Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow

Stage 1: Evidence Review

Department for Transport

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Executive summary

- There is a need for a "systems of systems" approach to understand the various factors that can influence road capacity – including technology, capability, adoption, legality and driver behaviour.
- There is evidence that the improved provision of data from connected vehicles – and the people in them – has the potential to improve network performance and increase capacity.
- Significant gaps in knowledge exist concerning the potential impacts of connected and autonomous vehicles, with much uncertainty around the expectations of technical capability.
- Concerns exist around a low penetration of autonomous vehicles worsening road capacity, particularly on the strategic road network, due to cautious behaviour when mixing with the existing vehicle fleet.
- There is a clearly potential for conflict between comfort, capacity and safety; trade-offs are likely in this area as the balance between network-optimal and user-preference is found.
- They key to understanding the impact of CAVs on traffic flow and capacity is too rooted in the capability they will offer – we do not yet know how the market will determine the characteristics of CAVs.
- This report captures thinking as of early 2016. Technological advancements in particular are advancing at a great rate, and so this report must be considered carefully alongside emerging findings from a wide variety of studies.

Connected and Autonomous Vehicles (CAVs) could have many impacts on UK roads and drivers. This work focuses specifically on the impact on road network capacity, and hence traffic speeds, delay and journey time. There are many other likely areas of impact – such as safety, emissions, car ownership and travel demand – that are all subject to on-going research.

As a first stage, this report captures current thinking and gaps in knowledge to steer future work on capacity. It focuses on recent scientific evidence, backed up by discussions with leading researchers and industry globally. This focus is needed because much of the headline information attached to CAV benefits comes from think pieces, and evidence drawn from early speculative work. Much of this is now outdated, as both technology and market needs have changed. Early work tended to assume 100% fleet penetration of CAVs, that no pedestrians or cyclists exist, used hypothetical roads and assumed high levels of user compliance. Later work has explored mixed penetration using examples of real-world situations, and undertaken real-world testing to understand how drivers and other road users might react to the technology, and how they might use it (or even turn it off). This work has refined and reduced the headline capacity benefits from early studies and, in some cases, highlighted disbenefits. However, it is important to recognise that there are still many unsupported and unsubstantiated claims about the capacity benefits of CAVs.

Through considering the evidence base and through discussion with experts, it is clear there is little in the way of "top down" policy specific appraisal of impacts of CAVs on network capacity as a whole. Most policy evidence in this area focuses on safety and emissions. However, there is much valuable work relating to traffic flow and capacity that is technology led ("bottom up"), which looks at the impacts of different CAV technologies on vehicle operation and traffic flow. There is therefore a need for a "system of systems" approach to understand how all the varying factors – technology capability, penetration, legal aspects, consumer / business attraction of CAVs and driver behaviour of existing vehicles all interact considerably in complex, interconnected ways, impacting not just capacity but demand, car ownership, emissions, safety and an array of other factors.

Due to this complexity, it is worthwhile separating "connected" from "autonomous" vehicles, as the timescales, evidence base and benefits are likely to be different. A connected vehicle provides data from the vehicle (or driver) and receives information, but the control action is left to the driver. Autonomous vehicles then, to various extents, take over this control from the driver. There is evidence of the benefits of connecting autonomous vehicles to other vehicles and infrastructure on both capacity and safety, and there is a logical step of moving from connected to connected and autonomous. However, overall there is far more research on capacity from connecting vehicles, and particularly at low levels of automation than high levels (tending to full) of automation.

There is good and consistent evidence that data from vehicles and information passed via connected vehicles can improve capacity and reduce delays, as a “quick win” on many types of network. Examples are delay reduction in UK traffic signal control systems through better vehicle location information, better motorway control, and better ability to recover network capacity after planned and unplanned incidents. There is enough known that pilots and tests of such approaches being planned in the UK context are likely to show real value. This does not necessarily require new in-vehicle technologies, as data from existing vehicles and devices can provide a large base of new sensors and useful data. The focus for policy impacts here must now be testing on real roads with real vehicles.

When considering connected and automated vehicles, there are many gaps in knowledge and conflicting evidence about capacity changes, from far fewer research works. Capacity change may come from platoons of vehicles “driven” by a lead vehicle, where there is useful (but emerging) simulation evidence of motorway capacity benefits.

Capacity increase may also come from connecting vehicles on motorways so that they form closer following groups, making better use of road space and to some extent dampening the shockwave impacts that cause congestion. According to many studies, this would require around 40% penetration of CAVs. There is mixed evidence here, but low penetration of unconnected (but autonomous) technologies may actually reduce motorway capacity. Other benefits could be from better lane use or through reconfiguring roads for additional lanes, but there is little research on this that can be considered relevant to the UK. CAVs can allow better management of smart and conventional motorways, and there is some evidence of capacity improvement from high levels of penetration.

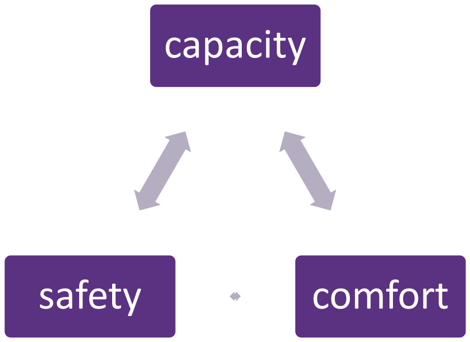
In towns, signalised junctions may benefit from reduced delays due to the enhanced data flows and improved traffic control efficiency. Conversely, delays may increase if automated vehicles take longer to start and pull away than existing human drivers for reasons of both comfort and safety. There is an expectation this aspect of CAV performance will improve over time, but there is still likely to be a fundamental shift in the way junctions and priority rules operate.

There is little existing work on UK roundabouts or priority junctions, but some evidence that current CAVs (when mixed with the non-CAV fleet) perform less well than human drivers in terms of junction delay. This could have future impacts on city road capacity. It is assumed that vehicle performance will improve considerably over time, else the vehicles are likely to be unattractive to customers, whether these be individuals or mobility providers.

Most of the work to date has concerned passenger cars, with the exception of platoon studies where HGVs are prominent. Some work has explored “mobility as a service” type vehicles, but little work exists on conventional public transport buses, coaches or other vehicles. There is emerging work on how drivers of conventional cars may change behaviour when near in close proximity to CAVs, and this may also have capacity impacts.

An underlying theme in all of the above is a tension between safety and capacity, and between capacity and user desires from their chosen vehicle. A vehicle with safety as its overriding priority may reduce junction capacity in urban areas if it “hesitates”, unlike less safe human drivers. Anecdotally, most of the accidents reported (by Google, for example) as part of driverless cars testing are a result of other vehicles hitting the back of the test car as it slows down for safety. It is not clear on the extent that this approach can be “tuned” to mirror levels of current driver behaviour to retain capacity.

In addition, vehicle headways required to retain current UK motorway capacity may not be considered desirable for users from a comfort or safety perspective. If users choose longer time gaps to the vehicle in front, reduced capacity will likely result. Headway preference in the UK is unknown, but it is clear that a vehicle designed for its users’ comfort, and hence ability to use the time for other activities (the primary user-centric benefit) could have unintended impacts on capacity for all road users.



Additionally, vehicles with performance characteristics, such as acceleration, selected for comfort may not give the same capacity as current vehicles. A vehicle designed for improving motorway capacity or joining platoons may result in direct increases in journey times, which may therefore reduce user attraction over the legacy vehicle fleet, especially if platoons are limited to the speed limit (or even lesser speeds). How users of CAVs trade-off any increases in travel time against the ability to better utilise that time (for work, for example) is key here. Market forces and how CAV benefits are portrayed to consumers (be they individuals or providers for mobility services) will impact the level of penetration desired and achieved. This is the key policy finding – we do not yet know how the market will determine the desirable characteristics of CAVs, which will in turn impact traffic flow and capacity. Mobility as a service concepts of shared vehicles may help to reduce this tension, and this is an opportunity for further exploration – can industry develop a mobility service that both safeguards capacity, yet is attractive enough to users to obtain high penetration? And what steps might need to be taken to influence this trade-off?

1. Introduction

1.1. Context

The Department for Transport (DfT) have commissioned Atkins and White Willow Consulting to better understand the potential impacts of connected and autonomous vehicles on traffic flow and road capacity. This research project consists of two distinct phases:

- Stage 1 – an evidence review of the impacts of CAVs on traffic flow and road capacity; and,
- Stage 2 – analysis to quantify the potential impacts of CAVs on traffic flow and road capacity.

This report comprises the primary deliverable for Stage 1 of this project. Whilst the outputs of Stage 1 will inform the approach adopted in Stage 2, the evidence review is not constrained to the tools and methods available.

The DfT has identified that the impacts on traffic flow and road capacity with regards to connected and autonomous vehicles (CAVs) is a key area where existing evidence is limited. There is much speculation about the positive or negative impacts of CAVs on traffic flow and road capacity, but there is very little robust evidence that addresses the question.

The capability of CAVs is progressing at a great rate, with particular focus on technological performance, and much associated work around safety, operation and regulatory issues. Whilst useful, existing evidence is often limited in terms of scope, scale, approach or underlying assumptions, and has not sufficiently addressed questions about large-scale impacts on traffic flow and capacity which are required to inform robust policy decisions. Additionally, there is little examining the UK policy or traffic context. This is considered to be a key evidence gap that requires additional, quantified evidence in the short-term, in advance of any further evidence that may be delivered by planned research and development activities.

This project aims to address this evidence gap by creating an evidence review of existing and ongoing UK and international evidence and research on traffic flow and road capacity impacts of CAVs (Stage 1), and providing a detailed analysis to quantify the potential impacts of CAVs on traffic flow and road capacity in a range of scenarios (Stage 2).

The implementation of connected and autonomous vehicles represents a step change in how vehicles operate on the transport network. Traditional models of driver behaviour and response to behavioural stimuli may not apply, and consequently our understanding of how traffic and transport systems work must be readdressed. CAV capability and deployment on the UK network will impact observable vehicle dynamics and “behaviour” in many possible ways:

- Profiles of acceleration and deceleration;
- Signal lost time;
- Development of platoons and road trains;
- The interaction with legacy vehicle fleet;
- Lane positioning and vehicle alignment; and,
- Vehicle headways and gap acceptance.

Changes to these characteristics will combine to influence road capacity, safety, journey time reliability, emissions and other categories of effect. Due to the multiple factors and complex mechanism of action, it is not possible to definitively state how these will impact more classical, macro-level measures of network performance. By (1) collecting the most recent research and best knowledge and (2) carrying out a structured analysis in a modelled environment, this study can seek to answer those questions prior to wide scale deployment of CAVs.

Whilst the focus of the project is on changes in flow and capacity, clearly there are other benefits such as safety and the environment. These have not been researched in depth, but recorded where they subsequently impact on capacity and flow.

1.2. About this review

This report captures current thinking and gaps in knowledge to steer future work. It focuses on recent scientific evidence, backed up by discussions with leading researchers and industry globally. This focus is required as much of the headline information in "think pieces" and articles attached to the benefits of CAVs comes from early theoretical work or makes assumptions that do not fit the UK policy context. This initial work has now been outdated as both technology and market needs have changed.

The review gathers and reviews information from three broad sources:

- A structured literature review of scientific journals, transport conference proceedings and published papers using a variety of academic and technical search resources and key publications, as well as proceedings of the recent (2015) ITS Congress. The literature review has focussed on cited and referenced work where assumptions and methods are clear. Many "think pieces" and "grey" reports were not excluded entirely, with the key test being if they gave no evidence of where their data or conclusions were drawn from. Over 100 papers were reviewed and those relevant and up to date are included in this review;
- Discussions with key researchers in the field, both UK and internationally about unpublished and evolving material, and the ways in which impact on capacity has been assessed; and,
- A stakeholder workshop on 4th December at DfT attended by research, consultancy and automotive experts in the field.

Appendix A provides a record of research undertaken and key findings. Section 1.3 discusses the approach to expert engagement in more detail.

1.3. Approach to expert engagement

As discussed in Section 1.2 global industry experts were sought to provide their views. Due to the embryonic state of the CAV industry, there is understandably a lack of empirical evidence. Furthermore, the mechanisms for the impact of CAVs naturally covers several subject areas and industries – automotive engineering, information and communications technology, transport modelling and traffic engineering, and public policy. Combined, this makes drawing together evidence particularly challenging, and so this review has benefitted from expert support. A list of key contributors can be found in Appendix B of this report.

To this end, five broad categories of stakeholder were identified:

- Network operations;
- Transport planning;
- Government and public policy;
- OEM and automotive manufacturers; and,
- Research.

Network operators have a vital role to play in the future of CAVs due to their decisional impact on infrastructure development, which is likely to be a prerequisite to enabling / realising the benefits of CAVs. The research community is particularly important, both for providing an international perspective and for their active role in the emerging field. OEMs are also important for the development of future CAV driving behaviours (for example, caution or aggression) which will have a direct impact on road capacity. Given the scale of investment from the automotive industry, looking at both technology and customer interests, this is an essential input to this research question.

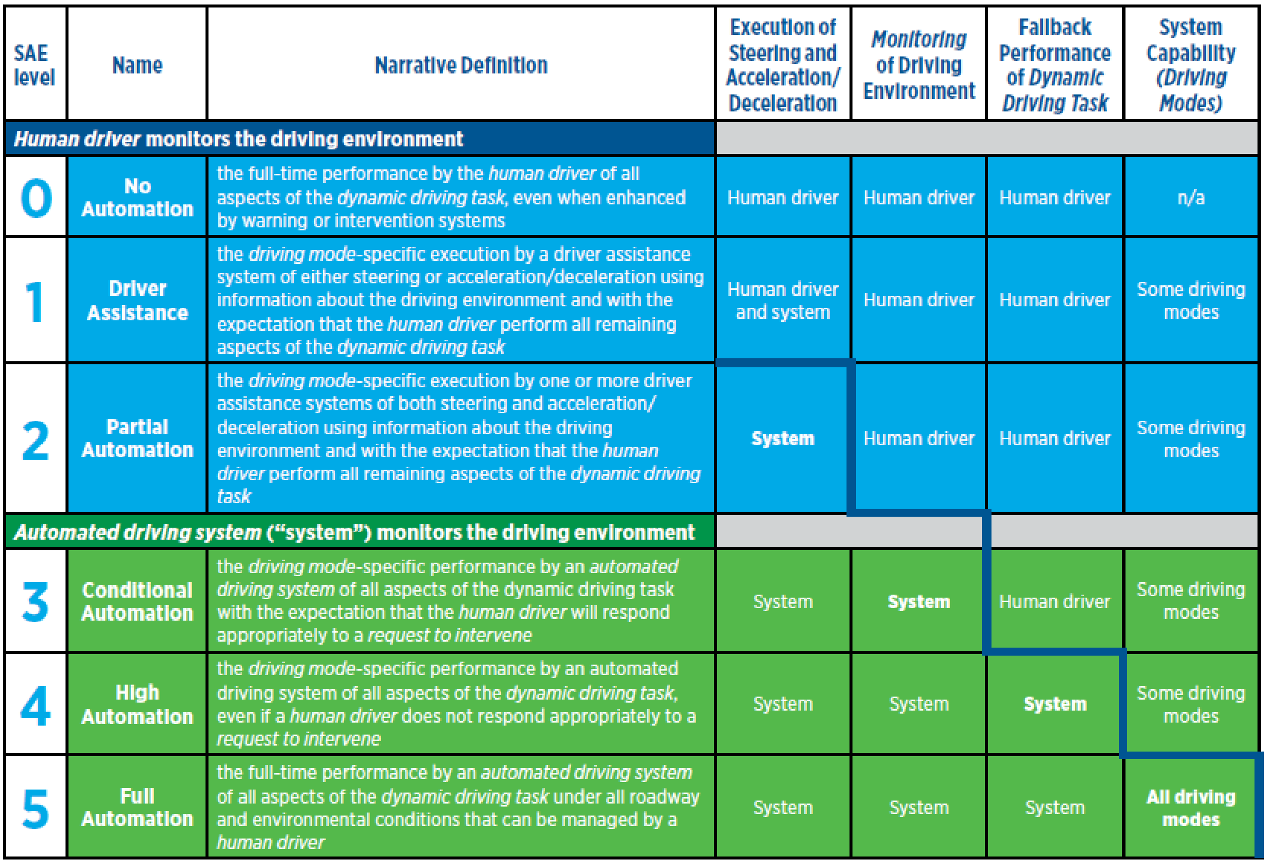
1.4. Definitions

Given the technical nature of this review, some familiarity with the subject area is assumed. However, it is also recognised that multiple definitions are available concerning connected and autonomous vehicles. The DfT's detailed regulatory review, "The Pathway to Driverless Cars"[1] uses two broad definitions to describe automated and self-driving vehicles.

Highly automated – a driver is required to be present, and may need to take manual control of the vehicle. Under certain traffic, road or weather conditions, the vehicle's automation systems may request the driver to take control.

Fully automated – a driver is not necessary, with the vehicle capable of safely completing journeys in all normally encountered traffic, road and weather conditions. The enables occupants to spend their time on other activities during the journey.

Commonly referred to definitions for autonomy include SAE International's levels of driving automation[2], as shown below.



SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Source: SAE International J3016

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These levels also make a distinction as to whether the human driver or the automated driving system monitors the driving environment – this is an aspect of connectivity.

A ***Connected Car*** is one which is able to connect to external networks, whether it be other vehicles, infrastructure or general information provision. Some of the benefits of connected vehicles may be realised without a vehicle specific connection – for example, a driver with a mobile phone which provides information to the urban traffic network, or an in-car satellite navigation system that can provide live route information.

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[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/401562/pathway-driverless-cars-summary.pdf

[2] J3016

The following definitions are included in the 2015 KPMG report, “Connected and Autonomous Vehicles – The UK Economic Opportunity”.

ACC	Adaptive cruise control is a technology which adjusts a vehicle’s speed to maintain a safe distance from the vehicle in front
Autonomous Car	A car which is capable of fulfilling the operational functions of a traditional car without a human operator
Connected Car	A car which has technology enabling it to connect to devices within the car, as well as external networks such as the internet
V2D	Vehicle to device communications is a network where vehicles and other internet enabled devices can communicate with one another
V2I	Vehicle to infrastructure communications is a network where vehicles and infrastructure can communicate with one another
V2V	Vehicle to vehicle communications is a network where vehicles can communicate with one another

Given the focus of this work on traffic flow and road capacity, some common definitions are used. Capacity is the maximum sustainable flow of traffic passing in a single hour under favourable road and traffic conditions. This definition is consistent with UK standards (TA 79/99) for the traffic capacity of urban roads. Headway (the average time separation of vehicles) is related to capacity in that it is the reciprocal of traffic flow. Therefore shorter headways allow for a higher throughput of traffic (flow) and hence greater capacity.

2. The evidence base

2.1. Approach

The approach undertaken in this review has been to focus on work exploring impacts on traffic flow and road capacity that is well documented, has clear assumptions and methodologies and, where possible, has been subject to peer review. Typically this means work published in academic journals, conference proceedings or other scientific reports. It tends to involve work that simulates capacity change by microsimulation or other vehicle simulation, although in some areas field test data have also contributed to knowledge.

In addition, discussions have been held with some key researchers concerning work in progress, including pre-publication access to some studies. An exception to this is large scale private trials being conducted in North America[3]. Given the level of testing of vehicles it is important we include the knowledge being developed but this is not presented in depth. We have assessed published content and media where available, but it should be noted the level of detail and evidence they present is not consistent with other scientific sources.

For EU research projects, several key institutions and project reviewers known to focus on traffic flow and capacity (rather than safety) have been contacted. We also liaised with the EU's CITS platform project to be aware of their top down benefit assessment.

Experts in CAV technology, including the VENTURER project, have been engaged, and we are grateful for assistance from SBD, a consultancy with detailed experience in vehicle systems, and infrastructure providers such as Telent and Imtech.

This project does not focus on how behavioural and economic changes may *indirectly* impact traffic flow and road capacity. For example, possible mechanisms by which CAVs and mobility as a service (MaaS) may impact traffic flow and road capacity:

- Higher vehicle occupancy due to different ownership models;
- Reduced non-essential trip making due to changing levels of car ownership;
- Increased trip making due to better access to transport;
- Fewer freight related trips due to increased efficiency of logistics;
- Due to better utilisation of commuting time, an increase in normal commuting distances; and,
- Implications on safety and consequently congestion.

Where these aspects have been referenced or are incorporated into capacity and traffic flow tests, they have been noted. The impact on vehicle emissions and subsequent changes to local air quality and the contribution to global climate change is also beyond the scope of this work.

In the first instance, this report adopts a "broad brush" consideration of network wide reviews that often form the basis for headline capacity change predictions, and then gradually explores the various elements that might change capacity, and how these impact various types of vehicles and roads. By testing the overall approaches against such "bottom up" detailed evidence we have been able to look at assumptions made and hence implications for the rest of the project.

Appendix A contains a summary table of key references with emphasis on applicability and assumptions, and citations for all evidence discussed.

2.2. Top down policy reviews

2.2.1. Evidence reviewed

Due to the policy-driven nature of the project, a first area was literature looking at the overall policy-related evidence of network-wide impacts on capacity as a whole. A widely referenced paper by RAND [1], "Autonomous Vehicle Technology – A guide for policymakers" is a useful start point. It highlights the benefits

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[3] Such as those carried out by Google

on capacity, safety, mobility and land use but clearly shows that whilst the cost of congestion might reduce if occupants do tasks other than driving, there may be an increase in the use of such vehicles. It therefore concludes that “the overall effect of AV technology on congestion is uncertain”.

Childress et al [2] explored possible impacts of automated vehicles in 2015. This assumed a 30% increase in capacity based on several papers[4] as a working assumption for scenario modelling of the Puget Sound area of the US. This showed that vehicle miles travelled would increase to take up the extra capacity and vehicle hours would reduce by around 4%. This paper is important as it highlights deficiencies in our knowledge about how people will make travel choices with CAVs, and that unsupplied demand may take up improvements in capacity and better travel experience in CAVs.

Shladover [3] from the California Path Programme, presented in 2009 the diverse opportunities and challenges of CAVs on a network wide and policy driven basis. He highlights the opportunities to make better use of road space, both along and across the road space, and the challenges this then brings. In 2015, a further paper at ITS World Congress [4] highlighted the dominance of safety as a benefit and the value of connected vehicles, before any higher levels of automation, also concluding that full automation may never occur.

Khan’s 2012 paper [5] highlighted the many factors that influence CAV adoption and policy impacts and their interconnectivity. Whilst not predicting capacity changes per se, this paper showed the national government level challenges and the many questions to be answered. A similar paper from Bohm [6] in 2015 examined the “Introduction of Autonomous Vehicles in the Swedish Traffic System” using a microscopic model of a typical road at low and high flow. Crucially, this work considered only 100% adoption of CAVs. This showed a 56% reduction in delay on the Uppsala town network and also examined some of the policy factors that would be required in order to gain this level of acceptance. It highlights that many of the benefits may come from partially automated or simply connected vehicles, and further confirms the need to investigate both low levels of penetration and connectivity of vehicles.

A paper by Kim [7] in 2015 looked at existing studies to quantify impacts on transport and land use in Korea, highlighting that impacts are “speculative” and that penetration is a key unknown factor. It also quotes a potential capacity improvement of up to 40%[5]. It also highlights the need for small time gap to have an improvement in capacity, for example a 0.5 second time gap with 40% penetration would give a 10% increase on expressway capacity and 15% on motorways. Substantial network benefits were shown, but once again assuming 100% penetration. It again highlighted issues with analytic frameworks based on unknowns such as changes in utility from autonomous vehicles.

The Centre for Urban Transport Research at the University of South Florida published in 2013 a paper for the Tampa Expressway Authority on “Highway Capacity Impacts of Autonomous Vehicles” [8]. It again highlighted the need for connectivity, but also that the way traffic is modelled may need to change if CAVs are included in the traffic mix. A natural conclusion of this is that further research is required regarding the performance of CAVs. This paper took a wide view of capacity by also discussing impacts on transport demand, behaviour, ownership models and market penetration. The interactions between many of these factors are unknown, but as they may impact long term infrastructure planning, they cannot be discarded.

A publication from Princeton University (Bierstedt et al) in 2014 [9] states CAVs “will either have no impact or at worst could degrade capacity as safety conscious programming of vehicle speeds and headways reduce vehicle densities”. However, the paper does refer to longer term operating efficiencies. This is an important paper as it examines with rigour impacts both on travel demand and capacity and explains well how automated vehicles may impact capacity, with a review of papers discussing capacity increases. It also shows, importantly, that the operating parameters of the vehicle, such as headway, are significant to capacity. Vehicle manufacturers are expected to implement these technology parameters conservatively for reasons of liability, and for driver comfort that matches their own behaviour. This view has been echoed by other experts engaged in the field; there is no particular reason why a connected and autonomous vehicle would be designed to optimise traffic flow or road capacity. This will be examined in more depth in later sections. They undertook a series of simulations looking at conservative vs aggressive parameters for systems. Their simulation suggests little capacity benefits until 75% of vehicles are CAVs, by which time more aggressive control of vehicles may

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[4] These papers are considered in Section 2.3

[5] Referencing the same studies as [2]

reduce delays by 45% or more. With a conservative system, delays increased against the no CAV "base case", as the spacing of vehicles was higher than observed in human drivers.

KPMG has provided a report for the SMMT on the "UK economic opportunity" [10] which states, "connectivity will allow for reduced congestion" and gives broad estimates of "more efficient journeys" but no evidence is given for how this was calculated. It says that an impedance-based approach was used, but it is not clear if this assumed any change in capacity.

The Victoria Transport Policy Institute in 2015 published a paper on "Autonomous Vehicle Implementation Predictions" (Litman) [11] which reviews existing literature and notes that only recently have transport practitioners started to explore how autonomous vehicles will impact planning decisions. Again, this work refers to the "considerable uncertainty" in assessing benefits of connected and autonomous vehicles.

A great deal of research has been conducted surrounding CAVs via EU FP7 and other framework projects. The vast majority of these works focus on safety or emissions, with capacity change a secondary interest. Malone et al in their paper on the DRIVE C2X project [12] provide simple calculations for delay change across Europe with in-vehicle signage and other functions with low SAE levels of automation – in fact, often simply connected vehicles with no autonomous functions. This results in an estimated 8% reduction in delay by 2030 for Europe if 100% of infrastructure was equipped. This work is not of sufficient spatial granularity to be applicable to the impact of traffic flow, but gives an indication of network-level impacts.

Emerging cost benefit studies are being undertaken for the European ITS Platform. These focus on early "bundles" of service and recognise the benefits of delay improvements for pan-European services.

2.2.2. Summary of "top down" studies

The works considered show:

- There is little material that examines *all* of the factors impacting transport policy implied by CAVs objectively and with clear assumptions based on a wide range of evidence. The recent study produced by Princeton [9] is a notable exception to this. This limitation is acknowledged in many of the studies;
- In many studies, 100% penetration is assumed to give a "best case" scenario. Related to this, other work shows little impact on traffic flow and capacity until relatively high penetrations of vehicles with high levels of automation;
- Headline benefits from other studies are often used as assumptions for the best case scenario without understanding the basis. This gives conflicting and inconsistent estimation and benefits, and often undermines these macroscopic analyses;
- There is evidence of the potential for demand to rise as capacity increases, or even if just the quality of transport increases (analogous with induced demand problems of transport infrastructure);
- The way CAV technology is deployed (especially in terms of time gap and the trade-off between comfort, time and safety) by vehicle makers will have a large impact on capacity, and hence policy implications; and,
- Studies are generally confined to self-driving passenger cars, with public transport, freight or alternative ownership models not considered.

2.2.3. Implications

These policy related studies of macro-level effects demonstrate that:

- A requirement for a "systems of systems" style assessment of all the factors that impact transport policy, over and above solely capacity. This is needed to understand the causal factors that may drive vehicle uptake, choice of headway, type of vehicle and many other factors that will, either directly or indirectly, impact capacity;
- There is mixed information and conclusions on capacity, ranging from a potential to reduce it, little change or large increases. These mainly depend on initial assumptions, and hence there is a need to delve deeper into those references by looking at the technology "bottom up";
- Analysis and modelling of CAVs should examine a range of scenarios of adoption and penetration and vehicles; and,
- Direct stated capacity benefits may be eroded through induced traffic or increased trip making.

3. Technology based reviews

3.1. Technology options

To look at the impacts from the bottom up, the mechanisms for which capacity may be impacted has been divided into the various technology components. This is not intended to be a detailed analysis into the dynamics of CAVs, but to allow a broad categorisation of work carried out to date. The following areas have been considered:

a) Vehicles are able to travel closer together at the same speed within a lane. This may increase capacity and avoid flow breakdown. This is typically, but not exclusively, on roads such as motorways and dual carriageways. This is referred to as **longitudinal spacing**;
b) Vehicles can travel closer together in more lanes on the same road space (be they narrow marked or virtual lanes) to increase **lateral capacity**. As above, this is typically on multi-lane roads.
c) Control of vehicles at **junctions** such as traffic signals or motorway merges, smart motorways, and how vehicles behave at other forms of junctions such as priority and roundabouts, where their behaviour as they move off may impact on other road users in the queue behind them. This applies to both urban and rural roads, and to more complex motorway and A-road junctions.

Each of these elements will be considered in subsequent sections.

3.2. Longitudinal spacing

3.2.1. Technologies

Examples of technologies and techniques for influencing longitudinal spacing are:

- Adaptive cruise control (ACC) which automatically adjusts time or space gaps to the vehicle in front by using sensor data and adjusting speed, with the driver in control of lane choice and with an ability to override. This is currently available in production vehicles.
- Connected adaptive cruise control, (CACC) as for ACC, but taking data from vehicles further ahead (an analogy to high level brake lights). Again, the driver retains lane choice. This is an emerging technology in Japan and the US.
- Platooning, where CACC is used but vehicles may also be controlled by lane, allowing “road trains” to be set up with reduced driver input. These have one single driver and typically much shorter time gaps, as the remaining drivers are then able to engage with other tasks. This has been modelled for the UK, with trials planned, but is not yet available.

It is important to recognise the difference between connected cruise control and platooning, even though much of the technology is the same. Platooning is a higher level of automation and will be further away in time, but may offer higher benefits to commercial fleet operators.

Note that these impacts mostly apply in motorway and expressway conditions, but variants may apply in urban conditions. However here it is more likely that junction (rather than link) capacity will act as the dominant constraint.

3.2.2. Evidence base

ACC and CACC

Firstly, ACC has been examined in depth by many researchers from the automotive field, but a view from traffic modelling is far less common.

Pueboobpaphan et al [14] stated in 2010 that capacity might be impacted by:

- Changed individual gaps between vehicles;

- ACC and CACC impacting “string” stability, by dampening out small spacing and speed errors between vehicles that causes shockwaves at high flows; and,
- Overall traffic stability.

There are many studies that have examined these stabilities in depth as mathematical problems. There is a lack of consensus about these impacts, and inconsistency of various approaches, which are examined in this section.

An often mentioned paper is “Highway Capacity Benefits from using Vehicle-to-vehicle Communications and Sensors for Collision Avoidance” by Tientrakool et al [15]. This used a highly aggressive braking parameter choice and shortened gaps between vehicles of 1.1 seconds. This study assessed a range of penetrations and showed that with sensors alone (ACC) and 100% penetration, capacity could increase by 43%, but with communicating vehicles via CACC this rise would be 273%. It notes that at 100% penetration, the gap is only 5m between vehicles. This paper also looks at why the capacity estimates are higher than most and concludes that this is due to shorter time gaps (1.1 vs 1.4 seconds for other studies) and from not modelling road merges. This paper is useful in that it shows an upper bound of effective platooning rather than cruise control based solutions, and in that it highlights the value of connectivity between vehicles. However, the use of “aggressive” driving parameters undermines these results, as comfort of the driver / passenger may be compromised. It also shows little change in capacity until 30% penetration is achieved.

This 43% “best case” increase in capacity has often been taken by other authors as a base assumption (such as in Section 2) for increase in capacity *without* understanding the underlying assumptions of aggressive or cautious vehicle behaviour. The 273% increase has also been taken out of context in some opinion pieces and grey literatures. This paper highlights that choice of vehicle behaviour parameters by vehicle makers can have a significant impact on capacity once higher rates of penetration are achieved.

Toyota has started to introduce CACC in Japan only. Apparently the headway has not been reduced compared to standard ACC and the main reason for the introduction at the moment is only to have a smoother ACC operation [16].

Bifulco et al [17] highlights ways that the system can learn from how a driver behaves without ACC, and adapts parameters such as time gap to fit their style using data from an instrumented vehicle. Taken to an extreme, this would have no change on capacity if the system allowed current time gaps and headways to continue. But if it set a lower bound, effective capacity may decrease.

Broqua [18] estimated with a 40% penetration and 1 second time gap, capacity would increase by at least 13%. Minderhoud and Bovy [19] found capacity gains of 4% with a one second time gap. Arnaout et al [20] investigated the complications of CACC at merges and found little impact until 40% penetration of the capability. Pueboobpaphan et al [14] demonstrated the need to consider merges for CACC with manual traffic only on the slip road. They looked at the likelihood of collisions which increased with CACC, although delay decreased. This is one of the few papers to consider safety specifically in terms of interaction with manual vehicles. A further paper from the same authors also showed that the result of stability analysis depends on driver, vehicle and traffic stream characteristics, and the way ‘stability’ is assessed.

Scarinci et al [21] explored ramp metering with CACC and showed issues for capacity and network operations, with later merging vehicles on the slip road unable to join the main carriageway. Van Arem et al [22] looked at capacity change at a lane drop on a motorway which became a CACC only lane, concluding that CACC cannot improve traffic flow directly in this situation, but would be likely to reduce shockwaves and recurrent congestion. It also concluded a CACC-only lane with 20% penetration would result “in severe congestion on the link before the lane drop”. This is important (as shown in the following section) as a CACC only lane introduction must be timed correctly at a given penetration rate.

Shladover et al [23] concluded that use of ACC was unlikely to change lane capacity significantly, but CACC could increase capacity especially if non CACC equipped vehicles were able to identify their location and speed to CACC vehicles.

Modelling and parameter selection

Much of the analysis conducted has been done using microscopic modelling. Ntousakis et al [24] showed some assumptions in this modelling and highlighted typical parameter values, including the ISO standard for some key parameters in an ACC system [25]. These are more conservative than those used in some other studies [15]. It also highlighted the worst case scenario of encountering a stopped vehicle in free flow conditions, the requirement for sensors with adequate range, and that the "comfort" level of the occupant is not often modelled. This work looks at capacity for different time gaps and levels of penetration from 0.8 to 2 seconds, and 0 to 100% penetration. It showed capacity increases as long as time gaps are less than 1.1-1.2 seconds (a typical gap for non-CAV vehicles) but that high penetration rates with long time gaps could reduce capacity. Finally, this work makes recommendations for how traffic management systems can impact on this time gap choice.

In terms of modelling, Hjelkrem et al [26] investigates use of a vehicle following rather than car following model, to reflect the different behaviours of driver and vehicles, and reduce the calibration required for heavy vehicles. Recently for the A14 in the UK, Hardy and Fenner [27] concluded if the identified minimum safe platoon headway of 24.46 m were to be applied at speeds of 70 mph (112·65 km/h) then traffic flow could reach 9213 vehicles/hour, more than coping with the demand during peak hours. Similar constant velocities and uniform headways could be maintained through high-volume vehicle co-operation, generating steady-state traffic flow and reducing stop and start conditions. The ability of all vehicles to adhere to close driving patterns would also dampen the amplification of speed variations as they propagate upstream. The effect of damping would reduce the frequency of instances when traffic stops for no apparent reason. However this 24.46m headway includes the length of the vehicle and is in two lanes. At 70mph this would be around a 0.6 second time gap. This also assumes 100% penetration.

Milanes and Shladover [28] also used experimental data for vehicles using commercial ACC with a 1.1 second gap and showed that strings of ACC vehicles (i.e. those not communicating more than the vehicle in front) are unstable and can cause congestion. Conversely, strings of CACC equipped vehicles can dampen this effect. This is important as it shows a potential negative impact of ACC on capacity at low levels of penetration.

A correspondence we conducted with Dr Shladover about this said:

"We are currently working hard on simulating the capacity effects of CACC under one of our major research projects, so this is a topic of strong current interest. We published a paper in Transportation Research Part C within the past year describing the car-following models we recommend to represent both ACC and CACC, based directly on experimental data with full-scale vehicles. This is important because all previous simulation studies of traffic impacts of ACC and CACC have been based on over-simplified models that do not correctly represent the behaviour of those systems. We were surprised to see how badly ACC degraded string stability, and that effect in particular has never been shown properly in simulation."

User choice

Whilst there is conflicting evidence, the majority of studies to date show that CACC will only have capacity impacts if high penetration is gained and low time gaps are adopted. Automotive manufacturers, who are not charged with optimising capacity on the road network, will enable user selection in time gap / headway. There is consequently an important trade-off between what is optimal for the network, and what is optimal for the user. The logical question is therefore "which time gaps would be adopted by users in the UK?"

A report from PATH in California [30] looked at time gaps chosen by experienced users in real vehicles with ACC and CACC. A gap of 1.1 seconds was used most frequently for ACC, for 50% of trips, but some users preferred 1.6 or 2.2 second gaps. For CACC, over 55% of the time the 0.6 second gap was taken but with a wide range of users. This suggests short time gaps, and the likely capacity benefits, may well be realised if the system is trusted. The US driving style may not transfer to the UK, and so this is a key gap in our UK knowledge.

Kesting et al [32] considered an ACC system with "comfort" and "capacity" modes. They also commented that the behavioural models used in traffic microsimulation and in ACC are very similar. There is therefore great potential to model the impacts of ACC within existing platforms. This raises a broader question as to whether a driver would be happy to sacrifice aspects of comfort or other immediate benefits for a more reliable journey.

There is much human factors research in other areas of ACC. Hoogendoorn et al [33] undertook a literature review on the relationship between traffic flow, automated driving and human factors, concluding that the interplay is complex and the current research has shortcomings. Viti et al [34] reported on drivers' interaction with ACC, showing that drivers do not use ACC the same way in congested conditions as free-flow, and may even turn it off. Whilst this does not detract from the *potential* benefits of the technology, any exploration of capacity impacts must acknowledge the likelihood of drivers to utilise said technology. Further to this, there is some evidence [35] that drivers use ACC predominantly in free-flow conditions, and hardly at all in congested conditions. If this trend perpetuates, capacity benefits may be minimal.

Larsson [36] undertook a questionnaire of 130 ACC users of the Volvo system, showing a wide range of real world usage patterns, and the consequent need for more research on how people adapt to new technology. Varotto [37] showed through driving simulator work how drivers can react to ACC, including both the choice of use and the impact of sensor failure. Jones et al [38] highlighted that users in CACC strings may not wish to stay in these platoons if they perceived they are being “held back”, regardless of actual network conditions. This is analogous with current lane changing behaviour on congested roads. Gouy et al [39] also suggest that non-CAV users many change gaps to adopt lower headways after passing road trains with low headways. Whilst not a real-world trial, this study utilised driving simulator data and therefore provides an indication of the response that can be expected. Many of these observed headways were below 1 second. In this case, it is likely the safety concerns would outweigh the capacity benefits.

In terms of user acceptance, Jamson et al [40] showed that drivers may be happy to forego supervisory roles in return for a more productive drive, but that in congested conditions, they paid more attention to the roadway. This work is being continued, with much study of driving simulator data, considering car following and lane changing behaviour.

All the above human factors research shows the complexity of human control being removed simply from following the vehicle in front to generate platoons. The use of high fidelity simulators has shown promise, but it is clear drivers adapt to the technology over time from exposure to regular use.

Platooning

CACC taken to its extreme with low time gaps and only one driver for all vehicles is platooning. The SARTRE project [41] has shown the need for CACC within platooning to synchronize vehicles for what are often called “road trains”. Kotte et al [42] showed potential efficiencies in overall traffic flow, but highlighted that this needed high penetration and “long length” platoons. Fernandes and Numes [43] showed that traffic impacts of communications delays between vehicles can almost be completely worked around, but with a prevailing conclusion that traffic simulations may be too simplistic for this problem.

In a study for the DfT, Harwood and Reed [44] showed for a UK style road a change in speed/flow relationships, with an increase in capacity for mixed road trains of up to 21% (with 20% of cars in road trains), due to increases in lane capacity in lanes 1 and 2, as well as smoothing of strings of other traffic at the speed of the road train. HGV only road trains needed 50% of HGVs to be equipped to gain a 2% increase in capacity. This is one of the few papers to consider the overall impact of platoons – a new speed/ flow curve is produced. If platooning develops in the future, such evidence will be valuable, not just in platoon road operations, but also the planning of future roads.

Considering delay, they concluded:

- Delays for all cars decreases as the percentage of road trains increases;
- Under otherwise unchanged conditions, the delay for a car in a road train is always greater than for a car *not* in a road train;
- In congested conditions, the delay for a car in a road train is less than the delay if there were no road trains; and,
- Even in congested conditions, more than 10% of vehicles must form road trains before there is any benefit to a driver joining a road train.

So in congested conditions, everyone benefits (in delay terms) from a significant proportion of vehicles joining road trains. But there is no guaranteed benefit to any individual of doing so. This raises a key question – why would a road train be joined by a driver if they were potentially worse off? There may be good reasons for HGVs to do this (such as extending working time), but drivers of passengers cars would need to be able to trade the extra journey time for other activities. This theme of comfort and utility versus journey time and capacity is central to our gap in knowledge of this subject.

Bishop et al [45] looked at the traffic flow impacts of a two-truck platoon, with 1.25 to 0.5 sec headway and 20% to 100% penetration using a model of an Alabama freeway. They concluded no impact on flow or delay until 60% market penetration. This is assumed to be because of the small platoon size. However, such platoons would still provide a business case for commercial operators.

Shladover and Nowakowski [46] makes a point that most work on ACC and regulatory challenges arising from it is built on a “metal model” of the first Google car, i.e. an adapted conventional car. As time has passed, new vehicles and proposed MaaS pods raise new questions, such as what time gaps might be set (or available for choice), and how connectivity[6] is not necessarily used. This will be explored in greater detail in Section 3.4.

3.2.3. Summary of longitudinal technologies

- CACC may increase overall capacity but not by the significant level some headlines suggest until very high levels of penetration. CACC is unlikely to have a large impact on capacity until >40% penetration is achieved;
- ACC may have a negative impact on traffic stability and hence capacity due to its lack of connection with downstream vehicles. But ACC may increase capacity, if time gaps lower than those currently chosen by UK drivers are acceptable to them;
- Platooning is unlikely to have a significant impact on capacity unless vehicles currently regarded as cars join road trains. The business case for a user trading a slower journey for more utility is fundamental to this outcome, as is a business case for HGVs to join platoons; and,
- Almost all work considers motorway/fast “A” road style scenarios. Work on urban roads tends to consider junction effects more (see Section 3.3).

3.2.4. Implications for modelling

- User acceptance of CACC short time gaps is not well understood in a UK context;
- Merges and lane drops offer significant problems for modelling due to the heterogeneity of behaviour expected as these sites;
- CACC only lanes need further exploration as they could reduce capacity;
- Simulation of CACC and ACC depends on good understanding of the drive behaviours as well as the CACC and ACC system; and,
- There is a clear question as to whether drivers will use ACC or CACC in congested conditions.

3.3. Lateral capacity

3.3.1. Types of technology

Shladover [47] analysed the opportunity for increased lanes as a result of connected and autonomous technologies. The typical US lane is 3.5m wide, but passenger vehicles rarely exceed 1.8m in width. The remainder is needed to allow for imprecise steering and heavier vehicles, which can be 2.75m wide. He notes automatic steering control could reduce lane width required if sufficiently accurate.

However, compared to longitudinal aspects, the volume of research on this opportunity is small. We understand that this is because even with a UK 3.65m lane, allowing for the movement of vehicles prevents a “two from one lane” approach and so other techniques such as “two lanes into three” may be needed. Taking lanes out of use for non-CAV vehicles has impacts as we will investigate later. The use of narrow vehicles has been considered, but this is potentially in conflict with the need to provide cabin space to allow drivers to utilise travel time for other purposes.

Work has been conducted as to how CAVs may enter and exit dedicated lanes. Van Arem [48] 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. Kachroo and Li [49] and many others have explored the mechanics of lane changing between CAVs and non-CAV vehicles, all highlighting that merging traffic at junctions is likely to be an issue. There is very little other work in this area. A particular unanswered question is around the mechanics of CAVs and non-CAVs merging into the same lane.

Park and Smith [50] modelled lane advisory systems to encourage early merging at junctions. This has the effect of reducing delays, but required high compliance of drivers. A recent webinar by Delphi showed that for a cross country automated drive, 99% of the distance travelled could be automated, but manual control was needed for freeway on ramps. This suggests that merging and diverging of CAVs with non-CAV is an area that will be researched from a vehicle perspective.

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[6] i.e. the vehicle uses remote sensing to understanding surroundings and inform decision making

Temporary traffic management measures in the UK are used frequently during highway works. In addition to lane restrictions, narrow carriageway widths are often implemented, with associated reduced speeds and the potential for reduced capacity. Whilst there may not be capacity benefits per se (for example, with reduced speed limits due to safety concerns), technologies that control lateral movements of vehicles may at the very least make for a more comfortable customer experience.

3.3.2. Summary of findings

Whilst increasing lateral capacity looks promising, the practicalities of adding additional CAV lanes (and getting CAVs in and out of them) may pose too great of a problem in the short and medium term. Most potential exists at higher penetrations of CAVs, and with a relatively homogenous vehicle fleet.

3.3.3. Implications for the project

Given previous results, there is little benefit in assessing CAV only lanes at low fleet penetration. CAVs may have little user advantage at low penetration as they will share existing lanes, and therefore may not reach the level of penetration they need to warrant these exclusive lanes. This does not consider the potential for intervention to encourage uptake of CAVs, but it is clear that any special infrastructure provision dedicated to CAVs any act would have short term negative effects on capacity. Furthermore, there is little work looking at common UK road scenarios, such as a lane drop.

3.4. Junctions

3.4.1. Technology options

Here it is particularly useful to consider not only the distinction between connected and autonomous vehicles, but also the different network types, urban and non-urban. Whilst there are of course some overlapping characteristics, methods of data control, data provision and behaviour are markedly different.

Looking at urban areas, connected vehicles can provide data on their position to help existing infrastructure control traffic. An example of this is better data on location of queues helping to improve traffic signal timings set by systems such as SCOOT or MOVA. The potential benefits of this are enormous, and are not confined to traffic flow and road capacity. Automated CAVs can modify this by behaving differently in terms of lane or speed or movement at a junction and hence may have impacts on capacity even if the control system does not change (for example, CAVs may move faster, or slower, away from traffic signal stop lines than human drivers, so impacting capacity).

Much of the grey literature on the subject uses the combination of the above to argue that traffic lights will no longer be needed, so dramatically increasing capacity. This is potentially an overly simplistic view, as in a UK context almost all traffic signals have cyclists and pedestrians using the junction too. Whilst it can be argued that advanced collision avoidance systems will enable more shared space environments, it is unlikely that urban traffic control in its current form will be completely removed in any considered time period. Providing dedicated facilities for CAV or non-CAV vehicles at junctions is unlikely in compact UK towns and cities, where such lanes are already a challenge for public transport and cycle provision.

3.4.2. Use of data to improve traffic control in urban areas

Currently, traffic control systems generally use fixed road infrastructure such as loops, radar and image processing to detect vehicles and provide a progressive model of the vehicle queue as inputs to control algorithms. These are typically limited in number (for example, a single loop per link) and so give information at spot locations. Use of data from vehicles to overcome this challenge, and also explore the need for less road infrastructure with associated maintenance costs, has been explored in many projects. These projects are now moving from theory to real world demonstrations. There is much evidence that data from vehicles (or the people in them) about location in the queue at traffic signals can improve current traffic signal performance, and also support new algorithms for control.

Data can be used simply to detect and manage congestion. Umehara [52] demonstrated a new concept of using vehicle derived data to determine the cause of congestion (such as a blocked lane) from movement characteristics. This may add an extra level of information above the current loop based approach.

There are techniques to develop better signal junction control algorithm performance even with low penetration rates (sub 20-30%) [Goodall et al, 53] and higher rates [Box, 54]. Both approaches show potential for significant reduction in delays on existing traffic control sites with existing algorithms. This work has been extended [Box, 54] to show reduction of peak delays on a UK junction with 20% penetration, and reduction in overall delays with 40%.

Guler et al [55] showed that this level of reduction can apply to unsaturated or near saturated conditions but may result in reduced performance against fully saturated conditions. This suggests a hybrid approach of using data from vehicles to delay the onset of congestion. A new algorithm is proposed to make the most of the opportunities for platooning of vehicles. It also shows there is only marginal benefit beyond 60% penetration. Goodall et al [56] looked at new algorithms that do not need point loop detectors. These can improve delays with over 50% penetration, but again performance of the technique worsens in saturated conditions. This is a key point – the benefits are typically in delaying the onset of congestion rather than in improving congestion once it has occurred, at which point traditional infrastructure based approaches currently do better. Hence a hybrid approach would be needed at small penetration to fill in data gaps, and in saturated conditions. This is being investigated by the authors cited here.

Work has also been undertaken into "Signal Phase and Timing (SPaT)" where the vehicle-driver unit is advised of the future settings of the next signals they will encounter, as well as (or instead of) the traffic signals using their location to decide timings. Huang et al [57] showed that this can help manage queues and reduce delays (by 13% for the junction examined). The Compass 4d [58] project has demonstrated this in the UK, with 11 non-emergency ambulances given priority at traffic signals using a UTMC system. This study looked at wider work on the "energy efficient intersection" using this approach. TfL have also experimented with SPaT messages in a SCOOT environment [Burke et al, 59] and showed how the adaptive nature of SCOOT presents a challenge over fixed time approaches (such as those currently undertaken by Audi in Ingolstadt).

Kaths et al [60] provides a useful overview in "Traffic Signals in Connected Vehicle Environments" and concludes that with regards to benefits "high expectations arise from all sides (municipalities, car manufacturers and road users)" but that "obstacles on the way to large scale deployment are still faced". However, it is concluded that communications and data flow between vehicles and infrastructure will be important in the future.

The UR:BAN project in Germany [61] has been exploring heavy truck platoon management at signals as part of a smart intersection. This explores benefits in many capacity related areas at signals such as:

- Better starting, stopping and waiting by the vehicle;
- Better timing of entrance to an intersection (SPaT);
- Better decision support (better signal setting); and,
- Better following (creating platoons).

There are other areas of connected benefit in urban areas that might impact capacity. For example, better parking information, HGV routeing and the ability to monitor congestion over a network. These are already at field test stage. IMTECH has a system called ChaCoSy that is currently in pre-production as a demonstration but will be available as a live system in 2016 [Blokpoel, 62] and other system providers such as Siemens, Telent and IDT are active in this area in terms of infrastructure for data collection from vehicles.

Work in this area is transitioning to real-world trials, considering both the operational and institutional aspects. These trials will provide a wealth of empirical data and evidence on potential for improving capacity.

3.4.3. Use of data to improve traffic control in non-urban areas

Data can also be used to identify vehicles on motorways, both for incident and congestion detection and longer term planning, as well as being used in existing navigation services. INRIX has over 1 million probe vehicles in the UK providing such data (a service used by Highways England through the NTIS project) with TomTom, Here and Google also having significant location data. Even these limited examples indicate the wide range of information that connected vehicles may provide to network operators. These applications do not necessarily require a *connected* vehicle, but rather means of providing data from the vehicle. For example, an app on a mobile phone of the driver can provide data to infrastructure providers, without necessarily providing any (direct) benefit to the driver. This technology is already available, and the benefits are being explored by infrastructure providers and MaaS pioneers.

The traman21 project deliverable "Overview and Analysis of Vehicle Automation and Communication Systems from a Motorway Traffic Management Perspective" [63] provides a detailed overview of the potential for both connected and autonomous vehicles. This again highlights the need for field tests rather than simulation. The

CHARM project deployed by Highways England is already exploring the use of data from connected vehicles in traffic control to reduce the reliance on fixed infrastructure. For logistical and MaaS purposes, there is also potential for further types of data from vehicles to optimise capacity for freight and passenger vehicles, such as loading and lateness. This will inevitably impact on demand and trip making, with downstream capacity effects.

Due to the strength of research in this area and emerging pilots and trials, this area has not been explored to the same detail as the impact of autonomous vehicles. The real UK benefits will be shown by these pilots and field trials, providing greater confidence than in modelling alone. It should be noted that these benefits will occur faster than capacity impacts for autonomous vehicles, but the level of connectivity of full CAVs may add additional benefits both in urban and non- urban areas.

3.4.4. Urban junction impacts from better control and changed behaviour

Less research has been conducted in this area. This is mainly due to a lack of technological development, particularly when compared to CACC. Work that has been conducted tends to focus on 100% penetration of automated vehicles [such as Li et al, 64] but recent papers such as De la Fortelle et al [65] have looked at technology architectures for mixed traffic. There is little simulation work here, and even less in the way of field test results.

Vehicle performance

High profile trials of vehicle performance (such as those carried out by Google) have been carried out in the US in mixed urban environments. Whilst there is much in the way of grey literature and anecdotal press items (including reports of accidents and excessively slow driving), there is little published technical information on the way vehicles behave, and nothing regarding the impacts on capacity or traffic flow.

The UK has three automated vehicle pilots. Two of these focus on mixed pod/pedestrian behaviour in car free zones, rather than in the more relevant urban and inter-urban road environments. Useful results are expected from real-world trials, such as VENTURER, which will assist in answering questions around traffic flow and road capacity.

A further complication in all these trials is that the technology is proprietary, and given the competitive nature of the industry, automotive manufacturers are understandably restrictive concerning published technical information. There are, however, key trade-offs to consider:

- Safety, comfort and capacity;
- User choice versus maximum vehicle capability; and,
- User optimal settings versus network optimal settings.

Without a clear view of how technology for CAVs will develop, including the relevant standard, regulations and type approval, studies of traffic flow and capacity will remain confined to what is “possible and plausible” rather than a scientific study.

The current level of performance of some vehicles is reported by Google and others to be limited due to its safety first approach [66]. These trials are formative, and therefore performance is highly likely to improve. The current level of performance is not expected to be made available to the market, and would also not be expected to be particularly attractive to consumers. However, the extent to which such factors as driver comfort, allowing the ability to work without nausea and spacing of vehicles may be limiting factors to either uptake or performance (particularly in terms of rapid acceleration and deceleration and cornering at speed).

Le Vine et al [67] examined the tension between occupant experience and capacity by looking at the impact at a signalised junction. If the level of comfort required was the same as for high speed rail (in terms of acceleration and deceleration on all three travel axes), reductions in capacity of between 21% and 54% were shown (with 25% penetration and depending on assumptions). The simulations carried out for this work do not assume connectivity, which may mitigate this impact as described above. This is therefore a “worst case” as some drivers may not need the level of comfort for rail. However it does illustrate the inherent comfort vs capacity tension, also seen in CACC, and the potential for significant early changes in capacity at low levels of penetration. Furthermore, it is clear that there is need for more research in this area, particularly when considering complex networks.

The interaction between CAV and non-CAV vehicles is a key consideration. If a CAV has to assume that a human driven vehicle will unexpectedly decelerate at its maximum rate, this may lead to long headways and capacity impacts, particularly for vehicles at junctions. A further (currently unpublished) paper presented in 2016 [68] looks at this “defensive driving” for processing a 100% automated queue at a signal stop line. It shows that queues can be cleared faster than human driven equivalents, but that this clearly requires all vehicles to be CAVs – a single slow “human” driver will have an impact in this case. Another consideration is the impact of the “Assured Clear Distance Head Criterion” – i.e. that the vehicle is at a speed that allows it to stop within the distance that the driver can see a dangerous event ahead. This is the basis of the “following too close” approach in law and in insurance liability. This criterion – which clearly does not apply on motorway platooning work discussed above – may have impacts in urban areas, for example in allowing for pedestrians crossing the road. Equally, emergency braking systems may also impact on this as they can stop quicker than humans if required. However, the criterion as applied does mean that the benefits of discharging a queue of CAVs may not be as high as expected, as this time gap has to be built up.

The possibilities of vehicles co-operating to limit their deceleration rates are covered but this paper raises a further key question about how close a following vehicle can be in an urban area legally and in insurance terms, and how the close following aspects of platooning could be applied in urban areas. Hence this discussion around capacity distils again to the chosen gap or headway:

- For physical comfort (to allow work);
- For peace of mind (for the user to be comfortable with the vehicle in front being close); and,
- For safety, legal and insurance reasons.

At a current UK stop line, vehicle flows do not follow the criteria above as drivers pull away with what may be considered to be unsafe headways. However, their reaction times are slower than CAVs – it is the balance between these two factors that is the core of junction capacity changes. This work may highlight an “edge case”, but does show that safety-driven legal and institutional aspects may have as much impact on capacity as technology.

Other types of junctions

Traffic signals are not the only junctions in urban areas. Zohdy and Rakha [69] considered the use of CACC to optimise trajectories on roundabouts and show savings in delay of 80% at an approach similar to motorway merges. However this requires full (100%) penetration of CACC to identify gaps and uses a US style roundabout, as opposed to a UK “mini roundabout”, for which no research has been found. This is a significant omission, although there is some evidence that four way stop lines in the US have proven a challenge for CAVs. Whether these techniques would work in a much smaller UK junction such as a mini roundabout is an area to explore. This also suggest that priority junctions, lane drops at merges after signals and other areas where vehicles come into conflict (both CAV and non-CAV) may be key constraints to capacity.

3.4.5. Motorway junction impacts from better control and changed behaviour

There is more work in this area due to the depth of work on ACC. Davis [71] found that ACC vehicles might induce congestion at bottlenecks, but that co-operative merging via CACC and roadside infrastructure could enable improvements in mixed traffic flow. Gou et al [72] presented an architecture for such an approach and Roncoli et al [73] looked at a framework for co-ordinated motorway management at various penetration rates.

Areas of capacity exploration

By combining ramp metering, lane control and variable speed limits with data from vehicles, true co-operative driving could be delivered. The infrastructure tools for this are already in place on many UK motorways but the addition of extra data and the ability, for example, to control the seed of vehicles directly provides a new level of control. Using these approaches, even with 2 second headways, improvement in travel time of 18% was shown with only 1% penetration. This may be a network specific element, but does indicate potential.

Some work has also looked at better traffic management during congestion and incidents using CAVs. Cyra and Wolshon [74] show the ability to reroute traffic following a major incident, while Lei et al [75] demonstrate the ability to increase travel time reliability in accident conditions. This study also cited the potential for impacts on traffic flow if the systems are “user centric” rather than “network optimal”. Finally, it highlighted the important role (and associated uncertainty) of human factors.

There is a particular need for further work in a UK context. For example, it is expected that there is potential to enhance smart motorway control systems, both in normal operation and incident scenarios (such as lane closures).

3.4.6. Summary of junction impacts

There is much modelling and simulation evidence that data from vehicles, and messages such as SPaT, can improve current signal junctions. Some field tests are in place to further the case for this application. The capacity and traffic management impact on the UK could be significant, but more local, urban tests are required. Similarly, there is evidence of improvement outside urban areas.

Conversely, there is some evidence that automated vehicles behaviour, especially when pulling away at a signalised junction, may reduce capacity. This is particularly the case if the vehicle behaviour is optimised for comfort and safety, rather than for traffic flow. There is not enough evidence from current US automated vehicle trials to understand the speed of change of these factors, the implications for UK specific junctions such as mini roundabouts nor the human factors, legal and institutional aspects, all of which are likely to have an impact on ‘headline’ capacity.

There is some work to show improved overall network management with low penetrations of CAVs due to the ability to control them directly in speed and lane at congested motorways. Again, the critical factors are the tension between settings, such as headway and comfort, human factors and penetration. There could be significant negative capacity impacts from CAVs at low penetration unless the current level of performance improves.

3.4.7. Implications for this study

- There is little value in further modelling the benefits of connected (but not necessarily autonomous) vehicle data, with value expected to come from field test knowledge than further simulations;
- The choice of key factors for urban junctions, such as headway and reaction times of the vehicle, should be modelled to understand the potential impacts on capacity at low capability and low levels of penetration. These should include UK-specific situations, such as roundabouts, priority junctions and UTC;
- There is also a tension between capacity and user comfort parameters that may be chosen for vehicles – whilst the motivation of users and automotive manufactures are unclear, a systematic approach to parameter variation is most sensible;
- Motorway merges and diverges appear to be an opportunity for connected vehicles to improve, yet may present particular challenges for high levels of automation. The timing of deployment will be key here and assumptions about level of connectivity are also important;
- Smart motorways may be an area where both the connection and automation of vehicles again has different timings and benefits; and,
- There is little work exploring mixed queues of vehicle types at junctions (for example, CAV and HGV) and where the benefits, costs and trade-offs will apply.

3.5. Other findings

Much of the research work has been around narrowing the breadth of knowledge – from assumptions of 100% penetration through to lower values, from addressing hypothetical values of vehicle parameters to users’ chosen ones, and from hypothetical networks to real ones. But despite narrowing the gaps this still leaves us with a wide range of possible variations. The tensions between comfort and capacity have been well recognised [67] but may only reflect the desires of current drivers. It may be that the next generation of “drivers” may well accept a more jerky level of CAV behaviour which would improve capacity and move from this edge case – but there is little work exploring this.

3.5.1. Simulation modelling

Much of the work involved in measuring capacity has used microscopic simulation models, notably PTV VISSIM. The work has highlighted the relative ease of changing some vehicle and driver parameters to model CAVs, but also the assumption that the base human driving behaviour is well modelled. Whilst human drivers exhibit a range of behaviour, CAVs may be expected to be more homogenous with their driving style[7]. The focus for simulation models should therefore not be on the fidelity of the base case, but the changes CAVs imply once deployed.

Other modelling of individual vehicle to vehicle interaction is often undertaken, providing useful information on vehicle dynamics but with limited application to network evaluation.

3.5.2. Lack of OEM input to research

Only in a few cases where real vehicles were involved did OEM supplied equipment (such as ACC) feature in research – typical algorithms tested are hypothetical or generic. This may be because of the lack of product maturity, or a reluctance of OEMs to expose proprietary technology. Regardless, this can be expected to improve as the industry develops further real-world trials and empirical data becomes more readily available to research.

3.5.3. Lack of vehicle variation

In both simulations and field tests, typically, only a single type of CAV capability is considered. These CAVs are assumed to have the same performance. Little work has been done reflecting that different OEMs will be likely to adopt different solutions and control algorithms. Furthermore, there is expected to be an element of user choice in connected and automated vehicles. Any study should realistically look at a similar level of heterogeneity as is inherent in current traffic streams. Owczrzak and Zak [76] have looked at how users might choose different types of MaaS vehicles, but there are few studies on the impact that such new vehicles might have on demand rather than capacity.

3.5.4. Safety in congestion

Only one paper has been found that specifically considers safety impacts of changed congestion, and congestion impacts of changed safety. This is because of limitations in most simulations on how accidents are modelled. Shladover and Zak [77] show that the current US exposure to an accident is rare, so understanding CAV related accidents with a large benefit in safety will be a challenge.

However, as in the UK, around 25% of congestion is caused by incidents [78] and so a reduction in accidents may have a significant benefit, and may ultimately outweigh the potential disbenefits from CAVs highlighted earlier in this report. Conversely, Brownfield et al [79] showed congestion can reduce accident risk in high flow environments. Whilst the complex interactions are beyond the scope of this study, the need for a "system of systems" approach is clear.

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[7] For a given automotive manufacturer / control algorithm

4. Conclusions and implications

4.1. Summary of review

The work reviewed here reflects the benefits of connected vehicles and increased automation. Safety and emissions have been the subject of much work, as has been the potential increased utility of travel time. Few of these studies explore the changes in traffic flow and road capacity in depth, and a limited number make reasonable assumptions about vehicle mixes and performance.

Much work has come from the US, reflecting the long history of research in this area, especially for motorway like environments. Much of the EU work is understandably focussed on safety, but is beginning to provide increased information on traffic management. The emerging UK work on platoons takes a pragmatic view and examines capacity well, and there is growing amount of UK-specific research emerging.

4.2. State of knowledge

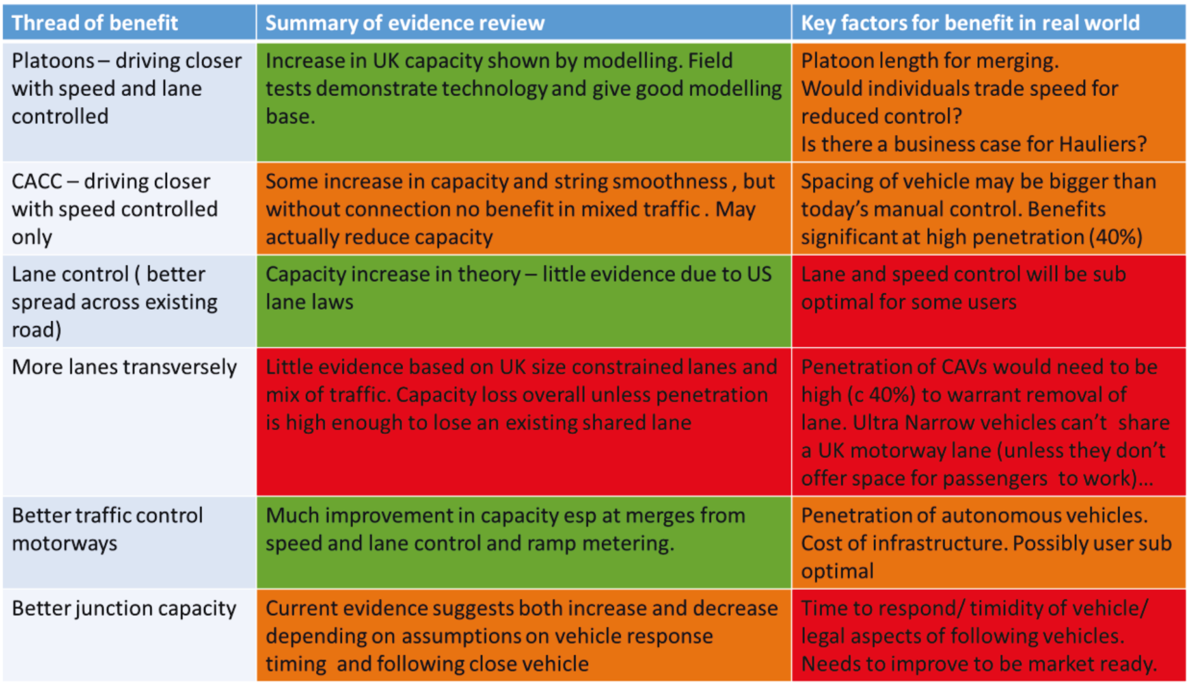
The table below summarises the various threads of potential capacity change, and our knowledge on potential changes for autonomous vehicles, as well as practical factors that might influence this. This is additional to improvements in capacity that may come especially at urban junctions from better connectivity of existing vehicles:

- Red – implies lack of evidence or an area where there may be issues in deployment that impact capacity or take up significantly
- Amber – implies areas where there is mixed evidence or areas that may impact benefits
- Green – implies areas where there are likely to be benefits

Key areas of potential benefit are from platoons, lane control in existing road space and better traffic control on dual carriageways and motorways.

Areas of potential disbenefits are CACC, depending on parameter setting and high penetration, extra lanes and changed urban junction capacity. This again reflects unknowns about vehicle performance.

Table 4-1 Potential CAV capacity benefits and key factors for realisation



Thread of benefit	Summary of evidence review	Key factors for benefit in real world
Platoons – driving closer with speed and lane controlled	Increase in UK capacity shown by modelling. Field tests demonstrate technology and give good modelling base.	Platoon length for merging. Would individuals trade speed for reduced control? Is there a business case for Hauliers?
CACC – driving closer with speed controlled only	Some increase in capacity and string smoothness , but without connection no benefit in mixed traffic . May actually reduce capacity	Spacing of vehicle may be bigger than today's manual control. Benefits significant at high penetration (40%)
Lane control (better spread across existing road)	Capacity increase in theory – little evidence due to US lane laws	Lane and speed control will be sub optimal for some users
More lanes transversely	Little evidence based on UK size constrained lanes and mix of traffic. Capacity loss overall unless penetration is high enough to lose an existing shared lane	Penetration of CAVs would need to be high (c 40%) to warrant removal of lane. Ultra Narrow vehicles can't share a UK motorway lane (unless they don't offer space for passengers to work)…
Better traffic control motorways	Much improvement in capacity esp at merges from speed and lane control and ramp metering.	Penetration of autonomous vehicles. Cost of infrastructure. Possibly user sub optimal
Better junction capacity	Current evidence suggests both increase and decrease depending on assumptions on vehicle response timing and following close vehicle	Time to respond/ timidity of vehicle/ legal aspects of following vehicles. Needs to improve to be market ready.

4.3. Key gaps and implications

In the course of this evidence review and engagement in with industry experts, key gaps have been identified where further work is required. Whilst not exhaustive, this list represents areas of particular concern in the context of UK policy.

- The need for a “system of systems” view of the whole concept and its policy interactions;
- A lack of short term low penetration/low CAV capability modelling for UK roads;
- Whether system-optimal (rather than user-optimal) solutions will be accepted by users;
- Acceptable level of risk and hence time gaps – specifically UK users’ chosen headways for various vehicle types and situations (from real vehicles not simulators);
- How a CAV only lane might be introduced in a UK context and behaviour at lane drops and merges downstream of signals;
- How lane behaviour may be improved for UK roads;
- Platooning at UK junctions;
- CAV behaviour at UK specific junctions (such as mini roundabouts);
- Non-CAV Driver behaviour impacts on and interactions with CAVs;
- A lack of real world results for better use of data (such as signal junction delay savings are all simulated so far);
- Behaviour of vehicles other than passenger cars, such as shared pods, buses and HGVs;
- The level of communications infrastructure needed for various levels of CAV connectivity;
- How CAV users might want to use the time otherwise spent driving, and the impact this has on for example the ability to control the vehicle under failure conditions;
- The trade-off between comfort and journey time people may be willing to make; and,
- Resilience and failure modes.

Further to this, there are specific areas of concern that make the modelled evaluation of connected and autonomous vehicles difficult.

Basic mechanisms of how CAVs may influence traffic flow are well understood. For example, CAVs may:

- Change vehicle headways;
- Change acceleration and deceleration behaviour; and,
- Change vehicle gap acceptance.

Whilst the mechanism is not disputed, the actual change is unclear. Many studies assume improvements to these behavioural parameters, thus leading to capacity improvements. This is arguable, and is underpinned by issues of user acceptance, safety and comfort.

Considering the gaps in knowledge, and the deficiencies and limitations of previous studies, Table 4-2 contains implications (and priorities) for future modelling exercises. This shows that short term priorities for future modelling exercises should therefore focus on changes to longitudinal spacing and junction behaviour.

Table 4-2 Implications of current knowledge on future modelling

Area of benefit	State of the art / evidence to date	Potential impact on capacity	Implications for modelled analyses
Connected vehicles – data at signals to and from vehicles	Much previous modelling and simulation, now at field test stage	Potential for reduction in delays and better network management	Being considered in real-world trials – further modelling should be informed by these results Key questions are around ownership, communications and operator benefits
Connected vehicles – data on motorways	FVD in day to day use for location, other data becoming available	Potential for better traffic control on motorways through better data, secondary impacts through reduced accidents	Being considered in real-world trials – further modelling should be informed by these results
Autonomous vehicles – longitudinal spacing	Platoons have been considered, but CACC not well understood Trade-offs with comfort (and regulations of safety) will be key	Reduction or small increase in capacity depending on choice (user or manufacturer) of headway and penetration Secondary impact through reduced accidents and incidents	Need to explore various headway choices and impact on capacity in various scenarios, including urban networks Vehicle mix (including capability) and level of homogeneity needs further thought
Autonomous vehicles – lane balance improvement	No work in UK context but promising modelling work elsewhere	Increase in capacity but potential problems at merges and other junctions	Explore various lane balancing scenarios for better utilisation of road space
Autonomous vehicles – virtual lanes / CAV only lanes	Little real work – acknowledged to require very high penetration	Increase in capacity if lane timing correct	Explore reduction of existing lanes, but only for high penetration scenarios – not a short term priority
Autonomous vehicles – behaviour at (all) junctions	Expected levels of performance unclear – currently focussed on safety	Reduction in capacity unless performance improves	Explore capacity impacts of vehicle performance vs capacity on signals, priority and roundabouts in UK context
Autonomous vehicles – control in smart motorway	Some modelling work but not in UK context	Potential to increase capacity and improve resilience above and beyond lane spread	Explore potential for enhanced control algorithm development

4.4. Ongoing studies: Empirical data collection

There is a recognised need to improve understanding of CAVs through empirical data collection. Whilst trials are being undertaken worldwide, the primary research objective is rarely to investigate the impacts on traffic flow on road capacity, but rather to test the capability of the vehicles, better inform design and make the safety case. Due to the stage of development, many of these trials are not taking place in real-world environments.

To understand the impact on road capacity, CAVs must be tested on public roads and parameters related to flow and capacity must be measured, leading to an analysis of the associated impact on capacity. There is a significant amount of testing work which needs to be completed to ensure reliability of hardware, software, and to better understand the interaction with other road users. Millions of test miles on prototypes in controlled test environments and real world scenarios are required and this could take several years to complete. Some existing trials on public roads are detailed below:

- Audi Piloted Driving – Audi is one of a number of OEMs actively involved in the development of AVs. Audi's Piloted Driving System, which allows a vehicle to accelerate/decelerate, steer and change lanes autonomously, works at speeds of up to 100km/h. In January 2015, Audi took its piloted-driving concept car on its first long-distance test drive. The Audi A7 drove from California's Silicon Valley to Las Vegas, a distance of about 900 kilometres, successfully changed lanes, overtaking other vehicles, and undertook night driving, reaching its destination safely.
- The SARTRE project, funded by the European Commission and led by Ricardo UK Ltd with the involvement of Volvo and a number of industry and academic partners from 2009 to 2012. The project successfully trialled the use of vehicle platooning technology on a public highway in Spain with the deployment of three Volvo cars and a truck for 124 miles. The truck was able to communicate with the following vehicles on how they should accelerate, decelerate and navigate along the route.
- YUTONG Driverless bus – the Chinese bus manufacturer Yutong has been developing a driverless bus for the last three years with the help of the Chinese Academy of Engineering. The bus had travelled 32.6km of an intercity road between Zhengzhou and Kaifeng at the end of August 2015. On its journey, the bus successfully responded to 26 traffic lights and undertook complex driving acts, including lane change and overtaking.
- One-North AV Testing Ground – one output of the Singapore Autonomous Vehicle Initiative (SAVI) is the trial of driverless vehicles on public roads, using a 6km route within One-North Business Park. JTC, as the master planner and developer of One-North, will provide test routes that consist mainly of low traffic roads, but including stretches with moderately heavy traffic.

A wide range of stakeholders are involved in trials of CAVs, including automotive manufacturers, academics and public bodies. The latter play a key role in trials by facilitating their implementation through enabling legislation, funding, and aiding in collaboration. For instance, the UK has established the Centre for Connected and Autonomous Vehicles (C-CAV) which co-ordinates government policy on CAVs and has also funded three public trials – VENTURER, Autodrive, and GATEway, featuring road trials of driverless vehicles in Coventry, Bristol, Greenwich and Milton Keynes. These projects, which also include low emission vehicles, provide insight into capability, real-world behaviour, interaction and public acceptability. Studies such as these will be invaluable for understanding the impacts of CAVs, including on traffic flow and capacity. Once deployed, test beds such as VENTURER, will seek to provide the facility to test increasingly complex scenarios in a realistic environment.

Internationally, Singapore is also active in this area through the Singapore Autonomous Vehicle Initiative (SAVI) set up by Land Transport Authority (LTA) to oversee and manage AV research, test-bedding and the development of applications by industry partners and stakeholders.

Safely testing CAVs on public roads requires appropriate legislation concerning vehicle standards, driving and traffic behaviour through certification and benchmarking. Liability issues should also be solved thanks to clear rules and guidelines. The UK has published a Code of Practice for testing driverless vehicles and a fully review and amendment to domestic vehicle and traffic regulations is planned by mid-2017, aligned with liaison at international level to further amend international regulations by the end of 2018.

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Appendix B. CAV research studies

The following papers have been recorded in more detail as they either:

- Inform about assumptions such as time gap or maximum deceleration;
- Inform on general modelling approaches;
- Show edge cases of testing (for example, with large or small time gaps); or,
- Include key findings.

This table only provides a general overview – the study in question should be examined in closer detail and cited directly.

Ref no	Network	Connected	Autonomous	Test approach	Technology assumed	Time gap secs	Maximum deceleration (m/s^2)	Result re capacity/ congestion	Comment
6	National view of Sweden - junctions	Yes	Unclear	Microsim (VISSIM)	Unclear	0.5	Unclear	Not a fully congested network but all 12 simulations show speed improvement/ reduced no of stops up to 50%	Highlights unknowns re acceleration. 100% penetration
7	National view of Korea	Yes	Yes	Calculation	Unclear	0.5	Unclear	Simple assessment of standard headways with increased speed to 100mph gives 67% journey time improvement	Highlights land use impacts and ability to increase speed limit
8	General network view	Yes	Yes	None	Unclear	NA	NA	Good overview from network management perspective	Highlights need to change traffic modelling approaches

Ref no	Network	Connected	Autonomous	Test approach	Technology assumed	Time gap secs	Maximum deceleration (m/s^2)	Result re capacity/ congestion	Comment
10	High level view	Yes	Yes	Unclear	Unclear	NA	NA	Says £15bn savings from efficient journeys using RAND data	Little evidence given re sources
11	General network view	Yes	Yes	Lit review	Unclear	NA	NA	Highlights optimism in predictions but that only recently has autonomous vehicle impact on planning been considered. Highlights considerable uncertainty in benefits and suggests not until "most vehicles can self-drive"	Highlights demand impacts and penetration - little on flow. Sees dedicated lanes in 2040s
14	Ramp/ merge	Yes	No	Bespoke simulation	CACC	1.2 man. and 0.5 CACC	1	Wide range of interesting results trading capacity vs collisions	Mixed ramp and mainline traffic. Highlights role of deceleration rate not all vehicles merge. Has collision count approach
15	Single lane freeway	Yes	No	Unclear simulation based on spacing reciprocals	ACC and CACC	1.1 for human driver	8.5	Linear growth with sensors and V2v	Often cited but ability of driver to accept such short headways and high braking rates questionable
17	Freeway	No	No	Simulation with real-world data	ACC	Varied	Varied	Not covered	Adaptive cruise control drives like a human… shows the impact of ACC without connection
20	Ramp/ merge	Yes	No	Microsim (FAST)	CACC	0.5 seconds for CACC 0.8-1s when not following CACC	Unclear	Capacity improves but at low penetration CACC vehicles impacted by others. 40% needed for significant change	Will CACC be viable at low penetration? Uses different scenarios of demand and varied drivers

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21	Ramp/ merge	Yes	No	VISSIM and bespoke simulation	CACC	Unclear	Unclear	Reduced late merges	Could ramp metering work with platoons?
22	Multi lane freeway with a lane drop	Yes	No	Microsim (MIXIC)	Mix of manual, ACC and CACC	0.5	2	10% increase in capacity with high penetration rates >60% of CACC. Safety implications of poor merge	Many problems with human vehicles merging into CACC platoons. CACC only lane decreases capacity
23	Freeway	Yes	No	Microsim (AIMSUN)	CACC	User defined - 1.1 to 0.6 sec	2	ACC will not change lane capacity. CACC can improve capacity to 4000 veh per lane	"Here I am" message from connected vehicle improves capacity
24	Freeway	No	No	Microsim (AIMSUN)	ACC	0.8 to 2	2	Highlights relationship in ACC between time gap and capacity	Individual vs string stability. good discussion on limit values and safety in models
26	Freeway	Yes	No	Bespoke simulation	NA	NA	3 but varies with vehicle type	Shows that one "car" following model may not apply to all vehicle types	Vehicle following model not car
28	Platoon	Yes	No	Road test and bespoke simulation	CACC and ACC	0.6 to 1.1	2	Shows v2v really needed in platoons - ACC unstable	Very useful paper as combines road test with simulation
29	Mixed	Yes	No	Field test	CACC	Unclear	Varied	No overview data but interesting measures of both string stability and signal throughput	Much more about co-operation between vehicles than impacts
30	Freeway	Yes	No	Unclear simulation	ACC	Unclear	Unclear	10% ACC has no negative impact on delay	Old and conclusions not strongly supported by later work
31	Freeway	Yes	No	Questionnaire and field test	N/A	1.6 on average	Unclear	No capacity evaluation	gaps around 1.6 seconds but wide Range

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32	Multi lane motorway with merge and lane change	Yes	No	Microsim (MOBIL) plus detector data	CACC	1.5	2	25% penetration results in elimination of congestion from test bottleneck	Maybe a solution to tension between capacity and comfort but would users / OEMs adopt it?
34	ACC	No	No	Field test	ACC	Typically 1	NA	NA	Frequent deactivations of ACC in dense conditions. Safety may be affected
38	Summary of human factors	Yes	No	Vehicle simulation	CACC	NA	Unclear	Throughput doubles once over 40% penetration	Many human factors issues captured
39	Platoon	Yes	Yes	Driver simulator	Platoon	NA	NA	Closer headways imply greater capacity	Platoons reduce time headways for non-platoon drivers
41	Platoon	No	Yes	Field test	Platoon	7m @ 85kph = 0.3 secs	4	None - highlights need for v2v data	Shared vehicle data removes string stability issues. Useful data on lateral wandering
42	Platoon	Yes	Yes	Microsim (PELOP)	Platoon	NA	NA	Improvement in capacity from "significant number " of platoons	6 vehicle max for merging
43	Platoon	Yes	No	Bespoke simulation	Platoon	NA	Unclear	No traffic assumptions	Time of comms between vehicles is important
44	Platoon	Yes	Yes	Microsim (VISSIM)	Platoon	Unclear	NA	Capacity increase roughly 1% for each % vehicles in road trains (more cars add more capacity) and due to smoothing as well as density. Platoon Size is important. Network but not individual benefits to car users	Looks at mixed car and HGV. Shows new speed / flow curve.

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50	Ramp/ merge	Yes	Yes	Microsim (Paramics)	CACC	Unclear	Unclear	Increase speeds by 9% but requires high compliance	Again why would a driver comply?
55	Intersection	Yes	No	Bespoke simulation	Location data	NA	NA	7% decrease in delay	Good lit review but suggests saturated conditions are different.
64	Arterial intersection	Yes	Yes	VISSIM	Individual vehicle time / space	NA	NA	Significant increase but assumes all vehicles connected.	Highlights impact of congestion on AV for PT. Has a surrogate safety measure. Most use for information on VISSIM modelling of AVS.
67	Arterial intersection	No	Yes	Microsim	Traffic controller but with vehicles with comfort selected acceleration	NA	As rail/ tram (0.54 and 1.34)	Reduction of 53-4 %	Perhaps an edge case but very worth considering. Highlights role of design to allow vehicles to stop and importance of max deceleration being a) known and b) chosen.
68	Arterial	Yes	Some scenarios	Kinematic analysis	UK / US signals control	Dynamic	-4.9	10-110% increase in “sat flow”	Raises interesting questions on braking in CACC vs legal situation.
69	Roundabouts	Yes	No	Unclear	CACC	NA	NA	Savings in delay of 80%	Special case of ramp metering.

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71	Multilane freeway with ramp	Yes	Yes	Unclear simulation	ACC plus gap creation	NA	Not defined	ACC has issues at on ramps, only modest improvement at 50%. Co-operative merging need at 50% penetration – throughput then up by 18%.	Lock up at merges as simulation does not cope well.
73	Motorway ramp meter and speed control	Yes	Yes	Microsim (AIMSUN)	CACC, lanes and ramp metering	0.7 to 2	NA	Depends on penetration. At low headways even 1% shows 18% reduction in travel time	Large benefits from lane change.