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Autonomous vehicles and cycling: Policy implications and management issues☆,☆☆

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ABSTRACT

Cycling as a form of active transport has great benefits for individuals and society, yet prevalence rates in many countries are low. The advent of autonomous vehicles (AVs) is likely to have substantial implications for cyclists, however little is known about the nature and magnitude of the likely impacts and the resulting implications for government planning and policy. The aim of this exploratory study was to consult with a range of stakeholder groups to identify relevant issues and stimulate debate about future efforts to maximize the benefits of vehicle autonomy for cycling outcomes. Interviews were conducted with key stakeholders representing government (local, state, and federal departments responsible for transport, health, and/or infrastructure), cycling organizations, technology firms, AV manufacturing/servicing companies, trade unions, the law, insurers (public and private), transport policy consortia, and academia. The results suggest that AVs have the potential to increase cycling prevalence while reducing cycling accidents, but that a range of issues will need to be addressed to optimize these outcomes. In particular, informed decisions need to be made about the infrastructure and equipment investments that could encourage larger numbers of commuters to select cycling as their primary form of transport.

1. Introduction

Cycling has the potential to provide both individual- and societal-level benefits in the form of increased physical activity, enhanced mental health, reduced risk of chronic disease, increased city vibrancy, greater social cohesion, and reductions in carbon dioxide emissions and air pollution (Cerin et al., 2017; Chapman et al., 2018; Keall et al., 2015; Mason et al., 2016; Saunders et al., 2013). Economic analyses indicate that investments in infrastructure to facilitate cycling are highly cost-effective and generate returns on investment many times the value of the incurred costs (Chapman et al., 2018; Macmillan et al., 2014). Furthermore, sustainable transport interventions aiming to reduce vehicle emissions, improve public transport, and promote active travel (i.e., walking and cycling) can help prevent a wide range of non-communicable diseases (Conlan et al., 2018). As such, there is considerable policy interest in identifying and implementing strategies to encourage cycling across broader sections of the population (World Health Organization, 2018).

In Australia, the context of the present study, cycling prevalence is very low. Around 6% of those aged 15+ years report cycling for recreation within a 12-month period (Australian Bureau of Statistics (ABS), 2015), and only 1% use a bicycle for commuting compared to 74% taking a car, either as a driver (69%) or passenger (5%) (ABS, 2014). This low prevalence may be in part due to the geographic spread of Australian cities, with an average work commute of 16.5 km (ABS, 2018). The Australian National Cycling Strategy (Austroads, 2017) notes the importance of encouraging more people to "get on their bikes" to improve environmental, traffic congestion, and health outcomes, but the current low prevalence suggests the existence of major systemic barriers to increased uptake.

The linking of public health and travel policies is relatively recent, particularly in Australia. Pucher and Dijkstra (2003) suggested cycling and walking could be part of the solution to the growth in incidence of obesity (which has itself been linked with growing motorization) as it contributes to the 150–300 min of moderate intensity activity per week for adults recommended by the World Health Organization. There is widespread consensus that policies shifting people out of cars and into more active modes should improve the overall physical activity and well-being of the population. A caveat is the increased risk of an accident associated with cycling and walking. However, evidence suggests that benefits from cycling-related physical activity outweigh the risks related to injuries or air

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pollution in all but the most extreme situations (Götschi et al., 2015; Tainio et al., 2016). However, the perception of risk can prevent cycling uptake if it is larger than actual risk.

Policies promoting active travel would also provide many other benefits, such as air quality improvements and reduced congestion. The Covid-19 pandemic has placed a spotlight on the benefits of active travel. London, for example, has closed some major central arterial routes to all but bus traffic to provide more space for pedestrians and cyclists (Taylor, 2020). In Sydney, advocates are highlighting the opportunity to complete the Principal Bicycle Network to support cycling in city areas in the next 3 years instead of the planned 40 years (Miletic, 2020).

The transport sector is in a phase of rapid change due to the emergence of autonomous vehicles (AVs) (Crayton and Meier, 2017; Fagnant and Kockelman, 2015). Numerous AV trials are in progress at sites all around the world, and anticipated user response has been the subject of an increasing number of studies (e.g., Kyriakidis et al., 2015; Bansal and Kockelman, 2017; Pettigrew et al., 2018, 2019b). AVs are projected to have a significant impact on the future of urban mobility, and it is widely expected that they will have the potential to offer door-to-door solutions, which could be especially beneficial for those with mobility limitations (Kovacs et al., 2020; Pettigrew et al., 2019a). However, although widespread use of AVs in coming decades is forecast (Litman, 2018), little is known about aspects of the likely outcomes of public adoption of AVs, including the potential impact on physical activity, equitable access, injuries, and the environment. Of specific interest to the present study, very little is known about the likely implications of the advent of AVs for cycling behaviors and whether the overall effect will be positive or negative (Behrendt, 2019; Latham and Nattrass, 2019). For example, once AVs are in common use, individuals may feel either safer on the roads or more concerned about being close to traffic (Blau et al., 2018; Pyrialakou et al., 2020). It is also unknown whether the convenience of door-to-door, affordable, and shared AV services may increase or decrease the numbers of those choosing to cycle (Botello et al., 2019; Truong et al., 2017). The limited exploratory work available to date suggests that there may be substantial declines in cycling once affordable, convenient, automated options are available (Booth et al., 2019).

There are likely to be many other consequences of AVs that will influence future cycling prevalence and patterns. In the absence of existing data relating to these potential consequences, the aim of the present study was to prompt discussion and debate by exploring stakeholders' expectations of potential cycling outcomes once AVs are in common use. The results provide insight into the factors that will need to be addressed to encourage greater uptake of cycling and counteract any trends toward shifting from cycling to AV use in the impending AV era.

2. Method

As part of a larger study (Authors, 2018a, 2018b), 39 stakeholder interviews (individual and group) were conducted with 44 interviewees representing a wide range of relevant sectors to explore the likely potential social impacts of AVs and propose areas of future focus and debate. Most of the interviews were conducted in Australia ($n = 29$), with the remainder undertaken in the UK ($n = 4$), the European Union ($n = 5$), and the US ($n = 1$) to provide an international perspective. Three of the Australian interviews were conducted with multiple representatives from the same organizations and the remainder were individual interviews.

Reflecting the need to interview individuals with specialist knowledge, recruitment occurred via selective identification based on interviewees' profiles and snowball sampling (Biernacki and Waldorf, 1981). The final sample comprised representatives from government (local, state, and federal departments responsible for transport, health, and/or infrastructure), technology firms, AV manufacturing/servicing companies, trade unions, the law, insurers (public and private), transport policy consortia, and academia. Of specific relevance to the present study, the sample also included representatives from two cycling organizations – one member-based association advocating for cyclists and one supplier of cycling-related products and services.

The interviews were largely unstructured, with each interviewee asked to discuss the advent of AVs according to their specific area of expertise. The average interview length was around 70 min. The interview transcripts were progressively imported into NVivo 11 qualitative data management software for line-by-line coding and thematic analysis. Due to the minimal prior work in this area and the resulting need for an emergent coding hierarchy, an inductive coding process was employed that involved the progressive creation of NVivo 'nodes' based on issues identified in the transcripts and related concepts in the literature (Huberman and Miles, 1994). This emergent process necessitated the use of a single coder (the first author), which is an appropriate approach when the objective is to yield new insights rather than testing a pre-existing theoretical framework (Smith and McGannon, 2017).

The transcripts were initially read in full, followed by iterative coding processes (as per Glaser and Strauss, 1967). Issues relating to the effects of the emergence of AVs on cycling were raised in 28 interviews with 33 interviewees (25 Australian and 8 international), which form the basis of the findings reported below.

3. Results

Numerous likely implications of the introduction of AVs for cycling trends were discussed by the interviewees. These ranged from changes in the way individuals behave to the way cities are structured. Table 1 lists the six primary identified implications, along with example quotes from the interview transcripts.

Safety issues were especially salient, with interviewees discussing the potential to reduce cycling accidents due to AVs' greater ability to detect and monitor the full range of road users. Specific points noted were the eradication of blind spots due to AVs' long-range detection sensors and

Table 1
Implications of autonomous vehicles for cycling.

Implication	Example quotes
Increased safety	"The cyclist is safer if they're next to the AV." (Interviewee #13, Transport policy advisor, Australia) "We developed messaging that could effectively…make sure that both the vehicle is alerted and also the cyclist and pedestrian are alerted." (Interviewee #5, Telecommunications representative, Australia)
Complementarity	"It would be amazing if a car could pick me up, take me to where I wanted to be, if I didn't want to cycle that day or didn't want to walk." (Interviewee #2, Transport engineer, UK)
Increasing use of E-bikes	"E-bikes do change it (*arrangements to separate AVs from cyclists*) because older people will ride with e-bikes. People that have had less experience on bikes are riding with e-bikes." (Interviewee #37, Cycling organization representative, Australia)
Increased space	"One of the constraints that we have around when we try to put good cycling infrastructure in, we've always had to choose between the side walk, parking bays, and cycle lanes. It is always a compromise between those three things. When you know you can take out a whole bunch of your parking because it's not required anymore because there's no need to park and wait around for the owner to come back, you've got a much better way of actually putting in much better separated cycling infrastructure, separated lanes." (Interviewee #6, Government representative, Australia) "Property developers really should be getting rid of all the carparks underneath their buildings and starting to develop places where they can receive and safely exit all types of mobility options. Whether that's a bike, a footpath, ride share vehicle, or a taxi." (Interviewee #27, Transport agency representative, Australia)
Vibrant cities	"…claiming that back for people for walking, for cycling, for those kinds of things. I think's going to actually really have that ability to make much more livable neighborhoods…I think we actually will see car ownership, individual car ownership, drop. Cars will still be in use as a form of transport, but certainly more and more cycling." (Interviewee #6, Government representative, Australia)
Reduced road rage	"A lot of cyclists do tend to be victims of road rage by drivers, particularly if they hold them up, whereas an autonomous vehicle is not going to exact any kind of revenge on a cyclist if it gets delayed…An autonomous vehicle won't behave badly." (Interviewee #32, Transport consultant, UK)

the potential ability of bicycles and/or bicycle helmets to communicate with AVs via transponders. In addition, it was noted that recently implemented regulations in Australia about the distance drivers are required to keep from cyclists on the road (1 m) would be much easier for AVs to maintain due to their greater perceptual capabilities.

It was generally anticipated that greater safety would encourage more people to choose cycling as a form of transport, thereby reducing dependence on cars. This potential outcome was related to the concept of complementarity among transport modes. The availability of shared AVs in particular was seen to liberate individuals from needing to own a personal car because they could rely on bicycles for many trips while having access to affordable automated car transport when needed (e.g., during inclement weather). The potential possibility of many road users electing to forego a personal car in favor of a bicycle in the AV era was also discussed in the context of the emerging popularity of electric bikes (e-bikes) that can make cycling feasible for those with longer commutes. There were parallels in the presumed reliance of both AVs and e-bikes on developments in battery technology and the potential ability for e-bikes to communicate with AVs.

Some interviewees discussed the implications of AVs for the physical and social characteristics of modern cities. It was noted that parking lanes could be removed in favor of cycle paths, and that the narrower lanes required by AVs could also potentially free up space for cycle paths. In terms of social outcomes, facilitating higher levels of cycling was expected to enhance city livability and vibrancy by encouraging more people onto the streets while reducing the negative influence of road rage, a phenomenon that was perceived to be increasingly common between drivers and cyclists.

These implications were viewed as being associated with a range of issues that will need careful management by governments to optimize the potential benefits of AVs for cycling. Table 2 lists the five main management issues discussed by the interviewees, most of which relate to logistical problems that will require resolution to promote cycling uptake once AV use becomes common.

One area of occasional disagreement was whether the emergence of AVs would enable greater mixing of road users or strengthen the case for separate lanes for different users. Some viewed AVs' technologically advanced sensors and algorithms as reasons to blend cyclists with motorized vehicles on roads because of the greater ability of AVs to perceive cyclists relative to the visual capacities of human drivers. Others described scenarios in which AVs' efficiency would be impeded because of the need to program them to be highly sensitive to pedestrians and cyclists. Interviewees in the latter group recommended investment in segregated pathways to allow all three groups to enjoy optimal speeds without endangering or inconveniencing others.

The lack of human communication options available when interacting with AVs (e.g., eye contact cannot be used to assess intention) resulted in interviewees focusing on the need for alternative communication mechanisms to ensure cyclists' safety. These mechanisms were discussed in terms of bicycle-to-vehicle communication and human-to-vehicle communication. Although the technology to enable some degree of bicycle-to-vehicle communication was described as being already developed and available, it was anticipated that strategies would need to be devised to overcome resistance from cyclists due to the need to make an additional purchase and the extra weight on the bike. Incentives or subsidies may be needed to overcome these barriers. Human-to-vehicle communication was seen to be manageable by ensuring AVs can register and interpret human hand signals used to indicate turning.

An outcome of more people relying primarily on bicycles is that transport systems may need to be redesigned to better facilitate multi-modal trips that include cycling components. It was noted that increased use of bicycles due to safer road environments will mean that train and bus stations will require secure and convenient bike storage facilities to enable commuters to combine these forms of transport. However, issues relating to congestion around public transport hubs were also discussed in terms of cyclist safety and the corresponding need to ensure pick-up and drop-off points are established a short distance from these hubs to encourage dispersal of traffic.

A final management issue raised was the weaker bargaining power of cyclists compared to other key stakeholders who are likely to lobby for particular forms of road and infrastructure design in response to the advent of AVs. The potential health benefits associated with higher levels of cycling were described as a key issue for governments to consider when planning and implementing policy and infrastructure changes.

Table 2
Management issues.

Management issues	Example quotes
Infrastructure requirements	"If we can repurpose the space that's already available by having smaller lanes, you can see the very late future when we've got autonomous vehicles, smaller lanes, introduction of cycle lanes, or more pedestrianized areas, then that would be a benefit." (Interviewee #26, Transport consultant, UK)
Bicycle-to-vehicle communications	"Certainly if I was riding a bike and a good proportion of the fleet was at some level of automation, I would probably want to have my bicycle talking to those cars because it would have helped to protect me. It's like having a shark repellent device." (Interviewee #35, Insurance agency representative, Australia)
Human-to-vehicle communications	"Non-verbal communication happens between drivers and other drivers and drivers and pedestrians and bicyclists, so this is something that automated vehicle developers are eventually going to have to deal with." (Interviewee #9, Transport researcher, US)
Multi-modal trip facilitation	"It (*planning cities for AVs and cycling*) is very much a part of the long-term planning of the network here…There'll be train lines where many train stations don't have an appropriate place to put your bicycle. So if you're using your bicycle for that last mile, to then catch the train to town, some stations do it really well - others non-existent." (Interviewee #34, Government representative, Australia) "If you were to say that no one should be dropped off (*in an AV*) closer than 200 m to a railway station unless they have a disability, then your level of congestion around the railway station is far less. That's important for bike riders and pedestrians." (Interviewee #37, Cycling organization representative, Australia)
Lack of market power	"We do not have the industry in terms of bicyclists. The muscle that they have is not there compared to the car industry." (Transport researcher, Sweden)

4. Discussion

While some prior work has recognized that AVs will have substantial implications for cycling behaviors (Blau et al., 2018; Booth et al., 2019; Thompson et al., 2020; Truong et al., 2017), little is known about the nature and scale of these implications. This exploratory work provides some initial insights into the range of issues that are likely to be relevant to the ways in which AVs and cyclists will co-exist. Overall, the key stakeholders involved in the study expressed positive expectations about the potential for improved outcomes for society in general and for cyclists in particular from the wide-scale use of AVs. Although some problems were anticipated, it was expected that these could be resolved through careful planning.

A primary issue identified by the interviewees was the need to make decisions about the infrastructure requirements of transport systems featuring AVs to encourage optimal use of active transport options. The view of many interviewees that ride-sharing models of AV use have the potential to reduce rates of private car ownership are supported by analyses of consumer responses to traditional (i.e., non-autonomous) ride- and car-sharing services (e.g., Uber) on car ownership levels (Liao et al., 2020; Schmidt, 2020; Ward et al., 2019) and modeling of the anticipated further effects once ride-sharing services are available in autonomous mode (Pettigrew et al., 2019c). Research investigating the benefits of providing cycling infrastructure in the pre-AV environment has found that improved facilities can increase participation rates in a highly cost-effective manner (Aldred et al., 2018; Goodman et al., 2013, 2014; Keall et al., 2015). The results of the present study highlight the potential for these benefits to be amplified with the introduction of AVs, thereby giving more commuters the confidence to use cycling as a primary transport mode. Rapid increases in the popularity of e-bikes may further enhance cycling uptake levels (Fishman and Cherry,

2016; Guidon et al., 2019), and app-enabled shared bicycle schemes are making it easier for citizens to access bikes, although such schemes are very much in their infancy in countries such as Australia (Heymes, 2019).

Implementation of cycling infrastructure can be controversial within communities, with some strongly in favor of such investment and others considering it to be misplaced (Aldred et al., 2018). The infrastructure requirements that are likely to arise from the advent of AVs are multifaceted and include road demarcations, secure bike storage facilities at public transport hubs, and the establishment of pick-up/drop-off sites at appropriate locations. A related concern is that the pick-up and drop-off behaviors of AVs will consume kerb-side space (ostensibly freed up by reduced parking requirements), which could otherwise be used to improve facilities for walking and cycling. In addition, although AV sensors will greatly improve vehicle awareness of cyclists, outcomes are likely to be enhanced if cyclists are encouraged/incentivized to make use of communications equipment (e.g., transponders) and practices (e.g., uniform hand signals) that maximize their visibility to nearby AVs. The decisions to invest in these forms of infrastructure and community education should be informed by consideration of the benefits in terms of the physical (e.g., crash reduction) and social (e.g., more vibrant cities) outcomes that are likely to eventuate. Also relevant is that cycling has been shown to be positively influenced by the so-called 'neighborhood effect' whereby an individual's transport mode choices are influenced by those of their social neighbors (Wang et al., 2015). This indicates that social learning (Bandura, 1978) will be an important determinant of usage rates, highlighting the importance of limiting any decline in cycling with the advent of AVs and promoting increased usage to enhance visibility and therefore likely emulation.

This exploratory study represents an initial canvassing of expert opinions to stimulate further debate on the management implications of the inter-relationship between cycling and autonomous forms of transportation. It was limited by the qualitative design, the modest sample size, and the inclusion of relatively few stakeholders from outside Australia. In particular, the broad range of stakeholders with a lack of critical mass per group prevented analyses of any differences in perceptions according to stakeholder type. Finally, as per thematic analysis procedures, the identified themes reflect the more common views expressed by the interviewees and it was not possible to incorporate all opinions on all the covered topics in the presented results. As a result of these limitations, the findings are tentative and further work is needed to inform the development of public policies designed to optimize cycling once AVs are in common use. Future research could employ large-scale surveys disseminated to a broader range of respondents across a larger number of countries covering a wider range of related topics to assess the extent to which the issues identified in this and other studies apply in varying contexts and to gauge the relative importance of these issues to different stakeholder groups.

In conclusion, AVs hold great promise for enhanced mobility across multiple forms of transport. The extent to which cycling flourishes with the advent of AVs will be largely determined by policy decisions that will inevitably prioritize some forms of transport and some road users over others. Working toward a future in which cycling is a favored form of transport for substantial proportions of the population will take active planning and considerable foresight, along with an explicit commitment to leveraging the advent of AVs to optimize human welfare outcomes.

CRediT authorship contribution statement

Simone Pettigrew: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Writing - original draft. **John D. Nelson:** Conceptualization, Writing - review & editing. **Richard Norman:** Funding acquisition, Writing - review & editing.

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