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T01 - Connected and Autonomous Vehicles

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1 Introduction

Autonomous Vehicles are in a developmental phase, largely driven by private organisations. These vehicles will however eventually be driven on the public highway – the responsibility for which rests with the relevant highway authority. An increasingly common question from highways authorities is "how do we prepare for autonomous vehicles?" Currently highways authorities provide hard infrastructure in the form of roads and signalling (including: painted lines and signage), which are interpreted by human drivers to inform their decision making; however with the introduction of autonomous vehicles very little is understood as to the infrastructure provisions and signage required for their decision-making capabilities. This study seeks to understand what infrastructure might be required by examining recent Level 3, 4 and 5 autonomous vehicle trials, and further sources, to understand what infrastructure might be required. In doing so, it will aim to address the following questions:

1. Can these systems operate using existing infrastructure meaning no changes are required?
2. What condition does this infrastructure need to be in? i.e. does the existing infrastructure require upgrading to ensure a high quality system?
3. Will new road infrastructure need to be added?

To answer these questions the following 4 research tasks were undertaken to address the above research questions:

1. Examine international autonomous vehicle trials (comprising level 3, 4, and 5 autonomy), and select trials for assessment
2. Understanding more about the operating requirements of trialled autonomous vehicles[1]
3. Identify the infrastructure requirements for CAV in urban environments
4. Identify the infrastructure impacts for local highways authorities using a publicly available / academic materials

Each of these tasks is explored in the following sections of this report which lead to the project summary and conclusions.

[1] It should be noted that the majority of CAV trials undertaken have been conducted in a largely simplistic highway environment and therefore do not consider the infrastructure (signage and traffic signals) present in local highways and urban areas

2 Selection of international autonomous vehicle trials (comprising level 3, 4, and 5 autonomy)

This research assessed the various worldwide autonomous vehicle trials, focussing on Society of Automotive Engineers (SAE) Levels 3 – 5 (Table 1) to provide a representative sample of technologies capable of driving without human input within the industry to determine their technological capabilities and requirements.

Table 1, Society of Automotive Engineers (SAE) Levels of Automation

SAE Level of Automation	**Description**
Level 0: No automation	A vehicle requiring continuous driver input
Level 1: Driver Assistance	Driver is in control, however elements of the driving task are automated, e.g. adaptive cruise control
Level 2: Partial Automation	Vehicle has combined automated functions such as acceleration and steering, but driver must remain engaged with the driving task and monitor the environment at all times
Level 3: Conditional Automation	Driver is a necessity, but is not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.
Level 4: High Automation	Vehicle is capable of performing all driving functions under certain conditions. Driver may have the option to take control.
Level 5: Full Automation	The vehicle is capable of performing all driving functions under all conditions.

Four key trials, all of which use on-board systems which observe and react to their environment were identified, and the characteristics in terms of autonomous vehicle levels and sensor technology for each were consolidated in to Table 2. It should be noted that this information was compiled from publicly available materials and therefore may have gaps with regards the full capabilities of technologies where commercially confidential systems and processes are concerned. For example the Google/Waymo system reports using GPS, however this would likely require some form of mapping. Similarly the Ford and Volvo systems use 3D mapping but have not reported using GPS, which seems unlikely. However a core selection of detection technologies has emerged from this exercise.

Table 2, Description of sensor technologies deployed in autonomous vehicle trials

Type	Description	Google/Waymo	Ford	Volvo	Tesla
Autonomous vehicle level	Level 3			x	x
	Level 4	x	x		
	Level 5				
Sensor technology	LiDAR	x		x	
	Radar	x	x	x	x
	Vision Systems	x	x	x	x
	Audio Detection	x			
	GPS	x			
	Ultrasound			x	x
	3D mapping		x	x	x

2.1 MEDC (Michigan Economic development corporation)/ PlanetM

In addition an assessment of the autonomous vehicle test tracks, worldwide, was undertaken to understand the infrastructure systems that will be required on public highways.

An example of this is the MEDC test track, which is a purpose built autonomous vehicle driving system with two centres. The infrastructure includes:

- Urban and suburban environments
- Traffic signs
- Traffic signals
- Footways (sidewalks)
- Street lights/benches and other streetscape furniture.
- High speed roads
- Off-road areas
- Rural areas
- Residential areas
- Commercial environments.

This set of infrastructure suggests a heavy focus upon built-up areas rather than simply motorways. In the UK most built up areas are the responsibilities of local highways authorities, which largely fulfil these responsibilities using Department for Transport guidance.

3 Understanding more about the operating requirements of trialled autonomous vehicles

Further research was undertaken regarding Google/Waymo, Tesla, and Volvo trials to understand more about their operating requirements as this may point towards infrastructure requirements, and these are shown in Table 1 below.

Table 1 Autonomous trials operating environments

Operating environment	
Google/Waymo	It is understood that the system has been used on highways, city streets, and residential areas in over 25 cities within the USA. The following cities represent some of the areas: Austin Texas, Kirkland Washington, Mountain View California, Santa Cruz, San Francisco and residential areas in Phoenix Arizona; Chandler, Tempe, Mesa, Gilbert and Ahwatukee. They have driven in excess of 6 million miles on urban and city roads.
Tesla	The operating environment for Tesla's autopilot system appears to be for highway use at Level 3 automation (i.e. the system can undertake some autonomous tasks but will fall back to human intervention when required). This suggests it is not yet ready for local roads.
Volvo	The Volvo system presently operates only the main arterial routes around the city of Gothenburg. These are all 2 to 4 lane dual carriage ways. Currently they are operating at Level 3 automation and believe that 2021 will see the introduction of their first level 4 vehicle.
How the vehicle "sees" infrastructure	
Google/Waymo	The technology on board these vehicles would appear to read and understand its environment exactly as a human would in respects to observations and anticipation. These do not appear to rely upon external information that cannot be directly seen (for example local radio signals), except for GPS and mapping.
Tesla	
Volvo	
Any stated infrastructure requirements	
Google/Waymo	All of these systems appear to be working within the existing environment, rather than requiring that the environment around them be modified for them. However it might be noted that these systems are being used in heavily defined areas such as highways which are often very uniform in construction and maintenance which may offer a relatively simple working environment compared to urban areas.
Tesla	
Volvo	
Reliance upon on-board sensors or external connectivity	
Google/Waymo	Whilst these systems do appear to have some external connectivity to GPS, any requirement to connectivity to cellular networks is less

Tesla	clear.
Volvo	

4 Infrastructure requirements in urban environments

A key finding is that these trials operate in highways environments. Highways environments are relatively simplistic (and arguably may have more standardised layouts and maintenance) when compared to urban and rural environments. In the UK many of the highways are managed by national highways authorities (such as Highways England), whereas urban and rural areas are generally the responsibility of local highways authorities. Autonomous vehicle operation in urban areas may require far more complex sensing and infrastructure requirements but because trials to date have been largely based upon highways there is little empirical evidence to indicate what this infrastructure might be. This report therefore looks to the sensing technologies used to date and questions the extent to which these will work within urban/rural environments, and this may provide an indication of future infrastructure/maintenance requirements.

4.1 LiDAR

LiDAR (Light Detection and Ranging) works irrespective of ambient light levels by beaming out millions of laser pulses per second—in 360 degrees—and measuring how long it takes to reflect off a surface and return to the vehicle. LIDAR provides high resolution 3D map information that can be used for autonomous navigation, as well as pedestrian and bicycle detection. It is known to be impacted by snow/rain/dust/smoke, and affected by incident sunlight. This may require local highways authorities to improve snow clearance operations, and address glare from highly reflective surfaces.

4.2 Radar

Radar uses wavelengths to perceive objects and movement. These wavelengths are able to travel around objects like rain drops, making radar effective in rain, fog, and snow, day or night. Radar is used for automatic cruise control, forward collision warning, lane change assistance, parking, and pre-crash applications. These are known to have issues with beam blockage, which may require increased consideration of roadside items which might block the view (for example around junctions) and increased maintenance of vegetation which might grow and block the view of radar.

4.3 Vision Systems

Vision systems use cameras to see around the vehicle, so rely upon line of sight. These require good lighting so there may be a requirement for increased lighting in some areas. These systems are also used to help with identifying such items as traffic lights and signage, and for this reason there would be a need to ensure line of sight (cleanliness and vegetation) and good maintenance.

It is understood that autonomous vehicles utilise camera systems to detect vehicle lane markings to help steer the vehicle. For this reason there would be a requirement for clear road markings – in many locations off the highway these simply do not exist, and where they do they may be obscured by dirt or standing water. There may be a considerable requirement for improved lane marking and maintenance.

4.4 Audio Detection

Audio detection systems can hear police and emergency vehicle sirens up to hundreds of feet away. Audio sensors can detect the direction sirens are likely to come from, improving the vehicles' ability to respond in both a safe and timely manner.

The extent to which audio detection will be impacted by infrastructure or maintenance influenced by any local highway authority is not fully understood.

4.5 GPS

GPS is a system of satellites which provide information about the latitude, longitude and altitude of the vehicle. The position is obtained by triangulating the microwave signals generated by at least four different satellites (the receiver takes between 30 and 60 seconds to establish the initial position). Speed and direction can be then estimated. This technique can be used at any time of the day and everywhere, since the satellite net is such that there are at least four of them visible from any point of the surface of the earth. Moreover, it is not affected by the presence of snow, rain, smoke, etc.

GPS has a maximum resolution of 1 metre, which is not enough for obstacle avoidance. However, it is possible to increase it up to 1cm when combined with another signal from a known terrestrial position. Nevertheless, autonomous driving cannot rely exclusively on this technology, since the radio signal can suffer from interferences or be blocked in certain locations (e.g. tunnels, dense urban environment). For these reasons in some environments there may be a requirement to add additional local terrestrial systems.

4.6 Ultrasound

Ultrasound at 50 kHz is generated and the waves bounced back by the surrounding objects are detected. The time interval between the emitted and received wave gives information about the distance of the object.

These sensors are useful for detecting nearby cars, especially when they encroach on the vehicle's lane, and provide guidance when parking.

The extent to which ultrasound will be impacted by infrastructure or maintenance influenced by any local highway authority is not fully understood.

4.7 3D mapping

3D mapping allows an autonomous vehicle to navigate by understanding its position within a map. Whilst the bounds of a highway may remain relatively unchanged for many years, this is unlikely to be true of urban or rural areas which may have both frequent changes to road layouts, signage, and road lining, and informal changes within the bounds of any road from vegetation or local informal activity. The extent to which local highways authorities would be required to update or inform 3D maps of any changes is as yet unknown however this may bring additional burdens to them.

4.8 Enhanced connected technologies

The sensor technologies above are largely independent of local infrastructure per se, with the key requirements generally being uniformity to standardised layouts and the maintenance of them.

To enable a safe autonomous journey there needs to be absolute certainty of sensor information. In relying on car sensors there are concerns such as: Will the morning sun saturate car cameras and LiDAR optics? Can the vehicle analyse correctly a situation on a foggy highway or in urban night traffic in a heavy rainstorm? V2X communications (the collective term for vehicle-to-vehicle communication and vehicle-to-infrastructure communication) add a new layer of certainty to every operation e.g. exactly how many cars are in the vicinity? What are their speeds and trajectories? What are the intentions of out-of-sight vehicles and what objects do they observe? Did the car stop around the corner to yield a pedestrian?

The delivery of V2X services would require both the installation of roadside sensors and a robust electronic communication system.

Roadside sensors are devices which can supplement vehicle-based devices e.g. communication beacons which may replace traffic signals, provide vehicle position info etc

Implementing a system of roadside sensors would not be without its challenges for local highways authorities which may have to work with systems suppliers:

- Such systems require buried protective ducts for wires, construct poles, and permit wireless sites on public property. This becomes a challenge in urban areas which typically have decades-worth of underground structures competing for space.
- This urban infrastructure is often jointly owned and regulated; gaining permission to dig up streets and attach thousands of roadway sensors would be time consuming and expensive.
- The lifetime of the device will have to match that of the road surface or the infrastructure in which it will be embedded and an adequate power supply will have to be provided.

There is also a likely enhanced required for cellular connectivity from such systems, however the extent to which this responsibility would fall upon local highways authorities (as opposed to private organisations which presently provide cellular infrastructure and connectivity) is unclear.

5 Literature review of infrastructure impacts for local highways authorities

Other studies have taken a wider approach to the infrastructure impacts of autonomous vehicles and these have been examined for key information which may impact local highways authorities. Many of these reports focus upon infrastructure opportunities for local highways authorities, such as reduced needs for space.

Report	Impacts upon highways authorities
RAC – Readiness of the road network for connected and autonomous vehicles	• Improved road maintenance to allow vehicles to sense environment – with large financial impact upon the government. • There may be issues in mixing different levels of autonomy. • Need for roadside communications such as DSRC. • A reduced need for high-friction surfacing as CAV would reduce the need for sharp braking • Greater track wearing on surfaces due to more consistent lane positions • A suggestion that more precise communications/mapping may actually reduce the need to maintain road markings. • Potential reduction in need for local parking (from which authorities can gain revenue) as drivers will send their CAV away to self-park elsewhere
Transport Systems Catapult – Future proofing infrastructure for connected and autonomous vehicles	• Heavy reliance on mapping and the difficulty faced in interpreting areas which do not match this, such as roadworks. New approaches might be required by highways authorities to ensure the roadworks are 'read', which might include mapping updates on a regular basis, and geo-fencing roadworks using special cones • The reliance upon clear and consistent road markings and signage, which may require cross-border harmonisation. • Improved maintenance so that sensors are not confused. • The report noted that CAV systems could be used to report road condition issues which could assist

	with management and maintenance of roads • The report mentioned a potential need for 'safe-harbour' areas for vehicles to stop if human intervention was required. Such locations might presumably need to be provided by the highway authority • It was noted that private parking areas may not always comply with conventional road markings and that this may create issues. • The report considered issues in the way CAV are used. A model which uses CAV as part of an automated demand responsive transport system would need areas in which to stop vehicles (similar to the way buses require a bus stop). Highways authorities might be requested to provide these. • Crossings and junctions were seen as challenges that would require vehicle to infrastructure communications. Given infrastructure is generally owned and operated by the highway authority this will require an infrastructure intervention. • The impact of platooning on bridge structures was raised. This is due to platooning vehicles typically being both heavy and in close proximity.
WSP – Adapting infrastructure for a driverless future	• Highway authorities will need to improve their digital infrastructure/control systems because the impact becomes more critical in an environment which depends heavily upon it. • Considered that feedback from CAV can help to better manage roads, including; maintenance issues; weather issues; allowing the introduction of pricing models; and allowing closer vehicle running which will improve road use efficiency.
Atkins – Connected and autonomous vehicles	• Considered that the benefits of CAV could be enhanced through better connectivity which would allow for optimised journey times and reduced congestion. • Considered that computer vision may be inadequate and that low-latency wireless networks would be required for this. It considered highway authorities should put in place the required digital infrastructure.
Arcadis – Infrastructure	• Considered that in the long term CAVs will increase the capacity of existing roads which should reduce the need for new infrastructure. However this would come at a cost of; improved

smart vehicles	standardisation of road markings and signage; issues of mixing CAV and non-CAV at roundabouts; a changed demand for parking including a reduction in on-street parking allowing for increased road capacity; the potential for CAV-only areas; the potential for higher expenses in purchasing and maintaining sophisticated electronic infrastructure and higher levels of road surface maintenance. • Challenge of commonality of approach across CAV markets and the need for open interoperable data standards.
SMMT – Connected and Autonomous Vehicles Position Paper	• Considers that digital communications coverage is essential. • Calls for clear road markings to work with CAV camera systems.
ARUP – Autonomous, connected, electric and shared vehicles	• Considers that "the approach to building design, use of space and integration of facilities, including traditional parking requirements" needs to change due to CAVs. • Considered that roads could become smaller/narrower as the distance between vehicles could reduce, and that elements such as crash barriers might be reconsidered. It also considered a need for dedicated CAV lanes on interurban roads. • Considered that parking will change, with reductions in requirements and smaller parking bays as people would alight the vehicle before the vehicle parked itself.
Highways England – Connecting the Country, Planning for the Long Term	• Considered that the rise of connected and autonomous vehicles (CAV) is expected to be one of the most significant and potentially disruptive changes in future personal mobility, and noted the uncertainty around pace of change and variations in solutions. • Considered the extent to which Highways England as the network provider would have to provide information to vehicles, and the challenges of managing a mixed fleet of CAV and non-CAV vehicles.

5.1 Discussion of further infrastructure requirements

The following section discusses any further infrastructure requirements detailed in the sources reviewed that have not yet been addressed in earlier sections:

- Levels of standardisation for signals, signs and road markings – Need for better standardisation to improve perceptual abilities for CAV.
- Traffic Management measures – Methods in which to communicate with CAV about planned or emergency road works. For planned road works this could be geo-locating cones on a site to set up a geo-fence and for emergency road works a warning could be issued to CAVs to alert them to a route with an unusual state. It would rely on maps to be continually updated and for good connectivity.
- Parking facilities – size, use and distribution of parking may need to change. Currently occupancy levels of city centre car parks may reduce as drivers send their vehicles away to park, which will have revenue implications for cities. Any move towards car-sharing models which might be enabled by CAV may result in a reduction in demand for some types of parking e.g. residential, park and ride and shopping centres due to reduction in car ownership. Increased need for parking facilities for CAVs which are for hire e.g. stations. Parking facilities and related signage and markings will need to be consistent.
- Roundabouts – Roundabout may be better suited to CAVs than systems that work on the same principles as current traffic signals.
- Pick up and drop off areas – need to be defined in the instance of automated demand responsive transport. Provisions could be made dependent on pedestrian/traffic density, types of development, types of road and availability of space. Areas such as shopping centres, train stations and hospitals would benefit from designated areas.
- Maintenance – Road markings, signs and signals may need to be better maintained. Also road surfaces e.g. potholes could be very dangerous. Requirement for new revenue streams if road tax and petrol tax revenues fall.
- Road Surfaces - CAV may run consistently in the same lane positions (although note that the present Tesla vehicles are reported to wander within the lane) which could bring greater wear and tear in wheel tracks.
- Autonomy enabled roads – Progressive adoption of measures to encourage technology transition e.g. CAV-only areas in city centres and partial segregation on highways.
- Road geometry – In the future it might be possible to have narrower streets with wider curbs (cycle space) and tighter corner radii. But these changes would make them not suitable for non-CAV traffic.
- Road verges – better design and managed to ensure sensory systems that depend on line of sight can work effectively e.g. better control vegetation.

6 Conclusions and recommendations

Highways authorities within the UK fall in to two broad types – those such as Highways England which operate highways networks, and those such as local authorities which operate more local roads/urban areas. CAV trials have started on highways and appear to be largely independent of any special roadside infrastructure. Trials on local roads/urban areas are less advanced however there are indications that these will require more maintained environments and roadside equipment. There is considerable uncertainty about the pace of change and the variations of solutions that will be adopted. The key trials examined in this report are being operated by private organisations, and this brings a risk that CAV development in urban areas will require proprietary roadside equipment in an already crowded roadside and sub-surface urban environment.

Local highways authorities may also question the extent to which they *should* provide for CAV. A do-nothing approach may force the CAV providers to ensure their vehicles can work within the existing built environment. Whilst it is not yet clear which parties would be responsible for providing any roadside or sub-surface facilities (it might be argued that this would be service providers), there are potentially elements required by urban CAV which fall within the remit of local highways authorities such as improved lighting, surface and line quality, drainage, and infrastructure compliance with standards. It might be argued that at present human drivers can accommodate imperfect road conditions and departures from standard and this effectively reduces present construction and maintenance costs for highways authorities. Any requirement above this would imply increased costs.

Regardless of uncertainty, spatial planning and infrastructure investment decisions today will determine the development of the UK for decades. To avoid wasting money or preventing the development of CAV, it will be important for authorities to employ an on-going adaption of the UK's road infrastructure by:

- Aligning all new investment to systems that are based on open, interoperable data standards and this may reduce the likelihood of roadside clutter and multiple reinstatements.
- Maintaining traffic modelling and traffic planning capability to be able to plan and prepare for anticipated changes in traffic
- Considering the impact of future changes in transport in the design and procurement of new traffic management systems. [2]
- Potentially addressing the backlog of existing maintenance needs for road infrastructure (estimated to be 14 years with estimated cost of £11.8 billion)[3], should urban CAV systems require improved levels of maintenance

[2] https://www.arcadis.com/media/4/2/C/%7B42C33130-E82C-4D5D-8C4B-D4FC73DE8546%7D9920_Smart%20Vehicles%20Whitepaper%2025-07-17.pdf

[3] https://www.racfoundation.org/wp-content/uploads/2017/11/CAS_Readiness_of_the_road_network_April_2017.pdf

- In the long term reducing investment in structures such as parking facilities and instead looking to raise revenue from kiss-and-drop zones/city entry charges as drivers have their vehicles drop them near destinations and have the (level 5 autonomous) vehicle drive away to park elsewhere.

Future Transport Visions

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