can also support the vibrancy of the city centre economy.

Better Road Network Performance

Travel plans are regularly employed across business parks with the goal of shifting employees to more sustainable forms of transport. Maintaining and enhancing accessibility to employment sites is a key issue to enable access to a wide and skilled pool of employees. Sustainable travel should continue to be encouraged, but often is not an option for all employees or those living far from the site. A range of factors influence the propensity of staff to adopt sustainable travel modes including access to showers, parking facilities, incentives, culture and the wider public infrastructure. CAV shuttle services, connected to major transport hubs, could significantly reduce the need for cars, linking the business park to a range of long-distance transport options. If the effects are aggregated across a number of parks, the impact on network performance could be substantial. The modelling of specific sites would need to be conducted to fully quantify this.

There are also open questions about the effect of business park traffic on the Strategic Road Network. Developers are often keen to site commercial developments close to the SRN to provide access to wider markets, but the impact of this could be to draw local traffic onto the SRN in some locations. By addressing business park access through the retrofit of private roads and potential minor changes to local roads, CAV-based strategies could enhance the performance of the SRN in key locations.

Improved journey quality

Where business parks are characterised by high levels of private car traffic, with limited connectivity to public transport, these can be key areas where congestion is high. Models developed by City Science (2016) can be used to demonstrate how the organic clustering of industrial sites and business parks naturally results in road-based congestion around key junctions. Shuttle-based systems within a Dedicated Driverless Space could provide much more reliable journey times to key transport hubs and in many cases improve travel times. Any implementation would need to be combined with high quality digital signage, seamless and simple payments and real-time routing and journey time information via smartphone to ensure quality of the end-to-end journey.

FEASIBILITY

Affordability / Utilisation of Existing Network

Commercial property developers can benefit considerably from the removal of private vehicles. It is anticipated that the capital investment for a scheme could be fully funded through private means. The development of each acre currently assigned to parking could release at least £500k of value. Based on our analysis of case studies in Exeter, up to a third of existing business park land could currently be assigned to parking – for a 100-acre business park, you can see how ~£16.5m could become available for new infrastructure. These sums could facilitate high-quality links to a range of longer-distance public transport hubs.

Public Acceptability

CAV shuttles are already in operation or trial in many business parks and private campuses around the world. These are considered one of the lowest risk areas for deployment of CAVs. Being private land there are often restrictions on the type and volume of traffic. In some cases, existing peak hour congestion on business parks is a considerable problem. Therefore, if CAV shuttle can demonstrably enhance accessibility and journey times for employees and businesses then public support could be high.

Other Infrastructure Considerations

Road markings and signage on private land are less well controlled compared to those which fall under the Traffic Signs Manual. Consistency between these private and public markings should be encouraged to ensure it is easy for CAVs to navigate between these different zones (TSC, 2017).

OUTCOMES AND NEXT STEPS

As a result of this project we aim to engage widely with property developers to further the potential for these models.

AUTONOMOUS SHUTTLES: DYNAMIC LANES FOR EVENTS

Concept

The ‘Congestion, Capacity and Carbon’ report refers to the potential of dynamic lane re-allocation where there are strong ‘tidal’ flows (NIC, 2017). In this section we focus on the dynamic reallocation of road space for specific events where parking and access are major constraints e.g. access to a stadium on match day. This is different to the business park / campus typology because here the majority of the automated vehicle’s journey is expected to be on public roads and the timing of the peak flows is specific to the fixture or event. Because of the limited frequency of match fixtures, it would also not be justified to create permanent, fully segregated infrastructure which might be detrimental to other road users during normal commuting periods.

Many stadia or sites already offer increased parking and dedicated bus services on match days as part of their travel strategies. Events are often during leisure time (e.g. weekends), so could in theory utilise idle shuttles which usually operate on commuter routes. In order to facilitate this type of reallocation of capacity however there needs to be a mechanism to enable priority to be given to autonomous shuttles at specific times in a dynamic way. These types of trial operation, if successful, could pave the way for greater future use of dynamic network features within the overall transport system design.

How will it work?

- The Dedicated Driverless Space in this case would be a dynamic zone conferring priority to the Autonomous Shuttle. Other road users would be expected to slow down as they would with an L-plated driver and give way to the CAV operation.
- The Dedicated Driverless Space will minimise interaction with other road users to:
    - Provide clear priority for shared mass transit services
    - Ensure safety and reduce risk
    - Provide defined zone for operation (comms infrastructure, mapping etc.)
    - Encourage parking away from the venue to minimise congestion impacts on the city.
- The dynamic zone would be active at set times, agreed in advance as part of the event’s transport strategy. The dynamic zones would be developed to promote parking sites away from the venue where it makes sense to do so.
- ANPR would be active during operation only.
- Times of activity would be publicised in advanced via variable message signs to road users regularly using that route. Times of activity would also be available on the web and published as open data to mapping agencies.
- Interventions need to be as low cost as possible – no more expensive than provision of cycling infrastructure of similar length. It is anticipated that these types of intervention could be partially funded by the stadium or event space.
- The lanes will need to be ‘certified’ from a maintenance perspective (see chapter 3) and the ITS system will need to communicate signal timings to vehicles (e.g. at signalised roundabouts).

FEATURE	
Level of Segregation	The Dedicated space will be differentiated through the use of different materials, and colours with the dynamic element indicated via variable message signs, LEDs and lighting.
Speed Limit	30-35 mph.
Road Rules and Regulations	The Dedicated space, when in operation, would confer priority to the Autonomous Shuttle indicating for other road users to slow down and give way as they would with an L-plated driver.
Traffic Management	Traffic management systems would need to be upgraded to communicate with the autonomous shuttle.
Target Cost / km	£1-2m/km
Operating Model	Licensed operators only, certified lane, certified I2V infrastructure.

FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	Operational
Technical Feasibility	Challenging
Public Acceptance	Mixed
Commercial Viability	Good
Overall Concept Readiness	Pilot

BENEFIT COMPONENT	RAG RATING
Congestion Reduction	Localised
Efficient Use of Vehicles	Good
Improved Journey Quality	High
New Travel Opportunities	Not applicable
Land Use Enhancements	High

BENEFITS

Better Road Network Performance

The overall aim of the use of Dynamic Lanes in our example is to ensure the smooth flow of traffic to major events. Designing these systems appropriately will require an understanding of the base-line and specific event flows. In most cases, there is considerable planning and coordination between public transport operators, local authorities, organisers and other public sector bodies to ensure accessibility to ticket-holders. Network performance and accessibility are expected to be enhanced overall, but analysis would be required on a case-by-case basis as part of an overall event planning strategy. The technology used, could also be applied to create dynamism in other shuttle operations – for example providing greater response to traffic "tidal flows" within Last and First Mile systems.

More efficient use of vehicles

One of the key benefits is to provide additional utilisation of vehicles at off-peak times. For example, within a system designed to serve commuting flows, there may be excess capacity available at the weekends. By redeploying vehicles for expected and known leisure flows outside of peak hours, additional revenue could be gained to recover vehicle costs while also improving network performance.

Improved journey quality

The planned but flexible nature of these CAV redeployments within the city could enable considerable capacity to be redeployed to serve events since most of these will be in hours of leisure, outside of the main commuting or educational trip patterns. The availability of such a fleet could radically improve journey quality to stadia. It would be essential to ensure seamless ticketing linking with public transport operators and very frequent services to minimise waiting time.

New Travel Opportunities

The Campaign for Better Transport (2013) independently assessed and ranked access to the major football stadiums on match day. In this survey, 52% of fans said they would like more choice in how they travel to matches. Last mile CAV systems could be co-ordinated alongside longer-distance on-demand bus services. Operators such as Zeelo are specifically targeting transport to Festivals and Football matches. In theory, temporary coach parking provision could be co-ordinated with the last mile of the journey with the end-to-end journey promoted through the event organiser's site. These new opportunities would relieve pressure on existing networks and provide new opportunities to travel to events.

Land Use Enhancements

Enhancing accessibility to sites can enable expansion, such as hotels or other leisure facilities. We have encountered a range of sites which could deliver significant economic benefits but where transport accessibility is currently a limiting factor to growth.

FEASIBILITY

Affordability

Planning access for major sporting events is a considerable undertaking. For London 2012, the Olympic Delivery Committee (2012) invested £500m in schemes to support transport to the venues across the UK and a further £500m on operations to support access during the Games. While on a smaller scale individually sporting stadiums across the UK need to ensure they can support the flows of ~700,000 fans every week. Infrastructure or operational investment could be unlocked from direct investment into event travel or through the land-value uplift that it can potentially bring.

Public Acceptability

In the short-term music, sporting events and business expos, offer a multitude of opportunities to engage the public with CAVs. Events, more than any other use-case, offer the opportunity to close roads and provide a diverse range of people opportunities to interact with CAVs. Using one-off events, example routes could be introduced within minimal risk. Public opinion could be surveyed and based on growing trust and confidence the case made over time to develop more regular services.

Future-Proofing / Flexibility

The concept of dynamic lanes provides additional flexibility over the long-term. By their nature they provide a certified road space, with minimal barriers for mixed traffic on most occasions. Through their development, they provide infrastructure that will be of use by CAVs more widely as technologies enables these possibilities. Major sporting events provide the opportunity to design networks which could provide an infrastructure legacy while providing a bold vision of travel to fans and event-goers promoting the forward-thinking culture of the city.

OUTCOMES AND NEXT STEPS

Upcoming events such as the Commonwealth Games 2022 present a strong opportunity for shuttle-based CAVs. We recommend TfWM explore the potential for CAV shuttle routes, how these could be trialled in the lead-up to the Commonwealth games and how they could be used during the games to promote the innovation of the West Midlands.

BIRMINGHAM 2022
XXII COMMONWEALTH GAMES

CAV ONLY ZONES

Concept

If Dedicated Driverless Spaces in First Mile, Last Mile and A-road contexts are successful they could result in a growing series of networks across a city or suburb. The concept of CAV Only Zones anticipates that at some point certain zones could become surrounded by these routes, either organically or by design. Assuming the mass transit routes fulfil their function of driving mode shift away from private cars, the option may become available to reduce conventional traffic completely within the zones, hence creating a CAV-Only environment. With CAVs only performing last mile freight or the final portion of shared or personal journeys the remaining CAV traffic could be slowed to 15-20 mph. This could allow the full inner core of a zone to become a shared space, embracing priority for cyclists and pedestrians. Entry and exits to the zone could be signalled by 'single lane working chicanes' or 'priority narrowing' accompanied with new 'CAV Only' signage.

Over time, conventional roads within these zones might simply become a thing of the past, replaced by green infrastructure and areas that encourage community activity. These types of schemes would create safe outdoor spaces for communities in dense urban areas but could be equally applied to residential zones in the suburbs or retail areas.

How will it work?

- The Dedicated Driverless Space in this case would be a zone bounded by high frequency dedicated mass transit lanes which would be readily accessible on foot or bicycle.
- The zone would be developed following sustained modal shift away from conventional vehicles based on the success of the mass transit / shared transit infrastructure. The zone would prohibit conventional manual vehicles from entry.
- Within the zone, CAV paths may be pre-programmed with vehicles guided by differential GPS, so movements patterns would be anticipated by pedestrians and cyclists. CAVs would also drive conservatively (maximum speed of 20mph), giving priority to pedestrian and cycling movements.
- Kerb sides would disappear leading to a shared space comprising pedestrian-priority, community gardens, street furniture and public realm infrastructure to encourage meetings, play and physical activity.
- Interventions would be funded over time. In city centres zones could be introduced as part of urban redevelopment or when new developments are established. In suburban settings, central areas could be converted through public realm enhancements. Communities could be allowed to apply to become CAV-only zones and may even privately fund the changes where the economics make sense (for example if house price appreciation results from such schemes).
- The infrastructure would be 'certified' for low speed operation. The GPS routes within the shared space would be registered and provided specific maintenance attention to ensure safe operation. Due to the lower speeds and non-car mode shares expected, infrastructure might be expected to endure longer than existing roads.
- No ITS system would be in place to price access to deliveries within the zone. However, peak-hour, day-time deliveries would effectively be deterred due to the pricing system operating on the surrounding network (see more on freight pricing later).

FEATURE	
Level of Segregation	The zone would be fully segregated from conventional vehicles but would be shared between CAVs, pedestrians and cyclists at lower speeds. CAVs would be segregated only by their regular GPS paths through the space which would be learned by other users.
Speed Limit	15-20 mph.
Road Rules and Regulations	Residual CAV traffic would yield to pedestrians and cyclists who would be given priority. Access restrictions would be policed by conventional means.
Traffic Management	Traffic management would be minimal except on entry / exit to the zone where I2V and signage would need to signal lower speed limit and vehicle restrictions.
Target Cost / km	Scheme and funding dependent.
Operating Model	GPS-based routes would formally be part of the Public highway but with minimal marking and no kerb required. Restrictions would apply to a wide range of conventional vehicles. Some zones with space restrictions may even restrict CAV by width (giving preference to smaller vehicles e.g. dimensions of Renault Twizzy).

FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	Low
Technical Feasibility	High
Public Acceptance	Moderate
Commercial Viability	Not applicable
Overall Concept Readiness	Low

BENEFIT COMPONENT	RAG RATING
Congestion Reduction	High
Efficient use of Vehicles	High
Improved Journey Quality	Moderate
New Travel Opportunities	Not applicable
Land Use Enhancements	High

BENEFITS

Land Use Enhancements

One of the challenges that we have encountered for Dedicated Driverless Spaces is a concern from some stakeholders that segregation between traffic modes would lead to increased community severance. We believe that Dedicated Driverless Spaces can enhance public realm for pedestrians and cyclists. Through reduced reliance on private cars, lower emissions and enhanced safety, Dedicated Driverless Spaces can provide a transformational positive effect on places and quality of life. The concept of CAV Only Zones represents a future opportunity which could lock in positive outcomes within residential zones:

- ✓ *Zero congestion*
- ✓ *Zero emissions*
- ✓ *A safe environment for children, pedestrians & cyclists.*

When CAV Only Zones are feasible traditional roads could disappear in their entirety, replaced by pedestrian-priority, community gardens, street furniture and public realm infrastructure to encourage meetings, play and physical activity. This could deliver significant enhancements to the environment in dense urban contexts and sub-urban contexts alike.

Improved Road Safety

It is proposed that CAV Only Zones could be introduced only after certain mode share levels have been achieved through the other interventions developed in this study. In areas where CAV Only Zones are considered beneficial, speed reductions on private cars could be introduced during the transition to further promote sustainable and shared travel modes. There can be no doubt that decreasing vehicle travel speeds reduces stopping distances and impact speeds, and thus the incidence of serious casualties and fatalities (Johnson, 2004). This slowing of traffic to encourage behaviour change, would have immediate positive effects on road safety and would encourage greater use of the shared space by cyclists and pedestrians.

Better Road Network Performance

The role of CAV Only Zones would largely be to enable the retrofit of existing zones in ways which lock in the positive benefits that CAVs can provide. Through creating these zones at trip origins, the goal is to enable sustained behaviour-change away from privately-owned vehicles. If sustained mode shift can be achieved, the pressures on the network from private cars would reduce. This would allow greater flexibility in wider network changes to increase capacity and availability of CAV-based mass transit.

Improved journey quality

CAV-only zones would enable end-to-end journeys on fully certified streets for CAV users and safer journeys for cyclists and pedestrians. The minimisation of traffic in these areas and subsequent improvements to public realm, would offer high quality links by active modes to the key shared transport hubs.

New Travel Opportunities

For the elderly, vulnerable and those currently unable to drive, CAV-Only zones would open up a range of new opportunities. Door-to-door travel would create easy links to transport hubs while the quiet, safe, high quality spaces would minimise barriers to short-distance movement within the neighbourhood. While these new opportunities may increase overall demand, the wider network changes, giving priority to shared mass transit, will ensure that the impacts on the network can be accommodated.

FEASIBILITY

Affordability / Utilisation of Existing Network

Given the anticipated phasing of these zones, much of the infrastructure to enable wider travel will already be in place. Traffic calming measures could naturally follow, which would mainly include the cost of signage and any restrictions on entry to the zone. New developments and redevelopments would provide obvious choices for initial trialling as funding will be readily available.

Resilience Impact

The opportunity to introduce climate-resilient urban design into CAV-only zones could aid cooling, drainage, biodiversity and prevent heat stress. This could make the urban environment more resilient to climatic extremes.

Public Acceptability

If, as proposed, modal shift can be delivered prior to consideration of a CAV-only scheme, then public acceptance should be improved. If the public has already accepted alternative modes to the private car, then traditional resistance will be reduced. Research by the CIHT (2018) on shared space schemes found that 'some user groups, including but not limited to, visually impaired people' have had 'significant concerns' with these types of schemes. The removal of a kerb might create navigation difficulties for those with visual impairment for example. The needs of all potential users should therefore be considered in the planning phases to maximise public acceptance.

AUTONOMOUS BRT: COST-ENGINEERING & THE CONVERGENCE OF RAIL AND ROAD

One of the main benefits of CAVs as enablers of mass transit is their ability to accurately track lateral distance and precisely perform within specific functional requirements. This could enable fast direct travel on existing infrastructure without the need for costly track development. In the next typology a number of themes converge – namely the use of mobility or transit hubs; and the radical cost-engineering of traditional mass transit based on battery and autonomous technologies.

Interchange penalties, service reliability and directness of route are barriers to the use of traditional bus services. Traditional services might involve waiting ten minutes or so at the stop, and a circuitous route to the final destination (TSC, 2016). Mass transit systems like trams aim to redress these challenges – service reliability is delivered through dedicated routes which are designed directly based on the main flows of travel. Frequency is also built into the operating model, often combined with clear passenger information. From a capacity and network performance perspective, BRT and Tram solutions provide much more efficiency than car-based systems as shown in the table below.

TRANSPORT MODE	TYPICAL MAXIMUM CAPACITY PER LANE INBOUND PASSENGERS PER HOUR
Car (1.2 people – current commuter average)	720
Bus	1,800
Bus Rapid Transit	2,100
Tram	2,880

Maximum system capacity for different modes of transport.
Source: NIC (2018)

The tram is an aspiration for many cities, but for the cost. Conventional tram systems are unviable for the majority of cities. Recent projects have cost in the order of £64m/km (SDG, 2018b) with those in city centre locations potentially rising to ~£100m/km (Coventry CC, 2018). BRT on the other hand can provide a cheaper solution in aggregate (recent projects have equated to £4.5m/km (see SDG, 2018b)) however, these costs include both segregated and non-segregated sections. Non-segregated sections do not confer the same reliability, speed and service benefits as segregated routes.

A number of UK projects are currently seeking to re-engineer the delivery of tram-like services but at a much lower cost. For example, the Very Light Rail system being developed by Warwick Manufacturing Group has a target 'all in' cost of £7m/km (Coventry CC, 2018). Analysis shows there would be a positive business case for a system in this price range in Coventry (ibid). Through cost engineering, light rail begins to look like a feasible option that could be deployed– for example one simple cost-reduction strategy is to use battery technology to remove the need for overhead wiring (ibid). This is identical to the thought process engineers at Cambridge University are pursuing in the development of the Affordable Very Rapid Transit system (AVRT). AVRT is being developed into a concept which might serve Cambridge, the wider region and similar cities across the UK (Smart Cambridge, 2015). The system is designed to address the 'tidal flow' effect of commuters and visitors entering the city at peak hours. The cost-reduction strategy is as follows:

- Utilise electric battery technology to remove need for overhead wiring
- Replace rails & sleepers with simple road surfaces
- Replace steel wheels with rubber tyres
- Simplify the concept of operations
- Narrow the vehicle size so that supporting infrastructure can be minimised.

This concept could deliver equivalent or higher service quality to light rail at half the capital cost. The convergence of rail and road, enabled by 100% electric, zero emission, autonomous vehicles, is one of the most exciting trends within the technology landscape and we believe these concepts should be actively embraced and supported. This is an area where the UK has the opportunity to take a position of leadership as international OEMs are far less invested in these technologies.


© WMG

Warwick Manufacturing Group Very Light Rail Concept

AUTONOMOUS BRT

Concept

The NIC (2017) 'Congestion, Capacity and Carbon' report identifies the need to reallocate road space for fast bus and tram services. Average delays along urban A-roads have increased 27% since 2014 (DfT, 2018) at the clear detriment to all road users – including both passenger cars and buses. Conventional buses remain an unattractive option to many - buses have become 10% slower every decade (Begg, 2016). Low reliability, frequency and directness are key barrier to public transport use. Public transport operating without clear, sustained priority along direct routes will always be subject to the external impact of growing road congestion to the frustration of both passengers and operators.

A number of concepts now exist that aim to minimise the cost of direct light rail or road-based rapid bus services making these technologies more viable for medium-sized cities. Based on simple dedicated infrastructure, these types of services could unlock connectivity in highly congested urban areas. One such concept is the AVRT described above (Smart Cambridge, 2015). Cambridge is representative of a number of UK cities, originally built around a river with bridges acting as a natural bottleneck; a historic centre which has developed organically over many centuries; significant constraints on road space on arterial routes; major new development outside of the city; and while congestion is high, insufficient commuter volumes to make traditional mass transit options financially viable. Our work in Exeter confirms a similar 'tidal flow' originating from six large radial commuting towns along key arterial access routes. Automated solutions that can effectively address these 'tidal flow' effects will combine the most important characteristics of mass transit systems – namely service frequency, reliability and directness.

How will it work?

- The Dedicated Driverless Space in this case would be a permanent, segregated network of higher speed routes.
- The Dedicated Driverless Space will minimise interaction with other road users to: provide clear priority for shared mass transit services; improve safety and reduce risk; provide defined zone for operation (comms infrastructure, mapping etc.); and enhance service frequency and reliability.
- To maximise journey times, the number of stops will be reduced to a minimum and crossings designed as they would be for an equivalent tram system.
- The aim is to provide a flexible, modular design that enables the build out of key routes sequentially over time. In order to achieve this, it is proposed that alongside individual scheme proposals, a long-term network plan be developed to ensure that the scheme could form part of a wider series of integrated interventions – in particular transport hubs and first / last mile solutions.
- Infrastructure cost will be minimised by use of the existing road surface segregated by a kerb, street furniture or plantings and autonomous operation.
- As a system of segregated lanes, the lanes will be 'certified' (see chapter 3) and operators will be licensed prior to use. Signage, ANPR/Cameras and street furniture will provide physical and non-physical deterrents against other users entering the space.

FEATURE	
Level of Segregation	Segregated via kerbs, islands or plantings.
Speed Limit	40 mph.
Road Rules and Regulations	Signage, ANPR and road markings will provide non-physical deterrents against unauthorized DDS use. Priority would be given to Transit services.
Traffic Management	Similar principles to a high-quality tram operation.
Target Cost / km	£7m-£15m/km or lower.
Operating Model	Initial model for licensed individual operators. A future model might allow high occupancy shared vehicle platoons to enter / exit the DDS under strict rules.

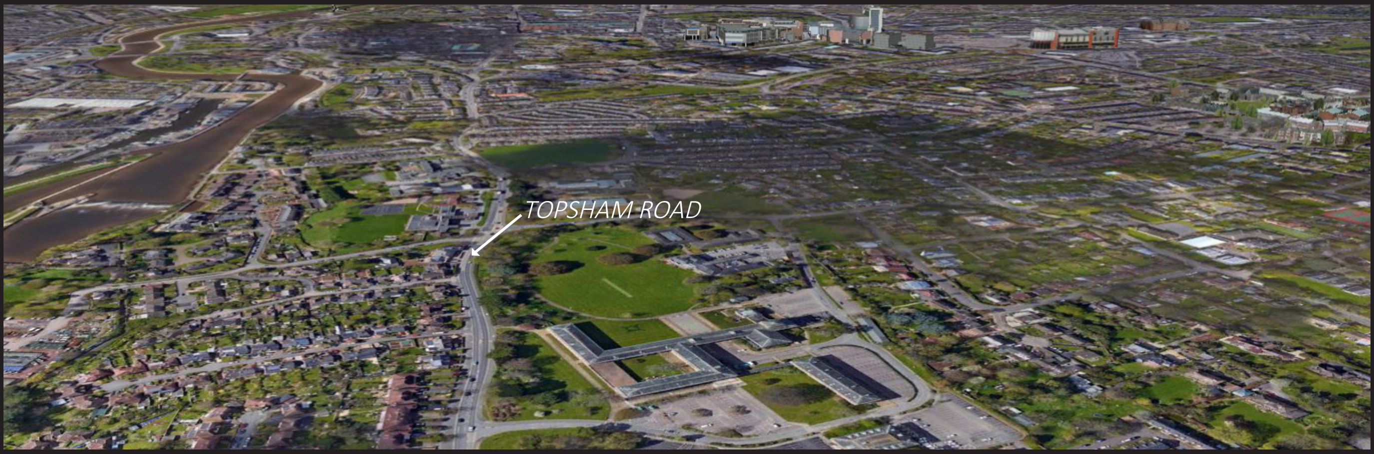
FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	In development
Technical Feasibility	Large project
Public Acceptance	Moderate
Commercial Viability	High
Overall Concept Readiness	Pilot

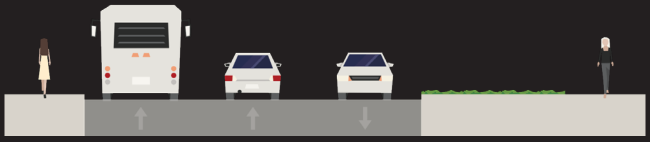
BENEFIT COMPONENT	RAG RATING
Congestion Reduction	High
Efficient use of Vehicles	High
Improved Journey Quality	High
New Travel Opportunities	Improved
Land Use Enhancements	High

CASE STUDY: AUTONOMOUS BRT

TOPSHAM ROAD, EXETER

Topsham Road is a busy arterial route into the city providing key links between the centre, the motorway and the suburbs. The route includes key demand generators such as County Hall and the city's main hospital.





BEFORE

10.5m carriageway including bus lane
Under-utilised verge
Shared pedestrian & cycle paths

AFTER

Bi-directional dedicated autonomous BRT lane
Two-way regular vehicle flow
Dedicated space for cyclists

BENEFITS

Better Road Network Performance

As stated in 'Congestion, Capacity and Carbon', the capacity on city road networks cannot easily or sustainably be expanded and using the existing road space more efficiently is the only realistic and sustainable option (NIC, 2017). AVRT-style systems offer the potential for capacity benefits on par with those seen for tram-like mass transit (almost 4-fold), at a cost closer to city-wide priority bus schemes. These technologies could significantly improve access to jobs, leisure activities and housing in and around medium-sized cities across the UK.

Improved journey quality

A survey of ride-hailing service users found that only 14% considered public transport a viable transport alternative (Babar, 2017). Without sufficient priority over cars, public transport journey times can be slow. In cities outside London bus passenger numbers have fallen by over 10% over the last ten years, even as city populations have been increasing (DfT, 2018b). Through a dedicated lane, Autonomous BRT concepts provide the reliability of service and enhanced journey quality public transport needs to compete.

Autonomous BRT services would need to be so frequent and reliable that no timetable is necessary (Smart Cambridge, 2015). In order to achieve behavioural change the service must be of the high quality the public expect. This can be delivered by prioritising services linking transport hubs along key arterial routes and adopting a simplified concept of operations. A system with integrated payments between modes and real-time digital information, would make available to medium-sized cities high-quality travel that, once fully-built out, could offer equivalent services to the metro systems of major cities (e.g. the Tube).

Transfer waiting times between vehicles within the span of a single journey significantly increase traveller resistance to using a public transport system. Efficient interchanges are therefore also a critical part of the system design to enable seamless end-to-end journeys. There is clear evidence that where effective transfers can be combined with fast and frequent onward travel then traditional transfer penalties are reduced – the London Underground is a perfect example (Smart Cambridge, 2015).

In order to ensure improved journey quality, all these elements need to come together collectively. If public transport is to compete in a world of CAVs, then this is a challenge authorities must address and deliver against.

Improved Road Safety

A less car focused approach to urban transport can also bring about a range benefits. For example, high-quality public transport can help develop city centres focused on people's needs, support pedestrianisation schemes or other opportunities to develop city centres with place-making or improved safety in mind. As we demonstrate in our case study, this includes the opportunity to provide better, safer provision for cycling and walking alongside Autonomous BRT schemes.

New Travel Opportunities

High quality public transport networks can provide travel access to young, old or disabled people who may not currently have access to a private car. Good design to support a wide-range of user groups will be critical to ensuring maximum up-take.

Land Use Enhancements

As with CAV shuttle schemes, the reallocation of space from roads and parking to pedestrianised areas, leisure amenities and green space will enhance city centres. The fast links offered by Autonomous BRT services can provide a key infrastructure to unlock new land. Docklands Light Railway, for example, shows how infrastructure aligned with schemes can help regenerate entire areas of cities by bringing brownfield land back into use. The cost-effectiveness of AVRT and other emerging solutions could put new ambitious regeneration opportunities within the reach of medium-sized cities across the UK.

FEASIBILITY

Technology Feasibility

The level of autonomous capability required for Autonomous BRT is low since systems can be designed simply, based around repeated journeys on strictly segregated routes (Smart Cambridge, 2015). The TSC (2016) previously concluded similarly that 'road based public transport may be amongst the most attractive first applications of driverless transportation as vehicles follow fixed routes, the infrastructure can be extensively mapped and adapted along those routes to aid the vehicles and removing the driver could significantly reduce the operating cost, whilst improving the efficiency and service level of the system'.

Affordability / Utilisation of Existing Network

With the benefits of segregated, dedicated lanes accepted as the most practical means of raising service quality for mass transit, the question then turns to how to minimize the capital cost. As discussed, a number of groups are working on this issue with target costs ranging between £7m-£15m/km. Smart Cambridge (2015) modelled a city-wide AVRT system construction cost in the region of £500 million - £800 million with their demand modelling suggesting the system could cover its operational costs from farebox revenues alone, without any need for public subsidy. This is a potentially game-changing opportunity for cities since 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 (ibid). Systems opening up new sites will also create significant land value uplift, affording additional opportunities to capture funding.

Note on Tunnelling and trends in affordability

Tunnelling is, in general, also cost prohibitive for cities. Many of the UK's cities, however, have historic centres which can limit the intervention options at grade. For this reason, it is also important to note the emerging trend of integrating CAV strategies with cost-engineering of tunnels. Professor Begg has suggested that if CAVs can operate safely with smaller headways then this increased capacity could change the economics of tunnelling (ITS, 2014). Oxfordshire's vision of future transport includes tunnels operating underneath the city centre making room for pedestrian and cycling areas above ground (Oxfordshire CC, 2017). Cambridge's AVRT concept also includes tunnelling as a key concept to address city centre access. Work here suggests that if the tunnel bores can be kept below 3.7m in internal diameter tunnelling for these small necessary sections could be achievable within the overall financial envelope. Elon Musk's Boring Company are testing a variety of techniques to cost-engineer tunnelling, for example, the conversion of bored material into construction products on site (Musk, 2018). Cost-effective tunnelling to accommodate high-precision, low width autonomous vehicles could offer new options for capacity constrained cities. The UK has strong expertise in tunnelling and should create an expert task-force to consider cost-reduction opportunities.

Future-Proofing / Flexibility

Autonomous BRT systems can be designed so that they are flexible. Use of tarmac means that systems could accommodate a range of vehicles, for example modular personalised pods at such time that these systems demonstrate sufficient safely and would benefit the city overall. Flexibility can also be built into the roll-out of such a system with new lines being added incrementally over time to minimise risks.

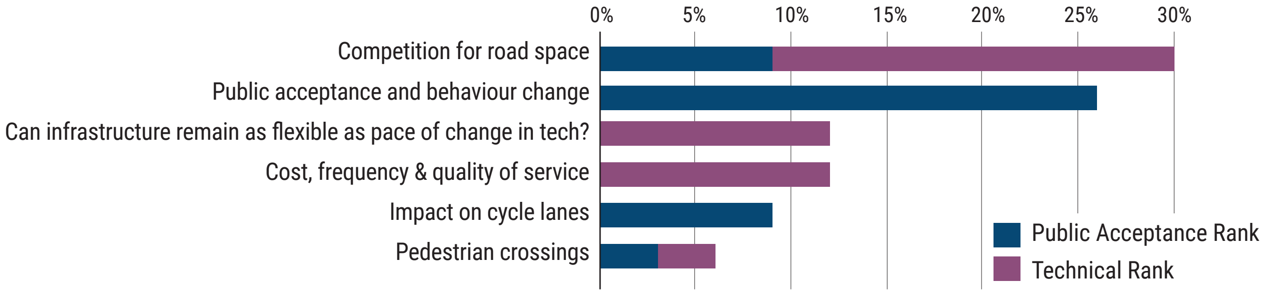
Resilience Impact

Autonomous BRT systems can radically improve resilience by reducing private cars and enhancing capacity. System design will play a critical role to ensure it can perform under stress and that maintenance can be accommodated in off-peak periods.

Public Acceptability

Public acceptability of Autonomous BRT schemes was tested during our expert workshop. The key challenges and identified solutions are outlined below.

Autonomous Buses: Key Challenge Areas Identified by Expert Workshop



Challenge Area	Possible Solutions Identified by Expert Workshop
Competition for road space	Clear commitment to prioritise most efficient modes (mass transit and active travel) above single occupancy vehicles. Incentivise narrower vehicles more generally. May be preferable to remove cars from central zones in a single scheme. Combine with cycling and walking infrastructure.
Public acceptance and behaviour change	Achieve mode shift through a city-wide strategy, not just isolated schemes. Change road pricing and disincentives for parking. Ensure service is frequent, reliable and has high-quality digital information. Provide direct routes in an attractive fleet.
Infrastructure flexibility	Modular system, created to be extensible and flexible for a range of vehicles.
Cost, frequency and quality of service	System operation design to ensure fast running on segregated uncongested route. Clear resilience plan to ensure service operation. Penalties and compensation for late arrival / departure. Real-time travel information.
Impact on cycle lanes	Make clear use of autonomous buses prioritising longer-distance corridors (5-8km). Combine changes with infrastructure promoting active travel. Integrate cycling and walking provision for first and last mile for those who are able.
Pedestrian crossings	Ensure scheme design provides appropriate, high frequency crossing points for pedestrians. Dynamic signals for pedestrian crossings. Well-designed bridges, underpasses or raised / tunnelled sections where high demand conflicts occur.

Outcomes and next steps

The public sector has considerable ability to steer innovation funding towards vehicles and schemes that will deliver large-scale benefit to cities. Innovation funding should be directed towards the development and testing of mass transit systems within our overall transport innovation strategy. Similarly, a team should be funded to investigate and, if successful, commercialise low-cost tunnelling. Finally, a number of partner cities should be secured where these ideas can be developed into fundable schemes and moved forward to demonstrate the benefits.

FREIGHT: TECHNOLOGY REVIEW

Freight within urban environments covers a wide range of different purposes including deliveries to shops & direct to consumers via traditional home delivery, refrigerated vehicles & bicycles (e.g. Deliveroo / UberEat).

Urban deliveries also often operate under a number of different constraints, including narrow streets with limited accessibility, and access restrictions (Alessandrini, 2015).

Statistics show that vans are the fastest-growing traffic segment in the UK, with 70% growth in road miles over the last 20 years, compared to 12% for cars and 5.5% for lorries (RAC, 2017b). While e-commerce represents part of this mix it is important to note that some new forms of deliveries may have a substitution effect on personal shopping trips. The RAC conclude that further work is required to fully understand the growth in van traffic (ibid). The NIC is aware of this issue and is progressing a freight study for publication in Spring 2019.

At the same time, given the large and growing importance of delivery services a range of new start-ups and concepts are emerging to cater for urban freight in an autonomous age. Many of these may seem like science fiction, for example Amazon's patent (shown below) depicting a system of airborne warehouses distributing goods to citizens via drone. Other start-ups (Workhorse) are also exploring drone-based systems. Autonomous start-ups such as Nuro, UDelv, Dispatch and Starship Technologies are developing road-based solutions ranging from small pods to autonomous supermarkets. New systems of delivery, have also been proposed in innovation projects for example CityMobil2 (Alessandrini, 2015).

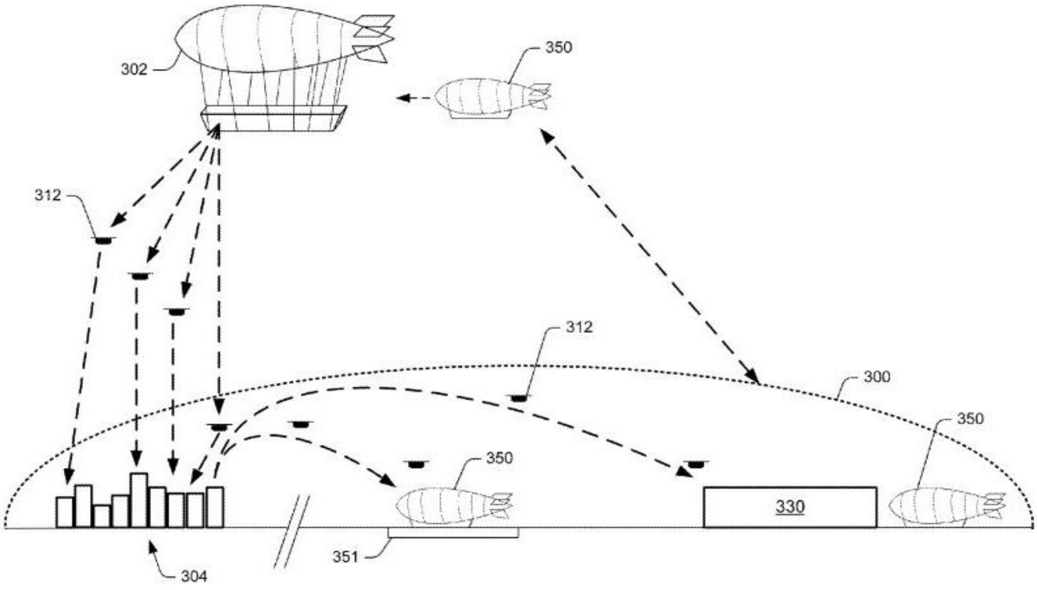

© Starship Technologies

Starships self-driving robotic delivery vehicle


© Robocart

Robocart driverless grocery store

The pace of change in freight technology is as strong as for the passenger car and the wide range specifications and vehicle characteristics creates significant challenge. Having a clear plan for future forms of autonomous freight on our roads is therefore essential.



© Amazon's 'airborne fulfillment centre'

LAST MILE FREIGHT SOLUTIONS

Concept

The NIC (2017) has described urban freight as "too often overlooked". A lack of capacity on urban networks adds costs and delays which are ultimately passed on to firms and consumers (Ibid). The technology review above shows many start-ups emerging in this sector based on the demand for a wide range of freight within cities. Growing demand for online services spanning the purchase of clothes, groceries, take-away deliveries and more means that the requirements for freight (in particular home deliveries) in urban environments is only likely to grow.

While it is assumed that freight in cities will follow the low emissions and electrification trajectory of conventional vehicles beyond that limited attention has been paid to planning for Freight. Having assessed the diverse range of emerging automated freight technologies and use-cases for freight, the project team concluded that a Dedicated Driverless Space concept specifically for a single freight type would be difficult to justify. However, if a certified network can be justified on the basis of connecting the first-mile of residential journeys the same network could conceivably then be utilised for a wide range of freight deliveries. The last mile freight solution concept therefore proposes to use the first mile passenger network to conduct deliveries at off-peak hours – quiet, zero-emission, automated vehicles could even conduct deliveries at night.

A recent study by the Transport Systems Catapult focused on the potential role of Urban Consolidation Centres (UCC). A UCC is defined as a logistics facility that is situated relatively close to the area that it serves. Goods destined for the area served are dropped off at the UCC and are sorted and consolidated onto suitable commercial vehicles, for delivery to their final destinations (TSC, 2018). Such a concept could be even more compelling if integrated into an autonomous-ready road-based delivery network, giving proximate or direct delivery access to a customer's front door.

How will it work?

- The Passenger First Mile Network developed principally for autonomous shuttles would provide a certified network upon which urban freight services could operate. The First Mile Network would be principally licensed to shuttle operators to transport people.
- A UCC could be integrated into the network, located at the interface between the Major Road Network and the suburb. The consolidation centre would manage the last mile of the delivery journey to businesses and residents based on a standardised system of container sizes.
- The operation of the consolidation centre would also be fully autonomous.
- A code-based identification system would enable users to collect small goods from pick-up / drop-off points on the network within designated time windows (for non-perishable, non-time-critical goods such as clothing).
- Individualised door-to-door deliveries by pod-based technologies (e.g. Starship Technologies, Savoike) could be enabled through the identification system.
- Delivery on the network would be conducted according to time-slots. Slots would be priced according to overall network demand where it is expected that overnight deliveries would be cheapest. Peak hour deliveries when freight would be competing with shuttle-based passenger traffic would the most expensive.
- Bicycle-based delivery systems on the cycle network (e.g. Deliveroo) would also be encouraged from the UCC.

FEATURE	
Level of Segregation	Dedicated spaces will be differentiated through the use of materials, road markings, colours or light, while keeping cost to a minimum.
Speed limit	20-30 mph. Door-to-door vehicles may require a minimum speed in order not to impeded other traffic.
Road Rules and regulations	Signage, ANPR and road markings will provide non-physical deterrents against unauthorized DDS use. Priority would be given to shuttle services.
Traffic Management	Residents should give way to CAVs as they do for crossing traffic today.
Target Cost / km	<£0.5m/km
Operating Model	UCCs with slot-based system for onward freight deliveries. Standardised container sizes. Network slot timings priced to minimise congestion.

FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	Operational
Technical Feasibility	Medium
Public Acceptance	Challenging
Commercial Viability	Potential
Overall Concept Readiness	Pilot

BENEFIT COMPONENT	RAG RATING
Congestion Reduction	Localised
Efficient use of Vehicles	Not applicable
Improved Journey Quality	High
New Travel Opportunities	Not applicable
Land Use Enhancements	High

CASE STUDY: FREIGHT LAST MILE

SUBURBAN COMMUTER TOWN, EXETER

Autonomous freight utilises the certified network of routes developed for passenger first mile. This will become a more attractive option once the network grows in size such that the majority of consumers can be reached.

Edge of town Consolidation Centre

Smaller freight uses last mile Dedicated Driverless Space to reach the end customer

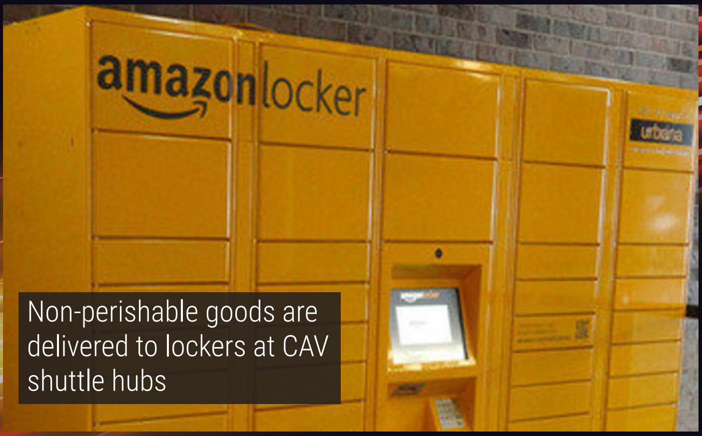

© Tesla

Zero emission long-distance freight incentivised to travel at night and use Urban Consolidation Centre through road pricing regime


Range of autonomous vehicles make last-mile deliveries at night

© Nuro

Pricing systems regulate day-time delivery volumes



Non-perishable goods are delivered to lockers at CAV shuttle hubs

©Escargo

Cargo bikes & e-bikes become wide spread for daytime deliveries, utilising cycle paths

BENEFITS

Better Road Network Performance

Research for the Cabinet Office found that 50% of urban traffic in the 10 years to 2008 was due to light vans (Cabinet Office, 2009). There are now 3.8m vans registered in the UK, an increase of 74% since 1996. Research by TfL indicates spare capacity on many trips – the average load factor in London was found to be 38% while 39% of vans were found to be less than a quarter full (TfL, 2013). In order to address the challenge of freight there are a number of options including:

- Reduce demand
- Shift delivery timings
- Re-route traffic to lower impact areas
- Shift to cleaner vehicles or modes.

The Last Mile Freight solution would include a UCC linked to the CAV-certified network. Road network performance would be greatly enhanced through the transition to autonomy, in particular if deliveries can be shifted to overnight patterns. Freight operators would be required to buy a 'slot' in the schedule to operate on the network. Access to the network would effectively then be priced to encourage overnight deliveries and disincentivise individual deliveries during peak hours. By ensuring that CAV network interventions are co-ordinated with suitable cycling infrastructure, day-time deliveries could be shifted to cargo bikes further freeing up capacity on the road network.

In theory, a UCC could also be integrated with inland waterways where this would make sense from the perspective of a specific scheme. Although a complete exploration of this concept was deemed out of scope of this research wider road network performance and efficiency enhancements might be achievable through such a strategy. Transporting goods via water requires one tenth of the energy compared with transporting the same goods via road and more than 50% of the UK's population resides within 5 miles of an existing canal or river. In theory, autonomous vehicles operating on canals could shift demand away from road freight. This idea may seem far-fetched, but trials of autonomous barges are already planned in Belgium and the Netherlands where five 52m-long zero-emission barges are expected to replace 23,000 diesel trucks (Boffey, 2018).

More efficient use of vehicles

It is often the last mile of freight journeys that is the least efficient in terms of time, emissions and congestion (ITC, 2017). The consolidation of deliveries centrally could have considerable benefits in terms of efficiency. There are complex multi-criteria optimisation decisions which need to be made to maximise the overall benefits. Having maximum visibility across the deliveries taking place will ensure that strategies can be developed which, for example, minimise the impact on traffic, minimise energy use or maximise load factors.

Improved journey quality

Simply shifting deliveries to overnight will improve journey quality for travellers. Cyclists and pedestrians would benefit from fewer light vans and HGVs during the day and car drivers would see reduced congestion. This benefit of automation is currently 'under-sold' within the literature. All citizens would also benefit from improved air quality. Vans make up 15% of road traffic but contribute a higher proportion of emissions such as NOx and CO2. 96% of registered vans are Diesel fuelled (UTG, 2018). The electrification of the urban freight fleet would radically reduce these impacts.

FEASIBILITY

Affordability / Utilisation of Existing Network

The concept for Freight Last Mile is based on two underlying assumptions: firstly, since it will largely be serving residential zones and businesses, it could operate within the same Dedicated Space as the passenger last mile solution; and secondly, that freight operators would pay for use of the Space i.e. a system of road pricing would be introduced. Since autonomous vehicles can operate overnight there is a unique opportunity to promote this shift within the system design. The delivery of a highly reliable end-to-end service for passengers will be a priority for the network during the day, and a pricing system can best provide this incentivisation and balancing mechanism. This would also allow contributions to the cost of the infrastructure and its levels of maintenance to be recovered. Therefore, the system design considers passengers and freight together, and in doing so improves the commercial and financial viability of the system.

Public Acceptability & Resilience

Public acceptability challenges for the passenger first mile network have been considered earlier in this report. There is likely to be strong support for moving deliveries to overnight. This change will also lead to resilience improvements as well, reducing the likelihood of parked vehicles and/or congestion events during daylight hours.

OUTCOMES AND NEXT STEPS

The economics of this typology are expected to depend on demand, number of 'slots', logistics strategies and capital and operational costs of both freight and passenger operations. If it can be engineered that the road price for freight is lower than the existing cost of the driver and the additional handling interchange, then freight operators will be incentivised to shift to CAVs while also accepting a road pricing regime. These economics have not been fully modelled as part of this study but this is a potentially exciting area for future research.

INTERCITY CRUISE LANES: DYNAMIC MANAGED LANES

Concept

Motorway driving, in congested conditions have emerged as some of the preferred use cases for automated vehicles in public perception surveys (Payre, 2014). However, modelling for the DfT, demonstrates that high levels of penetration are likely to be required before wider capacity benefits are felt. For the SRN, a 40% improvement in delays could be achieved assuming 100% penetration of assertive CAVs but benefits are found to be negligible with CAVs making up only 25% of the fleet (DfT / Atkins, 2016b). The research therefore suggests that while many would seek to use CAVs on the SRN, the benefits may be limited while the fleet is mixed and therefore a strategy is required during the transitional period to CAVs. The Dedicated Driverless Space in this context is an intercity cruise lane that combines the potential capacity benefits of 100% CAVs with a dynamically managed lane concept to maximise throughput on the SRN.

The Dedicated Driverless Space will respond based on two key pieces of information communicated digitally:

1. the overall volume of vehicles on the motorway road section
2. the overall proportion of CAVs on the road section.

Based on a framework proposed by Hussain (2016), the managed lane will enter CAV-only operation only during specific periods where it will benefit overall motorway throughput. The mathematics show that these periods will occur when the conventional capacity of the motorway is being reached and the proportion of CAVs within the fleet is above a certain threshold. This approach could also be targeted towards sections of motorway that regularly enter congested conditions (i.e. where the benefits of the intervention are maximised) with the required infrastructure likely to be vastly more cost effective per kilometre than new or expanded lanes.

How it will work

- The Dedicated Driverless Space in this case would be a permanent managed lane on a motorway. Each managed lane will be 'certified' for adequate use by CAVs (see chapter 3) and the vehicles themselves will be required to meet certain standards ("Qualifying CAVs") before being granted permission to use the lane (CAVs not meeting specified safety and headway standards would be prohibited alongside conventional vehicles).
- The status of the lane would operate in two states: Qualifying CAVs-only, or mixed traffic. The lane would not be physically separated but would rely on lane markings, variable message signs & I2V communications.
- Existing volume tracking systems would communicate overall road section volumes. Qualifying CAVs would communicate their position to the traffic control centre which would aggregate the total number of Qualifying CAVs on the road section. System algorithms would then calculate the most beneficial status of the lane based on a throughput optimisation approach, as suggested by Hussain (2016). Smoothing algorithms would ensure safe transitions between operating statuses (to avoid frequent changes in state where the real-time calculation is at the boundary between states).
- Pedestrians and cyclists are not permitted users of the motorway and so interactions will be restricted by default. When operating, the Dedicated Driverless Space will minimise interactions with conventional vehicles through strict penalty enforcement and policing.

FEATURE	
Level of Segregation	Separated only by lane markings, variable message signs and V2I signal.
Speed Limit	70-80mph
Road Rules and Regulations	Mixing of traffic could have major safety implications and as a result lane behaviour will likely require strict enforcement via ANPR and policing systems.
Traffic Management	Similar principles to a high-quality tram operation.
Target Cost / km	£2m-£3m/km or lower.
Operating Model	The road section itself will need to be 'certified'. Higher levels of maintenance will be undertaken as part of its operation. Individual vehicles will also need to be licensed and tested to meet specific standards for safety, headway and communications resilience.

FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	Low
Technical Feasibility	High
Public Acceptance	Moderate / High
Commercial Viability	Not applicable
Overall Concept Readiness	Model

BENEFIT COMPONENT	RAG RATING
Congestion Reduction	Localised
Efficient use of Vehicles	Optimised
Improved Journey Quality	High
New Travel Opportunities	Not applicable
Land Use Enhancements	High

SYSTEM OPERATION OVERVIEW

In order to fully understand the benefits and feasibility of the system, it is important to have a full understanding of how the system will work and the design choices that have had to be made. Managed lane (ML) strategies are being applied to motorways to improve network performance, including travel time, travel speed, traffic flow, fuel consumption, safety and congestion reduction in a range of contexts (Hussain, 2016). The concept integrates CAVs into a Managed Lane strategy based on the assumption that CAVs are able to run with less spacing and headway compared with manual vehicles or mixed traffic. Under these assumptions, allocating a lane exclusively to CAVs can be shown to improve overall throughput of the network in certain circumstances (Hussain, 2016). Vehicles able to travel closer together at the same speed within a lane offers the opportunity of increasing capacity and avoiding flow breakdown (DfT/Atkins, 2016).

Hussain (2016) proposes a model to evaluate the motorway flow in mixed traffic and to determine the optimal number of lanes that should be dynamically allocated to CAVs. The optimisation framework discussed in this paper could be used to determine the conditions under which a managed CAV lane would be activated in order to maximise network throughput. In simple terms a mathematical process would continuously monitor the proportion of CAVs on the roadway and open the CAV-only lane when it benefits all road users to do so. The precise benefits will depend on the headway that vehicles can operate with and the proportion of vehicles in the fleet.

Essentially where demand for the road is lower than its capacity, the traffic is in free-flow conditions and there are no benefits from opening up the Managed CAV Lane.

Here the mathematics shows that allocating any lane to CAVs does not change the overall traffic throughput. Where demand exceeds capacity however, the motorway begins operating under congested conditions. In these cases, allocating a number of lanes to CAVs can improve the total throughput.

In congested conditions, the effect of opening the Managed CAV lane is subtle generating two separate effects: firstly the capacity of the non-CAV lanes drops since these lanes now operate only with human-driven vehicles; secondly, the capacity of the CAV lane increases due to the tighter headways. In the model, the capacity drop on non-CAV lanes must be lower than the increased throughput in the dedicated CAV lane before the lane will become operational.

The system can be technically implemented by allowing only certified vehicles to use the lane. As part of the certification process, vehicles would need to meet secure communication standards with the system operator, minimum standards of headway performance and robust levels of safety in high-speed platooning operations. The implementation of the ITS and managed lane system is likely to be easier than developing and testing vehicles to meet the required safety and headway standards.

Lane Options

The other key choice to make in the design of such a system is how to select the lane to be managed. In an example three lane motorway, we can effectively rule-out the middle lane. A platoon of CAVs separating conventional vehicle lanes would not be desirable since it would materially impair lane changing for other users. This leaves two alternatives:

- **Inside lane:** Proximity to the hard shoulder is beneficial from a safety perspective, for example if a participant of a platoon enters difficulty and needs to move quickly to a safe harbour area. A critical concern that arises however is that long platoons operating in the inside lane will prevent other vehicles exiting the motorway (TSC, 2016). Arnaout et al (2011) investigated the complications of CACC at merges and found little impact until 40% penetration of the fleet, but many other studies (Scarinci, 2015; Kachroo, 1997, DfT/Atkins, 2016) have demonstrated difficulties in merging vehicles joining the main carriageway. Merges and exits are a common feature of the UK motorway and so would create a major challenge if a managed CAV lane were to be implemented on a multi-section run. One option that has been proposed to circumvent this difficulty is to limit platoons to no more than 3-4 vehicles, but this results in minimal benefits and still creates potential obstructions.
- **Outside lane:** This allows longer journeys and platoons to be accommodated but will require higher standards of safety and the imposition of a minimum speed limit which freight vehicles in such platoons would also need to conform to. Conventional drivers would need to be restricted from overtaking in this lane when CAVs have priority.

CASE STUDY: MANAGED CRUISE LANE

BENEFITS

Better Road Network Performance

Despite the complexities discussed above, motorway driving, is one of the preferred use cases for automated vehicles (Payre, 2014) and significant benefits could result. The NIC (2017) modelling projects that, for Great Britain as a whole, road usage will grow by between 37-61% by 2050, therefore cost-effective improvements to capacity will be essential to maintain the journey times upon which the economy depends.

As we have seen in Chapter 4, the calculation of capacity benefits largely depends on the reduced headways that vehicles can provide (Broqua, 1991; Minderhoud, 1999). Results of modelling for the DfT demonstrate that for the SRN a potential improvement in delay of 40% could be achieved assuming 100% penetration of assertive CAVs (DfT / Atkins, 2016b). Based on the headways assumed in Hussain (2016) there are demonstrable benefits to the managed lane system. For a four-lane motorway, the allocation of a single lane can improve the flow for the whole system when the total proportion of vehicles is between 12%-56% (ibid). When modelling vehicles with the most aggressive headway, a single Managed CAV lane is sufficient to improve the throughput of even a 6-lane motorway. With a system designed to maximise the throughput at all times it could be constantly managing the flow, d providing much more reliable journey times. In our interviews, Mobility Start-up SN-AP, suggested that such a system could be extended to take account of vehicle occupancy and capacity. This would enable the SRN to optimise throughput of passengers, providing dynamic priority to high occupancy vehicles to provide reliable journey times for road-based intercity transit.

40%
improvement in delay could be achieved

Platooning

One of the other benefits of lanes which are pre-certified for CAVs in terms of road markings, surfaces and communications is that they would enable freight platooning. Platooning involves two or more vehicles travelling very close to each other and linked electronically so that the driver of the lead vehicle has both longitudinal and latitudinal control of following vehicles (TSC, 2016). Alongside the cost savings to the operator, this saves fuel because the close proximity of the vehicles reduces drag. It is also speculated that platooning could lead to smoother traffic flow, with less braking and accelerating between vehicles *(see Research Gaps section below)*. The NIC (2017) believes the pilots of “platooning” truck convoys on motorways and major A roads may open the way to radical improvements in the efficiency and capacity of major freight distribution by road in the future. The research suggests that co-ordinated platooning is now technically feasible but not operational because many benefits require dedicated lanes (Litman, 2017). The Dynamic Managed Lane could be implemented at the same time as roadways are prepared for platooning and the objective function could be adapted to dynamically maximise the throughput of freight as the penetration of platooning-enabled vehicles rises within the overall fleet.

More efficient use of vehicles

The optimisation system proposed would not only work to maximise overall network throughput - similar approaches could be extended to manage overall vehicle occupancy. For example, such a system could be implemented today to give managed lane priority to high occupancy vehicles at times of congestion. This type of system would then maximise the journey times for the most number of users, improving overall performance.

Land Use Enhancements

Managed cruise lanes could encourage new development in surrounding areas if journey times are improved. The introduction of 100% electric CAVs onto the SRN will also reduce noise and emissions which could make residential developments adjacent to the SRN more viable and desirable. By targeting interventions on the highest congestion areas, where it makes sense to do so, the benefits of noise and emissions reduction will also be maximised.

Remaining Research Gaps

While the Dynamic Managed Lane concept shows promise and could be extended to a wide range of uses we have identified some specific research gaps that require more understanding.

In our expert workshop, this concept was a popular one which participants perceived to have high levels of feasibility. However, we would add some caution here based on our wider findings. Because they are proposed for motorways where CAV and non-CAV vehicles are likely to mix, this concept deviates somewhat from the other Dedicated Driverless Spaces we have identified and raises additional complexities that should be fully understood.

Traffic Flow Stability: The overall effect of platoons on traffic flow stability is not yet fully understood. Some have noted that Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) dampen out spacing and speed errors that cause shockwaves at high flow, improving stability (Pueboobpophan, 2010). Other authors have demonstrated differences in traffic flow stability in between ACC and CACC platoons (Ploeg, 2012). Using a minimisation optimisation problem to adjust acceleration of the following vehicles, Gu (2015) showed improved stability in CACC platoons. Milanes and Shaldover (2014) however showed that consecutive strings of ACC vehicles are unstable, amplifying the speed variations of preceding vehicles. The interactions of the different types of platoons that may operate on the motorway (e.g. combinations of non-platooning vehicles, ACC and CACC platoons) and their aggregate effects will require further investigation.

Formation effects: A second limitation is understanding the impact of different platoon formation strategies. Authors have proposed alternative formation strategies such as formation in lorry parks (McKinnon, 2016) or active assembly on the road (Bergenhem, 2010). For the purposes of this work we assume that a suitable distance for platoon formation could be calculated based on known platoon dispersion principles. But there would likely be other formation effects such as lane changing which may give rise to additional congestion. Van Arem (2006) looked at congestion forming upstream of the start of a CAV only lane, finding both unsafe effects from merging and reflecting that at under 40% penetration, overall capacity would be worse. Therefore, detailed modelling of different platoon formation strategies is also warranted to ensure a CAV-only lanes do not introduce any unintended consequences.

Human Behaviour: There are many gaps in our understanding of how human drivers would interact with CAVs in practice. Researchers have previously noted the behavioural considerations at play such as drivers turning off cruise control (Viti, 2008; Alkim, 2007); drivers wanting to leave platoons if they are perceived they are being “held back”, regardless of actual network conditions (Jones, 2013); or non-automated drivers being influenced by CAV platoons to attempt lower headways (Gouy, 2014). Driver behaviour may differ when they are following a CAV from when that same driver is following a manual vehicle, since the driver may have different expectations of vehicle dynamics. There are likely to be other effects that have not yet been observed which may influence the overall congestion benefits or impacts on safety.

Fleet Characteristics: The specific characteristics of the fleet are currently not known. Typically, in simulations, only a single type of AV capability has been modelled with CAVs assumed to have homogenous performance. Models, including Hussain’s (2016) are simplifications of this potential future and do not currently represent the full potential behaviours within the system. Therefore, they may not anticipate other congestion effects. Little work has been done reflecting the different performance across the potential spectrum of technologies and the differences in capability and heterogeneity of vehicle types is currently unknown (DfT/Atkins, 2016).

Improved Road Safety

The research gaps related to human behaviour may have a significant bearing on road safety and should be borne in mind throughout the discussion below. While motorways have no pedestrians, bicycles or level crossing, and barriers separating the two directions of traffic, they also operate at high speeds which has a considerable influence on safety, especially with regards to stopping distance. Some studies have provided estimates of headway in terms of the space between vehicles. One example suggests that under aggressive headway scenarios the gap could be as low as 5 meters per vehicle (Tientrakool, 2011). The relevance of these potential headways becomes clear when considered against highway policy governing safe vehicle spacing. The UK Highways Agency recommends that a spacing of 2 seconds is maintained between all highway vehicles travelling at 70mph allowing the average driver to interpret and react to potential hazards quickly enough to avoid or cause collisions. A headway of 2 seconds equates to 62m at speeds of 70mph. Practical testing of CACC has so far demonstrated that platooning has potential to facilitate headways of less than 62m, but its ability to safely control headways of below 10m requires further testing (Hardy, 2015). Safe headways within CACC platoons depend on the maximum latency of safety critical information within V2V communication systems. Connectivity and signal strength and security will be essential in practice to enable lower headways. Mechanical variations between vehicles, tyre tread and weather conditions will also greatly influence the headways which may be deemed safe.

How will the technology ensure this critical functionality can be made available as a failsafe in all circumstances?

Related to the platoon and safe stopping distances is the question of leaving a platoon in an emergency. We have previously discussed the potential role of the hard shoulder as a safe harbour area but long term, if the Cruise Lane is in the outside lane, accessing the hard shoulder will have additional complexity, especially at high speeds. It is unclear what safety features would enable a vehicle to change lanes and move to a safe harbour in the case of system failure – how will the technology ensure this critical functionality can be made available as a failsafe in all circumstances? Ensuring that there are robust mechanisms to manage the failure of individual vehicles will be essential.

FEASIBILITY

Affordability / Utilisation of Existing Network

The concept of an eLane was introduced by CityMobil on the basis of a design which aimed to keep costs as low as possible - clearly visible lane markings, communications network and data infrastructure only. Here, the main disadvantage was the view that devoting road space exclusively to automated vehicles would be expensive (Toffetti, 2009). A Dynamic Managed Lane overcomes this issue with minimal additional cost. Managed motorway strategies have been shown to deliver a higher Benefit Cost Ratio (BCR) than traditional motorway widening schemes at a lower capital cost. Research by the IET documents BCRs of 7.6 for a managed motorways, compared to 2.3 for standard motorway widening (IET, 2011). The overall capital outlay is also 70% lower than traditional widening. However, it is important to note that there will be additional operational costs such as higher levels of on-going maintenance. With the potential capacity improvements that could be afforded from CAVs operating in platoons, the capacity benefits may also be higher than traditional lane widening – for example Hardy (2015) shows an effective 2.5x increase in capacity for a "safe" headway of 24.4m. If the system enabled such platooning to operate safely, this would be equivalent to adding 1.5 more lanes at less than a third of the cost. It would also enable much greater utilisation of the existing network. A strategy of upgrades could be prioritised based on the most congested road sections, potentially enabling even higher BCRs to be achieved.

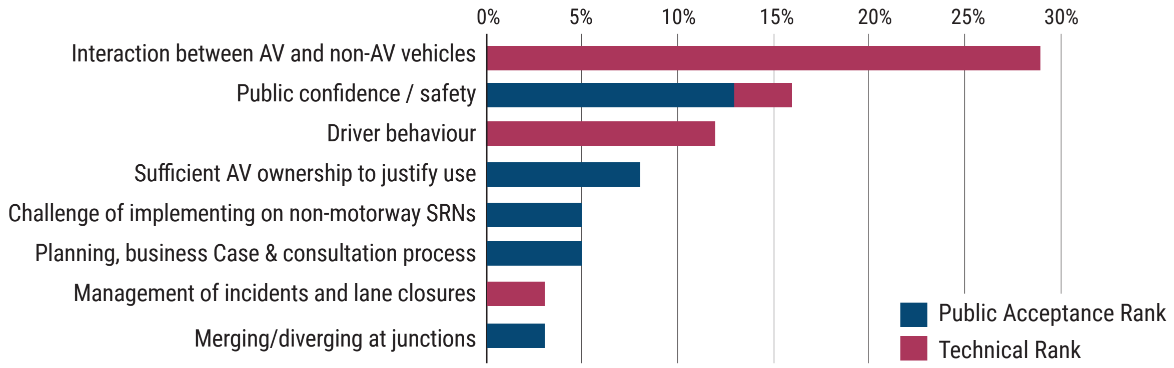
Future-Proofing / Flexibility

The Dynamic Managed Lane concept creates a future-proofed and flexible portion of road space that can respond to changing demand and use of CAVs, in particular managing integration with the fleet during the transition period, but also creating the required infrastructure to support platooning and the use of CAVs more generally. Small trials could commence in the inside lane between junctions, focused on small portions of road. With appropriate technology standards agreed these small sections could over time be extended to larger parts of the SRN.

Public Acceptability

The issues around public acceptance were explored in our expert workshop. Traffic engineers, planners and consultants identified, categorised and ranked over 30 potential challenges for the Dynamic Managed Lane (outputs in the chart below). This analysis shows that the main public acceptance issues relate to safety and confidence in the systems; the sufficiency of CAV penetration to justify the scheme; the planning and consultation process; and driver behaviour. Participants then generated potential solutions to overcome the identified challenges which are documented below.

Intercity Cruise Lane: Key Challenge Areas Identified by Expert Workshop



Challenge Area	Possible Solutions Identified by Expert Workshop
Interaction between AV and non-AV vehicles	Clear segregation with fixed lanes. Understand appropriate management strategies to move CAVs to the managed lane without causing additional congestion. Consider rules, behaviours and policing of the interactions e.g. ANPR cameras and fines.
Public confidence / safety	Full transparency regarding test results. Rigorous testing and validation of safety systems. Demonstrate on a test route first (the M6 toll road was given as a potential example). Clear consultation covering a wide range of demographics.
Driver behaviour	Education & information on technology & requirement to respect the CAV lane. In-car management through driver assistance systems. Penalties for lane mis-use.
Sufficient AV ownership to justify use	Incentives for AV use, stimulating demand for qualifying features. Deliver sales penetration of cars that are “AV-ready”, prior to introduction of concept. Only introduce after minimum % of fleet are CAVs. Fully explain operation stressing the capacity improvements to all road users.
Implementation on non-motorway SRN	Prioritise schemes on viable multi-lane link sections where benefits can be demonstrated through detailed modelling.
Planning, Business Case & Consultation	Resource planning now to allow sufficient time to develop political buy-in. Collaboration with local authorities. Establish manufacturer working group to align regulations, policies and safety requirements. Design flexible infrastructure to keep pace with technology and avoid obsolescence.

Resilience Impact

The flexibility of the lane means that closures would be managed as they are today and would not impede emergency vehicles for example. With a connected system, predictive analytics could be employed to open the CAV lane before congestion arises, preventing its onset. Once there are multiple CAV lanes and CAVs communicating with the infrastructure there would be more information to actively manage the entire network with a view to improving resilience. The opportunities afforded by this data would likely enable a range of new resilience prevention measures.

Other Infrastructure Considerations

There are a number of further features which should be considered which weigh additionally on the feasibility of the solution. Firstly, because CAVs will run consistently in the same lane positions there may be greater wear and tear in the wheel tracks. This could potentially require the road area beneath the tracks to be strengthened, or to be more frequently maintained (Lamb, 2015). Secondly, the impact of closer headways on traffic loadings on specific structures such as bridges or other road sections would need to be closely investigated. River crossings are often of critical importance to the SRN. Combined modelling of highway performance for different headway assumptions should be combined with load models to understand the specific trade-offs that would be required to certify a road section for platoons. Thirdly, detailed assessment of centrifugal and braking forces of platoons may require testing to ensure existing structures can handle these new requirements. Scheme by scheme modelling and assessment of these issues in a coordinated way will be essential for delivery.

OUTCOMES AND NEXT STEPS

The concept relies on two major pre-requisites – firstly, that CAVs can operate at speed with shorter headway than conventional vehicles; and secondly, that they can do so with absolute guarantees of safety. A final consideration is the detailed modelling of the effect of different vehicles and platoon types within the motorway. As discussed earlier in this document, each of these issues requires further work.

NEW DEVELOPMENTS: INTEGRATING CONCEPTS TO MAXIMISE HOUSING

Concept

TSC (2017) has previously suggested that when planning new developments, consideration should be given to automated public transport vehicles. To fully promote autonomous vehicles, increasing numbers of new developments should be designed and built with them in mind. The NIC's (2017) 'Congestion, Capacity and Carbon' report calls for well-designed cities with integrated plans for housing and transport offering more homes. Housing cannot be created without the underpinning of transport and utilities, and smart, sustainable and liveable communities depend upon reliable and high-quality infrastructure. In turn, the value of new and existing infrastructure is enhanced if it enables new housing to be built, giving people greater choices of where to live and work.

The palette of interventions brought together by the earlier typologies could be applied to new developments, encouraging more car-free, zero emission and low carbon developments. Combined with energy and building stock interventions, this could result in 'net positive energy' developments (developments which generate more energy than they consume contributing positively to the UK's decarbonisation targets). In urban areas and areas with bold commitments to walking and cycling (e.g. London), car-free developments will be essential to meeting mode share targets and, as long as transport planning provides high-quality connections for residents, could enable more housing within the same footprint.

How it will work

- New developments will be required to consider Connected and Autonomous Vehicles as part of the transport planning process. Travel Plans or Transport Assessments will be required to reference connectivity to the locally planned "Long-term CAV Network Map" and the Local Cycling and Walking network (from LCWIP).
- Developments would be expected to demonstrate their connectivity with existing transport hubs, jobs and services via public transport. This will be enabled by requiring accessibility isochrones within Travel Plans to evidence how journey times and accessibility to a broad range of services and jobs compare with private car. These analyses should be performed for today's baseline, and the forecast result from the long-term CAV network map.
- The NIC's (2017) 'Congestion, Capacity and Carbon' report states that the UK needs infrastructure that helps create desirable, thriving communities rather than a series of loosely-connected developments. The development of New Garden Towns should explicitly consider how the palette of Typologies discussed could enable greater intracity connectivity and integration.
- If an evidence base can be developed demonstrating that shuttle-based, mass transit schemes and CAV-only zones are successful, and accepted by the public, developers will have a natural incentive to design out parking spaces and increase the overall number of dwellings or property sizes.

FEATURE	
Level of Segregation	The new developments would submit plans demonstrating how they can be segregated from conventional vehicles over time, building in preparation for CAV-only Zones into elements of public highway. CiL Payments may fund connection to other existing or future segregated infrastructure.
Speed limit	30 mph but community zones should be restricted to 15-20 mph.
Road Rules and regulations	Rules and regulations would follow those of the individual typologies.
Traffic Management	Traffic management would be minimal. Plans would need to be in place to enable CAV-only zones in the future e.g. on entry / exit to zones within the development.
Target Cost / km	Based on range of typologies previously discussed.
Operating Model	Operating model for Dedicated Driverless Spaces would be as each typology describes. Any GPS-based routes would formally be part of the Public highway but with minimal marking and no kerb required.

FEASIBILITY COMPONENT	RAG RATING
Technical Readiness	High
Technical Feasibility	High
Public Acceptance	Moderate
Commercial viability	High
Overall concept readiness	Deployment

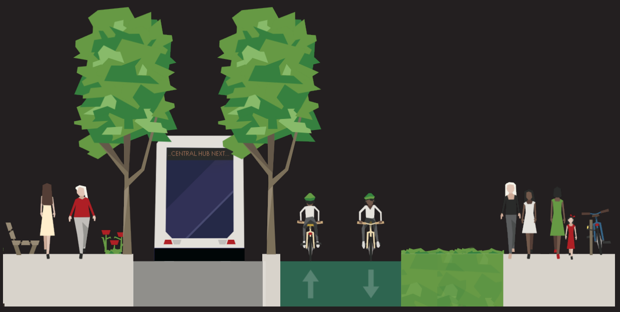
BENEFIT COMPONENT	RAG RATING
Congestion reduction	Localised
Efficient use of vehicles	High
Improved journey quality	High
New travel opportunities	Localised
Land use enhancements	High

CASE STUDY: NEW DEVELOPMENTS

TAUNTON GARDEN TOWN, SOMERSET

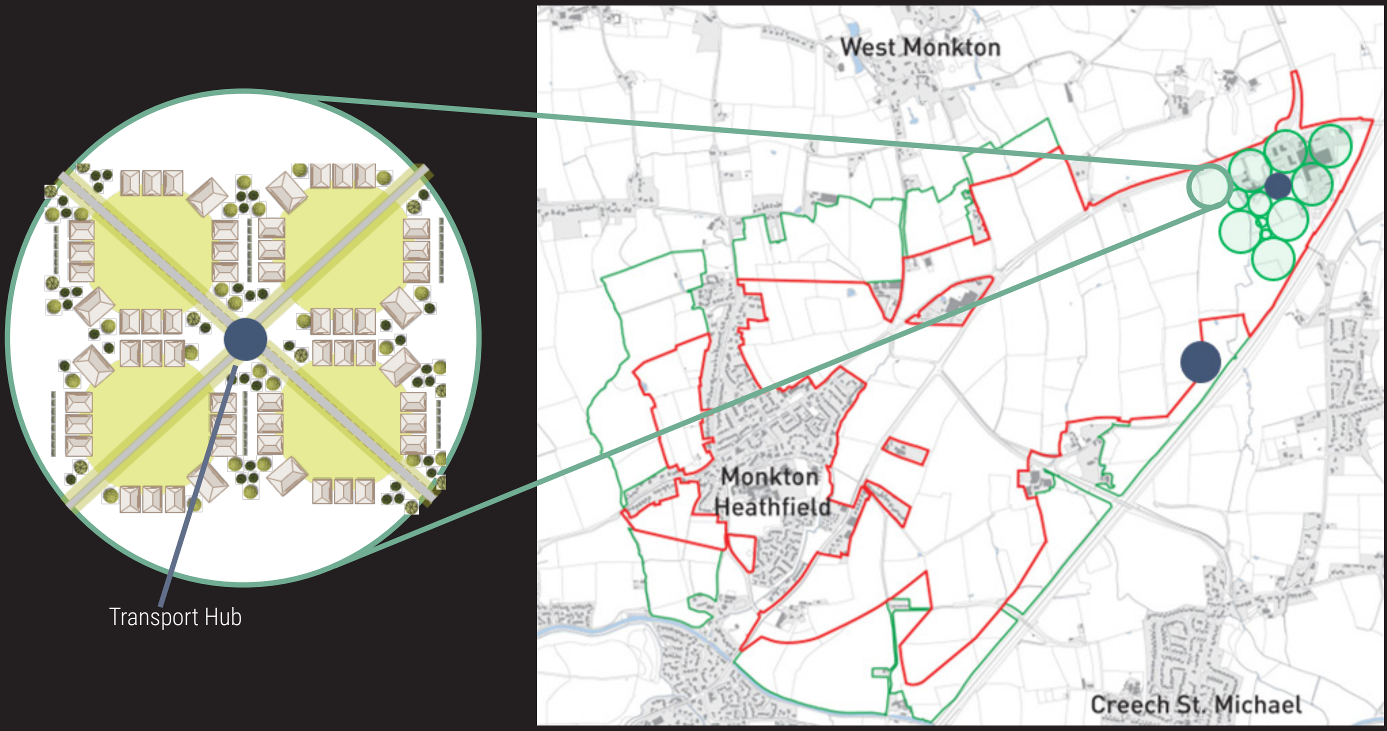
Taunton is the first town in the South West to achieve Garden Town status which is expected to act as a catalyst for business, investment and growth. In total, Taunton is expected to add ~10,000 new dwellings. For Taunton, Garden Town status is about creating an even better place for people, communities and business to live, work and prosper.

BEFORE *Typical new development designed around the private car*



AFTER *Residential areas offer ample walking, cycling & green space. An on-demand first mile solution removes the need for car ownership.*

In central areas shallow trenching is delivered alongside ground works to house underground CAV operation. This enables new opportunities for the development to be designed around community space.



We have imagined the Monkton Heathfield site developed based on clusters of housing, integrated around transport hubs. On-demand CAV shuttles weave throughout the quiet dedicated roadways, linking residents to key services and to a larger transport hub serving onward journeys. This enables greater shared space and an active and vibrant community within the Garden Town site.

BENEFITS

Land Use Enhancements

Throughout this document we have presented a vision for a future in which our infrastructure is designed to lock-in the benefits that can be derived from CAVs while preventing against the potential threats that they also hold. Nowhere are the possibilities more open than in the design of new developments. It is also imperative that we build more houses in ways that fulfil the Industrial Strategy's vision for clean growth. Communities can be designed with connectivity at their core. Our vision demonstrates how new developments enabled by CAVs and the palette of interventions, could be cleaner, greener and more inviting places to live offering ample walking, cycling and open green space.

New Travel Opportunities

Over-stretched infrastructure fuels resistance to new housing, so designing in infrastructure enhancements from the beginning can help councils embrace growth and grant planning permission with fewer local objections (NIC, 2017). Shuttle services, and Autonomous BRT services can create new opportunities for connectivity, minimising the dependence on the private car. The lower cost of these schemes, as demonstrated in previous sections, could open up completely new opportunities for housing, for example, connecting brown-field sites to transport hubs.

Safety, Performance & Efficiency

In developments designed based on these principles, the number of local roads could be reduced and where they are retained, road safety will be vastly enhanced. All citizens will be able to feel safe cycling on designated routes and walking will be encouraged through inviting green spaces. Through reliable accessibility to employment opportunities, in these developments residents should not need to own a car. When required for a long-distance trip, pool cars available to the development could be used, greatly enhancing the efficiency of vehicles. Minimising the need for the car will enable more development to occur, while maintaining network performance.

FEASIBILITY

Affordability / Utilisation of Existing Network

Certainly, initially there may be concerns about the innovative nature of the concept and the market demand for car-free developments, especially in more rural areas. However, new development offers a significant opportunity to accelerate CAVs and should be a key area of focus for future work. Here, developers share the incentive to reduce parking spaces and create the most desirable and accessible places for people to choose to live. The CAV-based strategies outlined could add significant value to a new development site. Assuming that every 2 parking spaces could accommodate an additional 2-3 further rooms (based on standard densities – i.e. 2-3 storeys) considerable additional development could be created on a site. Taking average prices by size of property, the space unlocked could increase Gross Development Values by up to 65% (prices sourced from Zoopla). This is a considerable potential uplift in value which could be shared to deliver enabling infrastructure, additional affordable housing and to incentivise high-quality, energy efficiency or low carbon generation infrastructure. The key challenge will be to ensure that the development links into wider networks, which may still have a heavy reliance on private car. Brownfield sites where infrastructure could link to dense existing mass transit networks might provide the preferred initial options to develop these schemes.

Public Acceptability

Many planning authorities are seeking to facilitate reduced reliance on the private car. However, when making decisions, politicians will be mindful of scepticism of their constituents and may therefore be reluctant to approve developments that might be perceived as leading to knock-on effects such as additional on-street car parking etc. Influencing these parts of the regulatory framework (where necessary) will be important to opening up opportunities for car-free schemes (City Science, 2017). Robust information on movement patterns and accurate modelling will be essential to inform scheme layouts and to evidence the opportunities for car free development;

Resilience Impact

Through reduction in the number of private cars, many opportunities emerge to make the built environment more climate resilient, in particular through improved natural drainage and mitigation of heat-stress.

Other Infrastructure Considerations

Throughout, it is generally assumed that autonomous vehicles will be electrically fuelled. The interventions naturally minimise the need for distributed charging infrastructure due to the system design around transport hubs where charging can be coordinated. Within new developments, there is the opportunity for integrating energy generation and use, aiming for developments which are net positive from an energy perspective.

OUTCOMES AND NEXT STEPS

We believe that considerable opportunity exists within new developments and that all, in particular New Garden Towns, should be encouraged to develop a CAV strategy. This, at a minimum will ensure they are ready for CAVs, but exploration and trial of these concepts should also be promoted and supported.

CONCLUSION

“There's been a lot of over-promising and I think a lot of misinformation that's been out there. It's really important that we get it right, rather than get it quickly.”

- Bill Ford Jr., Executive Chairman of Ford Motor Company

This study has explored a wide range of potential opportunities to redesign roads to accommodate and accelerate CAVs. Demands on our infrastructure are only likely to grow and it is acknowledged that new ideas will be required to overcome the restrictions on space. As the NIC concludes – ‘we cannot build our way out of congestion’. Into this mix, CAVs present significant benefits, but also risks. The risks - higher congestion, reduced safety and more dispersed land use - cannot be left unaddressed. It is therefore critical that we carve out a clear, evidence-led path now that promotes growth for the UK, enables innovation, but also locks in positive outcomes for future generations.

Each of the 9 typologies of Dedicated Driverless Spaces identified have been demonstrated to enable a wide range of potential benefits including:

- Compelling enhancements to network performance, offering new cost-effective options for medium-sized cities. By embracing CAVs for mass transit and to re-imagine deliveries we can create significant improvements to congestion between and within our cities.
- The more efficient use of vehicles through a focus on CAV shuttles, optimal routing and freight logistics strategies.
- Improved journey quality through faster, more reliable journey times delivered through dedicated infrastructure, but also improving the quality of walking and cycling through re-imagining public realm.
- New travel opportunities delivered at low comparable cost, connecting new developments, brownfield sites and raising the accessibility of jobs and services to a wider range of residents.
- Significant enhancements to land use such as making places more liveable and more environmentally friendly with more green space and greater biodiversity; but also creating greater shared value enabling the delivery of infrastructure, greater levels of affordable housing and opening up new sites.

These Dedicated Driverless Spaces make best use of the UK’s extensive and mature road network adapting existing infrastructure in a way that is practical and, in many cases, eminently affordable today. Importantly Dedicated Driverless Spaces integrated with mass transit, prevent against outcomes where CAVs actively out-compete public transport which could result in severe consequences for extensive rail networks.

Dedicated Driverless Spaces are a practical way to manage the transition period, offering a system that can be regulated and approved, limiting the impacts of potential malicious activity or malfunction, and most importantly increasing confidence in the technology over time, providing the trust and certainty required for public acceptance. We cannot avoid the fact that the competition for road space is likely to be a contentious issue with the public, but we have shown that CAVs focused on mass transit could provide up to 4x the capacity of conventional vehicles, while promoting walking and cycling.

Dedicated Driverless Space typologies such as Last Mile solutions, Business Parks and New Developments have been demonstrated to be technically viable today and eminently viable from a financial perspective. In many cases, land-value uplift or the fare-box from services could make a substantial contribution to the cost of infrastructure. Other opportunities such as Autonomous BRT / AVRT could be technically and economically viable soon and should also be encouraged.

The shift to electric vehicles, centred around transport hubs will enable a managed approach to integrated infrastructure design, building in the essential charging and electricity network upgrades that enable the technology. This transition will also radically alter the environment of our cities, eliminating pollution, emissions and noise and opening up new opportunities for clean growth. Through a re-imagining of the urban realm planners will also be able to embrace opportunities for climate-resilient design, improved drainage, reduced heat-stress and greater biodiversity.

Finally, by reducing the strain on our existing road systems, improved use of data, real-time information and digital infrastructure we will make journey times more reliable.

It is clear that Dedicated Driverless Spaces offer a technically feasible, economically viable, managed approach to CAV deployment that provides confidence to citizens, maximises the efficiency of existing assets, embeds the benefits of CAVs and accelerates their uptake through practical yet visionary schemes which can be delivered today.

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