Autonomous vehicle interactions in the urban street environment: a research agenda

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Abstract

The Venturer project is trialling an autonomous vehicle (AV) in the context of use on urban roads. This paper summarises a literature review undertaken to assist in developing a research agenda for the trialling. The first contribution of the paper is a framework of four Use Scenarios for AVs as follows: 1) Fully segregated AV network, 2) Motorway or expressway network, 3) Typical Urban network, 4) Shared space. The paper then focusses on a review of the social interactions in the street environment and discusses issues concerning human behaviour in relation to autonomy. The second contribution of the paper is a set of research questions for AV trialling in relation to other road users, including, pedestrians and cyclists, which have emerged from the literature review.

1   Introduction

The direction of travel in technology development in the automotive industry is towards increasing levels of autonomy. This may result in a progressive transfer from the current predominance of human-controlled motorised vehicles on the public highway, towards use of vehicles with increasing degrees of autonomy. It is unclear, however, how Autonomous Vehicles (AVs) will integrate into the full range of existing types of public rights of way, and, more importantly, how they will integrate with the full range of road users, including pedestrians, cyclists and drivers and passengers of human-driven motor vehicles. To this end Innovate UK is funding a series of projects to trial AV technology. One of these projects, the Venturer project (www.venturer-cars.com) is undertaking trials using the Wildcat vehicle, see Figure 1. This paper is based on a review of literature (Parkin et al., 2016) undertaken to develop research questions to help inform the nature of the trials.

Figure 1 The Wildcat vehicle (photo credit Chris Bahn)

SAE International (2014, p2) summarise generally accepted levels of autonomy as follows:

- **Level 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.
- **Level 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 performs all remaining aspects of the dynamic driving task.
- **Level 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 performs all remaining aspects of the dynamic driving task.
- **Level 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.
- **Level 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.
- **Level 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

AV technology has reached Level 3 in the above hierarchy under test conditions. The information technology company Google is operating Level 3 vehicles on public roads with handover between the automated system and a trained 'safety driver'. Simonite (2013) reports Google's self-drive

project head as saying that hundreds of thousands of miles of travel shows that their AV accelerated and braked significantly less sharply than when humans were driving, and that the Google car was much better than human drivers at maintaining a safe distance from the vehicle ahead.

Volvo (2014) is using technology they call 'Autopilot', which can follow lanes, adapt speed, and perform merges autonomously. Further developments (Volvo, 2015) suggest they are ready for public trials, and this readiness is based on complete systems that will 'fail safe'. Audi (2015) has completed a 550 mile 'piloted' drive from Silicon Valley to Las Vegas. BMW is to introduce AVs already tested in Germany into Chinese cities in partnership with the search engine Baidu (Forbes, 2014).

More controversially, Level 3 capabilities are now being provided commercially, with caveats to users which suggest the systems should only be used in driver assistance mode, and not autonomous mode. Based on two deaths to date in Tesla vehicles, these caveats are of debatable effectiveness. Tesla (2015) has released an initial version of its technology (also called 'Autopilot') on the Model S vehicle. The Tesla Autopilot feature involves four elements: Autosteer, Auto Lane Change, Automatic Emergency Steering and Side Collision Warning, and Auto Park. Tesla states that 'The latest software update, 7.0 allows Model S to use its unique combination of cameras, radar, ultrasonic sensors and data to automatically steer down the highway, change lanes, and adjust speed in response to traffic.' (Tesla, 2015).

These developments suggest an urgent need to consider the implications of the increasing availability and level of assistance provided to drivers and their impacts on the full range of road users in the urban street environment. In addition, it is necessary to consider a future where vehicles might be used with full autonomy.

The focus in the Venturer project has been on an autonomous vehicle broadly the size and shape of a large car, and also a pod. The project will also involve testing the behaviour of the AV around a bus. The specific context for the study has been the urban highway. There are a number of interesting issues in relation to HGVs, and the focus here has been more on infrastructure to vehicle communication and platooning. Section 2 describes the very different scenarios in which AVs may be used. Interactions between AVs and other road users in the street environment are discussed in Section 3. Threads are drawn together in the form of recommendations for research based on the literature in Section 4, and the next steps for research on the Venturer project are outlined in Section 5.

2   Use scenario classification

There are a number of scenarios under which road-based AVs could operate. In the extreme, AVs might only operate in a system segregated from other, non-autonomously controlled, road users. Alternatively, were they to operate on an existing public road network in current types of traffic condition, then they would be subject to interactions with all types of vehicle, driver, cyclist, and pedestrian. These two extremes could hardly be more different in terms of what would be expected of an AV and the ways in which it would have to interact, manage, and negotiate its way through a system.

Skinner and Bidwell (2016) envision a future dominated by AVs and note the benefits and impacts in city centres, suburban spaces, motorways and rural areas. The set of AV Use Scenarios developed below further frame the discussion, and provide a defined scope for understanding the relevance of current and proposed research to AV use. These are as follows:

- **Use Scenario 1: Fully segregated AV network** – In whatever form this may be (for example pods or similar vehicles). AVs are completely segregated from other road users and operate within their own system. AVs would interact only with other AVs and the infrastructure of the network.
- **Use Scenario 2: Motorway or expressway network** – This scenario is a situation in which AVs operate alongside human-controlled vehicles, however only within a constrained subset of roads on the general network, i.e. high-volume, high-speed roads and where there may be a significant amount of instrumentation and management (e.g. Smart Motorways, Highways England, 2016). In this scenario AVs will interact with other AVs, human drivers, and the infrastructure of the road network (grade separated junctions with merges and diverges, lanes, and signage including variable speed limits), but no intended, or at least very few, non-motorised road users.
- **Use Scenario 3: Typical Urban network** – This complex scenario comprises the typical roads found in urban and suburban areas and includes arterial roads, distributor roads, high streets, access roads and local streets. There will be a wide range of different types of road user, as well as a need to navigate various forms of junction and other complex infrastructure and a high level of different types of regulation (e.g. speed, parking and loading). AVs will interact with other AVs, human drivers (of a variety of vehicle types including buses, delivery vehicles, taxis and motorcycles), pedestrians and cyclists, and with the infrastructure of the road network (signalised, roundabout and priority junctions, variable numbers of lanes and bus and cycle lanes, regulatory and direction signs, parking areas, a variety of traffic regulation orders, footways and pedestrian crossings).
- **Used Scenario 4: Shared space** – Shared space is an urban design approach which seeks to minimize the separation between different types of users in order to enhance priority for pedestrians and cyclists, which is often absent from much of the public highway. It does this by careful design to reduce motor traffic speeds and usually entails removing features such as kerbs, road surface markings, traffic signs, and traffic lights, and by introducing subtle and naturalistic forms of speed control through different surface colours and textures and roadside features. Increasing skill and knowledge about the nature of appropriately designed shared space is growing as more schemes are implemented. In this final scenario, AVs will need to navigate an environment which is less well defined and regulated than a typical urban highway network. AVs will be expected to interact with every type of user on an equal basis with no defined priority. AVs will interact with other AVs, human drivers, pedestrians and cyclists. A trial of autonomous vehicles has been taking place in Sion, Switzerland in this context (Postauto, 2016)

This paper is not concerned specifically with the Use Scenario where AVs operate on a fully segregated network, and these scenarios already exist within the transport sector, for example, the Heathrow Terminal 5 ULTra network of guided, electrically-powered 4 to 6-seat 'Pod' vehicles (ULTraglobalPRT, 2016). These 'AV system only' considerations form only a minor part of the whole issue of introducing AVs into the transport network. The challenge at hand is with the introduction of AVs into the existing highway network where there are other road users who are humans and who therefore behave as humans. Section 3 discusses these issues.

3   Social aspects of interactions in the street environment

To understand the complexity of the task facing AVs in successfully and safely navigating the road network, it is necessary to identify and explicate that which is currently known about interactions between its various users. Firstly, road use as a social practice is discussed, and this is followed by a discussion of one particular aspect of human behaviour in the street environment: aggressive behaviour. This is followed by a discussion of the physical manifestation of failure to resolve conflict, i.e. collisions, and a conclusion discussing the management of the environment from a regulatory point of view.

3.1 The car and driving as social practice

Wilde (1976) suggested that, despite the degree of anonymity available to road users, participation in traffic does not in fact take place in a social vacuum. Individual performance of the functions relating to road use takes place in the context of a collective of road users, characterized by social habits and social values, by certain expectations, and by methods of communication.

Thrift (2004) also notes that the system of driving or road use more generally has a significant social element and he suggests that the private car is a deeply ingrained cultural icon. He points out that the road system is hugely complex and well-established, with many types of interaction. Even non-drivers are likely to encounter the road network and its traffic almost daily. AVs are therefore not only entering a functional system within which humans operate, but they are also entering a system heavily laden with different meanings for different users.

Rules, customs, and bespoke modes of communication exist within this social layer of the system, which is laid on top of the functional elements of the road network. Drivers for example regularly wave, flash their lights, nod their head, speed up or slow down, beep their horn, and use hand gestures, all to communicate different things to other road users in different contexts. The implication is that AVs, in managing interactions with other road users, will need to have some degree of understanding of these socially-constructed elements of the system. AVs therefore must firstly be able to *recognise and respond* appropriately to social cues, but most importantly, may also need to *actively comply* with the informal rules and communications that occur.

Two significant challenges emerge. First, human drivers and other road users may not behave in a way that is sufficiently patterned for machine intelligence to be able to predict, reliably, what actions other road users are about to perform. It remains to be seen whether this is simply a temporary problem due to the availability of sufficient computing power and machine experience. Second, humans communicate their intentions on the road network in subtle and tacit ways. For example, they use gestures. Whilst machines are growing in their capacity to understand gestures, some of that understanding is not yet sufficiently robust for safety-critical applications.

Non-verbal communication is negotiated according to long-running and often national, culturally-specific expectations. For example, the UK highway code (and the equivalent in other jurisdictions) specifies a headlight flash as an alternative to the auditory warning of a horn. An Italian motorist flashing the headlights is an indication of an intention not to alter trajectory. However, in the UK, in practice, the headlight flash has an almost opposite meaning to the Highway Code definition: to indicate that priority is being yielded to another road user in a situation of uncertainty. Such variability of context-specific meanings remains one of the greatest challenges for AV decision systems.

3.2 Aggressive behaviour

Aggressive driving behaviours are relatively common, and thus it follows that an AV must be able to recognise, at least in terms of a behaviour pattern, and respond in an appropriate manner to instances where rational behaviour is overtaken by emotional responses by human road users. The American Automobile Association (2009, p. 10) notes that 'surveys consistently show that people believe aggressive driving is one of the most serious traffic safety problems'. This is therefore an area of particular concern for AVs.

Aggressive driving is engaging in dangerous or forceful manoeuvring of the vehicle but without the specific intention to harm someone else, while road rage is usually taken to mean an incident in which a driver takes actions with the specific intention of harming another road user (Schafer, 2015). Though both forms of behaviour are similar in that they place others at significant risk, the distinction is merited because of the differences in motivation, driver personality, and outcomes of each behaviour (Schafer, 2015; Hennessy, 2011; Miles & Johnson, 2003) and whether they are regarded as traffic violations or criminal acts (Schafer, 2015; Sanders, 2002). This important issue is picked up again in the next section.

3.3 Collisions and conflicts

The majority of collisions on roads are a result of human causes, and usually a combination of more than one type of human error or violation, plus possibly other vehicle and infrastructure factors (Sabey and Taylor, 1980). The UK Department for Transport (DfT, 2015a) suggest that the top five contributory factors are as follows: Driver/Rider failed to look properly, 46%; Driver/Rider failed to accurately judge other person's path or speed, 24%; Driver/Rider careless, reckless or in a hurry, 18%; Poor turn or manoeuvre, 16%; Loss of control, 13%. Such human factor-related concerns are promoted as a principal reason why all major governments including those in the UK, USA, and Europe are pursuing the agenda of AV development (e.g. DfT, 2015b, p. 4).

The propensity for unsafe human driving presents a significant challenge to AVs because the AVs themselves will be at risk of being involved in a collision or other unsafe situation which is the result of human error, and over which they may have little control. Therefore, understanding unsafe driving practices is important so that AVs may be equipped with the necessary technology and decision systems to respond in the most appropriate way when confronted with potentially hazardous situations.

Svensson and Hydén (2006, p. 380) define a conflict as 'a situation where two or more road users approach each other in time and space to such an extent that a collision is imminent if their movements remain unchanged'. A collision may therefore be defined as an unsuccessfully resolved conflict (Risser, 1985). The challenge to understanding conflict as a form of traffic interaction is that the majority of examples go unobserved. The majority of existing knowledge about road user interactions (especially empirical knowledge) focusses on serious conflicts and collisions, whilst the bulk of everyday road user interactions simply occur without incident and are thus not of particular interest from a traffic safety perspective.

Conflicts, or 'near misses', may, however, be of interest from the point of view of user experience, particularly non-motorised user experience because they may be unpleasant and hence discouraging (Aldred, 2016).

3.4   Managing the regulatory environment

Goldhill (2015) asks 'should driverless cars kill their own passengers to save a pedestrian?' This moral dilemma was first explored by Foot (1967) and became known as the 'Trolley Problem'.

Utilitarianism suggests the correct course of action is the one that 'maximises happiness', in this case minimising the loss of life. Others would argue that AVs should not be programmed to allow it to kill people external to the vehicle, with AV users knowing the risks.

Providing a preliminary popular resolution to the issue Bonnefon *et al.* (2015) found that 75% of a cohort of lay respondents (n=201) agreed that an AV should swerve into a barrier (killing its sole passenger) to save ten pedestrians. In an extension of their study (Bonnefon et al., 2016), they found, however, that this conviction weakened dramatically when *they themselves were the driver*. This result was revealed by a significantly reduced positive response to a question about how happy they themselves would be to either buy a utilitarian AV, and/or to accept government regulation mandating this type of programming. These crucial questions are being explored as part of the Venturer project, and they are not further dwelt on in this paper.

Adams (2015) examines how current visions of a driverless future neglect to take full account of pedestrians and cyclists and focus on vehicle-to-vehicle interactions controlled by algorithm. In the case of interactions between AVs and pedestrians and cyclists, programming to behave 'deferentially' could lead to AVs spending their time 'going nowhere', suggesting that AVs may not be a very efficient transport mode in urban environments. AV deference was exemplified by a chance encounter between a Google AV and a cyclist (Lewis, 2015) during a test drive on a public road in Austin, Texas. Although the car had arrived first at the intersection and had right of way, it was misled by the track stand manoeuvre executed by the cyclist while he waited for the AV to go, and was unable to move from the intersection for two minutes.

4   Recommendations for research

A series of research questions has been developed, answers to which would provide some clarity in relation to the introduction of AVs into existing urban road networks. The questions have been developed after a literature review of interactions between road users and the infrastructure (Parkin et al., 2016).

After introducing the relevant background literature, the resulting Research Questions (RQs) are introduced in bold type. The introduction of AVs is being promoted in the UK on the basis of a number of small scale trials of the technology. This appropriately cautious approach means that initial trials will use only a single or a very small number of AVs. Many RQs, however, would need a significant proportion of the motor vehicle fleet to be autonomous. To this end, many RQs will not be answerable in early trials.

As a context for the discussion, it should be borne in mind that pedestrians and cyclists have a right to 'pass and repass' on the public highway. However, the right to use the public highway using motor vehicles is subject to possession of both a vehicle licence and driving licence. These rights are subject to regulation orders put in place to manage the road environment.

4.1 Interactions between AVs and motor vehicles

Gstalter and Fastenmeier (2010) investigated errors committed in driving relative to the number of opportunities for errors based on a taxonomy of tasks and definitions for correct behaviours and errors in behaviour. **RQ: As a result of their greater predictability, will the presence of AVs introduce a degree of additional control into the vehicle mix, resulting in fewer errors by drivers?**

As discussed above a number of studies have found that the rate of aggressive driving in relation to collisions is high (Joint, 1997; RoSPA, 2011; Asbridge et al., 2003; Dąbrowski, 1998; and American Automobile Association, 2009). **RQ: How might an AV manage a situation in which another driver is**

being deliberately antagonistic, and driving in a manner with the intention to harm the AV and/or its occupants? While automation such as co-operative adaptive cruise control could help create uniform headway and similar velocities throughout a platoon, hence improving reliability and reducing collisions (Hardy and Fenner, 2015), decision making in mixed traffic streams would require AVs to respond to aggressive behaviour. **RQ: What decision making behaviour may be required of an AV to deal with aggressive behaviour of a human driver in a following vehicle?**

Harrell and Spaulding (2001) suggest that the decision to accept a gap when making manoeuvres at junctions is related to the *value* of undertaking the manoeuvre relative to the potential *cost* of undertaking the manoeuvre and use Gray and Tallman's (1984) model. Gap acceptance is understood and negotiated tacitly between drivers (i.e. a driver in the major stream who sees a vehicle in a minor stream at an intersection will have certain expectations about how that driver will behave, what gap is acceptable and so on). All of this is based on the way drivers select and view different areas of interest (Wickens et al., 2001; Lemonnier et al., 2015). **RQ: Do approaching AVs engender a different gap acceptance behaviour amongst other road users (including cyclists and pedestrians) at junctions and does this vary depending on how obvious it is that a vehicle is an AV?**

Shared space (Hamilton-Baillie and Jones, 2005), while still contested (Moody and Melia, 2014) is an urban realm improvement that seeks to reduce vehicle speed but then allow motor and other traffic to mix with pedestrians. Barriers, highway signs and road markings are replaced with subtle surface features, such as changes in colour and texture. **RQ: How will AVs behave in shared space?**

4.2 Interactions between AVs and cycles

In the context of creating appropriate environments for cycle traffic, various researchers have studied motivators and deterrents (e.g. Winters et al., 2011), and modifications to the built environment (Fraser and Lock, 2010). Others have focussed more on the cyclist and Dill and McNeil (2013) found most potential cyclists in the category of being 'interested but concerned', with others focussing on issues for women (such as Garrard et al., 2012). While there are complex and multi-factorial reasons why people may or may not cycle, there are significant groups of people who may be able to take advantage of the benefits of cycling if their perceptions of, and the realities of the hazards posed by motorised traffic can be ameliorated. **RQ: Will AVs assist, in the generality, in changing the perceptions of hazard posed by motorised traffic to cycle users? RQ: How does the presence of AVs with differing levels of automation affect interactions and decisions made by cyclists?**

Wood et al. (2009) note that poor environmental conditions can reduce a bicycle rider's conspicuousness. **RQ: To what extent would AVs be able to detect a cyclist in the road ahead when light and weather conditions are adverse?** They also noted that roads in built-up areas were associated with more door opening collisions. **RQ: Can an AV remain 'passively' safe by preventing passenger egress when it is not safe to do so?** Frings et al. (2014) studied attention allocation of cyclists and behavioural intentions in the context of the approach to the end of a queue of traffic. **RQ: Will cyclists allocate attention differently and behave differently around AVs in queueing traffic?**

Various commentators suggest changes to regulation in respect of cycles themselves (Robinson & Scoons, 2013) and traffic regulation (Phil Jones Associates Ltd, 2016) with particular emphasis on the value of a 'Universal Duty to Give Way' as obtains in many northern European countries. **RQ: What legislative changes might be particularly appropriate or helpful in the context of managing AV**

interactions with non-motorised road users? Various research has evaluated perceived risk of environments for cycling (e.g. Harkey et al., 1998; Wardman et al. 2000; and Parkin et al., 2007). **RQ: how may perceived risk be altered for cycle users by the presence of AVs in the vehicle stream?**

An important issue in relation to cyclist comfort is the distance of a motor vehicle overtaking a cycle. This has been well researched with many studies suggesting that cycle lane markings in typical road conditions do not significantly change passing distance and the effect on comfort and perceptions of safety is mixed (Walker, 2007; Parkin and Meyers, 2010; Shackel and Parkin, 2014; Stewart & McHale, 2014). **RQ: For different speeds, what is an appropriate distance to be provided by an AV when overtaking a cyclist in order to provide a minimum level of comfort for the cyclist?** Linked with this, research suggests that speeds are reduced when centre-lines are removed (DfT, 2007, see Figure 2), but the impact for cyclists lacks research (Stewart & McHale 2014). **RQ: Are AVs able to overtake cyclists both with and without centre line markings with no difference in the impact on cycle users' perceptions of safety?**

Figure 2 Passing distances are important in relation to cyclist comfort (Photo credit: John Parkin)

Road narrowings can be created by pedestrian refuges, central islands, pinch points, chicanes, build-outs and hatching and other carriageway markings. There has been increasing utilisation of such features as traffic calming measures within the UK. **RQ: How will cycle users negotiate road narrowings with AVs without the facility to use eye contact as part of negotiating the manoeuvre?**

Collisions for cyclists are more frequent at junctions than along links, with 63% of police recorded collisions in the UK between 2005 and 2007 occurring at junctions (Knowles et al., 2009). In around 50% of the reported collisions at junctions, the cyclist is going straight ahead (Phil Jones Associates Ltd., 2016). **RQ: How accurate are AVs in detecting cyclists who are making straight on manoeuvres at junctions across side roads either within the carriageway or on adjacent cycle tracks and what is the ability of the AV to come to a correct decision about its behaviour in relation to the cyclist or cyclists?**

Walker (2005) found that arm signals worked relatively well to inform drivers of the cyclist's intentions at junctions and were easier to perceive than informal signals. He also found that arm signals often slowed down decision-making processes, leading to a lower probability of their stopping in time when the cyclist was at risk. The same was true for informal signals in which there was eye-contact between the cyclist and the driver. These effects may come about because both arm signals and eye-contact are communicative acts and therefore produce extra stages of involuntary cognitive processing in the drivers, thereby slowing their reactions. **RQ: What is the extent to which AVs are able to decipher cyclists arm signals accurately at junctions?**

4.3 Interactions between AVs and pedestrians

The current UK Highway Code (DfT, 2016) advises pedestrians to yield to motorists in most circumstances and to abide by the traffic management measures provided for them. Underlying these rules is the notion that interactions between users of the transport network are predominantly controlled through traffic engineering and regulation, rather than through on-road negotiations between users. **RQ: how ought the Highway Code to be adapted to provide guidance to pedestrians (and other road users) on how to negotiate right of way with AVs?** This is linked in some ways with the 'trolley problem' discussed above. **RQ: how does the general population think AVs ought to be programmed to take action in the event of unavoidable collisions involving pedestrians?**

In a similar manner as for cyclists discussed above, there are issues about how AVs will detected and respond to pedestrians' signals and gestures. **RQ: How will AV sensing be able to detect and react to signals that pedestrians are gesturing and how will these be interpreted by the AV in its decision making?**

Pedestrians have different capabilities based on age and this is often manifest in walking speed (Cresswell et al., 1978; Wilson and Grayson, 1980; Griffiths et al., 1984). **RQ: How will AVs be able to detect different types of pedestrian (e.g. children and older people) in the environment and be primed to respond to potential crossing interactions accordingly? RQ: Will severance for pedestrians created by streams of motor traffic be increased or reduced by the presence of AVs?**

Interaction between pedestrians and AVs will occur mainly at carriageway crossings and hence an important interaction issue relates to gap acceptance (see for example Brewer et al., 2006). **RQ: Will pedestrians' intention to cross change as an AV (of varying levels of overtness) approaches and will this vary according to demographic (age, gender) or situational characteristics (traffic volume, road type, prior experience of AVs)? RQ: Should AVs signal that they have 'seen' waiting pedestrians and intend to give way, and if so, how should they do that?**

In a study of zebra crossings Varhelyi (1998) found that drivers give way less than half of the time, but they are more willing to stop if they are already travelling slowly. **RQ: Are AVs programmable to effectively and automatically adapt their speed within zebra crossing 'decision zones' regardless of whether pedestrians are present? RQ: What is the extent to which AVs are programmable to effectively and consistently respond to different types of crossing treatment?**

As Rule 8 of the UK Highway Code states, pedestrians have right of way across a side road if they have already begun to cross. This poses potentially interesting dilemmas depending on the relative speed of approach of the pedestrian and traffic within the carriageway. **RQ: How good are AVs at detecting pedestrians approaching and crossing side roads and are they able to respond accordingly? RQ: how do pedestrians react to an AV (of varying levels of overtness) when deciding whether to start to cross a side road?**

Pedestrian behaviour at signal controlled crossings has been studied by various researchers (e.g. Davies, 1992; and Parkin and Wilson, 2010). **RQ: What is the extent to which an AV will be able to detect non-compliance with signal controlled crossings by pedestrians who have become frustrated with the delay imposed on them by the signalisation of crossings? RQ: How will AVs respond to non-compliance (i.e. would an AV be required to defer to a pedestrian in its path in all situations when safe to do so, even on higher-speed roads)?**

Shared space has been extensively studied in relation to vehicle-with-pedestrian conflicts (Kaparias et al., 2013; Moody and Melia, 2012). **RQ: How do AVs affect perceptions of shared space amongst pedestrians? RQ: Will pedestrians feel more or less able to gain priority over AVs (compared to driven vehicles) in Shared Spaces?**

4.4 Final general themes

AVs, as they develop further, will begin to learn how to interact based on the recorded experiences the vehicles have had, and this machine learning will in some ways and to some extent parallel the way that humans have learned to interact on roads. This combination of machine and human learning and adaptation will co-evolve and the result will be revised 'cultures' and 'practices' in both the human and the machine. **RQ: How will the evolution of machine learning and related human learning take place while maintaining safe interactions between vehicles and cyclists? RQ: What roles will cyclists and pedestrians have in a driverless society and how will the presence of driverless vehicles change pedestrians' and cyclists' facility preferences and behaviour?**

The motor car changed social norms around how roads and streets are used and how urban areas are planned (Buchanan, 1963). Few would argue that mistakes have not been made in how engineers and planners and policy makers have responded to the technology of the motor car (Shaw and Docherty, 2013), but of course there are many who will emphasise achievements in highway and traffic engineering (e.g. Johnson, 2008).

De minimis, design may passively accommodate AVs and risk negative consequences such as more motorised traffic with commensurate reductions in priority for non-motorised road users. Alternatively, there is the potential for us to design systems in which AVs have a fundamentally different relationship with remaining non-autonomous traffic (be that human driven motor traffic, cycle users or pedestrians). Transport engineering and planning professions will shape those future relationships and indeed the shape of the urban public realm. **RQ: What will the main sources of influence be in shaping the philosophy of transport and urban planning and management in response to AVs?**

5   Summary and next steps

On the one hand, there are significant uncertainties and potentially long timelines to the introduction of Level 5 autonomy, particularly on urban roads. On the other hand, this is a rapidly developing field, with significant claims being made in some quarters. Table 1 summarises the research questions by thematic area that have emerged from the literature review and answers to these will help to reduce some of these uncertainties.

Thematic area	Research questions
AV Interactions with motor vehicles	MV 1. As a result of their greater predictability, will the presence of AVs introduce a degree of additional control into the vehicle mix, resulting in fewer errors by drivers? MV 2. How might an AV manage a situation in which another driver is being deliberately antagonistic, and driving in a manner with the intention to harm the AV and/or its occupants? MV 3. What decision making behaviour may be required of an AV to deal with aggressive behaviour of a human driver in a following vehicle? MV 4. Do approaching AVs engender a different gap acceptance behaviour amongst other road users (including cyclists and pedestrians) at junctions and does this vary depending on how obvious it is that a vehicle is an AV? MV 5. How will AVs behave in shared space?

AV Interactions with cycles	C 1.	Will AVs assist, in the generality, in changing the perceptions of hazard posed by motorised traffic to cycle users? RQ: How does the presence of AVs with differing levels of automation affect interactions and decisions made by cyclists?
	C 2.	To what extent would AVs be able to detect a cyclist in the road ahead when light and weather conditions are adverse?
	C 3.	Can an AV remain 'passively' safe by preventing passenger egress when it is not safe to do so?
	C 4.	Will cyclists allocate attention differently and behave differently around AVs in queueing traffic?
	C 5.	What legislative changes might be particularly appropriate or helpful in the context of managing AV interactions with non-motorised road users?
	C 6.	How may perceived risk be altered for cycle users by the presence of AVs in the vehicle stream?
	C 7.	For different speeds, what is an appropriate distance to be provided by an AV when overtaking a cyclist in order to provide a minimum level of comfort for the cyclist?
	C 8.	Are AVs able to overtake cyclists both with and without centre line markings with no difference in the impact on cycle users' perceptions of safety?
	C 9.	How will cycle users negotiate road narrowings with AVs without the facility to use eye contact as part of negotiating the manoeuvre?
	C 10.	How accurate are AVs in detecting cyclists who are making straight on manoeuvres at junctions across side roads either within the carriageway or on adjacent cycle tracks and what is the ability of the AV to come to a correct decision about its behaviour in relation to the cyclist or cyclists?
	C 11.	What is the extent to which AVs are able to decipher cyclists arm signals accurately at junctions?
AV Interactions with pedestrians	P 1.	How ought the Highway Code to be adapted to provide guidance to pedestrians (and other road users) on how to negotiate right of way with AVs?
	P 2.	How will AV sensing be able to detect and react to signals that pedestrians are gesturing and how will these be interpreted by the AV in its decision making?
	P 3.	How will AVs be able to detect different types of pedestrian (e.g. children and older people) in the environment and be primed to respond to potential crossing interactions accordingly?
	P 4.	Will severance for pedestrians created by streams of motor traffic be increased or reduced by the presence of AVs?
	P 5.	Will pedestrians' intention to cross change as an AV (of varying levels of overtness) approaches and will this vary according to demographic (age, gender) or situational characteristics (traffic volume, road type, prior experience of AVs)?
	P 6.	Should AVs signal that they have 'seen' waiting pedestrians and intend to give way, and if so, how should they do that?
	P 7.	Are AVs programmable to effectively and automatically adapt their speed within zebra crossing 'decision zones' regardless of whether pedestrians are present?
	P 8.	What is the extent to which AVs are programmable to effectively and consistently respond to different types of crossing treatment?
	P 9.	How good are AVs at detecting pedestrians approaching and crossing side roads and are they able to respond accordingly?
	P 10.	How do pedestrians react to an AV (of varying levels of overtness) when deciding whether to start to cross a side road?
	P 11.	What is the extent to which an AV will be able to detect non-compliance with signal controlled crossings by pedestrians who have become frustrated with the delay imposed on them by the signalisation of

		crossings?
	P 12.	How will AVs respond to non-compliance (i.e. would an AV be required to defer to a pedestrian in its path in all situations when safe to do so, even on higher-speed roads)?
	P 13.	How do AVs affect perceptions of shared space amongst pedestrians?
	P 14.	Will pedestrians feel more or less able to gain priority over AVs (compared to driven vehicles) in Shared Spaces?
General themes	G 1.	How will the evolution of machine learning and related human learning take place while maintaining safe interactions between vehicles and cyclists?
	G 2.	What roles will cyclists and pedestrians have in a driverless society and how will the presence of driverless vehicles change pedestrians' and cyclists' facility preferences and behaviour?
	G 3.	What will the main sources of influence be in shaping the philosophy of transport and urban planning and management in response to AVs?

It is clear that there are many questions to be addressed in relation to the interaction of technology with other road users as humans. An important question for the policy and research community is now concerned with how these questions might be prioritised. There are a number of domains that AVs will influence, including attitudes and behaviours in relation to transport generally and mode and route choice in particular and, of course, safety. One the one hand, technology stakeholders in this field of inquiry might be more principally concerned with developing minimum viable products to place in the market as soon as possible. On the other hand, policy makers have a key role in regulating not only the ultimate environments in which AVs might operate, but also the processes and procedures as the future unfolds. Based on the nature and extent of the questions, it could be argued, certainly in the context of urban roads, that the more pressing and safety critical issues concern interactions with cycle users and pedestrians. This is partly resulting from the rather different and more heterogeneous forms of interaction that exist between these user groups and motor vehicle drivers.

The introduction of new vehicle technology will have significant implications for the way that the design and management of urban road infrastructure is approached. The Venturer project is undertaking three sets of trials using the Wildcat vehicle. The first set observed the hand-over of control from the AV back to the human driver. The second set tested the trust of autonomous vehicle passenger in both the Wildcat and the Venturer simulator to being driven with other motor vehicles present. The third set of trials explores trust where there are pedestrian and cyclists present. The literature review that has been summarised in this paper, together with the resulting research questions that emerge, has been forming one of the inputs into the development of the design of the trials.

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