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Environmental and Equity Implications of Electric, Shared Autonomous Vehicles (SAVs) in Urban Transportation: A Case Study of San Francisco

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INTRODUCTION

Automated Vehicle (AV) technology has emerged as a new, transformational solution to the movement of goods and people with the potential to enhance safety, mobility, and environmental sustainability. Early analyses suggest that the most considerable gains could be fewer crashes,[1,2,3,4] less congestion[2,5,6], reduced vehicle energy and emissions,[7,8,9,10] reduced urban parking requirements,[11] and increased productivity.[12] While numerous studies have examined the effects of autonomous vehicles (AVs) on energy consumption and emissions, there has been a limited exploration of their impact on noise and air pollution. This lack of investigation suggests a gap in understanding the potential environmental outcomes of AV implementation.[13] Therefore, there is a clear need to conduct research and assess the potential impacts of AVs on public health and the environment.

Automated Driving Systems (ADS) technology is continuously being developed, becoming safer, more efficient, and even more innovative for passenger travel. Automakers and technology companies continue to research and pilot a variety of autonomous vehicles (AVs) to develop commercial use cases and prepare for deployment.[14] However, there continues to be a robust debate whether AVs can bring about positive social benefits or if they will cause a variety of negative externalities. Environmental impacts in terms of energy efficiencies are well established for Advanced Driving Assistance Systems (ADAS)[15,16] but the future environmental benefits of a fully autonomous U.S. vehicle fleet, while promising, is still to be determined. Air and noise pollution are priority issues from both the environmental and equity perspectives as they present adverse health implications. Policy recommendations regarding the environmental impact of AVs, specifically mitigating negative externalities, would be valuable. In this report, SAFE assesses the air quality and noise improvement available from widescale AV deployment in a case study city of San Francisco. Through this study we also assess the impact of air and noise pollution reduction through an equity lens.

LITERATURE REVIEW

Public Health Implications of Air and Noise Pollution

Assessing air and noise pollution in cities is crucial for understanding the adverse effects on public health and the environment. Numerous studies have highlighted the detrimental health impacts of air pollution, particularly fine particulate matter ($PM_{2.5}$) on respiratory and cardiovascular diseases.[17,18] Long-term exposure to high levels of $PM_{2.5}$ has been associated with increased mortality rates and reduced life expectancy.[19] Similarly, noise pollution has been linked to various health problems, including sleep disturbances, hypertension, and impaired cognitive function.[20,21] Therefore, assessing and mitigating air and noise pollution are critical components of urban planning and policymaking to protect public health.

Furthermore, understanding the geospatial distribution and sociodemographic patterns of air and noise pollution is essential for addressing environmental justice concerns. Studies have consistently demonstrated that marginalized communities, such as low-income neighborhoods and communities of color, bear a disproportionate burden of air and noise pollution.[22,23] These communities often face higher exposure to pollutants due to the location of industrial facilities, major roadways, and highway infrastructure in their neighborhoods. Consequently, they experience higher rates of respiratory illnesses and other health disparities. Assessing pollution patterns can help identify areas of environmental injustice and inform targeted policies and interventions to address these inequities.[24]

Air Pollution

When internal combustion engines (ICE) vehicles travel, they emit air pollutants that have several adverse impacts on public health. The combustion of fossil in ICE vehicles releases pollutants such as nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOCs). The impacts of transportation-related air pollution on public health include:

- **Respiratory Diseases:** Exposure to air pollutants from vehicles has been linked to the development or exacerbation of respiratory conditions such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD).[19] Fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO2) are particularly harmful to the respiratory system and can increase the risk of respiratory illnesses.

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- **Cardiovascular Disorders**: Transportation-related air pollution has also been associated with an increased risk of cardiovascular diseases, including heart attacks, strokes, and high blood pressure.[17] The inhalation of pollutants like PM and NOx can trigger inflammation and oxidative stress, leading to adverse cardiovascular effects.
- **Impaired Lung Development in Children**: Children exposed to air pollution from vehicles may experience impaired lung development, reduced lung function, and an increased susceptibility to respiratory infections.[25] Early-life exposure to air pollutants can have long-term implications for lung health.

Marginalized communities, including low-income neighborhoods and communities of color, are often most burdened by transportation-related air pollution.[19] Across the country, members of these communities are disproportionately suffering from the health risks associated with air pollution, like asthma and high blood pressure, due to their close vicinity to highways and major roadways. Survey data reveals that EV owners and those with the preference to adopt EVs have higher income, higher education, and tend to live in single-family homes they own. On the other hand, communities with low-income, Black and Hispanic households are less likely to adopt EVs because of the high cost and lack of access to charging infrastructure. Current residents in these communities miss opportunities to benefit from reduced emissions, lower lifetime ownership costs, and improved environmental and health outcomes associated with EV adoption. In this instance, shared automated, electric mobility can serve these communities thus better distributing the social and environmental benefits of vehicle electrification and automation without further financial burden of ownership.

Noise Pollution

Vehicle traffic is a major source of noise pollution, which can result in a litany of adverse health impacts. Noise from vehicle traffic comes from a combination of engine, exhaust, and tires.[21] Factors that contribute to vehicle traffic noise pollution are number of vehicles, traffic speed, vehicle fleet mix, and topography. To illustrate the influence of vehicle speed on noise pollution, a vehicle traveling at 65 miles per hour is twice as loud as a vehicle traveling at 30 mph. Likewise, traffic volume also impacts noise pollution: 2,000 vehicles per hour is twice as loud as 200 vehicles per hour.[20] Traffic is loudest during free-flow or non-stop traffic, which typically occurs before or after peak travel times.[26] Lastly, noise pollution effects are based on distance from bust streets and highways, those in closest proximity and most adversely affected by traffic noise.[27]

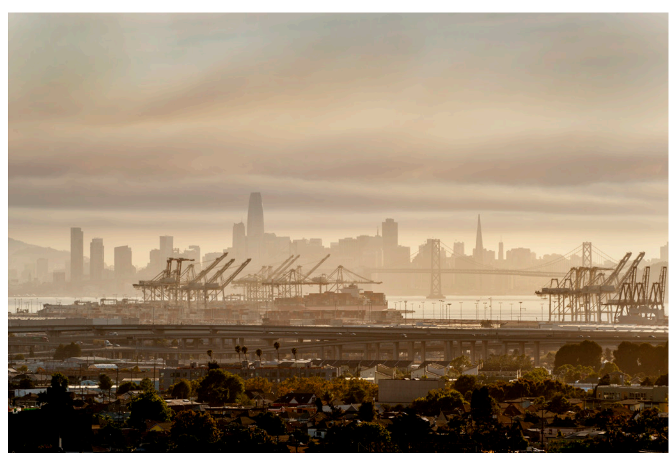
The impacts of transportation-related noise pollution can be observed in several ways:

- **Sleep Disturbance**: Excessive noise during the night can disrupt sleep patterns, leading to sleep deprivation and related health issues.[27] Noise from vehicles, especially in residential areas, can negatively impact the quality of sleep for residents.
- **Stress and Mental Health**: Prolonged exposure to high noise levels has been linked to increased stress levels, anxiety, and mood disorders.[26] The persistent noise from vehicles in urban environments like San Francisco can contribute to chronic stress and have adverse effects on mental well-being.
- **Cognitive Impairment**: Noise pollution, including that from transportation, has been associated with impaired cognitive performance, attention deficits, and reduced learning abilities, particularly in children.[22] Noise pollution can affect concentration and cognition.[28]
- **Quality of Life and Well-being**: Excessive noise can reduce the overall quality of life in urban areas. It affects residents' satisfaction with their living environments, outdoor activities, and overall well-being.[18] This means residents in noise polluted areas are unable to fully enjoy public spaces or their surroundings.

Noise pollution disproportionately affects vulnerable populations, exacerbating existing health disparities.[18] Low-income neighborhoods and communities of color in San Francisco may experience higher exposure to transportation-related noise, leading to additional health burdens. Addressing transportation-related air and noise pollution requires a comprehensive approach involving urban planning, traffic management, and noise mitigation strategies. Implementing measures such as traffic calming, sound barriers, and promoting alternative modes of transportation can help mitigate noise impacts. Electric vehicles have been found to reduce noise pollution on streets with speed lower than 30 mph.[28] Policies aimed at reducing noise levels and protecting vulnerable communities are essential to address the public health challenges associated with urban noise pollution.

Air & Noise Pollution in San Francisco

While the city has transitioned away from heavy industrialization, transportation-related pollution continues to contribute to localized sources of pollution that impact air quality in certain areas. Air quality in San Francisco is regularly monitored by the Bay Area Air Quality Management District (BAAQMD) and the Environmental Protection Agency (EPA). These organizations provide real-time air quality data and issue alerts or advisories when pollution levels exceed health standards. In 2022, San Francisco experienced 51 days with moderate air quality, which can present a health concern to certain sensitive individuals.[29] The high volume of traffic and the presence of major roadways can result in elevated levels of pollutants. Like many American cities, vehicle emissions, particularly from cars and trucks, contribute significantly to air pollution in San Francisco. Transportation-related noise pollution is a significant concern, so much so, it was declared a public health concern by the American Public Health Association in 2021.[30] The city's bustling roadways, dense population, and continuous traffic contribute to elevated noise levels that can have detrimental effects on public health. Addressing transportation-



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related air pollution in San Francisco requires a multifaceted approach that includes promoting sustainable transportation options, improving public transit infrastructure, and incentivizing the adoption of new vehicle technology powered by cleaner energy sources.

Shared Autonomous Vehicles (SAVs): Potential for Reducing Air and Noise Pollution

Shared autonomous vehicles (SAVs) have the potential to positively contribute to environmental mitigation efforts via vehicle electrification, novel vehicle design, and increased vehicle utilization from car and ride sharing. While SAV has been used as an acronym to be clear that AVs should be shared, here we use SAV in this paper to highlight that a successful reimagining of mobility is built on these vehicles being shared, autonomous and electric. Previous studies note an array of potential societal benefits although the magnitude and externalities, good or bad, of these impacts depend on assumptions, technologies, deployment schemes, and policies.[1,10,31] This study finds significant environmental benefits can be realized via SAV deployment, including reduced air pollution and noise levels.

First, all SAVs must be powered via an electric battery to optimally maximize the environmental benefits of the technology. Many studies have explored the benefits of transitioning from internal combustion engine vehicles (ICEV) to electric vehicles, asserting privately owned vehicles can reduce GHG emissions by 46 percent.[8] EVs emit zero tailpipe emissions and therefore contribute to dramatically reducing greenhouse gas (GHG) emissions, resulting in a cleaner and more sustainable environment. Whether privately owned or part of a fleet, EVs are a cleaner alternative to internal combustion engine (ICE) vehicles, ensuring that every mile driven in an EV significantly lessens the environmental impact and helps pave the way for a greener transportation future. Vehicle sharing, as available with SAVs, can reduce GHG emissions even further, upwards of 70 percent.[8] Vehicle electrification is also tied to reduced noise pollution from light-duty vehicles. One study[32] estimated that the deployment of electric

In our analysis an SAV fleet would represent 6.6 percent of the entire vehicle fleet in the city by year 2033.

autonomous vehicles could reduce traffic noise levels by up to 8 dB, reducing the noise by nearly half. This reduction comes from the electric powertrain combined with the roadway efficiencies that remove some traffic volume from intraurban roads. This study also assumed all ICE vehicles were replaced with EAVs, so by sharing a fleet of electric, autonomous vehicles one can expect an even greater reduction in noise pollution.

Second, SAVs lend themselves to innovative vehicle design as they do not need a human driver, prompting AV companies to develop new vehicle designs. Novel vehicle design allows for vehicle rightsizing and the subsequent opportunities to create tailored services to address a market need. In communities that are experiencing low vehicle ownership and low transit coverage, SAVs can provide mobility services[33] where large public transit buses for 40-60 passengers are not financially viable. Such a service would contribute to quieter and zero emission mobility options while filling existing service gaps in need of a solution.

Finally, when integrated into a transportation system, SAVs can optimize traffic flow, reduce congestion, and minimize the stop-and-go patterns typically associated with urban driving. By smoothing traffic patterns, SAVs can contribute to reduced noise

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levels and a quieter urban environment.[34] SAVs can significantly enhance traffic management by dynamically adjusting their routes and speeds based on real-time traffic data. Additionally, SAVs can strategically distribute their services across areas with high demand, efficiently serving multiple passengers with shared rides, which reduces the total number of vehicles on the road during peak hours. This optimized deployment not only eases congestion but also contributes to a more sustainable and space-efficient transportation system, making urban areas more accessible and less burdened by traffic gridlock. As a result, cities stand to gain not only from improved traffic flow but also from reduced greenhouse gas and less noise pollution. By streamlining traffic flow and maximizing road capacity, SAVs offer a promising solution to alleviate congestion and create more efficient travel.

Figure 1
Vehicle Ownership in San Francisco

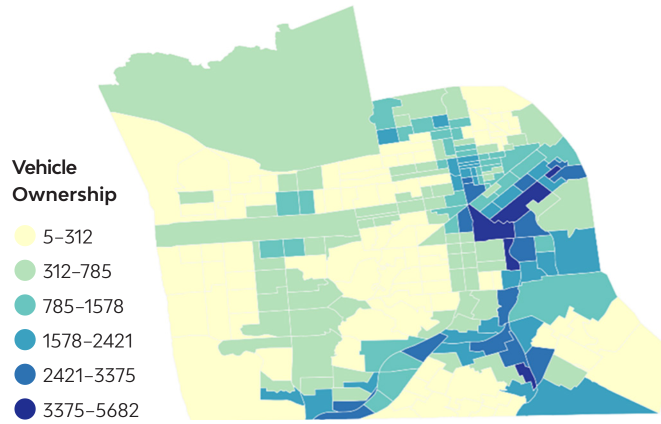
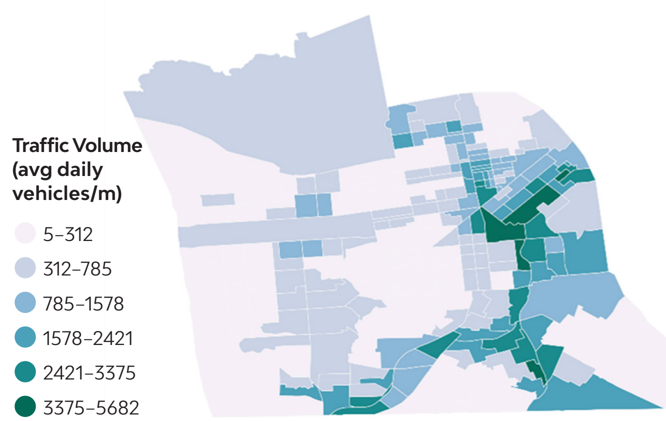


Figure 2
Traffic Volume in San Francisco



ANALYSIS RESULTS

Vehicle Ownership & Noise Pollution

While San Francisco 's public transit system is the eighth largest system in the United States,[35] many residents still choose vehicle ownership. Figures 1 and 2 illustrate the distribution of vehicle ownership and traffic volume, indicating where the noisiest communities are in San Francisco. Along the eastern side of the city vehicle ownership is the greatest, as indicated with the darker colored tracts in Figure 1. Likewise, Figure 2, traffic volume, the proxy metric for noise pollution, has a similar pattern; the same high concentrations of traffic volume can be found alongside the eastern and southern parts of the city.

Our model included the estimated the shared autonomous vehicle (SAV) fleet in San Francisco scaling to 10,200 vehicles1 over a 10-year period and 10% increase in service trips each year. In our analysis an SAV fleet would represent 6.6 percent of the entire vehicle fleet in the city by year 2033. We also assumed as more trips become available via SAV they will replace trips taken by personally owned vehicles adding to the ongoing decline in vehicle ownership. As a result, our analysis revealed an overall reduction of 36.9 percent of the light-duty vehicle fleet in San Francisco. This reduction in vehicle ownership and the integration of SAVs into the transportation system have far-reaching implications, including the potential to alleviate traffic congestion, reduce air and noise pollution, and enhance overall urban mobility and sustainability. Moreover, this transition toward shared and autonomous mobility is essential in achieving the city's environmental and transportation goals, while also addressing issues of equity and public health in transportation.

Road noise is one of the top two sources of noise pollution in the United States; vehicle ownership and traffic volume are metrics that indicate expected noise levels.[19] In our model, noise pollution was determined via vehicle trips, specifically, the number of ICE vehicles in San Francisco completing the national average of 1,500 annual trips. The analysis determined that declining ICE vehicle ownership in tandem with the increase in trips via a growing SAV fleet resulted in an overall decline in noise polluting trips over the

1 Estimate derived from interview with AV company, Cruise.

10-year time horizon. Noise polluting vehicle trips decreased by 61% by 2033. Although the SAV fleet share is conservative in our analysis, the all-electric fleet delivers more trips to city residents and does so with less noise than ICE vehicles. Overall, our findings highlight the significant role that SAVs can play in reducing noise pollution and creating quieter and more sustainable urban environments.

Air Pollution

To assess the impact of shared autonomous electric vehicles in San Francisco, we determined the current $PM_{2.5}$ concentration levels from existing databases from the state of California and the Environmental Protection Agency (EPA). In San Francisco, the average $PM_{2.5}$ concentration was 7.530 µg/m³. Figure 4 shows the location of the census tracts where $PM_{2.5}$ levels are highest in the city. Census tracts in the northeastern part of the city had higher concentrations of $PM_{2.5}$ that are reflected in the black tracts. These tracts are located around the downtown and financial district as well as the entry point for the Bay Bridge. Figure 4 also shows $PM_{2.5}$ concentrations gradually decreasing as the distance from the Central Business District increases, which is reflected in the yellow and orange tracts. Further, the distribution of $PM_{2.5}$ concentration levels indicate where city residents are more vulnerable to exposure than others. Our model included determining the potential air pollution improvements in the presence of SAVs by analyzing $PM_{2.5}$ concentration over the 10-year analysis time. Utilizing a simplified data model, in the 10th year we observed a noteworthy 40 percent decrease in $PM_{2.5}$ concentration levels associated with the increased presence of SAVs on the road. Despite the relatively small size of the SAV fleet size (10,200 SAVs or 6.6 percent) in comparison to the private vehicle fleet (74,500 vehicles or 93.4 percent) in San Francisco, the cumulative impact over the 10-year period proved to be substantial. This finding underscores the significance of the SAV fleet in reducing air pollution, particularly in terms of $PM_{2.5}$ levels.

These results highlight the potential of shared autonomous electric vehicles to contribute significantly to the improvement of air quality in urban areas. As the SAV fleet continues to expand, the positive impact on air pollution is expected to become even more pronounced, thus providing a promising pathway towards cleaner and healthier environments.

Equity and Environmental Impact

The geospatial distribution of low-income households and communities of color deepens insight of air and noise pollution impacts. As in many U.S. cities, San Francisco's marginalized communities are disproportionally impacted by negative externalities of transportation activity, including air and noise pollution. San Francisco has 71 out of 241 census tracts that are home to above average concentrations of low-income households and communities of color. When comparing air and noise pollution metrics to the city average, disparities are present. Table 1 details the equity prioritized census tracts to the average census tracts in the city. Most notably, these neighborhoods have lower rates of vehicle ownership,

Figure 3
Sociodemographic Metrics: People of Color

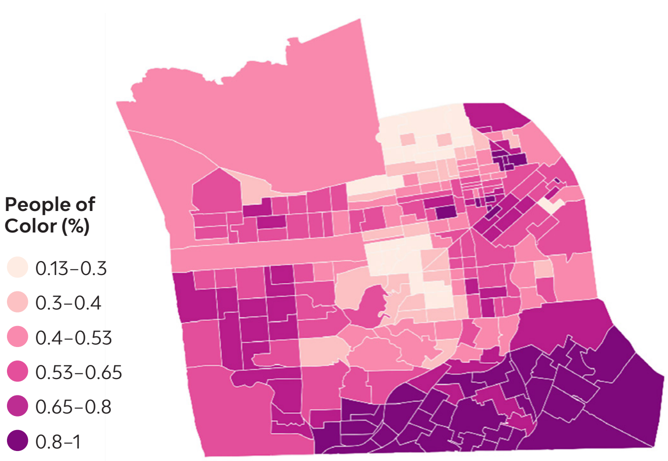


Figure 4
Sociodemographic Metrics: Low-income

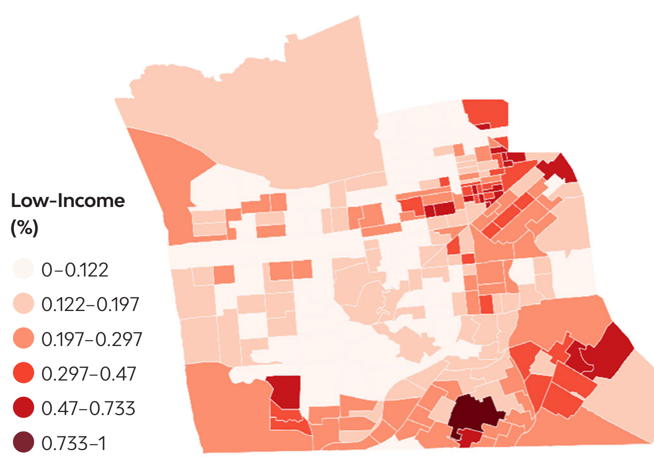
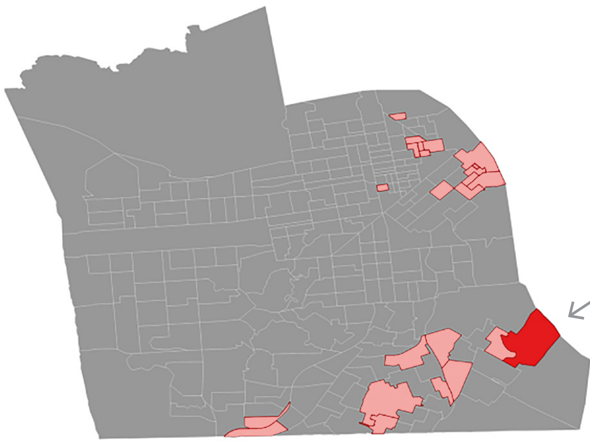


Figure 5

Priority Census Tracts in San Francisco.



Census Tract:	**6075023103**
Total Population:	**4,064**
BIPOC Households:	**100%**
Low-Income Households:	**70.6%**
$PM_{2.5}$ before:	**7.64 µg/m³**
$PM_{2.5}$ after:	**1.59 µg/m³**
Noise-Polluting trips before:	**99.75%**
Noise-polluting trips after:	**33.77%**

Note: These census tracts are of high priority as they have greater than average representation of low-income and BIPOC households. The callout box is an example census tract to illustrate the impact of scaled AV deployed tin the model.

yet these census tracts experience more noise pollution from traffic volume.

To gain a comprehensive understanding of the equity implications of SAV deployment, we conducted an in-depth analysis focusing on 24 census tracts comprising low-income and BIPOC (Black, Indigenous, and People of Color) households, which were prioritized for their equity considerations. Our study found that the equity priority census blocks demonstrated marked improvements in air and noise pollution factors with the presence of SAVs. $PM_{2.5}$ decreased on average by 50 percent, meaning these vulnerable communities are experiencing better air quality improvements compared to the city average. Vehicle ownership continued to decline, which may prove helpful for low-income households where car ownership is financially challenging. Finally, the equity priority census tracts were projected to experience a 40 percent decline in noise polluting trips, which is substantial compared to the 27 percent decrease found for the city average. Figure 5 serves as an example of one of the priority census tracts and the air and noise pollution outcomes. Since many of these communities are currently experiencing more air and noise pollution compared to other communities in the city, it is promising to see the air and noise pollution can be mitigated in areas with the greatest need through SAV presence.

CONCLUSION

In conclusion, this report highlights the transformative potential of Shared Autonomous Electric Vehicles (SAVs) in addressing environmental and equity challenges in urban transportation. SAVs, powered by electric batteries, offer a cleaner and more sustainable alternative to traditional internal combustion engine vehicles (ICEVs), significantly reducing greenhouse gas emissions and noise pollution. By optimizing traffic flow and reducing congestion, SAVs contribute to quieter urban environments, enhancing the overall quality of life for city residents.

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SAVs offer a promising pathway towards cleaner, quieter, and more equitable cities. By leveraging their innovative vehicle design, zero-emission capability, and efficient traffic management, SAVs can contribute to improved air and noise quality, enhancing public health outcomes for all residents. Policy recommendations based on this research can play a crucial role in shaping a future transportation system that prioritizes environmental sustainability and equity, while also addressing pressing urban challenges. As cities continue to grapple with air and noise pollution, the findings of this report provide valuable insights into the positive impact of SAVs, encouraging their widespread adoption to create a greener and more inclusive urban landscape.

The city of San Francisco serves as a case study for understanding the impact of transportation-related air and noise pollution and the mitigation effects from widescale AV deployment. Transportation, particularly fossil fuel-powered internal combustion engine vehicles, contributes to localized sources of pollution in the city, affecting air quality and noise levels. The high volume of traffic and major roadways in San Francisco result in elevated levels of pollutants and excessive noise, especially in residential areas. This noise and air pollution disrupts sleep patterns, increases stress levels, and impairs cognitive performance.

The results of the geospatial and sociodemographic analysis in San Francisco demonstrate the intersection of air and noise pollution with factors such as vehicle ownership, traffic volume, and $PM_{2.5}$ concentration levels. Certain census tracts in the city, particularly those with high percentages of people of color and low-income households, experience higher levels of air and noise pollution. These findings highlight the promising results, the adoption of Shared autonomous electric vehicles (SAVs) presents a promising solution. SAVs can contribute to substantial reductions in air and noise pollution through mechanisms such as the adoption of electric vehicles, improved vehicle utilization, transition to electric powertrains, and reduction in traffic congestion. By promoting sustainable transportation options, optimizing vehicle utilization, and integrating SAVs into well-designed transportation systems, significant environmental benefits can be achieved.

Addressing air and noise pollution in the context of AVs requires a comprehensive approach involving urban planning, traffic management, noise mitigation strategies, and the promotion of sustainable transportation. By considering the potential of SAVs to reduce air and noise pollution, policymakers can work towards creating healthier and more sustainable urban environments while ensuring equitable access to clean air and reduced noise levels for all residents.

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***SAFE** is a non-partisan, non-profit policy thought leadership organization dedicated to accelerating the real-world deployment of secure, resilient, and sustainable transportation and energy solutions of the United States, and its partners and allies, by shaping policies, perceptions and practices that create opportunity for all.*

*SAFE's **Autonomous Vehicle (AV) Initiative** develops policies to advance the adoption of evolving vehicle technologies that provide new opportunities for more energy efficient and accessible mobility options, greater roadway safety, economic growth, and increasing America's energy security.*

*Through its **Center for Automated Transportation Technology**, SAFE explores how to integrate AVs into existing transportation infrastructure by examining the barriers and benefits to wide-scale deployment and consumer adoption of Automated Driving Systems (ADS).*

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