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Sociomobility of the 21st century: Autonomous vehicles, planning, and the future city

Eva Kassens-Noor [*], Dana Dake, Travis Decaminada, Zeenat Kotval-K, Teresa Qu, Mark Wilson, Brian Pentland

Michigan State University, USA

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ABSTRACT

Autonomous vehicles are an emerging technology that can fundamentally change how our society moves and lives. We review the infant literature of 185 peer-reviewed articles on the social context of an AV-enabled mobility future. We develop a taxonomy based on *sociomobility* that illustrates how AVs reinforce the status-quo in our society as AV-mobility is primarily defined as an auto issue and not a mobility question. Absent from the literature are alternate mobility scenarios, land-use interactions, livability, the transition period when both AVs and human drivers occupy road space, and impacts on the natural environment.

Autonomous vehicles (AVs) are an emerging and disruptive technology that has the potential to change mobility, and thus the form and function of cities. Incorporating AVs into urban transportation systems must reconcile the ambition of transport innovation with the public purpose of planning (Legacy et al., 2019). AVs will demand significant public spending to integrate them into cities, while legal and ethical matters complicate their legislation. Autonomous vehicles represent a new form of mobility whose impact depends on how they are governed and used. How can decision-makers harness the benefits and minimize disadvantages?

AVs, also called automated, driverless, and self-driving, are vehicles with the capacity to undertake a wide range of tasks associated with driving, with the goal of being able to undertake journeys without any human driver assistance. One important distinction is between AVs and Connected AVs (CAV), with the latter linked to continuous information about road and travel conditions as well as information from nearby vehicles.

While the engineering elements of AVs have been advancing over the past decades, it is only within the past five years that the social context has received some, though little, attention. While there are over 100,000 academic articles on the engineering aspects of AVs, less than two hundred address planning and policy-making issues. We found a focus on AV use that tends to be defined primarily **as an auto issue and not a mobility question**. Research on the personal AV has dominated the literature: less than 10% have public transportation as their core focus. Even fewer articles discuss the impact that AVs could have on active transport methods such as bicycling and walking (Blau et al., 2018; Crayton and Meier, 2017; Guerra, 2016; Harb et al., 2018; Le Vine et al., 2015; Liu et al., 2017; Puylaert et al., 2018; Szell, 2018).

1. Sociomobility taxonomy

To understand the broader impacts of AVs on our society, we developed a taxonomy. A taxonomy is a systematic review explaining and justifying the process by which literature is selected, analyzed, and synthesized. To determine the current state of knowledge regarding the social aspects of AV development and deployment, we scored and organized the nascent social science literature of 185 peer-reviewed papers (see references supplement) using Reichman's hierarchy tree (Reisman, 1989, 1992) based on a concept we call *sociomobility* (Fig. 1). *Sociomobility*, links the users of the mobility system with their own knowledge, skills, and dispositions to the built, natural, and virtual environment in which AVs are expected to operate (please see methodological supplement and the taxonomy for details). We ask:

1) How do the authors of peer-reviewed papers portray the advent of AVs?
2) What will *sociomobility* look like in the 21st century?
3) What is missing from the current literature to advance our understanding of AV impacts?

* Corresponding author.
E-mail address: ekn@msu.edu (E. Kassens-Noor).

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The infant literature on AVs in the social sciences tends to be positive and generally accepting of AVs, with few articles questioning if they should come or how communities can best use them. As discussed below, AVs may reinforce the status-quo or worse expand the divide of economic, environmental, and social inequities. Largely absent from the literature is the presentation of alternate scenarios for future mobility. Further, the current literature ignores the period of transition, skipping several decades when both AVs and human drivers share road space. Studies on impacts on the natural environment, interactions with land-use, and livability are rare.

The social science literature on AVs currently promotes adoption of AVs (*sociomobility* 0.96) and accepts deployment as inevitable. Most *sociomobility* categories show a weak benefit to society. While AVs may enhance human capabilities (*knowledge 1.26*) on what humans are able (*1.26*) and need to do (*1.26*), the sociomobility taxonomy shows weaker or no benefit on human skills: how they feel (*0.83*), think (*1.28*), and communicate (*-0.04*) in an AV future. Humans further show a weaker benefit on what they value (*0.78*), e.g. privacy, in contrast to what they expect (*1.01*) from AVs. The environment (0.97) in which AVs operate is expected to achieve higher benefits in the built (*1.09*) than in the virtual (*0.85*) environment, while impacts on the natural environment (*no score* too few articles) remain opaque. Infrastructure (*1.06*), operations (*1.12*), and models (*1.07*) show greater benefits than learning (*0.63*).

In sum, the literature reflects a sense of technological determinism and generalization, accepting premises that engineering disciplines and businesses have suggested **without critically questioning AV deployment as good for whom and good for where**. In the section that follows, our paper provides a snapshot of the current literature on AVs in the social sciences.

1.1. *The human as the user of the AV-Enabled mobility system*

The introduction of AVs will come as an opportunity to those who have and those who can, providing an overall motivation to society to adopt AVs (*Human 0.95*). Humans have three dispositions (knowledge, skills, and dispositions) to function in any society and adopt innovations (El Zarwi et al., 2017).

1.1.1. *Knowledge (human ability and needs)*

Social benefits will depend on willingness to adopt (Bansal et al., 2016; Charness et al., 2018; Choi and Ji, 2015; Haboucha et al., 2017; Hudson et al., 2019; Hulse et al., 2018; Krueger et al., 2016; Liljamo et al., 2018; Shabanpour et al., 2018a; Wadud, 2017; Wu et al., 2019) and willingness to pay for AVs (Bansal and Kockelman, 2017, Bansal et al., 2016, Daziano et al., 2017, Talebian and Mishra, 2018), which accrue to those who are highly educated (Haboucha et al., 2017; Krueger et al., 2016; Liljamo et al., 2018) and earn higher incomes (Bansal et al., 2016; Shabanpour et al., 2018a; Wadud, 2017). Likeliness of adoption also is attributed to the young (Charness et al., 2018; Haboucha et al., 2017; Hudson et al., 2019; Hulse et al., 2018; Krueger et al., 2016;

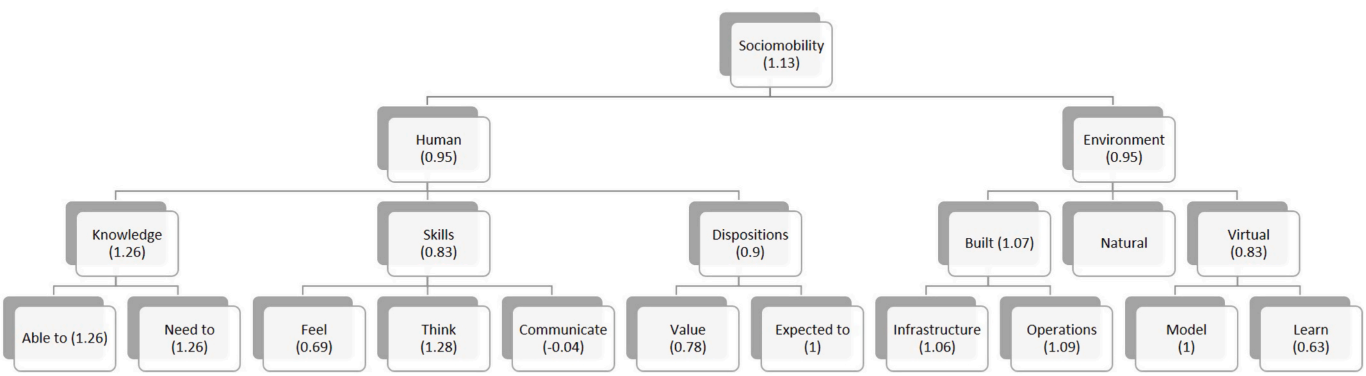

Fig. 1. Taxonomy of Sociomobility with Autonomous Vehicles

Note: Framework developed and coded according to supplements for taxonomy, methodology, and references. Negative numbers mean deterrents for society; positive number mean motivation for society. .Abdur-Rahim et al., 2016; Albini et al., 2018; Bahamonde-Birke et al., 2018; Banks and Stanton, 2016; Bansal et al., 2016; Bansal and Kockelman, 2017, 2018; Bärgman et al., 2017; Bellem et al., 2016, 2017, 2018; Bennett et al., 2019; Bigman and Gray, 2018; Bissell, 2018; Blau et al., 2018; Bonnefon et al., 2016; Bösch et al., 2018; Brożek and Jakubiec, 2017; Cannellos and Haga, 2016; Chapin et al., 2017; Charness et al., 2018; Chen et al., 2016; Choi and Ji, 2015; Coca-Vila, 2018; Cohen and Cavoli, 2019; Collingwood, 2017, 2018; Conschafter, 2017; Contissa et al., 2017; Crayton and Meier, 2017; Daziano et al., 2017; De Bruin, 2016; De Bruyne and Werbrouck, 2018; De Sio, 2017; Deb et al., 2017, 2018; Diels and Bos, 2016; Dixit et al., 2016; Doecke et al., 2015; Duarte and Ratti, 2018; El Zarwi et al., 2017; Endsley, 2017; Etzioni and Etzioni, 2017; Fagnant and Kockelman, 2015, 2018; Farhan and Chen, 2018; Favarò et al., 2018; Fazlollahtabar, 2018; Fleetwood, 2017; Fox-Penner et al., 2018; Foy and Chapman, 2018; Gandia et al., 2019; Geistfeld, 2017; Gelauff et al., 2019; Ghiasi et al., 2017; Greenblatt and Saxena, 2015; Guerra, 2015, 2016; Haboucha et al., 2017; Hacker, 2017; Harb et al., 2018; Harper et al., 2016; Hashimoto et al., 2016; Hawkins and Nurul Habib, 2019; Hensher, 2018; Hergeth et al., 2016; Hevelke and Nida-Rümelin, 2015; Hicks, 2018; Himmelreich, 2018; Hopkins and Schwanen, 2018; Horrey et al., 2015; Hübner and White, 2018; Hudson et al., 2019; Hughes, 2016; Hulse et al., 2018; Iacobucci et al., 2019; Kalra and Paddock, 2016; Kane and Whitehead, 2017; Kauffmann et al., 2018; Kelley, 2017; Koopman and Wagner, 2016; Krueger et al., 2016; Kuiper et al., 2018; Kumar et al., 1996; Le Vine et al., 2015; Leben, 2017; Lee et al., 2015; Lee and Mirman, 2018; Legacy et al., 2019; Lentzakis et al., 2018; Levin et al., 2016, 2017; Levin and Rey, 2017; Li et al., 2018; Liljamo et al., 2018; Lima et al., 2018; Lin et al., 2018; Liu, 2017, 2018; Liu et al., 2017; Loeb et al., 2018; Lohmann, 2016; LoRicco, 2017; Louie and Mouloua, 2019; Lu et al., 2017; Luetge, 2017; Lutin, 2018; Ma et al., 2019; Mahmassani, 2016; Masoud and Jayakrishnan, 2017; McGrath and Gupta, 2018; McMurry et al., 2018; Meckling and Nahm, 2018; Meneguette et al., 2016; Meng et al., 2018; Mersky and Samaras, 2016; Meyer et al., 2017; Mezei and Lazányi, 2018; Millard-Ball, 2018; Miller and Boyle, 2019; Mohan, 2016; Nair et al., 2018; Nazari et al., 2018; Nees et al., 2016; Niu et al., 2018; Noruzoliaee et al., 2018; Nourinejad et al., 2018; Nourinejad and Roorda, 2016; Nyholm and Smids, 2018; Ohnemus and Perl, 2016; Panagiotopoulos and Dimitrakopoulos, 2018; Papadoulis et al., 2019; Payre et al., 2016; Perboli and Rosano, 2019; Pérez-Marín and Guillén, 2019; Pickering and Byrne, 2014; Pinter et al., 2017; Puylaert et al., 2018; Rahwan, 2018; Raksincharoensak et al., 2016; Reisman, 2005; Richards and Stedmon, 2016; Roca et al., 2016; Rosenberger, 2015; Salatiello and Felver, 2017; Salonen, 2018; Sandry, 2018; Schoonmaker, 2016; Shabanpour et al., 2018a, 2018b; Shen et al., 2018; Siebert et al., 2017; Simoni et al., 2019; Singleton, 2019; Sinha et al., 2017; Soe and Drechsler, 2018; Sommaggio and Marchiori, 2018; Sousa et al., 2017; Sparrow and Howard, 2017; Stern et al., 2018, 2019; Stilgoe, 2018; Sucasas et al., 2016; Szell, 2018; Tajalli and Hajbabaie, 2018; Takeda et al., 2016; Talebian and Mishra, 2018; Talebpour and Mahmassani, 2016; Thomopoulos and Givoni, 2015; Thomson et al., 2019; Tokody et al., 2018; Tomsk State University of Control Systems and Radioelectronics and Churilov, 2018; Truong et al., 2017; van der Heiden et al., 2018; Vlakveld et al., 2018; Voß et al., 2018; Wadud, 2017; Walker and Trick, 2018; Wandtner et al., 2018; Wen et al., 2018, 2019; Wilson et al., 2019; Winter et al., 2018; Woldeamanuel and Nguyen, 2018; Wu et al., 2019; Yi et al., 2018; Zakharenko, 2016; Zhang et al., 2016, 2018; Zhang and Nie, 2018; Zushi, 2017; Evans, 1994; Reisman, 1989; Reisman, 1992; Vogel & Wetherbe and 1984Pub, 1984

Shabanpour et al., 2018a), males (Bansal et al., 2016; Charness et al., 2018; Hudson et al., 2019; Hulse et al., 2018; Liljamo et al., 2018), urbanites (Bansal et al., 2016; Liljamo et al., 2018; Shabanpour et al., 2018a), and Caucasians (Wilson et al., 2019). When mobility increases for these population segments, the elderly, female, non-white, and lower income segments of society may face greater marginalization. Some researchers posit that those without access to a vehicle or those who do not have a driver's license (Liljamo et al., 2018) would be "early adopters" of AVs, especially seniors, people with disabilities (Bennett et al., 2019; Lutin, 2018), and children (Harper et al., 2016). Further, there may be negative health impacts for people using driverless cars ranging from temporary discomfort (Diels and Bos, 2016; Kuiper et al., 2018) to long-term health implications due to a mode shift away from active and public transport towards AVs (Crayton and Meier, 2017; Kelley, 2017; Liu et al., 2017; Simoni et al., 2019).

1.1.2. *Skills (human feelings, thinking, and communication)*

One motivation for AVs introduction is safety, because in theory AVs can navigate the environment better than humans (Blau et al., 2018; Doecke et al., 2015; Papadoulis et al., 2019). However, as AVs take over simple driver skills, they can pose safety risks (Lee et al., 2015): as people reduce their time spent driving, they may lose coping skills for difficult driving situations (Banks and Stanton, 2016, Foy and Chapman, 2018, LoRicco, 2017, Payre et al., 2016, Sandry, 2018, Walker and Trick, 2018). Successful transition further assumes a human willingness to enter and trust a driverless vehicle (Choi and Ji, 2015; Dixit et al., 2016; Niu et al., 2018; Panagiotopoulos and Dimitrakopoulos, 2018), as well as a social relearning on how to behave as a mobility user (Deb et al., 2017, 2018; Millard-Ball, 2018); both may pose challenging for some. For example, while people may prefer AVs to be programmed to benefit society in the abstract, people do not trust (and would not purchase) cars programmed to sacrifice their own life for others (Shabanpour et al., 2018a). Notably, little work has been devoted estimating how this period of driving transition will impact society. This is concerning as our taxonomy highlights a disincentive for society to adopt AVs given human communication skills decrease.

1.1.3. *Dispositions (human values and expectations)*

US states develop their own regulations, frequently allowing AV manufacturers to decide how AVs make moral and ethical decisions, despite a pre-existing aversion within society against machines taking on this role (Dixit et al., 2016; Geistfeld, 2017; McGrath and Gupta, 2018; Niu et al., 2018; Rahwan, 2018). Largely unregulated, AV manufacturers algorithmicize our society's ethics, which heightens the risk that (a) our historical socioeconomic divides and injustices will be made implicit in the code (Liu, 2017; Rahwan, 2018), and (b) the programming of behavioral codes are designed to overcome human aversions to machines making moral decisions (Bellem et al., 2018; Bigman and Gray, 2018; McGrath and Gupta, 2018; Niu et al., 2018). At the same time, policymakers and businesses push developments, testing, and deployments of AVs through undemocratic, non-inclusive, and authoritarian governance processes accepting a significant loss in privacy (Collingwood, 2017, De Bruin, 2016, Hacker, 2017, Hopkins and Schwanen, 2018, Masoud and Jayakrishnan, 2017, Schoonmaker, 2016).AV deployment raises questions over liability and suggests scenarios how manufacturers, policy-makers, and individuals share liability (Brożek and Jakubiec, 2017; De Bruin, 2016; De Sio, 2017; Geistfeld, 2017; Hevelke and Nida-Rümelin, 2015; Lohmann, 2016; LoRicco, 2017; Salatiello and Felver, 2017). If and when AVs are fully deployed, US society's inequalities and discrimination is likely to persist if not widen (Liu, 2017; Wilson et al., 2019).

1.2. *Environment of the new AV-Enabled mobility system*

AVs will function at the intersect of the built, natural, and virtual environment. To date, authors have assessed the impact of AVs on the environment as positive (*0.97*) accepting that AV technology can deliver benefits that outweigh its costs.

1.2.1. *Built environment (infrastructure and operations)*

AVs will enable a safer built environment by reducing crashes significantly (Blau et al., 2018, Fleetwood, 2017, Doecke et al., 2015, Geistfeld, 2017, Papadoulis et al., 2019). To enable safe AV operations, significant new infrastructure investments are necessary (Chapin et al., 2017, Chen et al., 2016, Duarte and Ratti, 2018, Ghiasi et al., 2017, Guerra, 2016, Loeb et al., 2018, Mahmassani, 2016, Mezei and Lazányi, 2018, Noruzoliaee et al., 2018, Sinha et al., 2017, Sousa et al., 2017, Yi et al., 2018). However, higher income earners, like drivers and regular commuters, benefit the most when congestion reduces (Haboucha et al., 2017; Kalra and Paddock, 2016; Tokody et al., 2018; Cohen and Cavoli, 2019; Levin et al., 2017; Mahmassani, 2016; Singleton, 2019; Szell, 2018; Wadud, 2017). Due to reduced parking and driving space, new downtown areas will allow for living and working investments, once more benefiting the already wealthy (Duarte and Ratti, 2018, Ghiasi et al., 2017, Hawkins and Nurul Habib, 2019, Liu, 2018, Nourinejad et al., 2018, Meneguette et al., 2016). Notably, the underlying assumptions to achieve travel time savings are that AVs will operate as a last mile option (Ohnemus and Perl, 2016; Shen et al., 2018) and in shared form (El Zarwi et al., 2017; Fagnant and Kockelman, 2018; Farhan and Chen, 2018; Iacobucci et al., 2019; Nourinejad and Roorda, 2016; Ohnemus and Perl, 2016), while cities invest in transit-oriented development (Hawkins and Nurul Habib, 2019; Lu et al., 2017). However, shared mobility may not be acceptable for some as it will reduce security (Rahwan, 2018; Liu, 2017), and most papers lack to account for the possibility that AVs could cause different types of crashes (Etzioni and Etzioni, 2017; Wilson et al., 2019). Regardless, the premise of AVs being involved in fewer crashes will be non-provable in the first 100 years of operation (Kalra and Paddock, 2016).

1.2.2. *Natural environment*

Very few publications discuss how AVs will impact the natural environment, climate change, and energy consumption. Assuming the introduction of AVs as electric vehicles, greenhouse gas emissions will decrease unless, higher traffic volumes and congestion offset the potential savings (Bahamonde-Birke et al., 2018; Fox-Penner et al., 2018; Greenblatt and Saxena, 2015; Iacobucci et al., 2019; Meckling and Nahm, 2018; Mersky and Samaras, 2016; Stern et al., 2019; Thomopoulos and Givoni, 2015; Wu et al., 2019; Zhang et al., 2016; Zushi, 2017).

1.2.3. *Virtual environment (modeling and learning)*

AV algorithms will make mobility more efficient, increase safety, and provide improved comfort (Bonnefon et al., 2016; Contissa et al., 2017; Hacker, 2017; Hübner and White, 2018; Talebpour and Mahmassani, 2016), but they also may determine norms of social behavior and the emergence of social preferences (Choi and Ji, 2015). Because algorithms sit outside the democratic process, morality and ethics are outsourced to whomever owns the AV algorithm (Contissa et al., 2017; Hacker, 2017; Hübner and White, 2018; Leben, 2017; Masoud and Jayakrishnan, 2017; Rahwan, 2018). AI system stakeholders thus reprogram social and cultural norms, accepting implicit tradeoffs in peoples' privacy and freedom (Fagnant and Kockelman, 2015, Hacker, 2017, Rahwan, 2018). As a result of this encoding process, society's inequalities and discrimination are likely to persist if not widen when AVs are deployed (Liu, 2017). Especially, driver engagement during human to machine transitions remain a serious challenge for policy-makers pitting personal freedom against the ethical unlawfulness of human driving (Bösch et al., 2018; De Bruin, 2016; De Sio, 2017; Geistfeld, 2017; Hevelke and Nida-Rümelin, 2015; Pinter et al., 2017; LoRicco, 2017; Salatiello and Felver, 2017; Salatiello and Felver, 2017; Sparrow and Howard, 2017; Stilgoe, 2018; Tomsk State University of Control Systems and Radio-electronics and Churilov, 2018).

2. The role of autonomous vehicles in urban mobility

The AV-literature is auto-centric and minimizes the role of mobility choices predicting a shift towards the automobile (Deb et al., 2018; Hensher, 2018; Kane and Whitehead, 2017; Liu et al., 2017; Loeb et al., 2018; Simoni et al., 2019; Sparrow and Howard, 2017; Thomopoulos and Givoni, 2015). Most publications accept that cars are the dominating feature of the urban transport landscape of tomorrow, while there is no consensus as to whether AVs will impact public transportation for better (Bahamonde-Birke et al., 2018; Bennett et al., 2019; Fagnant and Kockelman, 2018; Farhan and Chen, 2018; Gelauff et al., 2019; Iacobucci et al., 2019; Puylaert et al., 2018; Shen et al., 2018; Wen et al., 2018) or worse (Bahamonde-Birke et al., 2018; Crayton and Meier, 2017; Gelauff et al., 2019; Harb et al., 2018; Kane and Whitehead, 2017; Liu et al., 2017; Simoni et al., 2019; Puylaert et al., 2018; Szell, 2018). Public transit with AVs may lead to greater efficiency, lower costs, reduced emissions, and increase accessibility and mobility (Bennett et al., 2019; Bösch et al., 2018; El Zarwi et al., 2017; Fox-Penner et al., 2018; Greenblatt and Saxena, 2015; Hensher, 2018; Mezei and Lazányi, 2018; Ohnemus and Perl, 2016; Shen et al., 2018; Sousa et al., 2017; Truong et al., 2017; Wen et al., 2018). Conversely, it may also decrease safety, security, accessibility, mobility, increase emissions, and lead to job loss (Bösch et al., 2018; Cohen and Cavoli, 2019; Crayton and Meier, 2017; El Zarwi et al., 2017; Fagnant and Kockelman, 2015; Harb et al., 2018; Hensher, 2018; Legacy et al., 2019; Lu et al., 2017; Millard-Ball, 2018; Salonen, 2018; Szell, 2018). How AVs will be integrated into existing transit networks is also unclear: some suggest medium-sized shuttles (Salonen, 2018; Wu et al., 2019), some argue for fleets of small publicly or privately owned shared-AVs (Fagnant and Kockelman, 2018; Farhan and Chen, 2018; Gelauff et al., 2019; Iacobucci et al., 2019; Nazari et al., 2018; Wen et al., 2019), some for individual demand-response vehicles (Liu et al., 2017; Loeb et al., 2018; Nourinejad and Roorda, 2016; Ohnemus and Perl, 2016; Truong et al., 2017), and few for autonomous rail (Mezei and Lazányi, 2018). Regardless, funding for public transit is a serious concern (Hensher, 2018; Lu et al., 2017).

3. Identifying literature gaps and implications

Our commentary provides a mid-2019 literature snapshot on AVs and identifies gaps in knowledge. Research tends to see AVs in isolation rather than one element in a mobility strategy. Active and public transit contributions are rare. Further, the literature has remained rather silent on the complexity of transition when both humans and autonomous vehicles navigate road space. Research findings on the impact of AVs on the natural environment is minimal. Finally, within the social science literature there is little research as to how autonomous technology could be retrofitted into existing infrastructures and vehicles, despite the potential of autonomous technology itself to increase safety. Research in these rarely explored issues is necessary to equip policy-makers with essential knowledge to develop policy for their wide-spread deployment.

Two areas of primary concern evolved from our review: researchers tended to recognize the benefits and overlook challenges and most scholars accept the premise that the AV age is upon us addressing the question of when, not whether, it should be. Throughout human history, breakthrough technologies have come with unintended consequences. As communities engage with AVs, it is important to be mindful of technological determinism: the acceptance of new technologies as an external force rather than one that can be changed. Instead of viewing AVs as inevitable, AVs should be seen as a technology useful for some applications that must be nested in the broader mobility challenges communities of the future face. Transport policy-makers are the vanguard of that future and the ways in which AVs are used in our communities.

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CRediT authorship contribution statement

Eva Kassens-Noor: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Dana Dake:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing - original draft. **Travis Decaminada:** Data curation, Formal analysis, Methodology, Validation, Writing - review & editing. **Zeenat Kotval-K:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing - original draft. **Teresa Qu:** Conceptualization, Data curation, Formal analysis. **Mark Wilson:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing - original draft. **Brian Pentland:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing - original draft, Writing - review & editing.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.tranpol.2020.08.022.

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Dr. Eva Kassens-Noor in an Associate Professor of Urban and Transportation planning in the School of Planning, Design, and Construction (SPDC) at Michigan State University (MSU). Her research interests address extreme events, autonomous futures, and transformative plans.

Dana Dake is a graduate research assistant in SPDC at MSU. Her research interests include sustainable urban design concepts and innovative transportation planning.

Travis Decaminada is a graduate research assistant in SPDC at MSU. His research interests include autonomous mobility and resilience against extreme events.

Dr. Zeenat Kotval-K is an Assistant Professor of Urban and Regional Planning in SPDC at MSU. Her research interests broadly encompass the health impacts of the urban built environment through travel behavior.

Dr. Tongbin (Teresa) Qu is an Associate Professor in the SPDC at MSU. Her research interests include: Active Transportation, Accessible Transportation, Multi-modal Transportation Planning and modeling, Transportation Planning with Big Data, Shared Mobility, and Autonomous Vehicles for People with Disability.

Dr. Mark Wilson is Professor and Program Director of Urban and Regional Planning in the School of Planning, Design and Construction at Michigan State University. Research interests address urban planning, autonomous and disruptive technologies, and mega-events.

Dr. Brian T. Pentland (Massachusetts Institute of Technology, PhD, 1991) is the Main Street Capital Partners Endowed Professor in the Department of Accounting and Information Systems at Michigan State University. His research is focused on the analysis of repetitive patterns of action, such as organizational routines.