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A constructive role for social science in the development of automated vehicles

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ABSTRACT

Automated vehicles (AVs) have the potential to cause profound shifts across a wide range of areas of human life, including economic structures, land use, lifestyles and personal well-being. Most current social science on AVs is narrowly framed. Research on public attitudes has focused on whether people are likely to accept and use AVs. We contend that failing to anticipate a wider range of profound social implications may have serious negative consequences, and that social scientists from a range of disciplinary perspectives can provide invaluable insights. Our conclusions are the product of a workshop in London held in 2018 to discuss the place of social science research in relation to the development of AVs. This paper summarises a core selection of our concerns, interests, theoretical and substantive points of reference and aspirations for a constructive role in this field of research and development.

1. Introduction and background

This article is jointly authored by a group of social scientists. It is the product of a workshop held in London in April 2018 to discuss the role of social sciences in the development of automated vehicles (AVs). The authors are mostly based in the UK, and come from a range of disciplines: transport studies, science and technology studies, sociology, social psychology, planning, anthropology, geography, politics, and social policy. The workshop involved conversations between ourselves as well as with a selection of actors involved in the development of AVs, including government researchers, policy makers, analysts, academic and commercial engineers and original equipment manufacturers (OEMs). The views stated in this paper are, however, our own.

The development of AVs brings potentially fundamental changes to daily life, and the degree and acceleration of investment in it by governments and private companies signals the extent of anticipation in their development. One estimate suggested that by 2017 more than $80 billion had already been invested (Kerry and Karsten, 2017). A more up-to-date survey would surely indicate a much larger number. Companies and national governments claim to be in a 'race' to develop driverless technologies and capture their economic benefits (Welch and Behrmann, 2018). AVs are often presented as inevitable. Debates about them are pushed by claims about the possibilities of new technologies, with substantial focus on a promised

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increase in safety. The starting premise for this paper is that framing issues in largely technological terms obscures both our understanding of the social and political complexities that might accompany any technological benefits, and the consideration of alternative mobility trajectories. The indeterminacies and uncertainties of innovation may mean that the technology ends up taking a very different shape from the narrow range of possible futures currently being imagined, and it would be foolhardy if not actively dangerous to neglect this broader view.

Alongside the growth of investment and political interest in AVs we have seen rapid growth in research publications. Gandia et al. record an average annual growth rate in publication numbers of 39% (2019, p. 15), confirming earlier findings by Cavoli et al. (2017). But the social has received less attention than the technological. Moreover, the significance of the social, and the role of social science, has been limited, as is so often the case with the development of new technologies and their surrounding scholarship. Social science and humanities research is often restricted to work on 'implications'. With genetics, for example, social scientists, philosophers and lawyers were asked to get involved in what came to be labelled 'ELSI-fication', researching the downstream 'ethical, legal and social implications' of new technological possibilities (Guston, 2004; Stirling, 2005). Sometimes the role of social sciences has been framed in even more instrumental terms, with its job being to understand public anxieties with the aim of smoothing the uptake of a predetermined technology – social scientists have often been cast merely as "experts in the study of public opinion" (Macnaghten et al. 2005, p. 271). While social scientists can provide much-needed rigour and clarity in doing this, their role in the emergence of AVs can and should be deeper and broader.

We are not alone in this line of thinking. Bissell et al. (2020) argue that critical sociology can and should play a constructive role in public debates about the development of AVs. We aim to push this argument further, and to persuade the reader that a larger spectrum of social sciences should also contribute actively to the development and governance of AVs. Our agenda is a critical one, challenging what we see as the dominant story, but it is also constructive. Our hope is that, through challenge, we can contribute to more robust patterns of innovation that, by engaging with social dimensions, are better able to realise opportunities for fair, safe, efficient mobility than if innovation was left to the relatively narrow set of interests currently leading the process. As well as providing social evidence and insight, social science can serve a purpose in understanding and integrating different perspectives. However, how to do so is not a trivial question. The answer is not just 'more social science'.

In our view, constructive social science means moving beyond the conventional and restrictive division of labour between the development of technology on one hand and assessment of it on the other. Practically speaking, this should entail new modes of collaboration with those involved in the development of the technologies. For example, an underappreciated benefit of the social sciences is in generating concepts that can, when built into use scenarios, help technologists and system architects increase the resilience and robustness of their thinking and planning. Models exist for this in other areas of technology development and implementation. For example, the regulation of water usage (Floress et al., 2015) has benefitted from such an involvement of social scientists. In a similar way, rather than only playing a role downstream in the assessment of impacts, implications and unintended consequences, we seek to make a contribution upstream, in the design and governance of sociotechnical systems and the transitions towards them.

The social sciences can offer tools for integrating perspectives at both philosophical and practical levels. We follow Flyvbjerg (2011) in advocating a mode of social science based on *phronesis* (practical wisdom) as well as *episteme* (scientific knowledge) and *techne* (craft knowledge). We see the role of social science not just in contributing to the knowledge base, but also in reframing questions and highlighting uncertainties and contingencies, with a view towards more "tentative" modes of governance,[1] putting technology 'in its place' in terms of both understanding and respecting the contexts in which it might be deployed.

We think that there is appetite for this mode of working, and we detect a willingness among stakeholders in AV development to understand the social dimensions of AV technologies. The more thoughtful innovators know that the technology, if it is to succeed in its own terms, must work with and incorporate the social complexities of the real world. From our own side, we appreciate and need to learn more about the perspectives of those other actors. We are acutely aware of the competitive drive to develop a technology that promises substantial economic and social benefits. And we know that any number of interests can shape the creation of new technological possibilities. We know that complex technological systems are defined as much by how they are diffused and used as by how they are developed in the laboratory. Many of us have been involved in the nascent debate on AVs, often in collaboration with engineers and/or policymakers. Some of us come with experience of previous transport debates or previous emerging technologies, from which policymakers and innovators have learnt sometimes hard lessons.

2. Themes

In the remainder of this article we offer a discussion of potential social science contributions with a view to developing a critical, constructive research agenda. We organise this thematically (rather than by academic discipline), as follows:

1. Single versus multiple futures
2. The public(s)
3. Distributional impacts
4. Safety
5. Physical infrastructure
6. Data
7. Environment
8. Governance and power

We do not claim to offer an exhaustive account of social-science thinking here; our text reflects the backgrounds of the particular academics who participated in the workshop and who have contributed to this paper. In particular, the majority of us are UK based and most, though not all, of our research on AVs is centred on high-income countries. In addition, the bulk of our discussion centres on AVs for personal transport; we make some references to the possible role of automation in transporting freight, but do not consider other areas of AV use. This paper is offered as a springboard rather than as a prescription, and we encourage other social scientists to add to and develop the thinking that we offer here.

In the sections that follow we aim to outline briefly relevant background in terms of AV development as well as in terms of social-science perspectives: frameworks that have been used, their strengths and limitations and, where relevant, suggestions for others that may be enlightening. We draw attention to particular areas of focus that we think are important, and offer ideas for potential contributions from the social sciences: issues to be researched, advocated for, actions to be taken. The value that social sciences can bring ranges from a broadening of understandings of a topic, enabling important nuances or complexities to be appreciated, to active involvement from the earliest point in the development of both the technology itself and its regulation.

2.1. Single versus multiple futures

One of the most important realisations for an overview of our subject matter is its inherent plurality. When possible AV futures are described in public, they may have various forms, even if each individual vision is presented with certainty, as a prediction. AVs may be imagined, for example, as an individually-owned car with someone in the driving seat who just happens not to be driving; they may be seen as part of robotaxi fleets that are integrated into Mobility as a Service (MaaS) systems; they may look radically different from conventional cars, with their own road infrastructure.

[1] As Kuhlmann et al. put it, "tentative" governance is contrasted with "definitive" governance and reflects the inherent uncertainties in emerging science and technology. "Governance is 'tentative' when public and private interventions are designed as a dynamic process that is prudent and preliminary rather than assertive and persistent" (Kuhlmann et al., 2019, p. 1091).

The social contingencies of each vision may be highly distinct, and likely to lead to very different public discussions, but these differences are often unacknowledged.

The dramatic changes implied by some AV futures are also often played down or not acknowledged. Much of the coverage to date on AVs suggests that the technology – in whatever form – will simply arrive on our roads, that people will start benefiting from it and that little else will change. This narrative is convenient for innovators but misleading, because it skirts around the profound questions about what such a potentially disruptive technology might mean. People and environments are shaped in response to technologies and, in turn, shape them. The narrative is also misleading because it encourages us to trust that all will be well and to postpone scrutiny of the purposes and consequences of the technology. Understanding the possibilities of AVs means understanding the inter-relationships between people, vehicles and environments, and the consequences of those relationships. Sometimes those relationships are conflictual or oppressive, and (looking forward to the themes of distributional impacts and power) a key role of social scientists is to scrutinise and challenge those dynamics.

The meanings involved in automation are as much about the new identities and subjectivities related to it as the hardware and software that drives it. As such, the field for social-science research is multifarious, and another part of our challenge is to map the terrain – for example, identifying what is meant by 'people', and how many different meanings are entailed in this term. Some AV developers may simply focus their attention on potential purchasers of private AVs, but consumption of AVs would likely entail a substantial impact on others who are forced to share the road with AVs, whether as other drivers, cyclists or pedestrians. The notion of a smooth transition to an AV world should not be taken for granted.

In this space of multiple possible trajectories, social scientists are not unique in their capacity to foresee the many possible 'AV worlds' but, given the many conceptual frameworks in our repertoire for making sense of complex social contexts, we can offer organising principles of thought to keep the possibility space tractable. The themes, concepts and disciplinary frameworks outlined in the next sections can contribute to this architecture.

2.2. The public(s)

Perhaps the most obvious role for social science in the development of any emerging technology, and the one in which technology developers are most likely to cast social scientists, is in understanding public opinion or attitudes. Research into users' reactions to and interactions with AVs is a central part of AV development; it falls under the heading of *human factors* research, typically carried out by psychologists within engineering research programmes. Developers of AVs need to know, for example, how users would behave and adapt to their new role when an AV takes control from or needs to hand back control to a driver.

These micro-level questions of human-machine interaction (HMI) have broader corollaries, arising from the profound changes to the constitution of the road that AVs suggest: how would humans (drivers, pedestrians, other road users) interpret the actions of AVs and vice versa? How might humans behave towards vehicles without a human driver? Technology-oriented HMI research does not account for questions about how AVs will be adopted and appropriated by people in their everyday lives, or more broadly how people's relationships with AV technologies might emerge and develop over time. This is one area where we think that social scientific approaches can provide valuable insights.

This task starts with a conundrum, however. According to classic attitude theories, attitudes may be inferred from the evaluative responses people express towards a defined attitude object, in the form of opinions, behaviour or other reactions (Eagly and Chaiken, 1993). But, asked about their attitudes towards AVs, different people will imagine different things by "AVs". People's future reactions to emerging technologies are therefore impossible to map definitively. Some may take this as an argument for disregarding public opinion altogether, but we would disagree. Moscovici's Social Representations Theory (SRT) proposes that people make sense of new information by anchoring it within pre-existing concepts, turning the unfamiliar into the familiar (Bauer and Gaskell, 1999). Abelson's (1981) Script Theory proposes that we organise our behavioural routines into expected scripts, so that new possibilities are integrated into existing patterns of behaviour. These theories offer some scaffolding for researching new technologies and, by presenting a range of possible futures to people, we can gain a richer understanding of the factors or principles that underlie their attitudes. Methodologically, we need to keep at the front of our minds that the way in which we frame or present new technologies to research participants is crucially important for how they react, and we need to do this reflexively.

Tennant et al. (2019) provide a simple overview of the framings employed in general public surveys of AVs. In the literature to date, we typically find majorities of respondents expressing discomfort at the variously framed prospects of AVs (e.g. European Commission, Directorate-General for the Information Society and Media and TNS Opinion & Social, 2015; European Commission, Directorate General for Communications Networks and TNS Opinion & Social, 2017; AAA NewsRoom, 2019), although in Asian markets survey respondents have tended to view the technology more favourably (Schoettle and Sivak, 2014). Surveys have elicited concerns over issues such as safety, cybersecurity, and anticipated cost, as well as doubting the usefulness of the technology (Cavoli et al., 2017). They also find enthusiasm for possible benefits, such as reduced congestion or time freed up by not driving, in some cases exploring the relationship between the two (e.g. Wadud, 2017).

Although a range of framings can be seen in this research, there is a notable tendency to situate the topic within the routines of private-car purchase and driving (e.g. Kyriakidis et al., 2015), and to focus on testing and explaining people's willingness to use and willingness to pay for self-driving technology, casting the role of the public narrowly as potential users or consumers of the technology. The Technology Acceptance Model (TAM) has often been deployed in this literature in an attempt to understand how to encourage people to 'accept' AVs and persuade them the technology is safe (e.g. Hutchins and Hook, 2017). The TAM usually focuses on perceived usefulness and ease of use of the technology as predictors of uptake. But the long history of attitude research in social psychology tells us that expressed opinions are often not consistent with behaviour. Myriad factors are at play in explaining people's behaviours, as well as their moment-specific attitudes, and context is key.

Understanding the heterogeneity of contexts in particular is crucial. The focus on whether people are willing to get in to and use AVs neglects the views of people sharing the physical space into which new mobility systems would be introduced. For most people, first encounters with AVs will be as drivers, cyclists or pedestrians required to interact with them. The TAM has historically been used to explain how new technologies succeed or fail as they are used by employees in organisational settings. This provides a naturally bounded and relatively homogeneous context, quite different to the diverse contexts that constitute public responses to a new mobility technology, or even system.

Transport researchers have long sought to understand the multiple roles that people enact in relation to the transport system, often employing segmentation analyses to differentiate people into distinct (potential) clusters (Rode et al., 2015; Bansal et al., 2016; Anable, 2005). They recognise that public opinion should not be treated as homogeneous, nor as a binary work/leisure transport, willing/unwilling to use/buy etc., but rather that multiple attitudes and behaviours towards AVs will emerge among multiple social contexts and, often, within individuals.

Hildebrand and Sheller (2018) offer an early study of the cultural context of AVs, following historical associations between automobility, gender and sexuality (Mellström, 2004). Their study of media promotions for Nissan's and Volvo's AVs shows a recalibration of masculinity. AVs, most likely powered by quiet electric engines, reduce the driver's control of the vehicle, mainly relegating *him* to the passive role of passenger and challenging tropes of mastery, noise, power, masculinity and heterosexuality that have been selling points for cars. We note that the retention of a 'driver' role differentiates the approaches taken by technology firms versus vehicle manufacturers, the latter seeking a continuity of custom from their existing market.

In the course of mapping diverse attitudes and multiple groupings in relation to AVs, we need to ensure that we range widely enough in the questions we ask research participants. AVs may have profound and far-reaching impacts, and we should be asking research participants for their reactions to major as well as minor alterations to daily life. For example, how do they feel about possible changes to land use and social norms that may result from AVs? How do they feel about shifts in responsibility for decision-making on the road, from human drivers to AI systems? How do people whose jobs involve driving, or running existing transport systems, feel about a technology that could lead to a restructuring of employment? What do people think of the possible wider health and economic impacts of the development of this technology?

We argue that it is necessary in modern democracies to engage with the public over these kinds of issues, as the technology is being developed. The relationship between, for example, biotechnologies and diverse publics (Gaskell et al., 2000) suggests that, however difficult they are to research, today's attitudes towards tomorrow's technologies need to be heeded. Public (and interest group) reactions may be surprising, antagonistic or mischievous as people engage with the technological novelty and guess at its social constitution. With many technologies, including genetically modified crops, nanotechnology and synthetic biology, promotors have failed to respect public opinion, and treated it simply as a challenge of educating the public into acceptance. This stance, exemplified in what some call the "deficit model" (e.g. Welsh and Wynne, 2013), has limited explanatory power because it imagines the public in narrow terms, and has also been criticised on normative grounds (Wynne, 2006).

AVs are being tested in some places on public roads, which means that some members of the public are already encountering a version of the technology. Here, prototype testing in social environments is framed as an opportunity for public engagement with innovation – as for example with the Gateway testing of pods in Greenwich park, London (McDowell-Naylor, 2018), or UK Autodrive testing in Milton Keynes and Coventry (UK Autodrive, 2019). The introduction of AVs into society entails a potential change in the very ways in which publics first encounter new technology, through experimentation in society rather than through public consultations on new regulatory frameworks (Lezaun et al., 2017; Marres, 2018).

Social-scientific research into attitudes towards AVs should not present 'the public' as an entity of one mind, nor be equated with market research designed to achieve AV adoption. There is considerable existing scholarship in researching the public's relation to other new technologies from which lessons can be learnt, and theoretical frameworks borrowed. Social scientists can offer ways of systematically exploring the multifarious nature of people's responses to actual and imagined AVs, and track their evolution over time. Social scientists can also offer models for public engagement that go beyond top-down education projects (e.g. Wilsdon and Willis, 2004).

2.3. Distributional impacts

Claims for technologies are often presented in terms of aggregate benefits, balanced against aggregate risks, with strong incentives to accentuate the positive. Promotors of AVs are no less utilitarian in their discourse. However, the promised gains of new technologies rarely match the actual pattern of eventual benefits. In blunt terms, we can expect there to be winners and losers, and we may not predict accurately how these play out.

Notwithstanding the multiple possible AV worlds discussed above, we can expect the hardware of AVs to be expensive, at least to begin with and perhaps for a long time. And we can reasonably expect that the use of AVs would not be universally affordable, even following bullish scenarios of the potential cost-savings from removing taxi drivers. Public attitudes to AVs will likely be differentiated by social groups and conditioned by perceptions of the uneven benefits and risks of the technology. Groups who stand to benefit most, including poor or disabled people, may be marginalised by the implementation of the technology, and – a warning for us – made invisible by social research conducted without sufficient thought about the multiple user and non-user groups. We need to ask who might "lose" or even be harmed by the introduction of the technology. There is a risk that the existing injustice caused by unequal access to conventional private cars (Lucas, 2012) may be exacerbated, for example. How might existing inequalities be reproduced, entrenched, or changed, with the introduction of AVs? Of course this hinges crucially on what form AVs take – so is strongly linked to the theme of 'AV worlds'. These inequalities might be usefully separated into two domains: technical design, and social-structural.

At the level of technical design, we should ask, for the various future scenarios, who would be able to use the new technology applications, who would be physically excluded, and who might be placed in a position of more physical risk. There is a significant gap between saying that the technology will assist those whose accessibility may be limited because of personal circumstances, and creating interfaces that are truly inclusive. Thought must be given to whether systems will be accessible to someone who may be blind, may not own a smart phone or hold a bank account. In terms of safety, we need to scrutinise how AVs make decisions in near-accident situations, and whether their dominance would eventually push certain other users off the roads.

At the level of social and societal structures, we need to ask, for the various future scenarios, who would have the opportunity and the means to use the new technology, and who would be economically or geographically excluded. AV developers will have incentives to follow likely consumers, which means wealthy professionals who are likely to already have mobility options. We need to ask what this means for those who are unable to afford to buy or rent such a vehicle and how this maps onto those with mobility needs. And the technology will be limited by geography, certainly in its early days. Many AVs systems may be 'geofenced' to particular cities (Fagnant and Kockelman, 2018) or constrained for use on particular road types. Most development attention currently seems focused on urban centres. Those who would rely on shared AV systems (where journeys are made in vehicles not exclusively owned by the user) may find that availability differs greatly between urban and rural areas, and between rich and poor areas. Even if AVs in principle can bring access to groups that have hitherto lost out, the practice may be very different. There is a clear role for government policy in helping to even out access to the technology. However, this might come at a substantial cost if infrastructure in rural areas, where people typically have less access to other modes of transport, needs to be upgraded to enable the vehicles' operation.

There is substantial interest in the question of when AVs will arrive as a workable technology. As social scientists, we would say the more pertinent questions are where, for whom and in what form might the technology arrive (Cohen and Cavoli, 2016, 2019; Cavoli et al., 2017)? And where, for whom and in what form(s) *should* it arrive? Social science can help focus policy attention on what society might want from the technology and outline how the technology might or might not help, feeding actively into policy decisions about how it is developed.

2.4. Safety

Promoters of AVs often make the safety case for them central to their communications: human error is responsible for the vast majority of motor accidents, and so the argument is made that removing people from the steering wheel will logically result in a vastly reduced number of accidents. However, the complexity of current road driving is an enormous challenge for AI. How to teach AVs to manage the road is a technical challenge, but it needs to be accompanied by social science input on two important questions: what defines acceptable levels of safety? And how will safety standards be developed and regulated, at both national and international levels?

Users of public transport expect a higher level of safety than they tolerate in their own driving – it has long been known that with a train or aircraft, passengers' levels of acceptable risk tend to be orders of magnitude lower (Starr, 1969). A majority of drivers believe that their driving skills are better than average (Sundström, 2008); this with the increase in control (and convenience) offered by driving offer some explanation of people's willingness to engage in this statistically riskier form of transport. So we need to understand citizens' perceptions of acceptable levels of risk from AVs: do the public expect AVs to be significantly safer than human drivers? How safe is 'safe enough'? (Fischhoff et al., 1978).

Some (e.g. Kalra and Groves, 2017; Sparrow and Howard, 2017) have argued that automated vehicles should be introduced very quickly, once it can be assured that they perform slightly better than average human drivers. But it is simplistic to compare new technologies against older ones on the basis of aggregate performance – and not trivial to decide exactly how to measure aggregate performance. The current hazards of driving are highly socially and geographically differentiated. Newer vehicles and, in particular, those with 5-star safety performance, are far safer than old ones (Lie and Tingvall, 2002; Kullgren et al., 2010) but cost more, with the consequence that their benefits are enjoyed by wealthier drivers. Road conditions and terrain, and driving culture, are also key determinants of safety statistics such as accident rates.

It follows that there may be segmentation in expectations of safety: for example there may be early adopters who would welcome AVs even with the qualification that there might be some risk in using them. Social-science studies of technological risk find that the question 'how safe is safe enough?' is tied to the imagined purposes and beneficiaries of the technology. The question becomes 'safe enough for what?' (c.f. Liu et al., 2019) and, we would add, 'safe enough for whom?'

It is crucially important to pose and discuss these questions, as the history of car use teaches us. In the USA, for example, for many years it was felt that a high level of death on the roads was a reasonable price to pay for enjoying the benefits of the car, and that it fell to industry and not government to address the problem (Norman, 1962; Vinsel, 2018). From the introduction of motor vehicles in the USA it took some 70 years, and the persistent action of people such as Ralph Nader (Center for Autosafety, n.d.), until there was concerted regulation of the safety performance of those vehicles.

Nowadays there are several regulatory models for safety at the national and international levels. There is also no shortage of new technologies that will save lives even in non-automated vehicles, as revealed by the evidence base for proposed revisions to the European General Safety Regulation on the minimum safety equipment for new vehicles (Hunt et al., 2017). Simple technologies to force compliance with existing speed limits alone would make driving substantially safer (Lai et al., 2012). But these technologies are not, for the most part, being promoted by vehicle manufacturers.

On this evidence, then, we should not rely on industry self-regulation for safety standards in AVs. This is not a controversial stance in, for example, the UK, where the Law Commission (commissioned by the UK government's Centre for Connected and Autonomous Vehicles) has been active in consulting for and developing proposals for regulation of AVs (Law Commission, 2018). The process of setting and assessing standards will be socially (as well as technically) complex, including verification of the automated driving system's performance in what have been hitherto human functions — understanding of both formal and informal rules, perception and reaction, gap detection and manoeuvring, and adaptation to changing road and traffic conditions. A slow response to fatal crashes by US regulators (National Transportation Safety Board, 2019; Shepardson, 2019) suggests that other countries may need to lead the international debate.

2.5. Physical infrastructures

Despite the narrative of autonomy, in which the promise is that AVs "change the world without changing the world" (Stilgoe, 2019), if the technology is to become commonplace, it will demand, to a greater or lesser degree depending of the form it takes, changes to physical infrastructures – such as transport systems, town and city planning, and architecture. Changes to infrastructure and the built environment have profound social, political and environmental implications (Tierney, 2017). Urban space in particular is highly contested. Different groups want different things from cities and their transport systems, and not all voices are heard equally. Changes to cities are path dependent: established cities represent the accretion of centuries of development and redevelopment as societies have evolved their technologies – especially those for mobility – and economies.

Even though the future deployment of the technology is not yet clear, we are already seeing proposals for design and redesign (e.g. Noyman et al., 2017; Guerra, 2016). Advocates for AVs suggest that the technology would have myriad planning benefits, but would not at first require any changes to infrastructure. Bilger (2013) quotes Sergey Brin, president of Alphabet: "A fleet of vehicles could operate as a personalised public- transportation system… streets would clear, highways shrink, parking lots turn to parkland." While developed cities will have slow, messy transitions to new technologies, developing cities may be designed around a particular AV technology, just as cities were planned around the car in the Twentieth Century.

But there will doubtless be unintended planning consequences of widespread adoption of privately owned AVs, MaaS, or both (Pangbourne et al., 2018). These could include large peri-urban vehicle depots to replace urban parking (Alessandrini et al., 2015; Heinrichs, 2016) and increased sprawl as reduced journey costs and freedom of movement encourage longer trips (Papa and Ferreira, 2018). As places are upgraded, regenerated or reimagined as 'smart cities', things that were accepted as facts of life are opened up for renegotiation. AVs are a seductive part of these visions (Calvillo et al., 2016), because they promise to turn the independent, unpredictable driver into something more legible.

Social scientists should play a role in understanding the impacts and inequalities of proposed changes to already unequal infrastructures and advising on alternative trajectories and their governance. We should not wait for an AV-related infrastructural disaster (Graham, 2010) before recognising the significance of the architecture and infrastructure on which the new technology depends.

2.6. Data

Though less visible, an equally profound and more rapid part of AV transitions will be developments in digital systems. The systems inside AVs and the connections they make with each other, other road users and other infrastructures (particularly in urban settings) will all be data-driven. The safe and efficient running of AVs will require communication between vehicles and data/information systems (Agrawal et al., 2018). The digital connectedness of vehicles has already been growing for the last few years, and the possibilities of automation suggest an increase and intensification of this data-gathering.

On a simple level digital systems are part of the theme of infrastructure, and key issues relate to capacity and designing systems that function adequately, and for social science about the nature of work in those systems. But the infrastructure and the content it collects have profound implications for privacy, security and freedom, and social science can play a role here, particularly in explicating and advocating for citizens' rights. Emerging social-science research into the politics of data and algorithms will be an important part of understanding and scrutinising possible AV systems. Questions of data bias, data ownership, data use and data sharing are likely to become even more politically important in the context of AV worlds, alongside those of accountability of machine learning systems in, for example, crash investigations (Winfield and Jirotka, 2018; Stilgoe, 2018). The questions surrounding data pertain not just to the safety and security of AV systems, but also to the distributional impacts in terms of who benefits and how.

Both digital and physical infrastructures, and the rules that emerge around them, can be understood as a form of "solidified politics": they are the accreted products of political contestation over time, that contestation being a multi-way process between diverse actors. When studied alongside cultures and patterns of social behaviour, we see that these systems are not just things to be "disrupted" by innovation, but can equally be understood as factors that may constrain attempts to deploy new technologies at scale. The dynamics of how these systems develop invoke questions redolent of many aspects of social science, including political theory, philosophy, ethics, law, social psychology and social anthropology. As with the theme of safety, leaving data systems regulation to accident or industry would be deeply irresponsible. The challenges and issues implied under the heading of 'data' will be viewed very differently in different political ideologies, by commercial organisations, governments and international organisations, and among citizens. Social scientists can help to theorise and operationalize the questions of what different data systems imply for people's security and privacy, what gains and losses they incur, and for whom.

2.7. The environment

The potential environmental benefits of AVs have been widely discussed and cited as motivations for their development. The move away from fossil fuels is not inherently tied to AVs alone, but most representations of AV development appear to assume the use of electricity (which will presumably be sustainably sourced). The potential energy savings from getting vehicles off the road is also often referenced in discussions of MaaS deployments of AVs. Carbon emissions of AVs will be a function of travel activity, the energy intensity of travel and the carbon intensity of the energy source. Early studies on impacts of vehicle automation have focused on energy or carbon intensity only. There are several mechanisms that could improve fuel efficiency of individual automated vehicles, including improved traffic flow through improved connectivity, platooning to reduce drag and lighter-weight vehicles if crash risks are demonstrably lower (Wadud et al., 2016).

However, AVs could also increase car use through widening access, increasing convenience and encouraging empty running, thus resulting in net environmental damage. Much research has suggested that AVs are likely to boost travel demand and energy demand (Wadud et al., 2016; Auld et al., 2018; Taiebat et al., 2018).

It seems, therefore, that governance is needed to ensure that any possible environmental benefits of AV are harnessed. While there is a strong synergy between electrification and automation of vehicles (e.g. higher utilisation of automated mobility services vehicles will likely produce a better economic return for electric traction than internal combustion), it appears the development of electrification would still likely be governed by policies and air quality concerns, rather than automation. The future will be determined more by the attitudes and decisions of users, citizens and policymakers than by any inherent characteristics of the technology. Even though developers of AV hardware and, in particular, software, claim that the technology is 'just around the corner', much of what needs to happen to enable a functioning, low-carbon transport system and a fair transition to such a system lies well beyond the control of technology developers alone.

Indeed, managing the transition is just as much a challenge as agreeing on an aimed-for future mobility scenario. In terms of both possible future AV worlds, and possible future journeys towards those AV worlds, there has already been a deal of varying speculation. The slow pace at which the vehicle fleet evolves must not be ignored: for many years and perhaps decades after the first putative fully automated, electric vehicle is offered for sale, the bulk of vehicles will be manually driven and powered by fossil fuel. And the likelihood of a dramatic switch from ownership to mobility services is uncertain. Arbib and Seba (2017) suggest every urban household would give up vehicle ownership, while Wadud (2017) is more conservative about such changes. Some have considered the likelihood or desirability of prohibition of private ownership of AVs in dense urban areas on sustainability grounds (Thomopoulos and Givoni, 2015), the assumption being that all AV use would instead happen through shared-use platforms. Each scenario could have substantial implications for environmental impact. As such, understanding the evolution of exclusive-use and shared-use mobility services is key to understanding the energy and carbon effects of automated vehicles.

2.8. Governance and power

Governance is the steering of social, political and technological change. It involves complex and polycentric power relationships, in which the authority to influence mobility is dispersed across different types of actors, scales, and institutions (Rhodes, 1996; Stoker, 1998; Hooghe and Marks, 2003). Theories of governance recognise the state as one player in decision-making and implementation processes. The rules for the function of mobility systems are determined by the state, non-governmental agencies, private sector and third-sector organisations interacting with one another. These actors' influence may be determined constitutionally (they have a specific role determined in law, for example), financially (through their ability to levy taxes or access private equity for example), or through their collection of, or access to, information and data (Rhodes, 1996).

Therefore, understanding the current governance system surrounding automobility, how it is changing and how it should be altered with the advent of AVs, is essential for realising the potential benefits of AVs, and mitigating their risks (Marsden and Reardon, 2018; Cohen and Cavoli, 2019). A transition to AVs could challenge the status quo in many ways, shifting power to different actors within the governance system. For example, successful integration of the technology for AVs requires interoperability, the rules and standards for which may need to be decided at the supranational level, which may reduce the autonomy or influence of subnational actors, such as local authorities, in determining the nature of road infrastructure and how it is used and managed. The locus (or loci) of power within the governance system will therefore be crucial in determining the nature of how AVs will operate, and the ability to effect change in the system once implemented.

Economics and political economy provide tools for understanding the implications of the state-market-society nexus for the emergence and governance of AVs. The role of data in the running of self-driving systems will make AV markets more susceptible than others to monopolistic competition. There are likely to be substantial economic returns to scale in AV systems, given a dependence on data and machine learning, and the efficiencies that are likely to come from running fleets as opposed to individual vehicles. Data hoarding could impede the possible safety benefits of AVs (Krompier, 2017).

Any scrutiny of power in a (developing) AV world needs to include an appreciation of the role of ideas in shaping political economies and eventually determining policy pathways (Rodrik, 2014). As in other new areas of transport (such as car clubs which, as part of the sharing economy, led to a reshaping of the relationship between the market and the state), the way in which consumers of an emerging technology are imagined by private- and public-sector stakeholders will influence what is offered to them and in what form (Akyelken et al., 2018; Bergman et al., 2017). This returns us to the theme of the "public", discussed earlier. With a particular concern regarding power dynamics, as social scientists we need to highlight (hidden) inequalities or absent voices – for example, that seat belt systems are designed for male drivers; that opinions are disproportionately sought and obtained from wealthy white males who already enjoy high access to mobility (Wigley and Rose, 2020).

Researching the nature, dynamics and evolution of governance specifically and power more broadly is not rightly the remit of parties who have interests in the system, be they manufacturers or regulators. And yet it is crucial to protect those citizens on whom power and governance is enacted, who live the consequences of those processes and structures.

3. Conclusions

We have used the themes above to illustrate our central arguments. We started from the uncontroversial premise that the development and emergence of AVs are likely to lead to profound and wide-ranging shifts in our world, with implications for economic structures, land use, lifestyles and personal well-being. We argue that these areas of impact have been given at best cursory thought to date, as attention has been concentrated on a relatively narrow set of considerations, mainly relating to the transport system itself. We contend that the narrowness of focus is in large part due to a preoccupation with the technological issues relating to AVs and a tendency to give less weight to the social issues. If technological issues continue to dominate the research effort, questions of huge societal importance will be either missed or dealt with superficially.

Social scientists are already active on AV topics and, in saying this, it is important to emphasise the diversity of social science as a group of disciplines. As noted earlier, some psychologists, for example, are relatively well embedded in the testing of AV technology, but much of their activity is focused on narrow questions of human-machine interaction. Our contention is that social science can make a more effective and constructive contribution if the full range of social-science disciplines is brought inside the wider AV research community. We have warned against the risks of postponing social research or defining questions narrowly. The best way of minimising these risks is by social science being involved early and in an ongoing, constructive way.

We have identified that social scientists can bring clarity to complex questions relating to AVs, using a wide range of organising principles, tools and approaches. We have identified particular opportunities in respect of exploring the range of possible futures, distributional impacts of the technology and the role, use and impact of data. On the specific question of introducing public opinion more successfully into the technology's development and governance, we have robust methods that will both cater to the diversity of opinion and enable members of the public to participate meaningfully in the process.

We do not ignore the challenges that this would bring. All cross-disciplinary activity requires participants to appreciate distinct approaches to questions, hypotheses, arguments and evidence. Disciplinary cultures encompass epistemology as well as empirical practice. Successful cross-disciplinary collaboration therefore relies on a degree of mutual understanding and respect. The effort required for such collaboration is surely justified by the importance of the subject matter.

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Declaration of competing interest

None.

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