

Article

The Rebound Effect of Autonomous Vehicles on Vehicle Miles Traveled: A Synthesis of Drivers, Impacts, and Policy Implications

Kyoungho Ahn ^{1,*} , Hesham A. Rakha ²  and Jinghui Wang ³

¹ Virginia Tech Transportation Institute, Blacksburg, VA 24061, USA

² Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061, USA; hrakha@vt.edu

³ Aramco Research Center-Detroit, Aramco Americas, Novi, MI 48377, USA; jinghui.wang@aramcoamericas.com

* Correspondence: kahn@vt.edu

Abstract

Autonomous vehicles (AVs), including privately owned self-driving cars and shared autonomous vehicles (SAVs), hold great potential to transform urban mobility by enhancing safety, accessibility, efficiency, and sustainability. However, their widespread deployment also carries the risk of significantly increasing vehicle miles traveled (VMT), a phenomenon known as the rebound effect. This paper examines the VMT rebound effects resulting from AV and SAV deployment, drawing on recent studies and global case insights. We conducted a systematic narrative review of 48 studies published between 2019 and 2025, drawing on academic sources and credible agency reports. We do not conduct a meta analysis. We quantify how different automation levels (SAE Levels 3, 4, 5) impact VMT and identify the primary factors driving VMT growth, namely: reduced perceived travel time cost, induced demand from new user groups, modal shifts away from transit, and empty VMT. Global case studies from North America, Europe, Asia, and the Middle East are reviewed alongside regional policy responses. Quantitative analyses indicate moderate to significant VMT increases under most scenarios—for example, approximately 10 to 20% increases with conditional automation and potentially over 50% with high/full automation, under the circumstances of no effective policy interventions. Meanwhile, aggressive ride-sharing and policy interventions, including road pricing and transit integration, can mitigate or even reverse these increases. The discussion provides a critical assessment of policy strategies such as mileage pricing, SAV incentives, and integrated land-use/transport planning to manage VMT growth. We conclude that without proactive policies, widespread AV adoption is likely to induce a rise in VMT, but that a suite of well-designed measures can steer automated mobility towards sustainable outcomes. These findings help policymakers and planners balance AV benefits with congestion, energy use, and climate goals.

Keywords: autonomous vehicle; AV; shared autonomous vehicle; SAV; VMT; rebound effect



Academic Editors: Adam Rosiński, Marek Stawowy, Jacek Paś and Michał Wiśnios

Received: 23 September 2025

Revised: 28 October 2025

Accepted: 6 November 2025

Published: 12 November 2025

Citation: Ahn, K.; Rakha, H.A.; Wang, J. The Rebound Effect of Autonomous Vehicles on Vehicle Miles Traveled: A Synthesis of Drivers, Impacts, and Policy Implications. *Sustainability* **2025**, *17*, 10089. <https://doi.org/10.3390/su172210089>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Autonomous vehicles (AVs) refer to vehicles capable of operating either partially or fully without human interventions. These vehicles are rapidly evolving from futuristic concepts into practical realities on roads around the world. AVs may offer benefits, including improved road safety, enhanced mobility for individuals who cannot drive, and

increased efficiency within transportation systems. However, AVs also present important challenges, a major one being the potential increase in vehicle miles traveled (VMT). This is often referred to as a rebound effect. This phenomenon occurs when the convenience of automated driving encourages individuals to travel more frequently, cover longer distances, or shift from using public transit and active transportation modes like walking and cycling to AVs or shared autonomous vehicles (SAVs). For instance, studies of partially automated driving systems (SAE Levels 2–3) show that drivers using such systems drive substantially more miles annually [1,2]. Early study by Fagnant and Kockelman predicted that induced travel and empty repositioning driven by automation could increase VMT [3].

Uncontrolled growth in VMT due to the widespread adoption of AVs can have severe implications [4,5]. From an environmental perspective, higher vehicle usage can result in increased energy consumption, greenhouse gas emissions, and air pollution [6]. Economically, elevated traffic volumes may raise infrastructure maintenance costs and intensify road congestion, ultimately reducing productivity and overall economic efficiency. Socially, AVs could expand mobility for groups that have long been underserved, including older adults and people with disabilities [7]. At the same time, they may widen inequities if access and benefits flow mainly to higher-income users or if new fees and service costs place a heavier burden on lower-income households. These dynamics can degrade congestion, energy, and climate goals unless pricing, pooling, and transit integration are in place. Automation is also advancing in urban freight and last-mile delivery, including drones, droids, and robotic vans, which affect logistics rather than passenger travel demand [8]. Our review focuses on passenger AVs and SAVs and does not analyze freight or air cargo systems.

Considering these significant potential impacts, proactive and informed policy responses are essential to guide AV deployment toward sustainable outcomes. This paper examines the VMT rebound effects associated with different levels of automation (SAE Levels 3 to 5). We also consider various models, including privately owned AVs and SAVs, and different global contexts by analyzing recent empirical and scenario-based studies (mostly published post-2019). This study specifically addresses three primary research questions:

- To what extent will VMT grow under various automation scenarios (Levels 3, 4, and 5)?
- What are the primary factors driving increases in VMT associated with AV use?
- Which policy strategies effectively manage and mitigate negative VMT impacts?

The paper contributes to existing research in several ways. First, it consolidates recent quantitative and qualitative evidence from various global regions, providing a current and comprehensive perspective on expected VMT impacts due to AVs. Second, it systematically identifies the factors driving these impacts. Third, the paper critically evaluates a range of policy interventions, offering practical recommendations and clear insights to assist policymakers, urban planners, and transportation professionals as they navigate the complexities of AV adoption and its implications for sustainable mobility.

2. Methodology

This study relies primarily on a comprehensive literature review to assess the rebound effects of AVs on VMT. Large-scale deployment of Level 4 and Level 5 AVs remains in early stages. Accordingly, our analysis focuses on synthesizing insights from existing quantitative modeling studies, empirical surveys and field trials, as well as recent meta-analyses and systematic reviews. We report estimates as reported by the individual studies. We do not compute pooled effects, weights, or confidence intervals.

We conducted an extensive literature search to gather relevant academic journal articles, conference proceedings, institutional reports, and policy studies. We searched Web of Science, Scopus, TRID, and Google Scholar for records from 2019 through 2025 using combinations of the following terms: AVs, SAVs, VMT or vehicle kilometers traveled, VKT,

induced demand, rebound effect, modal shift, empty vehicle miles traveled, eVMT, and AV policy impacts. To maintain quality and relevance, we prioritized peer reviewed academic journals, reports from established transportation research institutions, and credible government or international agency studies. Studies were selected based on their explicit focus on AV adoption, measurable impacts on travel demand and VMT, and consideration of policy implications.

In total, our analysis incorporated findings from approximately 48 recent studies representing diverse geographic and socioeconomic contexts. To ensure global representation, we deliberately included studies from multiple regions. For North America, we reviewed meta-analyses of U.S. urban projections, studies of California's statewide modeling scenarios, ride-sharing simulations, and empirical surveys of Tesla Autopilot users. For Europe, we analyzed outcomes from the L3Pilot project that explored user behavior in Level 3 AVs, as well as European agency reviews that emphasize transit integration and management of induced traffic. For the Asian region, where empirical data published in English literature remains limited, we drew upon known adoption trends and available studies. For example, we utilized findings from a study by Dai [9], which projected up to a 47% increase in VKT resulting from AV deployment in China. In the Middle East, acknowledging the increasing interest in AV strategies, we reviewed information from the Gulf region initiatives. These included Dubai's notably ambitious target to achieve 25% autonomous trips by 2030 [10] and Saudi Arabia's ongoing smart mobility initiatives [11]. We also included recent Saudi Arabian case studies examining policy needs for SAV adoption. We found very few recent English language studies from Africa or Latin America. Therefore, we do not generalize our results to those regions.

Quantitative data extraction involved systematically collecting key findings related to VMT impacts from each study. Specifically, we extracted quantitative estimates of percent changes in VMT across various scenarios of automation and ownership models. We included detailed assessments of how specific factors such as eVMT, induced travel demand, and modal shifts influenced total travel increases. We captured comparative data differentiating between conditional automation (SAE Level 3) and high-to-full automation (SAE Levels 4 and 5). For example, a study by Hardman et al. [1] provided empirical evidence on higher VMT among Level 2–3 (partial automation) AV users, while several other studies modeled scenarios assuming full automation (Level 5) in the future. The extracted quantitative results are summarized and presented in tables.

Additionally, we identified and analyzed policy measures proposed in the reviewed literature to manage AV-related increases in VMT and associated externalities. The policies considered were categorized broadly into road pricing strategies, incentives for shared vehicle use, integration with public transit, land-use planning approaches, and regulations aimed specifically at controlling eVMT. Sources for these policy recommendations included academic papers, institutional reports such as those from the National Association of City Transportation Officials (NACTO) [12], and examples of current or proposed legislative initiatives, such as ongoing discussions in the U.S. regarding a per-mile VMT tax for AVs.

Finally, we acknowledge inherent limitations arising from the current state of AV research. Since most large-scale AV deployments remain experimental, findings reviewed in this study primarily come from simulations, scenario analyses, and stated-preference surveys rather than extensive real-world data. This study reflects patterns across studies that use different designs, assumptions, and data sources. Such variation can influence the size and direction of reported effects. We attempted to address this limitation by clearly highlighting uncertainties and variabilities in the outcomes, noting explicitly where some studies predicted possible VMT reductions under optimal conditions for shared mobility. Additionally, while many studies integrate AV deployment with electrification and connec-

tivity trends, our analysis specifically attempted to isolate effects directly attributable to automation, such as empty vehicle travel and shifts in the perceived value of travel time. The differences in reported VMT impact magnitudes reflect variations in study design and assumptions rather than true disagreement. We therefore focus on identifying patterns by level, ownership, and policy context instead of emphasizing precise point estimates. A complete list of the reviewed studies, including region, ownership model, method, and key findings, is provided in Appendix A. Figure 1 summarizes the framework that links AV technology to drivers of VMT change and to policy responses.

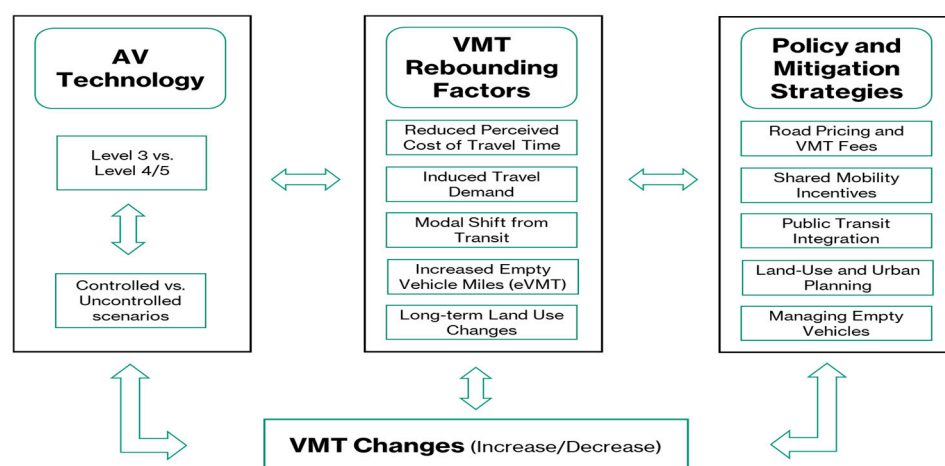


Figure 1. Conceptual Framework of AV/SAV Rebounding Impacts on VMT.

3. Quantitative Summary of VMT Impacts

3.1. VMT Impacts by Automation Level

Level 3 (Conditional Automation): Even conditional automation at SAE Level 3 can meaningfully increase total VMT. At Level 3, vehicles can handle certain driving tasks independently, but the human driver must remain ready to retake control. Recent empirical evidence highlights that drivers using Level 3 automation experience reduced stress and fatigue, encouraging them to drive longer and more frequently. For example, Hardman [1] found in a survey of Tesla Autopilot users that many participants increased their driving substantially after adopting vehicles equipped with partial automation features. Specifically, 19 out of 35 respondents reported traveling more frequently and making longer trips, both locally and across longer distances. Moreover, approximately one-third of participants switched from air travel to driving for certain long-distance journeys within the U.S. Participants primarily attributed this change to the reduced stress and enhanced comfort afforded by automated driving features. Similarly, Lehtonen et al. [2] investigated travel behaviors associated with Level 3 vehicles through a survey of 359 European drivers who experienced partial automation in real-world conditions. The findings indicated a clear trend toward increased travel frequency and longer trips. Specifically, 25% of respondents anticipated taking more trips, and 39% expected their trips to become longer due to automation. Notably, a large majority (81%) expected to use automated driving for their existing journeys, demonstrating that conditional automation is readily integrated into current travel patterns. Drivers were motivated by opportunities to relax and have a more pleasant travel experience while their vehicle managed driving tasks. These factors reduced the perceived burden of driving, leading to a moderate yet significant rebound effect on total VMT.

Level 4 and 5 (High and Full Automation): As vehicle automation progresses toward full self-driving capabilities (Levels 4 and 5), studies consistently predict even greater

increases in VMT, especially if there are no policy interventions or ride-sharing incentives. A comprehensive meta-analysis conducted by Naz and Mattingly [13] analyzed findings from 26 studies, primarily from the U.S., and concluded that overall VMT would rise by about 5.9% with the widespread deployment of AVs. The analysis further distinguished between ownership types, reporting approximately a 6.9% increase in VMT for privately owned AVs compared to a 5.3% increase for SAV fleets. This difference is largely attributed to the convenience and flexibility associated with private ownership, which facilitates additional usage, such as sending empty vehicles on errands or repositioning trips.

Empirical and simulation studies offer varied predictions but consistently suggest meaningful increases in travel demand. Several studies indicate moderate VMT growth between approximately 5% and 25%. For example, a simulation using MATSim software in the Minneapolis–Saint Paul region [14] examined the operation of SAV fleets serving up to 20% of trips in the central urban area. The study found that shared AVs increased total VMT by around 13% compared to current conditions, largely due to eVMT repositioning trips. Similarly, a microeconomic study based on the U.S. National Household Travel Survey [15] projected significant induced travel from fully autonomous privately owned vehicles. This study predicted potential VMT increases between 2% and 47%, depending on household income and travel cost assumptions. This research emphasized that wealthier households exhibited particularly high responsiveness to reduced travel time costs provided by automation. A systematic literature review [16] on the travel behavior impacts of SAVs highlights a consistent trend of increased VMT or VKT across various studies. For instance, research in Halifax, Canada projected a 1.73–14% increase in VKT even when SAVs served only 15–20% of trips.

More dramatic scenarios have forecasted larger increases, potentially doubling VMT under specific circumstances. For instance, a “do-nothing” scenario with mass private AV adoption (no policy intervention, predominantly single-occupant AV use) in one analysis projected VMT could increase by 50% by 2050 [6]. A naturalistic experiment by Harb et al. [17], simulating private AV use through chauffeur-driven vehicles, observed a substantial increase in participant travel of approximately 60%. This increase was primarily driven by previously latent travel demand becoming feasible when driving stress was removed. A recent study [18] found that AVs could significantly increase intercity travel demand also by removing driving stress. The research showed a 25% increase in monthly intercity miles per capita (149 to 186 miles) when long-distance trips no longer required active human driving.

Another study by Sun et al. [4] modeled future travel scenarios for California. The authors predicted VMT growth of between 30% and 60% by 2050 under privately owned AV scenarios without policy interventions. However, shared AV scenarios combined with per-mile pricing policies significantly reduced VMT growth, emphasizing the critical role that proactive policies play.

It is also important to acknowledge scenarios where AV deployment could lead to reduced VMT. Gurumurthy and Kockelman [19] simulated SAV systems with optimized dynamic ride-sharing in medium-sized cities, demonstrating potential VMT reductions of up to 39% due to improved vehicle occupancy and reduced eVMT. Similarly, a simulation study by Huang et al. [20] illustrated that integrating shared AVs effectively with public transit for first-mile and last-mile services could yield a modest reduction in total VMT (around 3.6%) by enhancing overall transportation efficiency through better pooling and reduced empty travel distances.

Overall, most studies reviewed highlighted a net increase in VMT associated with higher levels of automation. This was particularly true when privately owned vehicles dominated and when ride-sharing or policy measures were minimal. The consistent

theme across these analyses is that automation substantially reduces the inconvenience and perceived costs of travel, stimulating additional demand. Variability in the outcomes among studies typically depends on assumptions regarding user willingness to share rides, levels of automation deployment, and regional urban characteristics, such as density and existing public transit infrastructure. Table 1 summarizes VMT changes for SAE Level 3 compared with Levels 4 and 5, and Table 2 reports VMT changes from individual studies.

Table 1. VMT Changes for SAE Level 3 versus Level 4–5.

Automation Level	VMT Change	Key Findings and Factors
Level 3	Moderate Increases	Drivers report increased VMT due to reduced stress, fatigue, and a desire to make more frequent or longer trips. A survey of Tesla Autopilot users found many participants increased their driving, and about one-third shifted from flying to driving for some long-distance trips. Another study found 25% of respondents would take more trips and 39% would take longer trips.
Level 4 and 5 (no control scenarios)	Moderate to Substantial Increases	Most studies consistently predicted greater VMT increases. A meta-analysis found an average VMT rise of about 5.9%, with privately owned AVs showing a higher increase (6.9%) than shared AVs (5.3%). Some scenarios project VMT growth up to 60% in unconstrained conditions. This is driven by removing travel stress, enabling new trips, and generating eVMT.
Level 4 and 5 (controlled scenarios)	Potential VMT Reductions	While increases are the norm, VMT could be reduced in highly optimized, shared-mobility scenarios. Simulations show potential VMT reductions of up to 39% with dynamic ride-sharing and passenger pooling. Another study found a 3.6% VMT reduction when shared AVs were used for first- and last-mile connections to public transit

Table 2. VMT Changes from Individual Studies.

Study (Year)	Automation Level/Context	Reported VMT Change	Key Factors
Hardman (2021) [1]	Level 3/Survey of Tesla owners (California)	AV users drove more miles/year (19 out of 35 participants)	Partial automation (Autopilot) reduced driving effort, leading to more long trips (often replacing flights) and tolerance for congestion.
Lehtonen et al. (2022) [2]	Level 3/L3Pilot trial (Europe, Level 3 test rides, self-reported)	Likely increase (qualitative, many willing to take longer trips by AV)	Participants experienced partial automation driving; indicated higher tendency for long car trips and some new trips, due to ability to do other activities during travel.
Naz & Mattingly (2024) [13]	Levels 4–5 (no control)/Meta-analysis (26 studies)	+5.95% overall (+5.33% Shared AVs, +6.90% Private AVs)	Non-shared (private) AVs cause slightly higher rebound. eVMT identified as significant contributor to variability.

Table 2. Cont.

Study (Year)	Automation Level/Context	Reported VMT Change	Key Factors
Jiang, He & Ma (2022) [21]	Levels 4–5 (no control)/Investigated the impacts of connected AVs in Southern California	+10% total VMT	Intensified travel equity disparities across different income groups.
Fakhrmoosavi et al. (2024) [18]	Levels 4–5 (no control)/Modeled impact on long-distance travel (inter-city, Level 5)	+25% (miles/month per person)	Found VMT per capita for intercity trips rose from 149 to 186 miles when driving autonomously (people opt for car over other modes for long trips).
Harb et al. (2022) [17]	Levels 4–5 (no control)/Field experiment (Sacramento, private chauffeur provided)	+60% VMT (observed among participants)	Simulated private Level 5 AVs. Households made many extra trips (esp. long-distance and zero-occupant trips) when freed from driving. Extreme example of latent demand realized.
Sun et al. (2024) [4]	Levels 4–5 (no control and controlled)/California 2050 scenario—with vs. without road pricing	Private AV scenario: +30–60% SAV scenario: 0% to +18%	Strategic travel model: Without policy, substantial VMT growth. A per-mile fee eliminated the increase, keeping VMT baseline. Demonstrates policy sensitivity.
Gurumurthy & Kockelman (2022) [19]	Levels 4–5 (controlled)/Simulation (Mid-size city, high SAV with pooling)	−27% to −39% VMT	High shared rides (dynamic ride-share) & short walk to pooled pick-up/drop-off stops greatly reduced vehicle trips and empty mileage. Illustrates best-case SAV efficiency.
Huang et al. (2022) [20]	Levels 4–5 (controlled)/Simulation study using SAV pooling and minimizing eVMT	3.6% VMT reduction	Integrating shared AVs effectively with public transit for first-mile and last-mile services could yield a modest reduction in total auto VMT by enhancing overall transportation efficiency.
Dowds et al. (2021) [22]	Conceptual analysis (rural U.S., SAV introduction)	Uncertain (direction context-dependent)	In rural areas: SAV could serve new trips for those without drivers (increasing VMT), but low sharing and long distances make benefits unclear. Outcome context-specific.

3.2. Rebound Factors: Drivers of Increased VMT

Several interrelated factors explain why adopting AVs is expected to significantly increase VMT. This section identifies and examines five primary drivers of this rebound effect: reductions in the perceived cost of travel time, induced travel demand from underserved populations, mode shifts away from sustainable transportation, increases in eVMT, and long-term changes to land-use patterns.

3.2.1. Reduced Perceived Cost of Travel Time

A fundamental reason AVs encourage more travel is because they substantially reduce the inconvenience and burden associated with driving. In standard transport economics, automation lowers the generalized cost of travel by reducing the perceived cost of time. Under utility maximization and discrete choice, demand for car travel increases as generalized cost falls, and mode choice elasticities explain shifts away from transit and active modes. When drivers no longer need to continuously focus on driving, especially at high automation levels like SAE Levels 4 and 5, the time spent traveling can be used productively

or for leisure activities. This change can effectively reduce the perceived cost or disutility of travel time, encouraging individuals to travel longer distances or more frequently. Research clearly demonstrates this phenomenon. Kolarova [23] found that commuters significantly lowered their perceived value of travel time when riding in an AV compared to manually driving. As a result, commuters became more willing to travel greater distances for the same perceived overall cost. Similarly, Malokin et al. [24] highlighted that the ability to use travel time productively could encourage individuals to accept much longer daily commutes, substantially increasing single-occupant car travel demand.

Additionally, empirical evidence from early users of Levels 2–3 AVs (partially automated) supports this expectation. For instance, Hardman [1] found that drivers using Tesla's Autopilot reported reduced fatigue and stress, making driving more comfortable and encouraging users to take longer trips. Several drivers even reported substituting longer-distance car journeys for air travel due to the increased comfort of semi-automated driving. Furthermore, Gelauff et al. [25] projected a 5% to 25% increase in overall VMT due to suburban relocation driven by reduced commuting burdens, indicating that lowered perceived travel costs could reshape urban settlement patterns. Fakhrmoosavi et al. [18] reinforced this point by projecting a 25% increase in intercity car trips as AVs made long-distance car travel more appealing relative to air or rail alternatives. Overall, this reduced travel burden acts similarly to a decrease in monetary travel costs, promoting additional travel demand and contributing significantly to increased VMT.

3.2.2. Induced Travel Demand from New User Groups

A second critical factor driving VMT growth is the potential for AVs to extend mobility to populations who currently face barriers to vehicle-based travel. AV could significantly increase the travel capabilities of elderly individuals, youth without driver's licenses, persons with disabilities, and those who previously could not afford regular car access. By offering convenient, independent mobility, AVs would enable these groups to undertake new trips, thus generating substantial additional vehicle travel.

Harper et al. [7] analyzed the potential impacts of widespread AV availability on underserved populations, estimating up to a 14% increase in annual VMT in the U.S. This projection assumed that older adults, individuals with disabilities, and non-drivers would travel at similar rates to drivers within comparable demographic groups. The scale of potential additional travel is considerable, reflecting significant latent demand among these populations. Further, a study by Harb et al. [17] simulated AV use through chauffeur-driven cars. Participants demonstrated dramatically increased travel, particularly among seniors and mobility-impaired individuals, who experienced substantial improvements in their quality of life due to newfound independence and freedom to travel. Elderly participants, specifically, increased their VMT by over 120%, clearly demonstrating substantial latent demand becoming realized. Moreover, even among those who already regularly drive, AVs can still induce additional travel demand. For instance, owners of AVs might choose to send their vehicle on errands, increase discretionary leisure trips, or undertake additional trips that would otherwise be considered burdensome, thus further increasing total VMT.

3.2.3. Modal Shift Away from Transit and Active Transportation

Another significant factor increasing total VMT is the expected shift away from more sustainable transportation modes, like public transit, walking, and cycling, and toward AVs. Autonomous cars offer convenient point-to-point travel, potentially attracting current transit users and reducing transit ridership. This shift away from transit is problematic because transit typically carries multiple passengers with less VMT per passenger. Conversely, AVs, unless shared, would substantially increase per-passenger mileage.

Studies consistently indicated that such modal shifts are probable. A mode-choice survey conducted by La Delfa et al. [16] found that frequent public transit users expressed a strong willingness to switch to SAVs for their travel needs, indicating a substantial risk of declining transit use. Another report [26] also warns that without policies, AVs could negatively affect transit ridership. Additionally, AVs might take riders away from zero-emission modes like walking and cycling. If an autonomous shuttle or car is readily available, some people might opt for a one-mile AV ride instead of a short walk or bike ride, adding VMT where previously there was none. Additionally, a recent transportation analysis [27] suggested that if AV travel became significantly cheaper and perceived travel-time costs reduced notably, public transit ridership could decline by about 14%, while active modes like walking and cycling could see around an 11% reduction.

Such shifts toward AV travel would also negatively impact physical activity levels, further intensifying societal health concerns. Effective integration of AVs with transit networks could help mitigate these risks. However, without proactive policy interventions, this shift could lead to substantial increases in urban road traffic, congestion, and related externalities.

3.2.4. Increased Empty Vehicle Miles (eVMT)

An important issue arising from AV deployment is the significant potential for vehicles to travel without any passengers, increasing eVMT. AVs, especially shared fleets, frequently require repositioning between passenger pick-ups, increasing total VMT. Privately owned AVs may similarly travel empty when repositioning for cheaper parking or when dispatched by their owners to run errands independently.

Empirical and simulation studies highlight the magnitude of eVMT generated by AV operations. For example, Gurumurthy et al. [28] estimated that empty miles could represent approximately 14% of total VMT for city-scale SAV operations. Similarly, a simulation study conducted by Huang et al. [20] reported that roughly 25% of total AV fleet miles were empty repositioning trips. An SAV case study by de Souza et al. [29] of Bloomington, Illinois that used the agent-based tool POLARIS found that an estimated 17% of VMT was due to empty repositioning. These numbers imply that for every 100 miles driven by an SAV fleet, 15–25 miles might be eVMT.

Privately owned AVs could intensify this problem further. Owners might send their cars home or to distant parking locations rather than paying expensive urban parking fees. This behavior effectively doubles daily commute mileage, adding substantially to urban congestion and environmental concerns. This kind of additional, non-productive vehicle operation represents a direct rebound effect introduced uniquely by vehicle automation, increasing total VMT.

3.2.5. Long-Term Land Use and Spatial Changes

Finally, the widespread adoption of AVs could significantly influence urban form and land-use patterns, encouraging urban sprawl and promoting longer-distance travel. As commuting becomes easier and more comfortable with AVs, individuals might choose to live further from city centers, where housing may be more affordable or spacious. Over time, these longer commutes would become embedded in urban and suburban development patterns, permanently increasing overall travel distances.

Montoya [30] analyzed this possibility extensively, noting that AVs could dramatically accelerate suburban sprawl unless proactively addressed by zoning reforms and urban planning policies. He suggested cities actively use zoning and planning measures to encourage denser, mixed-use, and walkable developments to counteract AV-induced sprawl. Similarly, Kockelman [31] projected a substantial increase in average trip distances due

to AVs encouraging relocation farther from employment and amenities. This research also indicated that intercity travel by AVs could significantly replace shorter-haul air and rail trips, leading to increased roadway travel demand and environmental consequences. Another notable example is a Swedish modeling study by Rebalski and Johansson [32], which projected substantial daily VMT growth per driver due to AV-driven changes in commuting and residential choices. Even under scenarios aligned with climate targets, this increased travel would translate into substantial additional carbon emissions, highlighting the long-term environmental implications of AV-driven urban development patterns.

Overall, these five factors interact and reinforce one another. Lower perceived time cost induces extra trips and longer distances, draws new user groups into car travel, and shifts riders away from transit and active modes. eVMT rises through repositioning and zero occupant trips, which add traffic that slows buses and erodes service quality, further weakening transit. Over time these feedbacks make longer commutes acceptable and reshape land use toward more dispersed patterns, raising baseline VMT. Figure 1 summarizes these feedback loops, and Table 3 links each factor to typical magnitudes. These interactions show why policy must act on several levers at once, including pricing, sharing, transit integration, and eVMT control.

Table 3. Rebound Factors Driving Increases in VMT.

Factor	Typical Direction of Effect on VMT	Indicative Magnitude from Representative Studies	Key References (Examples)
Reduced Perceived Cost of Travel Time	Increases VMT as people make longer or more frequent trips	Commuters report lower cost of travel time in AVs and greater willingness to travel farther; modeling suggests 5% to 25% VMT growth from suburban relocation; intercity car miles rise about 25 percent when driving burden falls.	Kolarova 2021 [23]; Malokin 2019 [24]; Gelauff 2019 [25]; Fakharmoosavi 2024 [18]
Induced Travel Demand from New User Groups	Increases VMT by enabling travel for seniors, youth, and people with constraints, and by adding non-mandatory trips for current drivers	A 14% national VMT growth in the U.S. due to access for underserved groups; naturalistic “chauffeur” experiment shows total VMT up about 60% among participants and among seniors up about 121%.	Harper 2016 [7]; Harb 2022 [17]
Modal Shift Away from Public Transit and Active Modes	Increases VMT when riders move from high-capacity or zero-VMT modes to AVs and SAVs	Scenario results show potential declines of about 14% in public transit and about 11% in walking and cycling under lower generalized costs; surveys show frequent transit users willing to switch to SAVs.	La Delfa 2025 [16]; policy analysis 2023–2024 [27]

Table 3. *Cont.*

Factor	Typical Direction of Effect on VMT	Indicative Magnitude from Representative Studies	Key References (Examples)
Increased eVMT	Increases eVMT through repositioning, cruising, and zero-occupant trips	Across simulations and field trials, eVMT typically accounts for roughly 14% to 25% of fleet VMT, with a POLARIS case study reporting about 17%.	Gurumurthy 2021 [28]; Huang 2022 [20]; de Souza 2020 [29]
Long-term Land Use	Increases VMT by encouraging longer commutes and dispersion of activities	Models indicate that relocation alone can raise VMT by about 47%. Larger statewide and national scenarios show substantial growth when no policy interventions are applied. In Sweden, one study projected sizeable increases in daily travel, roughly 50 additional KMV per driver.	Kockelman 2021 [31]; Montoya 2024 [30]; Rebalski and Johansson 2024 [32]

3.3. Regional Case Studies

3.3.1. North America

The U.S. has emerged as a leader in testing AVs, with numerous pilot programs involving robotaxis operated by companies such as Waymo and Tesla. Many studies conducted across American metropolitan areas, which typically exhibit high levels of car dependence, have consistently indicated a potential for substantial increases in VMT due to AV adoption. Recognizing this risk, policymakers in several cities and states have started discussing how to manage the expected growth in travel demand. One widely discussed strategy involves implementing road usage charges such as a per-mile fee to replace declining gas-tax revenues and manage traffic growth. For example, Sun et al. [4] demonstrated that even modest per-mile fees could effectively curb higher VMT, despite widespread AV adoption in California.

Additionally, NACTO have recommended proactive measures to ensure AVs enhance rather than compete with existing public transit systems. Suggested policies include establishing dedicated AV pickup zones near transit stations and regulations to prevent heavily subsidized AV services from undercutting transit ridership through low fares [12]. Moreover, urban planners and researchers have advocated for zoning reforms that discourage urban sprawl induced by AVs. Suggestions also include repurposing surplus parking areas into more productive uses, thereby mitigating potential rebounds in car-dependent infrastructure [30]. The U.S. federal government has primarily focused on safety-related guidelines for AVs. However, local authorities such as those in San Francisco have expressed concerns about increased congestion due to uncontrolled AV proliferation, emphasizing the necessity for targeted municipal regulation [33]. As of 2025, most AV-specific policies aimed at VMT mitigation in the U.S. remain largely conceptual or in preliminary planning stages.

3.3.2. Europe

European countries generally benefit from robust public transit networks, positioning them favorably to integrate SAVs into their existing transportation frameworks. Eppenger and Richter [34] conducted a comprehensive study across four major European cities to evaluate SAVs' potential impacts on urban equity. They found strong correlations

between socio-economic factors, particularly education and income levels, and access to SAV services. To address potential inequalities, the researchers recommended that cities target SAV deployment in underserved districts and integrate these services closely with public transit systems.

A separate study by Polydoropoulou et al. [35] examined willingness to use SAVs in seven European countries, highlighting significant regional and gender-based differences. Their findings pointed to the necessity for specific security measures and educational campaigns addressing safety perceptions to ensure equitable SAV adoption across Europe.

The European Environment Agency's 2022 report [36] on SAV impacts further underscored the complexity surrounding AVs. Although eco-driving techniques associated with SAVs might improve fuel efficiency, these gains could be offset by increased energy demand from onboard autonomous technologies and a median projected VMT increase of 43%. The report emphasized that SAVs could be particularly beneficial as feeders to transit hubs, but without proper regulation, they might compete directly with sustainable transportation modes. The European regulatory environment, largely focused on vehicle safety standards thus far, needs to evolve to consider broader environmental impacts and public acceptance concerns. Currently, many Europeans remain cautious about fully automated travel, emphasizing the importance of proactive and well-informed regulatory interventions.

3.3.3. Asia

Recent English language evidence from Asia and the Middle East is limited relative to North America and Europe. We include the available studies to maintain global coverage, label the thin evidence, and avoid extrapolation beyond the study settings. Across Asia, studies from China, Japan, and Singapore illustrate diverse approaches to AV adoption and policy responses. Surveys conducted in Dalian (China) and Lahore (Pakistan) [37] found significant public interest in SAVs, driven primarily by factors like reduced travel time, cost-effectiveness, and convenience. Interestingly, public acceptance varied notably between cities. Lahore's respondents, especially women lacking private transport options, indicated strong interest in SAVs, emphasizing the potential social benefits. Conversely, in Dalian, current car owners expressed willingness to transition to shared services, highlighting potential shifts away from private ownership. A study by Guo and Huo [38] uses a multinomial logit model based on questionnaire data to examine how SAVs affect residential location choices in China's top-tier cities and finds that individuals with higher education, extensive driving experience, and positive views of SAVs are more likely to move downtown. The study demonstrates that most respondents in Chinese first-tier cities are more inclined to relocate to downtown areas under SAV travel conditions. SAV travel can make downtown areas more attractive because it is more convenient, cheaper, and faster to travel there. The authors conclude that, unlike in the West, SAVs will likely increase the appeal of downtown areas in China rather than cause urban sprawl. The study recommended targeted suburban policies to prevent excessive downtown congestion due to SAV concentration.

In Japan, Luo et al. [39] examined AV adoption in Gunma Prefecture, a region characterized by aging demographics and high car dependency. Their analysis projected VMT increases of approximately 22% to 44% by 2040, with corresponding CO₂ emissions rising significantly. This rebound effect was primarily attributed to previously non-driving elderly individuals gaining newfound mobility. The researchers highlighted the critical need for proactive policy measures, such as congestion charges or road pricing, to balance environmental concerns with enhanced accessibility.

Singapore's approach to AV adoption reflects careful consideration of transit integration and governance strategies. Oh et al. [40] simulated Automated Mobility-on-Demand

scenarios in Singapore, highlighting risks of increased traffic congestion and public transit displacement without regulatory intervention. To address these concerns, Singapore has implemented an adaptive regulatory framework, including AV regulatory sandboxes and formal safety assessments. These strategies are intended to promote controlled experimentation and iterative policy development. Tan and Taeihagh [41] documented an adaptive governance model, emphasizing Singapore’s proactive stance to managing potential AV-related risks and market impacts.

3.3.4. Middle East

The Middle East, particularly the Gulf region, has enthusiastically embraced AV technology within broader smart-city development goals. Dubai, in the United Arab Emirates, leads with an ambitious Autonomous Transportation Strategy targeting 25% autonomous trips by 2030, developed in partnership with Cruise [10]. Initial phases began in 2023, involving detailed mapping and testing of AV systems tailored to Dubai’s unique urban environment. However, achieving these goals faces significant hurdles. Challenges include adapting AV technology developed primarily in the U.S. to Dubai’s distinct road infrastructure, driving behaviors, climate conditions, and public acceptance levels. Overcoming these challenges to support the smooth integration of AVs into Dubai’s urban environment will require extensive data collection, thorough real-world testing, and focused public education initiatives.

Similarly, Saudi Arabia has recognized the transformative potential of AVs within its strategic mobility planning. Ullah et al. [42] investigated barriers and necessary policies for successful SAV adoption in Saudi Arabia. The research identified 24 critical barriers and 16 potential policies, as summarized in Table 4. The study recommended robust government-backed investment in technology development, targeted infrastructure improvements such as dedicated AV lanes, and close integration with public transportation networks. These recommendations are intended to maximize SAV benefits while mitigating risks of congestion and pollution for fostering a sustainable SAV ecosystem.

Table 4. Critical Barriers and Potential Policies for the Successful Adoption of SAVs in Saudi Arabia (KSA) [42].

Barriers to SAV Adoption		Policies for SAV Adoption	
Regulatory and Policy Barriers (RPB)	Insurance and liability, licensing and permits, compliance with local laws, data privacy and security regulations	Regulatory framework	Unified insurance framework, streamlined licensing and permitting, harmonized transportation regulations, data privacy and security standards, safety certification and audits
Public Perception and Trust (PPT)	Safety concerns, reliability and service quality, user experience, community acceptance	Public trust & user experience	Reliability and service quality guarantees, community awareness campaigns, enhanced user experience
Infrastructure Limitations (IL)	Parking and docking stations, road and lane infrastructure, charging infrastructure, urban planning integration	Infrastructure development	Development of SAV infrastructure, dedicated lanes for SAVs, urban planning integration
Economic and Financial Challenges (EFC)	High operational costs, funding and investment, pricing strategies, return on investment	Economic & financial support	Subsidies for operational costs, government-backed investment, innovative pricing strategies

Table 4. Cont.

Barriers to SAV Adoption		Policies for SAV Adoption	
Technological Barriers (TB)	System reliability, cybersecurity, integration with other services, sensor and hardware limitations	Technological advancement	Reliability and cybersecurity standards, funding for R&D in sensor and hardware
Market Competition and Dynamics (MCD)	Competitive landscape, demand fluctuations, market penetration, innovation pressure		

3.3.5. Summary and Comparative Insights

Comparative analysis across regions clearly highlights the importance of proactive and context-sensitive policy interventions to address the widespread VMT rebound risks associated with AV and SAV deployment. While the specific strategies vary according to regional characteristics, common themes have emerged. Effective policies typically involve strategic road pricing or congestion charges, integrating AV services with existing transit infrastructure, managing eVMT through regulatory measures, and promoting transit-oriented land-use planning to prevent induced sprawl.

In North America, discussions emphasize road pricing and integration with transit systems. Europe emphasizes integrating SAVs with existing public transport in ways that ensure they are complementary, affordable, and accessible to all population groups. Asian contexts emphasize strategic urban planning, with Singapore demonstrating exemplary adaptive governance practices. The Middle East, notably Dubai and Saudi Arabia, showcases ambitious top-down approaches with significant investments, but highlights the importance of localized adaptations to global technologies. Data on Africa and Latin America are limited in the post-2019 literature we reviewed. Our conclusions are thus restricted to regions with a sufficient number of studies.

Overall, these diverse international experiences suggest that managing AV-related VMT growth effectively requires well-informed, tailored policy strategies. By actively anticipating potential impacts and implementing proactive policies, regions can harness AV technology to enhance mobility while simultaneously mitigating associated environmental, economic, and social risks.

4. Policy Implications and Mitigation Strategies

A variety of policy measures have been proposed to address and mitigate the expected rebound effect associated with the widespread adoption of AVs. This section evaluates major policy categories, drawing on evidence from recent studies, pilot programs, and expert recommendations.

Road Pricing and VMT Fees: Research shows road pricing is one of the most effective ways to manage AV driven travel growth. Charging per mile, with higher rates in congested periods, offsets the lower perceived travel cost created by AVs and discourages unnecessary miles. According to studies, mileage-based pricing schemes effectively increase the overall cost of vehicle travel, thus discouraging excessive or unnecessary use. For instance, modeling in California demonstrated that introducing a moderate per-mile fee could entirely offset projected VMT increases even with substantial AV penetration [4,5]. Todd Litman emphasizes that without distance-based pricing, AVs could significantly worsen urban traffic congestion. Litman argues that relatively modest fees of a few cents per mile, strategically applied, could maintain acceptable traffic flow while providing funds for investment in public transit and alternative transportation options. Although politically

challenging, introducing such fees could be justified to the public by emphasizing their role in preventing severe congestion due to AVs, thereby maintaining urban mobility.

Shared Mobility Incentives: Encouraging the shared use of AVs over private single-occupancy models is another crucial policy approach to controlling VMT growth. Technology and automotive companies may prioritize private AVs or single-passenger robotaxis because these options promise higher profits and align with consumer preferences for convenience. However, from a broader societal perspective, shared mobility services such as pooled autonomous shuttles or robotaxis with multiple passengers offer substantial efficiency benefits. To incentivize shared use, policymakers might implement preferential policies, including tax credits, reduced fees, priority access to high occupancy vehicle lanes, and dedicated drop-off zones exclusively for pooled AVs. Cities could also adopt licensing strategies that prioritize operators of AV fleets demonstrating high passenger occupancy and minimal empty miles. Another approach is to create designated “AV zones” that allow access only to vehicles meeting minimum occupancy requirements. This would directly restrict single-occupancy trips and reduce unnecessary empty repositioning [43].

Public Transit Integration and Investment: Integrating AV technology into existing public transit systems is a widely recommended strategy for managing potential VMT rebounds. Transit systems effectively reduce per capita VMT by moving large numbers of people simultaneously, and AV technologies could play a critical role in solving common challenges like first- and last-mile connectivity. Autonomous shuttles providing seamless connections to transit hubs or rail stations could replace many individual car trips, thereby enhancing overall transportation system efficiency [20,44]. Such integration could involve coordinated fare systems that encourage multi-modal trips and help maintain robust public transit ridership. Feeder services could deploy SAVs that collect riders at homes or workplaces and deliver them to rail or bus rapid transit stations; in low density areas and off peak periods, on demand shuttles can replace sparse fixed routes while keeping people in the transit network. This improves connectivity for underserved neighborhoods, older adults, and people with disabilities by making the overall system easier to use [45,46]. Furthermore, it is crucial to avoid scenarios in which the convenience and affordability of door-to-door AV services draw significant numbers of riders away from buses and trains. Maintaining attractive and frequent transit services will remain essential, as AVs alone cannot replace high-capacity public transportation without creating increased dependency on cars.

Land-Use and Urban Planning: Land-use and urban planning strategies represent a slower but essential tool in managing AV-induced VMT impacts. Urban planners increasingly recognize the need to integrate AV scenarios into their planning models. The adoption of AVs will bring anticipated changes such as reduced parking demand and shifts in urban development patterns. Proactive planning policies could leverage these changes to promote transit-oriented and walkable developments, thus reducing car dependence and limiting travel distances. For example, reduced parking requirements associated with widespread AV adoption could enable cities to repurpose parking facilities for higher-density residential or commercial uses. This would decrease the need for long-distance commuting and promote more sustainable urban forms [47]. Conversely, without strategic land-use interventions, inexpensive and effortless commuting enabled by AVs could accelerate suburban sprawl, significantly increasing travel distances and associated VMT. Regional planning authorities might impose urban growth boundaries, encourage higher-density developments along transit corridors, or offer incentives such as density bonuses to developers creating communities specifically designed for shared AV use and reduced private vehicle reliance.

Managing Empty Vehicles (eVMT Regulations): The challenge of managing empty AVs circulating in urban areas is a new regulatory issue requiring proactive policy measures. Without clear guidelines, AVs could significantly worsen urban traffic congestion through constant empty repositioning, roaming to avoid parking fees, or running errands without passengers. Effective regulatory strategies could include restricting empty AV movements within congested city centers or applying fees specifically targeted at eVMT. Some cities are considering designated waiting areas or automated valet parking facilities located strategically outside busy urban cores, where AVs would wait until summoned by passengers, thereby reducing congestion impacts [16,48]. Additionally, clear regulatory frameworks established at an early stage can set industry expectations and encourage AV operators to integrate efficiency measures into their operational and business models from the outset.

Overall, the policy approaches described here—such as road pricing, shared mobility incentives, transit integration, land-use planning, and empty vehicle management—represent complementary strategies that collectively can significantly mitigate the anticipated VMT rebound associated with AV adoption. Figure 2 illustrates the key factors driving VMT increases linked to the policy strategies designed to mitigate them. The lines indicate the primary policy solution for each driver, while the diagram shows the interconnected nature of these strategies, highlighting how a comprehensive approach can address multiple issues simultaneously. By thoughtfully combining these measures, policymakers can guide the deployment of AVs towards enhancing mobility and sustainability, rather than exacerbating current transportation system challenges. Table 5 summarizes these policies, outlining their intended effects and providing examples of current or proposed implementations.

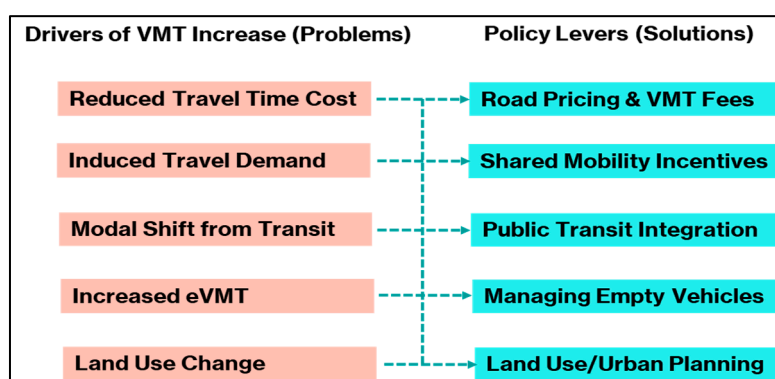


Figure 2. AV/SAV Induced VMT Growth and Policy Levers.

Table 5. Policy Strategies to Mitigate AV-Induced VMT Growth.

Policy Measure	Purpose	Examples/Evidence
Road Pricing & VMT Fees	Internalize external AV travel costs by charging per mile (possibly varying by congestion level or occupancy). Increases trip costs, discouraging excessive or empty driving.	Per-mile fees (\$0.05–\$0.25) could optimize traffic flow. California modeling: per-mile fee eliminated +18% VMT surge [4,5]. Congestion pricing examples include London and Singapore, and planned implementation in NY.

Table 5. Cont.

Policy Measure	Purpose	Examples/Evidence
Shared Mobility Incentives (SAV Incentives)	Encourage use of shared AV services and pooling over private AVs. Include incentives like tax credits, priority lanes, or reduced fees for pooled trips, discouraging sole-occupancy AV use. Aim to maximize vehicle throughput and occupancy.	Tax credits suggested for SAV use. HOV/HOT lane access for SAV pools, reduced tolls, and fleet permissions (cities licensing only shared AV fleets) [43].
Public Transit Integration & Investment	Strategically integrate AV technology into mass transit networks, using AVs for first/last-mile shuttles or on-demand feeders. Maintain robust transit service so AVs complement rather than replace high-capacity modes.	On-demand shuttle trials. Policy recommendations for AV integration into transit [12,20]. Fare integration proposals encourage multi-modal trips.
Land-Use and Urban Planning	Update zoning and policies to prevent sprawl and car-dependent development. Promote transit-oriented and walkable communities to minimize travel needs.	Urban containment policies, parking reforms, and new AV city designs (UAE's plan) [47]. Encourages dense, mixed-use development.
Managing Empty Vehicles (eVMT regulations)	Target empty cruising and deadhead miles. Ban AVs from driving without passengers in some areas or impose levies on zero-occupant miles. Require algorithms for efficient ride matching.	Zombie car bans, fines for AV roaming without passengers. Empty trip fees (higher per-mile charges or SAV fleet occupancy requirements). Geofencing AV access to dense areas [16,48].

5. Uncertainties and Future Research

Although this review offers comprehensive insights into AV impacts, considerable uncertainty persists about their exact effects on travel demand, congestion, and urban systems. Results remain sensitive to assumptions about value of time, adoption rates, and pooling disutility. Real world AV and SAV operations are still limited in scope and geography. Public, peer reviewed datasets reporting fleet VMT, empty miles, and mode shift are scarce. Thus, most estimates come from simulations, scenario models, surveys, and small natural experiments. Further research in several key areas is needed to deepen understanding and guide future policy decisions.

Behavioral Uncertainty: A major source of uncertainty stems from limited knowledge about how individuals will actually use fully automated vehicles in everyday life. Current research predominantly relies on surveys and simulations, which provide useful approximations but cannot capture the full complexity of long-term behaviors. For example, it is still uncertain whether AV adoption will encourage widespread suburban migration by making longer commutes easier, or whether the growth of remote work, accelerated by the COVID-19 pandemic, will counterbalance this effect. Early evidence from 2020 to 2022 shows notable changes in commuting habits, but how long-term telecommuting trends will interact with AV use remains unclear and requires further research.

AV Adoption Trajectory: Another area of uncertainty involves the timing and extent of AV adoption. Initial optimistic projections suggesting widespread availability of fully autonomous (Level 5) vehicles by the early 2020s have proven overly ambitious. Experts currently anticipate a more gradual rollout throughout the late 2020s, primarily focusing on geofenced autonomous ride-hailing fleets and automated freight operations. If privately owned AVs remain expensive or constrained by regulation, their impact on total VMT could be substantially limited or delayed. Conversely, technological breakthroughs or significant reductions in cost could lead to rapid and widespread AV adoption, dramatically amplifying travel demand and associated VMT. Ongoing research must continually reassess

the VMT impacts associated with AV adoption as clearer patterns and trends emerge over time.

Mixed Traffic and Congestion Dynamics: There is also considerable uncertainty about the impact of mixed traffic conditions, where AVs operate alongside conventional human-driven vehicles. Some analyses suggest AVs could initially reduce congestion through smoother and more efficient driving patterns, optimizing road capacity. However, improved traffic conditions might quickly attract additional vehicle travel, thereby offsetting early congestion reductions. It remains unclear at what point the penetration of AVs in traffic flows might significantly influence congestion dynamics. Detailed and sophisticated traffic simulations incorporating human behavior models alongside AV interactions are essential to understanding these complex dynamics and identifying critical thresholds where AV impacts on congestion become pronounced.

Environmental and Social Feedback: The environmental and social outcomes associated with AV adoption represent another critical area of uncertainty. Future research should integrate assumptions related to vehicle electrification, the relative prevalence of private versus shared AV ownership models, and the broader urban development implications. Another critical dimension is social equity. AVs offer promising opportunities to enhance mobility for traditionally underserved groups, such as elderly individuals, disabled populations, and those without driver's licenses. However, certain policy measures, including road pricing, intended to manage increased VMT could inadvertently restrict transportation accessibility for economically disadvantaged communities. Policymakers must therefore carefully consider and balance demand management strategies against ensuring equitable mobility access. For example, revenues from road pricing should ideally be reinvested into affordable transit and mobility solutions accessible to vulnerable populations.

Comparative effectiveness of policy types: Economic instruments change generalized travel cost directly. Distance based pricing and fees on eVMT can offset VMT growth in high automation scenarios when set at modest levels [15,41]. Spatial and service design measures raise average occupancy and retain riders on transit. Examples include pooled SAV requirements, access rules, and fare integration [16]. Land use and parking reforms act more slowly but create durable reductions by shortening trips and reducing car dependence. Future research should compare these approaches side by side in pilots and report common metrics such as VMT, eVMT, occupancy, and linked transit use.

Global Cooperation: Given that AV technology and associated companies operate internationally, global collaboration in AV policy development is essential. Sharing knowledge, policy experiences, and best practices across borders could significantly enhance policy effectiveness and streamline regulatory processes. Establishing internationally recognized standards, such as standardized communication protocols indicating vehicle occupancy status, could facilitate consistent global incentives and regulation. Ongoing dialogues among governments and organizations like the World Economic Forum could support this cooperative approach, improving outcomes for AV deployment worldwide. Coverage of AV research in Latin America and Africa remains sparse. Additional field studies in these regions are essential before any global cooperation can be reliably drawn.

Research Gaps: There are critical research gaps that need to be addressed through real-world field data collection and advanced models. As AV services like Waymo, Tesla's Robotaxi services, and Baidu Apollo continue expanding operations, it is essential to gather and analyze data on actual VMT patterns, trip lengths, empty vehicle travel frequencies, and mode-shift behaviors. These data enable calibration and validation of agent-based models and causal evaluation of policy pilots. The research should include before and after panels for new AV users to estimate the value of time and changes in mode and destination. Models should investigate travel and land use impacts with equity metrics, intercity shifts

from air and rail to automobile travel, and energy and emissions analysis. All studies should quantify uncertainty, various scenarios, and metadata to support replication and comparison across cities. Understanding whether AVs predominantly replace private car trips or, conversely, displace public transit use, is critical to refining impact assessments. Additionally, city-level policy experiments involving AV deployments would provide valuable insights into the effectiveness of various regulatory approaches, such as occupancy requirements, road pricing schemes, and transit integration efforts.

In summary, while increased VMT resulting from AV adoption appears likely, it is not inevitable. We do not rank these uncertainties. They are interdependent and each can change VMT by a large amount. Behavioral response and adoption set travel demand. Mixed traffic and fleet control shape capacity, empty miles, and delay. Policy design can offset or amplify these effects. Evidence shows large swings when any one element changes, including lower perceived time costs and higher miles after access to automation. Cities differ in baseline transit and land use. We therefore highlight all domains and recommend integrated multi-city pilots with common reporting. At a minimum, pilots should publish total VMT, empty VMT, passenger miles, average occupancy, wait time, detour factors, and linked transit boardings.

Effective and proactive policy interventions, including distance-based road pricing, high-occupancy vehicle requirements, transit integration strategies, and appropriate land-use planning, can help manage this growth and support a more sustainable and efficient transportation system. Policymakers must therefore act decisively, basing their decisions on evolving research evidence, and continuously adapting policy frameworks to guide AV deployment toward desirable societal outcomes.

6. Conclusions

The emergence of AVs offers both promising opportunities and significant challenges for achieving a sustainable transportation system. While AVs could enhance safety, accessibility, and travel efficiency, this review emphasizes the substantial risk that their widespread adoption, if not actively managed, may considerably increase total VMT. Early studies and pilot programs suggest that even partial automation could increase VMT by approximately 10–20%, and scenarios with fully automated vehicles forecast potential VMT growth exceeding 50% if policymakers do not implement effective controls. Privately owned AVs pose the highest risk of driving such increases, whereas SAV services might either substantially mitigate or further increase VMT, depending on their operational efficiency and the public acceptance of ride-pooling.

Increased travel volumes and associated negative impacts from AV adoption are not unavoidable. Policy interventions such as per-mile road charges, incentives for shared vehicle use, strategic integration of AV services into existing public transit networks, and regulations to reduce empty vehicle travel can substantially mitigate the rebound effect. Additionally, international cooperation through shared standards and best practices can enhance the effectiveness and consistency of these policy approaches.

To effectively incorporate AVs in the traffic system, policymakers should adopt proactive regulatory frameworks early during the adoption phase. Policy design should balance demand management with equitable access. Agencies should monitor real world outcomes, publish metrics, and refine policies as evidence evolves. AVs hold the potential to significantly improve urban transportation systems if policymakers strategically manage their deployment, steering them toward enhancing mobility without increasing congestion, emissions, or urban sprawl.

Author Contributions: Conceptualization, K.A., H.A.R., J.W.; methodology, K.A., H.A.R., J.W.; literature review, K.A.; data analysis, K.A.; writing—original draft preparation, K.A.; writing—review and editing, K.A., H.A.R., J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Aramco Americas (Grant number: ASC Agreement number CW48110). The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Jinghui Wang was employed by the company Aramco Research Center-Detroit, Aramco Americas. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AV	autonomous vehicle
eVMT	empty vehicle miles traveled
KSA	Saudi Arabia
NACTO	national association of city transportation officials
SAV	Shared autonomous vehicle
VKT	vehicle kilometers traveled
VMT	vehicle miles traveled

Appendix A

Appendix A lists all studies included in our review, each with a unique ID that maps to citations in the text. The columns report author and year, full title, study region, ownership model, and method, and the findings column states the size of VMT effects as reported by each source. We standardized terms so ownership model uses Private AV or SAV and method labels use survey, scenario model, simulation, field experiment, or policy analysis. Values are as reported in the source studies. No pooling or weighting was performed.

Table A1. Overview of Reviewed Studies and Reported VMT Effects.

Reference No.	Author-Year	Title	Region	Ownership Model	Method	Findings
[1]	Hardman, 2021	Investigating the decision to travel more in a partially automated electric vehicle	USA (California)	Private AV	Survey of Tesla owners	Many users drove more miles; 19 of 35 increased
[2]	Lehtonen et al., 2022	Why would people want to travel more with automated cars?	Europe	Private AV	Survey after real-world L3 exposure	25 percent would take more trips; 39 percent longer trips expected
[3]	Fagnant & Kockelman, 2015	Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations	USA	Private and shared AV	Early synthesis and scenario	Induced travel and empty repositioning likely raise VMT

Table A1. Cont.

Reference No.	Author-Year	Title	Region	Ownership Model	Method	Findings
[4]	Sun et al., 2024	Impacts of Connected and Automated Vehicles on Travel Demand and Emissions in California	USA (California)	Private and shard AV	Statewide strategic travel model	Private AV 30 to 60 percent; SAV 0 to 18 percent; per-mile fee neutralizes growth
[5]	Litman, 2025	Autonomous Vehicle Implementation Predictions: Implications for Transport Planning	Global	Private and shard AV	Policy analysis	Without pricing, AVs likely raise congestion and VMT
[6]	EESI, 2021	Autonomous Vehicles: State of the Technology and Potential Role as a Climate Solution	USA	Private and shard AV	Issue brief	Potential increases offset tech gains unless managed
[7]	Harper et al., 2016	Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions	USA	Private AV	Estimation using travel rates	Up to 14 percent national VMT increase from new users
[8]	Dabic-Miletic, 2023	Autonomous Vehicles as an Essential Component of Industry 4.0 for Meeting Last-Mile Logistics Requirements	Global	SAV	Conceptual review	Passenger VMT not assessed
[9]	Dai et al., 2024	Potential effects of automated driving on vehicle travel demand: A comparison of three case cities	China	Private and shard AV	Modeling comparison	VKT increase up to about 47 percent depending on city
[10]	RTA Dubai, 2023	Launch of Robotaxis in Dubai: Case Study	UAE (Dubai)	SAV	Case study	Not reported
[11]	Shatnawi et al., 2025	Toward AV-CAV deployment in the Kingdom of Saudi Arabia: A readiness assessment based on expert feedback	Saudi Arabia	SAV	Expert assessment	Not reported
[12]	NACTO, 2019	Blueprint for Autonomous Urbanism: Second Edition	USA	Private and shard AV	Policy guidance	Not quantified
[13]	Naz & Mattingly, 2024	Assessing Automated Vehicle Induced VMT: Meta Analysis of Current Research	USA	Private and shard AV	Meta-analysis	About 5.95 percent overall; private 6.9; SAV 5.3
[14]	Yan et al., 2020	Shared autonomous vehicle fleet performance: Impacts of trip densities and parking limitations	USA (Minneapolis, St Paul)	SAV	MATSim simulation	Around 13 percent due to repositioning eVMT
[15]	Taiebat et al., 2019	Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound	USA	Private AV	Microeconomic model with NHTS	From about 2 to 47 percent depending on value-of-time and income

Table A1. Cont.

Reference No.	Author-Year	Title	Region	Ownership Model	Method	Findings
[16]	La Delfa & Han, 2024	Sustainable Mobility and Shared Autonomous Vehicles: A Systematic Literature Review of Travel Behavior Impacts	Global	SAV	Systematic review	Many studies show higher VMT; a few show reductions with pooling
[17]	Harb et al., 2022	Simulating Life with Personally-Owned Autonomous Vehicles through a Naturalistic Experiment with Personal Drivers	USA (Sacramento)	Private AV	Field experiment	Total about 60 percent; seniors about 121 percent
[18]	Fakhrmoosavi et al., 2024	Self-driving vehicles' impacts on Americans' long-distance domestic travel choices	USA	Private AV	Modeling and survey	Monthly intercity miles per capita 25 percent
[19]	Gurumurthy & Kockelman, 2022	Dynamic ride-sharing impacts of greater trip demand and aggregation at stops in shared autonomous vehicle systems	USA (mid-size city)	SAV	Simulation	VMT down 27 to 39 percent under high pooling
[20]	Huang et al., 2022	Shared automated vehicle fleet operations for first-mile last-mile transit connections with dynamic pooling	USA	SAV	Simulation	About 3.6 percent reduction with strong transit integration
[21]	Jiang et al., 2022	Connected Automated Vehicle Impacts in Southern California Part-II: VMT, Emissions, and Equity	USA (SoCal)	Private and shard AV	Regional scenarios	About 10 percent total VMT
[22]	Dowds et al., 2021	Consideration of Automated Vehicle Benefits and Research Needs for Rural America	USA (rural)	Private and shard AV	Conceptual and review	Direction context dependent
[23]	Kolarova & Cherchi, 2021	Impact of Trust and Travel Experiences on the Value of Travel Time Savings for Autonomous Driving	Europe	Not specific	Stated preference	Lower perceived time cost implies longer trips and more car use
[24]	Malokin et al., 2019	How do activities conducted while commuting influence mode choice? Using revealed preference models to inform public transportation advantage and autonomous vehicle scenarios	USA	Not specific	Revealed preference models	Productive time increases tolerance for longer car commutes
[25]	Gelauff et al., 2019	Spatial and welfare effects of automated driving: Will cities grow, decline or both?	Europe (Netherlands)	Not specific	Economic modeling	Suburban relocation can raise VMT roughly five to twenty five percent
[26]	BCG, 2022	Shared, Autonomous, and Electric: An Update on the Reimagined Car	Global	Private and shard AV	Industry report	Not quantified

Table A1. Cont.

Reference No.	Author-Year	Title	Region	Ownership Model	Method	Findings
[27]	Howell et al., 2020	Multilevel Impacts of Emerging Technologies on City Form and Development	USA	Not specific	Urbanism Next analysis	Lower generalized cost may reduce transit by 14 percent and active modes by 11 percent
[28]	Gurumurthy et al., 2021	A system of shared autonomous vehicles for Chicago: Understanding the effects of geofencing the service	USA (Chicago)	SAV	Simulation	eVMT around mid-teens share; geofencing can limit roaming
[29]	de Souza et al., 2020	An Optimization-based Strategy for Shared Autonomous Vehicle Fleet Repositioning	USA (Bloomington IL)	SAV	Agent-based and optimization	Empty repositioning about 17 percent of VMT in case study
[30]	Montoya, 2024	Reinventing the Wheel by Taking It Away: How Autonomous Vehicles Will Shape Land Use Law	USA	Not specific	Legal analysis	Risk of sprawl and longer trips
[31]	Kockelman et al., 2019	The Rise of Long-Distance Trips, in a World of Self-Driving Cars: Anticipating Trip Counts and Evolving Travel Patterns Across the Texas Triangle Megaregion	USA (Texas)	Private AV	Regional modeling	More long-distance trips and higher VMT expected
[32]	Rebalski & Johansson, 2024	Too Far? Autonomous vehicles, travel demand, and carbon dioxide emissions in Sweden	Sweden	Not specific	National modeling	Sizeable daily distance increase per driver; emissions rise
[33]	San Francisco City Attorney, 2023	San Francisco Seeks Reprieve from CPUC Decision Allowing Unfettered Autonomous Vehicle Expansion	USA (San Francisco)	SAV	Legal filing	Not quantified; congestion concerns
[34]	Eppenberger & Richter, 2021	The opportunity of shared autonomous vehicles to improve spatial equity in accessibility and socio-economic developments in European urban areas	Europe	SAV	Comparative analysis	Not primary focus
[35]	Polydoropoulou et al., 2021	Who Is Willing to Share Their AV? Insights about Gender Differences among Seven Countries	Europe (7 countries)	Private and shard AV	Survey	Not quantified
[36]	EEA, 2022	Transport and Environment Report 2022: Digitalization in the Mobility System â€œ Challenges and Opportunities	Europe	Private and shard AV	Agency report	Median projected VMT increase around 43 percent; tech gains may be offset

Table A1. Cont.

Reference No.	Author-Year	Title	Region	Ownership Model	Method	Findings
[37]	Wang et al., 2021	Public Preferences of Shared Autonomous Vehicles in Developing Countries: A Cross-National Study of Pakistan and China	Pakistan and China	SAV	Survey	Not quantified; strong interest reported
[38]	Guo & Huo, 2023	Residential Location Selection in First-Tier Cities in China under Shared Autonomous Vehicle Conditions	China (first-tier cities)	SAV	Multinomial logit using survey	Greater downtown attraction; VMT effect context specific
[39]	Luo et al., 2022	Evaluating the impact of private automated vehicles on activity-based accessibility in Japanese regional areas: A case study of Gunma Prefecture	Japan	Private AV	Scenario modeling	VMT increase about 22 to 44 percent by 2040
[40]	Oh et al., 2020	Assessing the impacts of automated mobility-on-demand through agent-based simulation: A study of Singapore	Singapore	SAV	Agent-based simulation	Risk of higher traffic and transit displacement
[41]	Tan & Taeiagh, 2021	Adaptive governance of autonomous vehicles: Accelerating the adoption of disruptive technologies in Singapore	Singapore	Private AV	Governance analysis	Not quantified
[42]	Ullah et al., 2024	Unraveling the Complex Barriers to and Policies for Shared Autonomous Vehicles: A Strategic Analysis for Sustainable Urban Mobility	Saudi Arabia	SAV	Strategic analysis	Not quantified
[43]	Nahmias-Biran et al., 2021	Evaluating the impacts of shared automated mobility on-demand services: an activity-based accessibility approach	Global case study methods	SAV	Activity-based accessibility	Not primary focus
[44]	Soteropoulos et al., 2019	Impacts of Automated Vehicles on Travel Behavior and Land Use: An International Review of Modelling Studies	International	Private and shared AV	Review	Wide range; increases common; reductions possible with sharing
[45]	Sustainability Directory (accessed 2025)	Autonomous Vehicle Integration with Public Transit Systems.	Concept	SAV	Scenario description	Likely VMT reductions if integrated
[46]	Carrese et al., 2023	The Integration of Shared Autonomous Vehicles in Public Transportation Services: A Systematic Review	Global	SAV	Systematic review	Mixed; reductions when well integrated

Table A1. Cont.

Reference No.	Author-Year	Title	Region	Ownership Model	Method	Findings
[47]	Yigitcanlar et al., 2019	Disruptive Impacts of Automated Driving Systems on the Built Environment and Land Use: An Urban Planner's Perspective	Global	Private and shared AV	Planner perspective review	Risk of sprawl and higher VMT without planning
[48]	Tiwari et al., 2024	Smart Insertion Strategies for Sustainable Operation of Shared Autonomous Vehicles	Global methods	SAV	Operational strategies	Not quantified; aims to lower empty miles

References

- Hardman, S. Investigating the decision to travel more in a partially automated electric vehicle. *Transp. Res. D Transp. Environ.* **2021**, *96*, 102884. [\[CrossRef\]](#)
- Lehtonen, E.; Malin, F.; Louw, T.; Lee, Y.M.; Itkonen, T.; Innamaa, S. Why would people want to travel more with automated cars? *Transp. Res. F Traffic Psychol. Behav.* **2022**, *89*, 143–154. [\[CrossRef\]](#)
- Fagnant, D.J.; Kockelman, K. Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transp. Res. A Policy Pract.* **2015**, *77*, 167–181. [\[CrossRef\]](#)
- Sun, R.; Circella, G.; Jaller, M.; Qian, X.; Alemi, F. Impacts of Connected and Automated Vehicles on Travel Demand and Emissions in California. *Transp. Res. Rec.* **2024**, *2678*, 881–900. [\[CrossRef\]](#)
- Litman, T.A. *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning*; Victoria Transport Policy Institute: Victoria, BC, Canada, 2025. Available online: <https://vtpi.org/avip.pdf> (accessed on 22 September 2025).
- Environmental Energy Study Institute (EESI). *Autonomous Vehicles: State of the Technology and Potential Role as a Climate Solution*; Environmental and Energy Study Institute: Washington, DC, USA, 2021. Available online: https://www.eesi.org/files/IssueBrief_Autonomous_Vehicles_2021.pdf (accessed on 22 September 2025).
- Harper, C.D.; Hendrickson, C.T.; Mangones, S.; Samaras, C. Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions. *Transp. Res. C Emerg. Technol.* **2016**, *72*, 1–9. [\[CrossRef\]](#)
- Dabic-Miletic, S. Autonomous Vehicles as an Essential Component of Industry 4.0 for Meeting Last-Mile Logistics Requirements. *J. Ind. Intell.* **2023**, *1*, 55–62. [\[CrossRef\]](#)
- Dai, J.; Li, R.; Liu, Z. Potential effects of automated driving on vehicle travel demand: A comparison of three case cities. *J. Traffic Transp. Eng.* **2024**, *11*, 348–361. [\[CrossRef\]](#)
- Roads Transport Authority Dubai. *Launch of Robotaxis in Dubai: Case Study*; Dubai International Project Management Forum (DIPMF): Dubai, United Arab Emirates, 2023. Available online: <https://dipmf.ae> (accessed on 22 September 2025).
- Shatnawi, I.; Gonzalez, J.N.; Masoud, N. Toward AV-CAV deployment in the Kingdom of Saudi Arabia: A readiness assessment based on expert feedback. *Res. Transp. Bus. Manag.* **2025**, *60*, 101378. [\[CrossRef\]](#)
- National Association of City Transportation Officials (NACTO). *Blueprint for Autonomous Urbanism*, 2nd ed.; National Association of City Transportation Officials (NACTO): New York, NY, USA, 2019; pp. 1977–8449. Available online: https://www.nacto.org/wp-content/uploads/NACTO_Blueprint_2nd_Edition_Part1.pdf (accessed on 22 September 2025).
- Naz, F.; Mattingly, S.P. Assessing Automated Vehicle Induced Vmt: Meta Analysis of Current Research. *SSRN* **2024**, 5030045. [\[CrossRef\]](#)
- Yan, H.; Kockelman, K.M.; Gurumurthy, K.M. Shared autonomous vehicle fleet performance: Impacts of trip densities and parking limitations. *Transp. Res. D Transp. Environ.* **2020**, *89*, 102577. [\[CrossRef\]](#)
- Taiebat, M.; Stolper, S.; Xu, M. Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound. *Appl. Energy* **2019**, *247*, 297–308. [\[CrossRef\]](#)
- La Delfa, A.; Han, Z. Sustainable Mobility and Shared Autonomous Vehicles: A Systematic Literature Review of Travel Behavior Impacts. *Sustainability* **2025**, *17*, 3092. [\[CrossRef\]](#)
- Harb, M.; Malik, J.; Circella, G.; Walker, J.L. *Simulating Life with Personally-Owned Autonomous Vehicles Through a Naturalistic Experiment with Personal Drivers*; Institute of Transportation Studies, University of California, Davis and Berkeley: Berkeley, CA, USA, 2022. Available online: <https://escholarship.org/uc/item/79g921rp> (accessed on 22 September 2025).
- Fakhrmoosavi, F.; Paithankar, P.; Kockelman, K.M.; Huang, Y.; Hawkins, J. Hawkins Self-driving vehicles' impacts on Americans' long-distance domestic travel choices. *Transp. Plan Technol.* **2024**, *47*, 1262–1276. [\[CrossRef\]](#)

19. Gurumurthy, K.M.; Kockelman, K.M. Dynamic ride-sharing impacts of greater trip demand and aggregation at stops in shared autonomous vehicle systems. *Transp. Res. A Policy Pract.* **2022**, *160*, 114–125. [\[CrossRef\]](#)
20. Huang, Y.; Kockelman, K.M.; Garikapati, V. Shared automated vehicle fleet operations for first-mile last-mile transit connections with dynamic pooling. *Comput. Environ. Urban Syst.* **2022**, *92*, 101730. [\[CrossRef\]](#)
21. Jiang, Q.; He, B.Y.; Ma, J. Connected Automated Vehicle Impacts in Southern California Part-II: VMT, Emissions, and Equity. *Transp. Res. D Transp. Environ.* **2022**, *109*, 103381. [\[CrossRef\]](#)
22. Dowds, J.; Sullivan, J.; Rowangould, G.; Aultman-Hall, L. *Consideration of Automated Vehicle Benefits and Research Needs for Rural America*; Tech Report 2021; National Center for Sustainable Transportation: Davis, CA, USA, 2021. (In English) [\[CrossRef\]](#)
23. Kolarova, V.; Cherchi, E. Impact of Trust and Travel Experiences on the Value of Travel Time Savings for Autonomous Driving. *Transp. Res. C Emerg. Technol.* **2021**, *131*, 103354. [\[CrossRef\]](#)
24. Malokin, A.; Circella, G.; Mokhtarian, P.L. How do activities conducted while commuting influence mode choice? Using revealed preference models to inform public transportation advantage and autonomous vehicle scenarios. *Transp. Res. A Policy Pract.* **2019**, *124*, 82–114. [\[CrossRef\]](#)
25. Gelauff, G.; Ossokina, I.; Teulings, C. Spatial and welfare effects of automated driving: Will cities grow, decline or both? *Transp. Res. A Policy Pract.* **2019**, *121*, 277–294. [\[CrossRef\]](#)
26. Wegscheider, A.K.; Hagenmaier, M.; Bert, J.; Collie, B.; Palme, T.; Rose, J. Shared, Autonomous, and Electric: An Update on the Reimagined Car. Boston Consulting Group. 2022. Available online: <https://www.bcg.com/publications/2022/update-on-shared-autonomous-electric-vehicles-market> (accessed on 22 September 2025).
27. Howell, A.; Tan, H.; Brown, A.; Schlossberg, M.; Karlin-Resnick, J.; Lewis, R.; Anderson, M.; Larco, N.; Tierney, G.; Carlton, I.; et al. *Multilevel Impacts of Emerging Technologies on City Form and Development*; Urbanism Next, University of Oregon: Eugene, OR, USA, 2020. Available online: https://blogs.uoregon.edu/urbanismnext/files/2020/01/NSF-Report_All-Chapters_FINAL_013020.pdf (accessed on 22 September 2025).
28. Gurumurthy, K.M.; Auld, J.; Kockelman, K. A system of shared autonomous vehicles for Chicago: Understanding the effects of geofencing the service. *J. Transp. Land Use* **2021**, *14*, 933–948. [\[CrossRef\]](#)
29. Souza, F.D.; Gurumurthy, K.M.; Auld, J.; Kockelman, K.M. An Optimization-based Strategy for Shared Autonomous Vehicle Fleet Repositioning. In Proceedings of the 6th International Conference on Vehicle Technology and Intelligent Transport Systems VEHITS 2020, Prague, Czech Republic, 2–4 May 2020. [\[CrossRef\]](#)
30. Montoya, T. Reinventing the Wheel by Taking It Away: How Autonomous Vehicles Will Shape Land Use Law. *Ariz. Law J. Emerg. Technol.* **2024**, *7*, 5. [\[CrossRef\]](#)
31. Kockelman, K.; Huang, Y.; Quarles, N. *The Rise of Long-Distance Trips, in a World of Self-Driving Cars: Anticipating Trip Counts and Evolving Travel Patterns Across the Texas Triangle Megaregion*; The University of Texas at Austin, Department of Civil, Architectural and Environmental Engineering: Austin, TX, USA, 2019. Available online: https://sites.utexas.edu/cm2/files/2019/04/Year2_Kockelman_AVs.pdf (accessed on 22 September 2025).
32. Rebalski, E.; Johansson, D.J.A. Too Far? Autonomous vehicles, travel demand, and carbon dioxide emissions in Sweden. *Eur. Transp. Stud.* **2024**, *1*, 100006. [\[CrossRef\]](#)
33. City Attorney of San Francisco. San Francisco Seeks Reprieve from CPUC Decision Allowing Unfettered Autonomous Vehicle Expansion. 2023. Available online: <https://sfist.com/2023/08/17/sf-city-attorney-files-motion-to-halt-roll-out-of-more-self-driving-cruise-and-waymo-robotaxis/> (accessed on 22 September 2025).
34. Eppenberger, N.; Richter, M.A. The opportunity of shared autonomous vehicles to improve spatial equity in accessibility and socio-economic developments in European urban areas. *Eur. Transp. Res. Rev.* **2021**, *13*, 32. [\[CrossRef\]](#)
35. Polydoropoulou, A.; Tsouros, I.; Thomopoulos, N.; Pronello, C.; Elvarsson, A.; Sigþórsson, H.; Dadashzadeh, N.; Stojmenova, K.; Sodnik, J.; Neophytou, S.; et al. Who Is Willing to Share Their AV? Insights about Gender Differences among Seven Countries. *Sustainability* **2021**, *3*, 4769. [\[CrossRef\]](#)
36. European Environment Agency. *Transport and Environment Report 2022: Digitalisation in the Mobility System—Challenges and Opportunities*; European Environment Agency: Copenhagen, Denmark, 2022; ISBN 978-92-9480-519-5. Available online: <https://www.eea.europa.eu/en/analysis/publications/transport-and-environment-report-2022> (accessed on 22 September 2025).
37. Wang, Z.; Safdar, M.; Zhong, S.; Liu, J.; Xiao, F. Public Preferences of Shared Autonomous Vehicles in Developing Countries: A Cross-National Study of Pakistan and China. *J. Adv. Transp.* **2021**, *2021*, 5141798. [\[CrossRef\]](#)
38. Guo, C.; Huo, Y. Residential Location Selection in First-Tier Cities in China under Shared Autonomous Vehicle Conditions. In Proceedings of the IoTAAI 2023: 5th International Conference on Internet of Things, Automation and Artificial Intelligence, Nanchang, China, 1–3 December 2023; pp. 444–450.
39. Luo, L.; Parady, G.; Takami, K. Evaluating the impact of private automated vehicles on activity-based accessibility in Japanese regional areas: A case study of Gunma Prefecture. *Transp. Res. Interdiscip. Perspect.* **2022**, *16*, 100717. [\[CrossRef\]](#)
40. Oh, S.; Seshadri, R.; Azevedo, C.L.; Kumar, N.; Basak, K.; Ben-Akiva, M. Assessing the impacts of automated mobility-on-demand through agent-based simulation: A study of Singapore. *Transp. Res. A Policy Pract.* **2020**, *138*, 367–388. [\[CrossRef\]](#)

41. Tan, S.Y.; Taeihagh, A. Adaptive governance of autonomous vehicles: Accelerating the adoption of disruptive technologies in Singapore. *Gov. Inf. Q.* **2021**, *38*, 101546. [[CrossRef](#)]
42. Ullah, I.; Zheng, J.; Ullah, S.; Bhattarai, K.; Almujibah, H.; Alawad, H. Unraveling the Complex Barriers to and Policies for Shared Autonomous Vehicles: A Strategic Analysis for Sustainable Urban Mobility. *Systems* **2024**, *12*, 558. [[CrossRef](#)]
43. Nahmias-Biran, B.-H.; Oke, J.B.; Kumar, N.; Azevedo, C.L.; Ben-Akiva, M. Evaluating the impacts of shared automated mobility on-demand services: An activity-based accessibility approach. *Transportation* **2021**, *48*, 1613–1638. [[CrossRef](#)]
44. Soteropoulos, A.; Berger, M.; Ciari, F. Impacts of Automated Vehicles on Travel Behaviour and Land Use: An International Review of Modelling Studies. *Transp. Rev.* **2019**, *39*, 29–49. [[CrossRef](#)]
45. Sustainability Directory. Autonomous Vehicle Integration with Public Transit Systems. Available online: <https://prism.sustainability-directory.com/scenario/autonomous-vehicle-integration-with-public-transit-systems/> (accessed on 8 September 2025).
46. Carrese, F.; Sportiello, S.; Zhaksylykov, T.; Colombaroni, C.; Carrese, S.; Papaveri, M.; Patella, S.M. The Integration of Shared Autonomous Vehicles in Public Transportation Services: A Systematic Review. *Sustainability* **2023**, *15*, 13023. [[CrossRef](#)]
47. Yigitcanlar, T.; Wilson, M.; Kamruzzaman, M. Disruptive Impacts of Automated Driving Systems on the Built Environment and Land Use: An Urban Planner's Perspective. *J. Open Innov. Technol. Mark. Complex.* **2019**, *5*, 24. [[CrossRef](#)]
48. Tiwari, S.; Nassir, N.; Lavieri, P.S. Smart Insertion Strategies for Sustainable Operation of Shared Autonomous Vehicles. *Sustainability* **2024**, *16*, 5175. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.