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A transport justice approach to integrating vulnerable road users with automated vehicles

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A R T I C L E I N F O

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A B S T R A C T

Connected and automated vehicles (CAVs) are expected to revolutionise transport worldwide and transform urban life. However, there are many unknowns concerning the impacts of these technologies in terms of sustainability, justice, and safety. It has been suggested that CAVs may exacerbate inequities and safety disparities concerning the interaction of vulnerable road users (VRUs) with motorised transport. This paper investigates the justice issues that CAVs policy needs to address concerning VRUs. Our approach to studying CAVs' capabilities and their potential perverse outcomes uses transport justice as an evaluative framework. The justice-related outcomes discussed include: traffic injuries, impact on sharing road responsibilities, loss of on-street space, access to technology, inclusion for disabled and older adults, CAV technological development, and impact of congestion and air pollution. The paper proposes a future research agenda emphasising areas where CAVs may positively impact VRUs.

1. Introduction

Active travel—such as walking, cycling, and public transport use—has been promoted as a sustainable, healthy, accessible, affordable, and convenient form of mobility. Jurisdictions worldwide are increasingly prioritising and incentivising active travel. However, active travel brings safety risks to certain road users, particularly in relation to the interaction of motorised vehicles (cars) with pedestrians, bike riders, motorcyclists, elderly road users, and people with disabilities (Khayesi, 2020, Bailey and Woolley, 2017, Rod et al., 2021, Vaezipour et al., 2022). This is particularly the case in places where active transport infrastructure is inadequate and motorists dominate available public road space, such as in Australia and the US (Flatt and Odinsman, 2015, Saeidizand et al., 2022). The increased injury risk that active travellers experience has resulted in them being labelled *vulnerable road users* (VRUs).

VRUs constitute a disproportionate share of people killed and injured in road crashes worldwide (Khayesi, 2020). According to the World Health Organization (2019), more than 1.3 million people are fatally injured yearly due to road traffic crashes. VRUs account for

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more than half of all road fatalities. For instance, pedestrians and cyclists represent 26%, and motorcycle riders and passengers account for 28% of these fatalities. In 2020, the US National Highway Traffic Safety Administration estimates show that approximately 38,680 people died in motor vehicle traffic crashes, even when people drove less due to the COVID-19 pandemic. Pedestrians accounted for 6,236 fatalities (16.12%), cyclists for 891 (2.30%) and motorcyclists 5,458 (14.11%) deaths (National Highway Traffic Safety Administration, 2021). In 2021, more than 1,127 people died in Australia because of road crashes; 134 of these fatalities were pedestrians (11.88%), 39 cyclists (3.46%) and 234 motorcyclists (20.76%) (National Road Safety Strategy, 2021).

Pedestrians are perhaps the most vulnerable road users, at risk of injury, disability, and death due to collisions (Hashemiparast et al., 2017, Rod et al., 2021). This is partly because they do not have an external protective device that can absorb the physical impact of a road crash. Still, the absence of policies prioritising their safety is also a contributing factor (Tabone et al., 2021, Yannis et al., 2020, Hasan et al., 2020, Oviedo-Trespalacios and Scott-Parker, 2017). The vulnerabilities experienced by these road users are a symptom of inequities in the transport system. These vulnerabilities result in some road users being disproportionately more likely to suffer health consequences in a safety–critical situation than others. These inequities represent a significant barrier to active mobility and can negatively impact the sustainability of the transport system.

The pattern of pedestrians' and cyclists' safety risks is shaped by sharing road space with motorists. Connected and automated vehicles (CAVs) are an emerging technology deemed to improve safety, efficiency, and accessibility outcomes for all road users in the transport systems (Barnett et al., 2021, Shay et al., 2018). A CAV has two technology sets—connectivity and automation (Society of Automotive Engineers, 2021). These capabilities are necessary to exchange information and cooperate with other vehicles and infrastructure (Deb et al., 2018). A CAV will use various technologies to detect and identify people and objects, measure their speeds, anticipate their intentions, and make decisions in real-time (Inter-American Development Bank, 2020). Some practical applications of connectivity and automation when driving include real-time control, routing with micro-scale traffic information, and eco-mobility with guaranteed parking (Guanetti et al., 2018).

CAVs are likely to be on our urban roads in growing numbers in the coming years and generate significant economic benefits (Blas et al., 2020, Loke and Rakotonirainy, 2021). In the US alone, it has been estimated that the economic impact will be $1.2 trillion or $3,800 per American per year (Clements and Kockelman, 2017). Additionally, it has been argued that CAVs have the potential not only to reduce road crashes but also to improve comfort and health, reduce road congestion, and increase energy efficiency associated with the transport sector (Elliott et al., 2019, Chen et al., 2019). It has also been suggested that the widespread adoption of CAV may improve mobility for people with disabilities and the elderly (Pettigrew et al., 2018, Owens et al., 2019). However, although these new technologies have been lauded as delivering advantages over conventional vehicles, the fact that individual motor-vehicle mobility can become more attractive brings new challenges (Blas et al., 2020).

One of the central challenges of deploying CAV technology is the public acceptance (Afghari et al., 2021, Kaye et al., 2022, Kaye et al., 2022, Man et al., 2020), as the anticipated benefits of CAVs can only be maximised if this technology is widely implemented. This means that the introduction of CAVs should consider broader societal concerns, not just issues related to the technical efficiency of the transport system. Specifically, this requires consideration of current inequities in the transport system and assurance that these technologies will positively contribute to sustainability and justice (Strömberg et al., 2021). Although there has been significant research activity around CAVs in recent years (Haghani et al., 2021), some of the unresolved technical and policy questions regarding CAV adoption include how CAVs can be deployed to maximise their benefits in non-detrimental ways (Fagnant and Kockelman, 2015, Lee and Hess, 2020), including in relation to their interaction with other non-CAV road users (Dietrich, 2021, Latham and Nattrass, 2019).

Unless these concerns are explicitly recognised and addressed, there is a risk that CAV adoption may increase existing inequalities or introduce new injustices associated with being a VRU. For example, the major injustice that VRUs face today is the unequal exposure to risks of bodily harm in case of a crash (Dietrich, 2021). Recent crash data demonstrates that crashes involving VRUs and vehicles with autopilots can be fatal because these systems have trouble identifying VRUs (Wang and Li, 2019, Jefferson and McDonald, 2019). One of the most famous cases involved an Uber vehicle with an autopilot active that collided with and killed a pedestrian in Tempe, Arizona, in March 2018 (Rosenfield, 2018). It could be suggested that manufacturers of CAVs have not made significant advances in pedestrian protection systems due to an overwhelming preoccupation with addressing the technical aspects of vehicle automation (Milakis and Muller, 2021). Moreover, widespread adoption of CAVs could increase traffic volume, which could further reduce the street space available for pedestrians and cyclists (Soteropoulos et al., 2021). Therefore, this brings to question how to harness all the benefits from CAVs without perpetuating or exacerbating the current vulnerabilities and inequities that VRUs experience.

Prior research activity has focused on automated driving for relatively simple road environments such as highways (Tabone et al., 2021) or technology development issues related to the human–machine interface, security, communication, intersection control, and collision-free navigation (Elliott et al., 2019, Guanetti et al., 2018). Nevertheless, with the arrival of vehicle automation in cities, a critical issue that has not been completely understood is how these technologies will interact with VRUs (Epting, 2019, Brar et al., 2017). The current literature has been disjointed, and there is a lack of frameworks based on values such as justice in interactions between CAVs-VRUs. The recent *Ethics of Connected and Automated Vehicles* report by the Horizon 2020 Commission Expert Group (2020) highlights the need for all stakeholders to actively work to redress inequalities in vulnerability among road users while considering justice principles. This may require CAVs to adapt their behaviour around VRUs and not the other way around (Horizon 2020 Commission Expert Group, 2020). Unfortunately, current policies appear to support the expectation that VRUs should change their behaviour to remain safe around CAVs. For example, the US government is funding beacon technology that would need to be worn by pedestrians to allow detection by CAVs (Reid, 2021), which may displace the responsibility of a crash from the CAVs to the VRUs.

2. Transport justice applied to the CAVs problem

Transport decisions have long been dominated by a utilitarian logic that privileges cost-benefit analysis over justice considerations (Nazari Adli et al., 2019). Transport justice describes a normative condition in which no person or group is disadvantaged by a lack of access to the opportunities they need to lead a meaningful and dignified life (Karner et al., 2020) but also emphasises a more equal distribution of transport benefits and burdens in society (Pereira et al., 2017).

Transport justice has been widely applied in the field of transport planning. Karel Martens (2017) established a transport planning framework considering principles of justice based on his observation that the focus of transport planning and policy has centred on the performance of the transport system and ways to improve it without paying sufficient attention to the people using that transport system. Martens (2017) argues that applying a justice lens to transport is necessary because this dimension has received less attention, and theories of justice are typically aspatial and thus tend to overlook mobility. Martens provides a theoretical, philosophical, and moral basis for transport policy, criticising the current policy paradigms and practices (Vanoutrive and Cooper, 2019) by defining three principles of justice—equality, fairness, and accessibility—to analyse the state of the transport system and identify interventions that move the system closer to the fair ideal.

The first principle of justice, equality, is associated with the state of being equal, especially in status, rights, or opportunities (Victoria Law Foundation, 2019). In the transport context, the principle of equality is implicit in persistent inequalities between persons regarding travel speed, potential mobility or accessibility (Martens, 2017). The second principle of justice, fairness, is defined as impartial and just treatment or behaviour without favouritism or discrimination (Victoria Law Foundation, 2019). In transport planning, fairness or equity refers to distributing benefits and costs fairly (Martens, 2017). Inequity exists when there are fundamental differences in access to opportunity. Finally, the third principle of justice, accessibility, means everyone can use the resources, procedures, and institutions available in the transport system (Victoria Law Foundation, 2019). Accessibility planning has been developed in response to concerns about the contribution of transport systems to the exclusion of vulnerable population groups from mainstream society. Accessibility links transport to land use, and stresses that space creates tension, a barrier between origin and the desired destination (Martens, 2017).

Transport justice is often linked to mobility justice and the idea of the right to the city, which emphasises the right to physically access, occupy and use urban space (Verlinghieri and Schwanen, 2020). Nazari Adli et al. (2019) argue that transport justice must necessarily combine both egalitarian and sufficientarian or distributional justice outcomes. Outside critiques of public transportation investment and provision (e.g., See Nazari Adli and Donovan, 2018, Enright, 2019), the current applications of transport justice have been somewhat limited; however, they have been vital to closing the mobility equity gap worldwide. For example, Guzman et al. (2021) explored the relationships between mode share, street space distribution, and spaces' construction cost based on justice principles. The authors found imbalances in the prioritisation of space for specific street users in Bogotá (Colombia) because cars are prioritised over pedestrians.

In the Philippines, Sunio (2021) studied the injustices arising from the (non)legitimation of motorcycle taxis, the formalisation of jeepneys, and the high-priority bus system implementation. This empirical investigation of the contested politics of equitable transitions in the domain of mobility highlights the competing outcomes, tensions and conflicts that must be addressed to achieve transport justice, such as the protection of air quality, health and environment, financial affordability, social support, the prioritisation of incumbents, and job displacement, finding that these injustices are sources of discontent that may drive, resist or terminate just transitions (Sunio, 2021).

Studying the transport system in Malta, Attard (2020) exposed growing transport injustices associated with the high congestion costs, air and noise pollution, and disproportionate health impacts. In part, Attard (2020) found that these injustices are a consequence of political decisions aimed at providing more roads for cars without supporting alternate active modes of transport. Henriksson et al. (2022) explored a bike-sharing system initiated by a local authority in Sweden, finding from a justice perspective that the Linbike system has great potential because it incorporates two low-income areas whose residents traditionally have low accessibility. However, some studies reflect that cycling is not a global good; instead, like other modes of transport, it is classed and gendered (e.g., see Osborne & Grant-Smith 2017). Even with this progress in the field, a recent study by de Sio (2021) mentions that it is necessary to establish a broader debate on the ethics of transportation on road safety, privacy, fairness, and responsibility with the implementation of CAVs.

The potentially uneven and unjust consequences of adopting CAVs, particularly in relation to interactions with VRUs, require explicit consideration within this context. Verlinghieri and Schwanen (2020, p.1) argue that such exploration needs to be "just as much if and how such innovations will be co-opted by vested interests and elites or rather reshuffle existing socio-spatial stratifications and change discourses about rights, responsibilities, and opportunities with respect to transport and mobility". In other words, the future vision for CAVs should incorporate a broader set of ethical, legal, and societal considerations into this technology's development, deployment, and use.

Some progress has been made in transport planning. For example, Australia has enacted regulations regarding safety management planning and data monitoring of CAVs (Lee and Hess, 2020) and recognises that investment in digital and physical infrastructure is necessary to support these technologies (Manivasakan et al., 2021). Similarly, Emory et al. (2022) conducted a comprehensive analysis of AV-related policies that have equity implications for drivers. Their research showed that these policies could be grouped into three categories: access and inclusion, multimodal transportation, and community wellbeing. They concluded that a shared model for AVs is the most commonly designed AV policy with positive equity implications. Thus, it is suggested that a shared policy model of AV mobility should be prioritised rather than the private ownership model that dominates automobile travel today. It should be noted that Emory et al. (2022) did not address VRUs interactions with CAVs. Indeed, global policy developments are yet to consider and address the effect of CAVs on VRUs. Further, it has been argued that current approaches to transport justice have not considered how 'embodied differences' grounded in personal characteristics such as income, gender, race, or physical ability interact with the development of CAVs (Sheller, 2018). There is a need to develop nuanced frameworks of transport justice that consider these differences in the context of VRUs-CAVs interactions.

To address this gap, in this manuscript, we propose to answer the question: *what are the justice issues that CAVs policy needs to address concerning VRUs?* by applying a transport justice evaluation framework which explicitly considers the potential equality, fairness, and access impacts of CAVs on VRUs.

3. The contribution of transport justice to designing CAVs-VRUs interactions

A potential approach to measure and improve the safety of interactions between VRUs and CAVs is to minimise current and future inequities in the transport system. Rethinking interactions between CAVs and VRUs using a transport justice lens illuminates aspects within the transport system with the potential to improve equity that can be applied both as a policy framework and set of shared values to guide decisions. Such an approach considers the potential advantages which CAVs could deliver to serve individual mobility but also to address the systemic vulnerability of VRUs, such as pedestrians, cyclists, and motorcyclists, in relation to this. In the next section, we present examples of transport system inequities experienced by VRUs. Fig. 1 illustrates how a transport justice lens, based on the principles of equality, fairness, and access, can be used to identify such inequalities. In this framework, justice is positioned as central, while the identified inequities are dynamic and related to multiple principles of justice.

3.1. Crash involvement or traffic injuries

Road traffic injuries cause considerable economic losses to individuals, families, and countries. More than 1.3 million people are

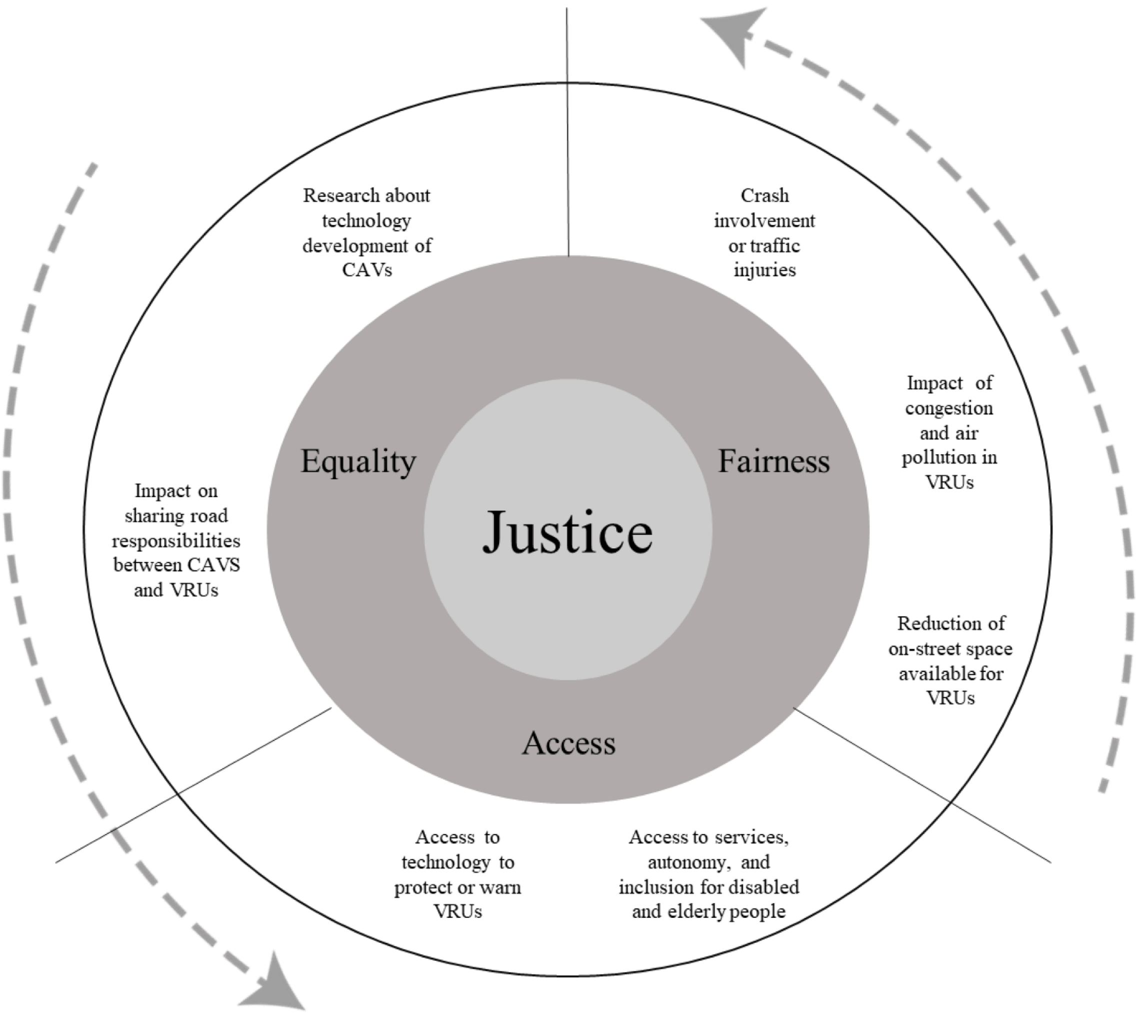

Fig. 1. Framework illustrating the contribution of a transport justice lens to designing CAVs-VRUs interactions.

fatally injured as a result of road traffic crashes every year. VRUs (e.g., pedestrians, cyclists, and motorcyclists) account for more than half of all road traffic fatalities (World Health Organization, 2019). A key narrative of car manufacturers, industry, and governments is that CAVs will reduce road crashes compared to the current vehicle fleet (Favarò et al., 2017, Department of Transport and Main Roads, 2019, Dixon, 2020). Indeed, it is estimated that CAVs could decrease injuries by 75% due to their ability to predict and react to oncoming hazards at a level unattainable by human drivers (Fagnant and Kockelman, 2015). However, this assertion is optimistic and not yet supported by empirical data (Papadoulis et al., 2019). Arguably, while numbers of road crashes may decrease, they will not be eliminated as no automated system is entirely failsafe (Ward, 2019).

Despite significant technological advances in automation, CAVs are not yet reliable in terms of road safety (Dixit et al., 2016), particularly concerning CAV–VRU interaction. Recent research shows that one potential risk of CAVs is system operation failure. These failures involve malfunctioning sensors when detecting VRUs and misinterpretation of data or poorly executed responses (Bila et al., 2017). Indeed, previous experiences with automation have already resulted in crashes with VRUs. The most famous case involved an Uber vehicle with an autopilot active that collided with and killed a pedestrian in Tempe, Arizona, in March 2018 (Rosenfield, 2018). The US National Transportation Safety Board (NTSB) found that the vehicle's automatic systems failed to identify the victim and her bicycle as an imminent collision danger in the way they were supposed to (National Transportation Safety Board, 2019). Moreover, Google reported that 13 manual disengagements would have resulted in collisions in their simulations, and 56 were safety–critical due to the wrong perception of traffic lights, not yielding appropriately to pedestrians and cyclists, or violations of traffic laws (Dixit et al., 2016).

Given that VRUs are overrepresented in road trauma and experience worse health outcomes in case of a crash with a vehicle (Olszewski et al., 2019, Amin et al., 2022, Shatu and Kamruzzaman, 2022), there is little evidence to suggest that CAV adoption will address this inequity. Without significant advancements in CAV design with a specific focus on CAV–VRU interactions, the injustice that VRUs face with regard to unequal risk exposure induced by a crash will likely remain unchanged (Dietrich, 2021). Transport system stakeholders, such as car manufacturers, policymakers, and insurance companies, need to ensure that the adoption of CAVs promotes justice outcomes, particularly fairness in the distribution of health outcomes. For that reason, there is an urgent need to design CAVs to protect VRUs and to develop CAV policy frameworks that are sensitive to the health impacts of transport decisions on all road users to deliver an equitable transport system.

3.2. Impact on sharing road responsibilities between CAVS and VRUs

CAVs have the potential to reduce crashes with other vehicles and improve roadway efficiency; even when all sensors, vehicle control components, and algorithms function perfectly, they are expected to crash occasionally (Goodall, 2014). Indeed, recent studies reveal that pedestrian fatalities have risen worldwide, even though vehicles are increasingly equipped with sophisticated safety and crash avoidance technology (Combs et al., 2019). This can be mostly explained because of a lack of education on the capabilities of these technologies and inaccurate mental models about their operational aspects (Haque et al., 2021, Oviedo-Trespalacios et al., 2019, 2021, Khakzar et al., 2021, Kaye et al., 2022).

Some technological proposals to protect VRUs from crashes when they are in contact with CAVs have been suggested (Schwebel et al., 2021). These recommendations aim to reduce disparities in the ratio of harm-relative-to-road-exposure between different road users: however, little is known about how to deploy these recommendations equitably. For example, the US government has proposed to equip cyclists and pedestrians with transponder beacons that can be spotted by sensors embedded in the CAVs (Reid, 2021). Nonetheless, it can be argued that wearing a transponder beacon might be a burdensome expectation for VRUs, a group that has been historically disadvantaged and often suffers disproportionately under existing power/protection asymmetries on the road. The main issue with this proposal is that it relies on VRUs taking on additional responsibility for protecting themselves. Such an unbalanced responsibility does not advance transport justice, as it places an unfair burden on VRUs to prevent harmful interactions and assumes that VRUs will have access to or can afford high-end technology to avoid crashes. The recent *Ethics of Connected and Automated Vehicles Report* (2020) explains that VRUs should enjoy the same level of safety as motorised four-wheeler road users when in contact with CAVs. Also, VRUs should not be expected to behave differently because of their vulnerabilities or adapt their behaviour to the new dangers of the road (Horizon 2020 Commission Expert Group, 2020). As such, we need to prioritise solutions that do not further burden VRUs when seeking better road safety.

3.3. Reduction of on-street space available for VRUs

Streets are multifunctional, used by all and give life to the city. However, despite the importance of providing safe street spaces for pedestrians to achieve spatially just urban environments (Tsoriyo et al., 2021), safe pedestrian movement is rarely prioritised in road transport planning (Mullen, 2021). Indeed, in many countries, such as Australia, the core of transport planning initiatives is centred on motorised vehicles (Flatt and Odinsman, 2015).

CAVs will be situated within socio-technical environments of human road users and other automated entities. As such, research activity has focused on developing and modelling road-sharing strategies for CAVs. For example, Chakraborty et al. (2021) proposed a freeway network design with exclusive lanes for automated vehicles that aims to improve the overall safety and traffic flow in a hybrid network of pedestrians, cyclists, and automated and regular vehicles. Ye and Yamamoto (2018) investigated the impact of CAVs' dedicated lane policy on traffic flow throughput. They explained that the performance of CAV in dedicated lanes can be improved by setting a higher speed limit for CAVs on the dedicated lane than the speed limit for vehicles on regular lanes. Importantly, this also means that people travelling on the dedicated lanes are the only ones benefiting from these policies.

The proposed road-sharing strategies are unfair because they imply a change in the current road infrastructure that prioritises certain high-income users with CAVs over VRUs. Also, these strategies promote an expansion of the transport network, which will affect green space. For example, the Inter-American Development Bank (2020) establishes that concerning affordability, it is clear that most of the Latin American population will not be in a position to acquire a CAV, especially in the first phases of its introduction in the market. This may negatively impact pedestrians and cyclists, as they may see their space reduced, noting that active travellers already have less space in many low- and middle-income jurisdictions than motorised transport (Creutzig et al., 2020). Arguably, regions such as Latin America could gain the most from the safety benefits of CAVs as they are among the worst-performing regions in terms of road safety (Haghani et al., 2022, Oviedo-Trespalacios and Scott-Parker, 2018).

To summarise, CAVs could introduce new inequities to the transport system because not everyone will have access to these vehicles due to their high cost. For this reason, policymakers need to ensure that the implementation of CAVs addresses these issues from a safety and justice perspective, given that currently, vehicles are taking up the space of VRUs and limiting active travel.

3.4. Access to technology to protect or warn VRUs

Research indicates that CAVs could further perpetuate existing societal inequalities in the transport system depending on the ownership, cooperation and access models (Dean et al., 2019). For example, if private ownership of CAVs is the prevailing model, high-income populations will be more likely to benefit from on-demand mobility, while lower-income populations may face decreased access to transport (Inter-American Development Bank, 2020). Also, CAV technology could increase racial inequities (Wu et al., 2021), given that the majority of AV algorithms are primarily trained with images of white people. In this case, CAV may recognise white pedestrians more accurately than pedestrians with darker skins (Wilson et al., 2019).

Another design attribute that relates to improved CAV–VRU interaction is the use of external vehicle interfaces. Recent research has recommended using extended reality in CAV–VRU communication (Perez et al., 2019). However, there are some views that safe and acceptable CAV interaction may be feasible without external human-machine interfaces (Tabone et al., 2021). This must be clarified to improve the design of these cars in terms of interactions with VRUs. Importantly, the development of external interfaces has continued. For example, Ford Global Technologies developed a method and system to enable communication between a VRU and CAV using mobile phones. In this case, an application will let a self-driving car send a message to a mobile phone that says, "I will not be stopping at the crosswalk" (Ford, 2022). We need to consider that not all VRUs may be in a position to interact with external interfaces as a result of disabilities or lack of knowledge. Moreover, non-inclusive design practice implies systematic unfairness in the development of CAVs and the relationship with VRUs; for this reason, proactive policies and regulations must be implemented on this issue.

3.5. Access to services, autonomy, and inclusion for disabled and elderly people

According to World Health Organization (2021), over 1 billion people – about 15% of the global population – currently experience disability. The statistics show that 253 million people are affected by some form of blindness and visual impairment, 466 million people have disabling deafness and hearing loss, about 200 million people have an intellectual disability, and 75 million people need a wheelchair daily (World Health Organization, 2021b). Moreover, the proportion of older people aged 60 + years is increasing. This population is expected to be 1.4 billion by 2030 and 2.1 billion by 2050 (World Health Organization, 2021a).

CAVs have been presented as having the potential to support positive changes in the lives of people with disabilities (Sundararajan et al., 2019) and older people (Faber and van Lierop, 2020) by giving them another mobility option. People who are not fit to drive may now be able to participate in activities and access jobs, education, and health care services (Sohrabi et al., 2020) when CAVs are adopted.

Policy frameworks must maximise the benefits of these cars while mitigating or eliminating negative outcomes. For instance, CAVs will be less affordable than conventional vehicles due to the high cost of the advanced technology that they will have (Litman, 2017). Considering the above, it is necessary to ask if people with disabilities and older people will have financial access to these vehicles. Additionally, it is essential to consider how CAVs technology can improve safety, justice, and accessibility to these populations outside and inside the car. Kuzio (2021) mentioned that due to the introduction of CAVs, the built environment would require changes in design standards that promote accessibility and a robust regulatory framework to ensure a smooth transition with all the transport system stakeholders.

3.6. Research about technology development of CAVs

Due to advancements in communication and computation, CAVs will likely revolutionise how we travel. However, it is crucial to understand the impact of CAVs on transport and society. Manufacturers have primarily invested in technology development related to the technical aspects of vehicle automation, such as engineering, computer science, transportation and automation control systems, and robotics (Clements and Kockelman, 2017), rather than in pedestrian protection systems or in improving the way VRUs and CAVs can equitably and safely interact.

Research shows technical uncertainties concerning the integration of CAVs and their interaction with VRUs. Gonzalez et al. (2016) found that different motion planning and control techniques have been implemented in autonomously complex drive-in environments. However, they concluded that challenges such as navigation in dynamic urban environments with VRUs require further efforts.

Although CAVs present several positive impacts, they also offer many uncertainties. Concerningly, research efforts have mainly focused on the technical aspects of the technology and general global impacts (Shiwakoti et al., 2020). Indeed, it is important to include the perspective of justice in academic research with the purpose of raising new questions about the impact that such vehicles will have on transport disadvantage.

3.7. Impact of congestion and air pollution in VRUs

Preliminary studies show how CAVs could reduce congestion and air pollution. Tu et al. (2019) found that this reduction could be possible due to the smoother traffic flow that may result from CAVs dampening traffic waves and the impact this has on the underlying traffic dynamics. Emissions reductions, fuel consumption reductions, travel time reductions and safety improvements have been the most covered themes (Shiwakoti et al., 2020). This is positive because air pollution can negatively impact the physical and mental health of drivers and VRUs (Dean et al., 2019) and be a contributor to climate change (Stanley et al., 2011). Based on current trends in the evolution of vehicle technologies, as demonstrated by Tesla, the vast majority of CAVs will likely be electric vehicles (Inter-American Development Bank, 2020). Nevertheless, an increasing number of studies highlight potential problems that may arise with CAVs related to air pollution. For example, Makridis et al., (2018) demonstrated that problematic interaction with human-driven vehicles, such as the inability to make decisions based on eye contact or body language and increased traffic demand, could serve to increase congestion and, therefore, air pollution. Lim and Taeihagh (2018) demonstrated in their study that the increase in transport demand associated with CAVs' adoption could increase air pollution and congestion through possible increases in vehicle-miles-travelled (VMT), affecting the health of VRUs. Another key concern when reviewing the literature on the impact of CAVs congestion and air pollution is that researchers often assume that people would share these vehicles (Shaheen and Bouzaghrane, 2019, Inter-American Development Bank, 2020), which is highly debatable.

4. Conclusion

The present manuscript considers how the current and latent inequities experienced by VRUs in thetransport system could be perpetuated and exacerbated in the future if they are not addressed when further integrating CAVs in the transport system. Additionally, we used the transport justice framework proposed (Martens, 2017) to illustrate the consequences of CAVs on the equity and safety outcomes of VRUs.

Table 1
Strategies proposed forward to develop safer and more equitable interactions between CAVs and VRUs.

Case of inequity	Research gap	Strategies
Crash involvement or traffic injuries	Uncertainty regarding the crash risk associated with CAVs' system failures.	- Promote research that provides a comprehensive vision of CAVs and road safety issues. - Design an equitable road environment considering CAVs and VRUs interactions. - Identify safety issues of CAVs. - Quantify how CAVs affect crashes' frequency, severity, and impact of restitution on the victim.
Impact on sharing road responsibilities between CAVs and VRUs	Absence of policies regarding sharing road responsibilities.	- Collect and analyse reliable system failure rates to promote better recommendations for VRUs safety.
Reduction of on-street space available for VRUs	Absence of guidelines that consider road infrastructure and street availability for VRUs in CAVs adoption.	- Consider market penetration of CAVs when designing and estimating road safety impacts. - Control transport infrastructure expansion. - Develop new funding strategies for road infrastructure.
Access to technology to protect or warn VRUs	Lack of knowledge and fair policies regarding CAVs implementation to prevent crashes that affect VRUs	- Identify which road, roadside objects, activities, or road users contribute most to crashes. - Develop and implement technologies that support policies or regulations related to CAVs and VRUs interactions.
Access to services, autonomy, and inclusion for disabled and elderly people	Lack of guidelines to support CAVs adoption in a way to improve disabled and older adults' mobility.	- Reduce barriers to using CAVs, including financial, technological, and cultural barriers. - Analyse CAVs' impacts on transport equity based on personal characteristics. - Develop policies to prevent harming marginalised communities throughout CAVs deployment.
Research about technology development of CAVs	Lack of a framework based on values such as justice to improve CAVs-VRUs interactions.	- Support normative and theoretical academic research on the technology advancement of CAVs and their interaction with VRUs. - Explore CAVs' adoption barriers.
Impact of congestion and air pollution in VRUs	Unknown impact of CAVs on health and environment.	- Encourage modal shift from private to collective/shared modes and public transport. - Prioritise fully electric CAVs. - Investigate the impacts of CAVs on public health.

The results show that although CAVs can offer benefits on many fronts, their adoption will also present significant challenges regarding sustainability, justice, and safety. Governments, car manufacturers, and other related stakeholders must address these issues. The transport justice framework provided in this paper can help to structure the potential problems associated with adopting CAVs concerning their interactions with VRUs. Some of these issues are easily avoided, while others will require significant policy reform and investment in infrastructure to reprioritise VRUs in the transport system. To consider principles of justice such as equality, fairness and access can ensure that positive outcomes for both CAV and VRU are optimised. Neither group should be required to bear a disproportionate share of the negative environmental, social, or economic consequences of the widespread adoption of CAVs. Indeed, the introduction of CAVs may serve as the tipping point required for this change and the delivery of transport plans and policies conducive to creating a more equitable transport system.

We identified that while some prior work has recognised that CAVs will have substantial benefits, e.g., better access to transport services for those who currently cannot drive, little is known about the nature and scale of the implications in the transport system regarding VRUs. Some of the outcomes analysed using transport justice were the overrepresentation of VRUs in traffic injuries, behavioural adaptation needed from VRUs, reduction of space available for VRUs, lack of academic research on VRUs interactions with CAVs, access to technology to protect or warn VRUs, increased congestion and air pollution impact and, lack of access to services for disabled and older adults. VRUs will continue to be vulnerable in the future, and CAVs advancements have not meaningfully considered the interaction with them. We anticipate that this paper could guide the design of safer and more equitable interactions between CAVs and VRUs by showing the importance of thinking about justice as a tool to reduce conflicts between them during the policymaking and technology development initiatives.

A future research agenda is proposed based on the analysis conducted in the present manuscript. Table 1 presents possible strategies to inform the design of safer and equitable interactions between CAVs and VRUs. We anticipate that this agenda can be used to advocate for transport justice related to equality, fairness, and access when designing interactions, plans, and policies before implementing these technologies.

To finalise, we want to highlight that many proposed strategies seek to improve our understanding of a future with CAVs. There are still many uncertainties, and such research is needed to develop evidence-based policy that enhances safety and other critical sustainability goals. Technology developers and policymakers should consider emerging approaches such as "Design for Values" that seek to include not only the functional requirements of technology but also the moral value, such as safety and justice, when planning for the interactions between CAVs and VRUs. Design for values is important because it can contribute to the success, acceptance, and acceptability of technological innovations and, as such, will also have productivity benefits for the transport system whilst preventing harm and inequities (van den Hoven et al., 2015). Implementing an approach of Design for Values will proactively reflect the safety and justice implications of the technology and policies surrounding its adoption and help identify vulnerable road users' concerns and needs early on. Given that CAVs are not currently deployed in the transport system, we have the unique opportunity to design an equitable and safe transport system for those that have been traditionally disadvantaged.

Authors contributions

The authors confirm contribution to the paper as follows: study conception and design: LMB AR, DGS, OOT; analysis and interpretation of the cases: LMB, AR, DGS, OOT; draft manuscript preparation and revision: LMB and OOT. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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