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ABSTRACT

Purpose of Review: The purpose of this review is to present findings from recent research on Shared automated vehicles (SAV) impacts on mobility and energy.

Recent Findings: While the literature on potential SAV impacts on travel behavior and the environment is still developing, researchers have suggested that SAVs could reduce transportation costs and incur minimal increases in total trip time due to efficient routing to support pooling. Researchers also speculate that SAVs would result in a 55% reduction in energy use and ~ 90% reduction in greenhouse gas (GHG) emissions.

Summary: SAV impacts on mobility and energy are uncertain. Researchers should carefully track SAV technology developments and adjust previous model assumptions based on real-world data to produce better impact estimates. SAVs could prove to be a next technological advancement that reshapes the transportation system by providing a safer, efficient, and less costly travel alternative.

Keywords: Shared automated vehicles, Travel behavior, Mobility, Greenhouse gases, Energy consumption, Shared automated vehicle policy

INTRODUCTION

Automated vehicles (AVs) employ technologies ranging from driver-assist capabilities to full automation to help move passengers or freight. In the last several years, advances in technology and artificial intelligence have fueled investment, development, and deployment of AVs across the globe. AV development has been primarily led by Germany, Italy, the European Union, and the USA [1–4]. There are five levels of vehicle automation, as defined by the National Highway Traffic Safety Administration and SAE International. These levels include: (1) level 0 (no automation), (2) level 1 (driver assistance), (3) level 2 (partial automation), (4) level 3 (conditional automation), (5) level 4 (high automation), and (6), level 5 (full automation) [5]. AV tests and pilots are now being conducted in many countries and are expected to become more common [6]. However, predictions on when highly automated vehicles (levels 4 and 5) will become widely available for public use vary broadly among researchers and experts, with some predicting that highly automated vehicles will be on public roads as early as 2020 [7].

Alongside AV developments have arisen shared mobility services, which provide customers with on-demand, short-term access to shared vehicles. Shared mobility services include a variety of modes (e.g., cars, bikes, scooters) and serve a multitude of purposes (e.g., movement of people, courier delivery). Shared mobility services can be shared sequentially or concurrently (e.g., pooled services) and can be operated through a business to consumer model or peer-to-peer network (e.g., transportation network companies, also known as ride sourcing and ride hailing). Smartphone technologies have enabled the mainstreaming of shared mobility. At present, AV and shared mobility technologies are converging, which could decrease trips costs and improve accessibility. Shared automated vehicles (SAV), coupled with supportive public policies, could help to reshape the transportation landscape by improving transportation efficiency, helping societies achieve more sustainable transportation systems and change how transportation infrastructure is designed and used.

While large-scale SAV deployment has yet to be achieved, understanding of the potential impacts is critical to maximizing the social and environmental benefits and minimizing the potential negative SAV impacts (e.g., induced demand, social inequities). There have been numerous academic studies investigating SAV impacts; many focus on mobility and energy. This article provides a comprehensive review of recent literature around SAVs and their potential impacts on mobility and energy. The authors present the findings of literature published on the subject over the past 5 years, highlight its limitations, and provide suggestions for future research.

RESEARCH METHODS AND STUDY LIMITATIONS

Understanding the potential impact of a technology not fully introduced to the market, such as SAVs, is challenging. As a result, researchers have used a variety of methods to answer questions about this topic. Researchers have employed surveys, stated choice experiments, agent-based simulations, and interviews with industry experts in their studies. The variety of methods reflects the diversity of approaches to the research question. However, a closer look at the SAV literature reveals several limitations. While the use of stated preference experiments is valuable in understanding the human decision-making process, in a future automated world, they are constrained to hypothetical scenarios that do not reflect real-world decision making, as people have not yet experienced these technologies and services. Although published research presents insights into demographic preferences, it reflects a static temporal perspective. To our knowledge, no study to date has examined how peoples' opinions of SAVs have changed over time. A longitudinal study could explore the evolution in perceptions and response, reflecting more accurate results. Agent-based models can sometimes lead to high variability in results due to simplistic assumptions made by the researchers about model structure, nature of SAV demand, and use of synthetic and symmetric urban grids instead of realistic urban networks. Relaxing some of the assumptions would allow researchers to explore more realistic scenarios with heterogenous individual preferences and fleet characteristics.

SAV MOBILITY IMPACTS

Our current transportation systems are experiencing significant technological transformations. These transformations will change how people and goods are transported and could have dramatic effects on our society. AVs and SAVs are manifestations of some of the technological transformations the mobility sector is undergoing. AVs and SAVs have attracted the attention of researchers, auto manufacturers, investors, governmental agencies, and legislative bodies across the globe [6]. This interest is due to the potential significant benefits of AVs/SAVs on safety, congestion, efficient travel time use, energy savings, and emission reductions. Google and Tesla have already announced plans for AV rollouts as soon as 2020 [8, 9]. However, experts have strong disagreements on when the technology will be fully available to the public, with estimates of full automation (level 5) ranging between 2025 and 2055.

Public Acceptance

Public opinion and acceptance of AVs and SAVs are critical factors in determining public adoption and market penetration rates. Many researchers have considered public perception and acceptance of AVs/SAVs. Nordhoff et al. [10] developed a conceptual model based on the technology acceptance management literature to explain and predict AV acceptance. Even if the model is not yet empirically validated, it suggests incorporating variables such as individual's socio-demographic, mobility, and psychological characteristics as well as vehicle and operating features.

Several studies employ surveys to explore the public's opinion of AVs. Kyriakidis et al. [11] conducted an Internet-based survey to investigate AV acceptance. Respondents were, on average, not entirely comfortable removing steering wheels on AVs. While respondents were not extremely concerned about data sharing to support AV safety and efficiency, they were unwilling to share data with insurance companies and tax authorities. In a different survey of people from the USA, UK, and Australia, Schoettle and Sivak [12] concluded that gender is an essential factor in determining AV favorability, with men finding AVs more favorable. Respondents consider safety, emission reduction, and reduced fuel consumption to be the main benefits of AVs, but they have concerns about privacy, hacking, liability, and equipment failure.

Researchers have also examined the heterogeneity in preferences toward SAVs across different socio-demographic groups. Krueger et al. [13••] found that young people and individuals with multimodal travel habits are more likely to pay for SAVs. Haboucha et al. [14] confirmed these findings by suggesting that young, better-educated people with high opinions of public transit and individuals who expressed significant concern for the environment are more likely to prefer SAVs to AVs. In a study focused on Texans, Bansal and Kockelman [15] reported that 41% of survey respondents expressed that they are not ready to use SAVs. However, respondents who live in densely populated areas expressed more interest in SAV adoption and use. A different study by Bansal et al. [16] suggested that high income, tech-savvy males, living in urban areas who have previous crash experiences expressed more interest in using SAV technologies. Nazari et al. [17] examined the impact of different latent variables on the public's interest in private AV ownership and a number of SAV configurations. The study concluded that safety concerns are critical in limiting public SAV acceptance, while familiarity with mobility-on-demand (MOD) services and the display of green travel habits were found to promote SAV interest.

SAV Service Characteristics

Given that AVs and SAVs could have a range of impacts on the transportation system, AV and SAV users could display different preferences about the benefits resulting from their deployment. Lustgarten and Le Vine [18] conducted a survey and reported that 48% of respondents stated that vehicle occupants should have the choice between prioritizing safety or congestion reduction, and another 43% expressed that AVs should be programmed to prioritize safety over congestion reduction. The remaining 9% thought AVs should prioritize congestion reduction over safety.

Cost plays a critical factor in technology adoption, and SAVs are no exception. AVs and SAVs should be effectively priced to encourage their adoption and use. Krueger et al. [13••] have found that SAV service attributes, such as fare and service time, are significant determinants of SAV use. Analysis by Haboucha et al. [14] revealed that only 75% of survey respondents would choose SAVs even when they are entirely free. Liu et al. [19] concluded that lower shared automated electric vehicle (SAEV) per mile fares result in a higher likelihood of an individual choosing a SAEV over a conventional vehicle. Also, SAEVs were found to be more attractive compared to public transit for short trips, and the flat cost of public transit made it more competitive for longer trips. Other service characteristics, such as wait time and efficient travel matching algorithms, could prove to be critical in determining public SAV adoption rates. Liu et al.'s [19] simulation showed that per mile SAV fares of $1 US and $1.25 US allowed one SAV to serve 7.7 travelers with an average waiting time of 3 min. In a study using mobile phone data from Orlando, Florida, Gurumthy and Kockelman [20] developed a dynamic ridesharing algorithm and were able to match 60% of the weekday single-person trips. Matching these trips added less than 5 min of total travel time for users. Additionally, the study demonstrated that as an individual's willingness-to-wait increases, the algorithm was able to match up to 80% of the single-person trips.

SAV operational costs will depend on different costs including vehicle costs, charging infrastructure, parking, and battery technology costs. Chen et al. [21•] used a combination of vehicle and charging infrastructure costs to estimate SAEV fleet operational costs. The authors concluded that SAEVs could be operated between $0.41 US and $0.47 US per occupied mile traveled. Bauer et al. [22] investigated the effects of SAEV cost components on SAEV operational costs and concluded that SAEVs could be operated between $0.29 US and $0.61 US per mile. Chen and Kockelman [23] found that as SAEV fares increase from $0.75 US to $1.00 US per mile, SAEV modal share decreases from 39% to 14%.

Integration with Public Transit

The introduction of AVs and SAVs could provide more transportation opportunities and would most likely result in modal shifts from currently available transportation modes. Pakusch et al. [24] found that SAVs would draw users from public transit as opposed to conventional vehicles. Thus, it is critical to understand if synergies between SAVs and public transit are possible, as SAVs could play a major role in increasing public transit ridership by serving first/last mile trips to and from major public transit hubs. Shen et al. [25] evaluated the performance of an integrated SAV-public transit system to provide first/last mile trips at a major public transit hub in Singapore and found that a fleet size of 17 SAVs could replace 11 buses that serve 10% of the demand. The authors reported that the SAV fleet resulted in lower out-of-vehicle times compared to the bus-only scenario, and a SAV-public transit system would be financially viable.

Travel Behavior

Understanding how emerging technologies generate new travel demand is essential. The introduction of SAVs and AVs would not only provide new transportation choices but could also serve vulnerable populations in accessing opportunities and services. In their study, Harper et al. [26] categorized underserved populations in three demand wedges: (1) non-drivers, (2) older adults, and (3) adults with travel-restrictive medical conditions. The study results show that AV introduction would increase the total annual light-duty vehicle miles traveled (VMT) by 14%. Sixty-five percent of this VMT increase would be from current adult non-drivers, while 16% is from older drivers without a medical condition, and 19% is from adult drivers with travel-restrictive medical conditions. Harb et al. [27] explored AV-related travel behavior shifts and concluded that AVs allowed underserved populations, such as retirees and children, to have more travel freedom. The study analysis results showed that there was an 83% overall VMT increase, 21% of which was zero-occupancy VMT.

A key impact that SAVs are expected to have on travel behavior is on the value of travel time. SAVs will allow users to divert their attention away from the driving task and use their travel time on other activities. Researchers disagree on whether people will make productive use of their time. Nazari et al. [17] found that while people enjoy productive use of their commute time, they do not value their time similarly for other trip purposes. Singleton [28] argues that AVs and SAVs may not result in a significant increase in productive travel time use. Mobility service providers are generally interested in deploying AVs to serve short-distance trips [29]. As a result, it would be difficult for users to productively employ their travel time with shorter trips.

Vehicle ownership is an essential aspect of travel behavior. There is significant evidence that MOD services can lead to a reduction in household-vehicle ownership rates [30]. As SAVs become more available and start to provide more flexible mobility options, there is an increasing likelihood that they will change how vehicle ownership is perceived. A study by Menon et al. [31] found among single-vehicle households that males were on average more unlikely to relinquish a household vehicle than females. In contrast, males were more likely to abandon a household vehicle than females in a multi-vehicle household. In both single- and multi-vehicle households, Millennials and graduate degree recipients were found to be more likely to relinquish a household vehicle in the presence of SAVs.

More innovative mobility services will emerge as SAVs become more commonplace. While the form of these services is not completely clear, Stocker and Shaheen [32] presented possible future SAV business models. (Table 1 below provides a summary of potential SAV business models.) The authors argue that as SAVs become more common, the boundaries between different shared mobility choices will blur. As a result, different combinations of SAV ownership and network operations will define the emerging business models. Different SAV service models could emerge as a result of the newly defined business models and will depend on multiple key factors including: technologies available, location, vehicle types, and ownership schemes [32].

Table 1 - Potential SAV Business Models

SAV Business Model	Vehicle Ownership and Network Operation
Business-to-Consumer	• Business-owned vehicles • Same entity owns and operates
	• Business-owned vehicles • Third-party entity operates
Peer-to-Peer	• Individually owned vehicles • Third-party entity operates
	• Individually owned vehicles • Decentralized peer-to-peer operations
Hybrid Ownership	• Hybrid Business/Individually owned vehicles • Entity that owns (some) vehicles operates a network
	• Hybrid Business/Individually owned vehicles • Third-party entity operates

Source:([33])

Land-Use Implications

The increase of suburbanization in the USA after World War II is often attributed to the interstate highway system [34]. AVs and SAVs also could be responsible for causing a significant shift in where people live. Gelauff et al. [35] found that SAVs make large urban centers more attractive, while personal AVs result in people leaving urban centers. Bansal et al. [16] reported that survey respondents expressed a higher inclination to move closer to central Austin, possibly to take advantage of the potential high availability of SAVs. SAV impacts could also influence residential demand, the housing market, and housing affordability, including for disadvantaged populations.

In addition, SAVs have the potential to impact parking demand and consequently reshape the public space throughout the urban grid system. Ma et al. [36] found that SAVs could result in up to 90% of the current curb space in downtown Austin becoming available for other uses. Similarly, Zhang et al. [37] found that a fleet size of 700 vehicles in a 10-mile × 10-mile city could result in up to a 90% reduction of urban parking demand. These estimates should be considered an upper bound since curb and parking spaces will be needed for SAEV charging, maintenance, passenger pick up and drop off, and staging of large fleets.

Policy

As the understanding of SAV impacts on mobility and the environment becomes more robust, it will be critical to enact evidence-backed policies and regulations to maximize their positive impacts [38]. There are numerous SAV pilots across the country, but there are very few SAV-specific policies (Fig. 1 below shows SAV pilots in the USA as of January 2019). Within the USA, there are currently 29 states and the District of Columbia with legislation or executive orders related to AVs [38].

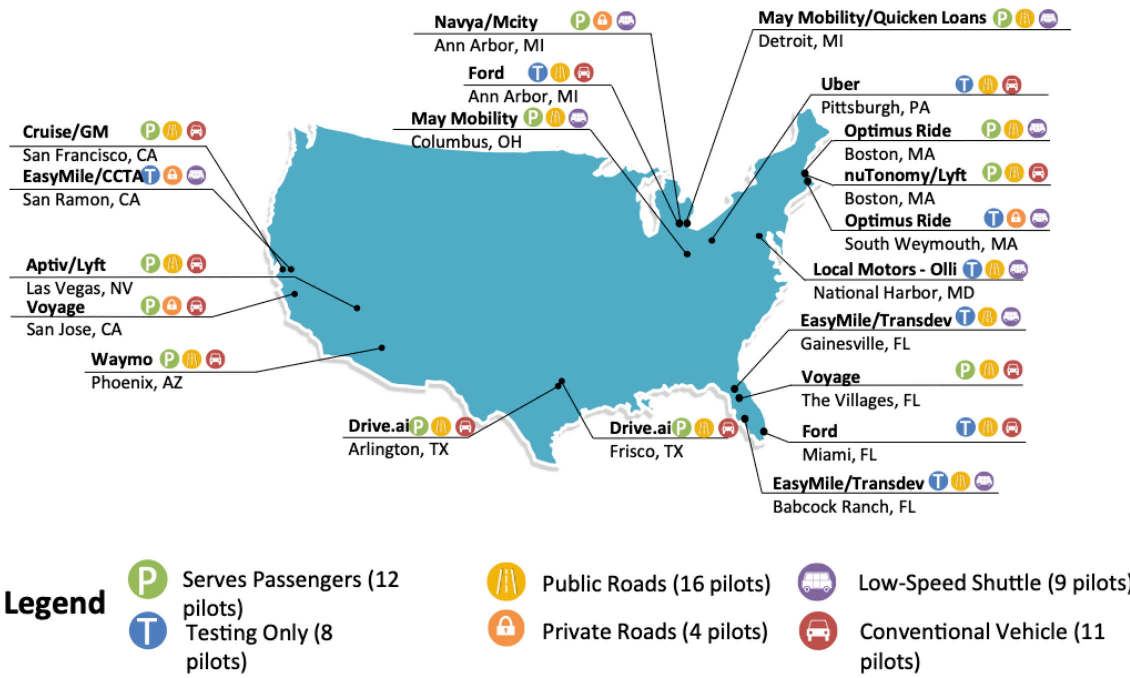

Fig. 1 – Active SAV Pilots in the U.S., as of January 2019 – Source: [39]

In the future, policies and efficient routing algorithms that incentivize and facilitate SAV pooling could be important to optimize system performance. Shaheen and Cohen [40••] highlight the impacts of pooling services on travel behavior, energy consumption, and emissions and provide policy recommendations for policymakers that would help in managing the convergence of AVs and shared ride services. Shaheen [41] argued that public policy is instrumental in accelerating the adoption of pooling and presented policy ideas on the national, state, and local levels of government. Governments could: (1) provide tax credits to auto manufacturers and mobility service providers, (2) subsidize travel using pooled services, (3) establish data standards to facilitate mobility data sharing, and (4) regulate the use of public space to encourage pooling [41]. Dynamic road charging schemes could be implemented to charge travel based on metrics such as time of day, geographical location, vehicle type, and occupancy [42]. Simoni et al. [43] investigated the impacts of different congestion pricing schemes under a range of future SAV implementation scenarios and found that SAVs yield significant congestion reduction. Over time, enacted regulations will need to be flexible as SAVs continue to develop and unforeseen hurdles and socio-economic contexts evolve. Haboucha et al. [14] found that a change in environmental concern can result in a significant improvement in a traveler's likelihood of choosing a SAV, suggesting that policies oriented toward changing attitudes and latent constructs (individual characteristics that cannot be directly observed) could be instrumental in incentivizing SAV use.

While SAVs might lead to reduced parking demand, this would likely result in increased curbside passenger pick-ups/drop-offs. This increase could present a street design challenge for cities and public transit service providers. Thus, it is critical that cities enact curb management strategies that prioritize SAV and public transit use in contrast to personal AVs [44]. Flexible curb space allocation strategies could also help cities adapt to emerging mobility services by: (1) ensuring the safety of street users, (2) providing high levels of access to all, and (3) ensuring the efficient movement of people and goods within the transportation system [45]. Furthermore, large-scale SAV deployments could have far reaching socio-economic impacts beyond the transportation system (e.g., labor, equity) [46].

SAV ENVIRONMENTAL IMPACTS

The US transportation sector has consistently been a large consumer of energy. The transportation sector's energy consumption has increased by approximately 27% between 1990 and 2018, and this totaled up to 28% of the US energy expenditures in 2018 [47]. The transportation sector was also responsible for 29% of the total US greenhouse gas (GHG) emissions is 2017, increasing emission levels by 22% since 1990 [48]. If current trends in population and economic growth and urban sprawl continue, transportation expenditures, VMT, and GHG emissions are expected to continue increasing. The introduction of SAVs could have notable impacts on travel safety, travel behavior, and land use. These mobility impacts will certainly influence the energy consumption of the transportation sector.

Fleet Size

SAVs would make it possible for individuals to "hire" vehicles on an on-demand basis. Allowing people to use vehicles as-needed could decrease vehicle ownership and reduce the fleet size across the transportation system [30]. Fagnant and Kockelman [49] concluded that under a SAV trip share of 3.5%, one SAV could replace approximately 12 privately owned vehicles. A study by Zhang et al. [37] has produced even more optimistic predictions and found that one SAV will be able to replace around 14 privately owned vehicles. As willingness to wait and shared rides increase among travelers, SAVs could replace even more vehicles.

Effective pooling strategies are crucial in helping maximize SAV fleet usage. Advances in real-time ride-matching algorithms could be important in reducing the SAV fleet size, wait times, and dead heading (i.e., zero passenger miles). Alonso-Mora et al. [50] presented a model for real-time high-capacity vehicles taxi splitting (i.e., shared taxi rides) in Manhattan and concluded that 3,000 SAVs with a capacity four could serve 98% of the taxi rides in Manhattan, reducing the fleet size by approximately 77%. The authors found that higher capacity vehicles would help reduce the total fleet size needed to serve current demand, result in shorter average waiting times, and reduce the total distance traveled by each vehicle [50]. Lokhandwala and Cai [51] found that introducing shared autonomous taxis in New York City would provide the same service level, while reducing the required fleet size by 59%.

SAEVs could have slightly different impacts on fleet size given their shorter vehicle range and charging needs. Chen et al. [21•] found that SAEV fleet size depends on vehicle range and battery recharging speeds. SAEVs could replace between five to nine privately owned vehicles, with fast charging capabilities being more important in reducing fleet size than vehicle range. Based on these estimates, providing appropriate charging infrastructure allows SAVs to serve more demand. Through numerous simulations to determine acceptable SAEV fleet size, vehicle battery range, and size of the charging infrastructure, Bauer et al. [22] found that increasing vehicle charging speeds could reduce the charging infrastructure needed to operate the smallest possible fleet size and claimed that the main obstacle to providing a reliable SAEV service is providing adequate charging infrastructure.

Changes in fleet size would automatically result in VMT changes. SAVs would be used to serve more people and could result in VMT increases due to unoccupied vehicle travel in-between trips or trip detours when pooled. Numerous studies suggest that SAVs could increase unoccupied VMT between 8% and 16% depending on the SAV market penetration rate [19, 20, 21•].

Energy and Emissions

Reducing vehicle fleet size could lower energy consumption and emission levels. Not surprisingly, researchers disagree on the magnitude of these impacts. Fagnant and Kockelman [49] and Zhang et al. [52] reported that SAVs would result in lower carbon monoxide (CO) and volatile organic compounds (VOC) emissions. Dispatching right-sized SAVs could help reduce energy consumption and emissions even further by allowing one and two-person trips to be served by smaller vehicles. Martinez and Viegas [53] claim that vehicle right-sizing under a SAV full adoption scenario in Lisbon, Portugal would result in a 40% reduction in carbon emissions. Greenblatt and Saxena [54] found that right-sized automated taxis could result in a reduction of up to 94% in per distance traveled GHG emissions compared to current day conventional vehicles. Wadud et al. [55•] claimed that vehicle right-sizing could result in up to a 45% reduction in energy reduction. However, not all researchers believe that SAVs will have a positive environmental impact. Lu et al. [56] concluded that due to total VMT increases, SAVs will result in higher energy consumption and GHG emissions.

Naturally, vehicle electrification has great potential to reduce energy consumption and GHG emissions. A smaller fleet of energy efficient SAEVs could help reduce GHG emissions even further. Bauer et al. [22] claim that SAEVs would result in up to a 55% reduction in energy consumption, a 73% re- duction in GHG emissions, a 95% reduction in CO emissions, and a 47% reduction in VOC emissions compared to nonelectric SAVs. Liu et al. [19] reported that SAVs are expected to cause a 22.4% increase in energy savings and between 16.8% and 42.7% in emission reductions compared to conventional vehicles.

CONCLUSION

AVs are thought up to be one of the most disruptive technological advancement to transportation systems since the automobile. Furthermore, advancements in telecommunication and software technologies are expected to accelerate the merging of AVs with shared mobility services—potentially providing more efficient transportation choices. Public perception and acceptance of SAVs will have a key role in determining market adoption.

As people adopt SAVs, a range of innovative mobility scenarios could emerge. SAVs could potentially: (1) shift travel habits, (2) redefine vehicle ownership, (3) allow underserved populations to have more travel flexibility, (4) change the value of travel time, (5) give rise to mobility advancements, (6) transform the public space, and (7) reshape the transportation sector as we know it. SAVs could also have significant environmental impacts by changing the energy consumption and emission levels of the transportation sector. Policymakers at all levels of government should closely monitor the evolution of SAV technologies/services and understanding. This can help to inform the transition to fully automated vehicles and identify best practices and policies that maximize the environmental benefits of SAVs.

The early published literature on SAVs can provide valuable insights into how SAVs might impact society in the future. Nevertheless, more research is needed to improve models and data inputs to reflect a range of future market scenarios. Modeling tools and assumptions should be refined to enable a deeper understanding of SAV impacts on mobility and energy use to reflect a range of land use and built environments. Furthermore, efforts should be directed toward the development of dynamic policy frameworks that vary based on geospatial and temporal scales to aid policymakers in adjusting policies to maximize the social and environmental benefits of SAVs.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: Susan Shaheen and Mohamed Amine Bouzaghrane declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent: This article does not contain any studies with human or animal subjects performed by any of the authors.

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- •• Of major importance

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