Title
Simulating Life with Personally-Owned Autonomous Vehicles through a Naturalistic Experiment with Personal Drivers

Authors
Harb, Mustapha, PhD
Malik, Jai, PhD
Circella, Giovanni, PhD
et al.

Publication Date
2022-08-01

DOI
10.7922/G2WH2N96

RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Simulating Life with Personally-Owned Autonomous Vehicles through a Naturalistic Experiment with Personal Drivers

Mustapha Harb, Ph.D., Department of Civil and Environmental Engineering, University of California, Berkeley

Jai Malik, Ph.D., Institute of Transportation Studies, University of California, Davis

Giovanni Circella, Ph.D., Director, 3 Revolutions Future Mobility Program, Institute of Transportation Studies, University of California, Davis

Joan L. Walker, Ph.D., Professor, Department of Civil and Environmental Engineering, University of California, Berkeley

August 2022

UC DAVIS Institute of Transportation Studies

Berkeley Institute of Transportation Studies

Report No.: UC-ITS-2018-09 | DOI: 10.7922/G2WH2N96

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**
UC-ITS-2018-09	N/A	N/A

4. Title and Subtitle	**5. Report Date**
Simulating Life with Personally-Owned Autonomous Vehicles through a Naturalistic Experiment with Personal Drivers	August 2022
	6. Performing Organization Code ITS Berkeley, ITS-Davis

7. Author(s)	**8. Performing Organization Report No.**
Mustapha Harb, Ph.D., https://orcid.org/0000-0002-5469-1770 Jai Malik, Ph.D., https://orcid.org/0000-0002-7137-7302 Giovanni Circella, Ph.D., https://orcid.org/0000-0003-1832-396X Joan L. Walker, Ph.D., https://orcid.org/0000-0002-4407-0823	UCD-ITS-RR-22-20

9. Performing Organization Name and Address	**10. Work Unit No.**
Institute of Transportation Studies, Berkeley 109 McLaughlin Hall, MC1720, Berkeley, CA 94720-1720 Institute of Transportation Studies, Davis 1605 Tilia Street, Davis, CA 95616	N/A **11. Contract or Grant No.** UC-ITS-2018-09

12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
The University of California Institute of Transportation Studies www.ucits.org	Final Report (October 2018 – December 2019) **14. Sponsoring Agency Code** UC ITS

15. Supplementary Notes

DOI:10.7922/G2WH2N96

This report builds upon research that has been published in these articles:

Harb, M., Malik, J., Circella, G., & Walker, J. (2021). Glimpse of the Future: Simulating Life with Personally Owned Autonomous Vehicles and Their Implications on Travel Behaviors. *Transportation Research Record*. doi:10.1177/03611981211052543

Harb, M., Walker, J., Malik, J., & Circella, G. (2022). Estimating short-term travel demand models that incorporate personally owned autonomous vehicles. *Travel Behaviour and Society*. doi:10.1016/j.tbs.2021.10.008.

16. Abstract

Forty-three households in the Sacramento region representing diverse demographics, modal preferences, mobility barriers, and weekly vehicle miles traveled (VMT) were provided personal chauffeurs for one or two weeks to simulate travel behavior with a personally-owned, fully autonomous vehicle (AV). During the chauffeur week(s), the total number of trips increased on average by 25 percent, 85 percent of which were "zero-occupancy" (ZOV) trips (when the chauffeur is the only occupant). Average VMT for all households increased by 60 percent, over half of which came from ZOV trips. VMT increased most in households with mobility barriers and those with less auto-dependency but least in higher VMT households and families with children. Transit, ridehailing, biking, and walking trips dropped by 70 percent, 55 percent, 38 percent, and 10 percent, respectively. The results highlight how AVs can enhance mobility, but also adversely affect the transportation system.

17. Key Words	**18. Distribution Statement**
Travel behavior, vehicle miles of travel, autonomous vehicles, households, travel surveys	No restrictions.

19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	35	N/A

Form Dot F 1700.7 (8-72) Reproduction of completed page authorized

About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

Acknowledgments

This study was made possible with funding received by the University of California Institute of Transportation Studies from the State of California through the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1), the Alfred P. Sloan Foundation, and the 3 Revolutions Future Mobility Program of the University of California, Davis. The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project. The authors would like to thank Patricia Mokhtarian, Maximilian Auffhammer, and Michael Anderson for their contribution to the study design and data collection, and Mollie D'Agostino for the discussion of policy implications. They also thank all participants in a meeting of the advisory board for this project that helped shape the research. Finally, the authors thank Bruce Griesenbeck and Shengyi Gao from the Sacramento Area Council of Governments (SACOG) for providing the 2018 SACOG household travel diary dataset, for helping us recruit participants, and for providing feedback at all stages of the research.

Disclaimer

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Simulating Life with Personally-Owned Autonomous Vehicles through a Naturalistic Experiment with Personal Drivers

Mustapha Harb, Ph.D., Department of Civil and Environmental Engineering, University of California, Berkeley

Jai Malik, Ph.D., Institute of Transportation Studies, University of California, Davis

Giovanni Circella, Ph.D., Director, 3 Revolutions Future Mobility Program, Institute of Transportation Studies, University of California, Davis

Joan L. Walker, Ph.D., Professor, Department of Civil and Environmental Engineering, University of California, Berkeley

August 2022

UC DAVIS Institute of Transportation Studies

Berkeley Institute of Transportation Studies

Report No.: 10.2489 in | DOI: 10.7922/G2WH2N96

Table of Contents

Table of Contents

Executive Summary

Executive Summary

Autonomous vehicles with self-driving capabilities can have intense impacts on individuals and households' lifestyles, travel behaviors and activity organization, the most significant aspect being that the users of this new technology will be free to perform other tasks while traveling. Another piece is the vehicle's ability to operate without the driver's presence. As it can be imagined, this innovation will provide convenience and better mobility for many. The associated changes in travel choices will likely lead to increases in vehicle miles traveled that will have major implications for traffic congestion and pollution.

Efforts to estimate the extent of potential travel behavior changes have been imprecise to date. Researchers and planners have typically relied on surveys asking people how they would change their behavior in a hypothetical autonomous vehicle future, or adjustments to existing travel simulations to model the impact of autonomous vehicles. In this study, we use a new approach to understand the potential influence of autonomous vehicles on travel behavior by conducting a naturalistic experiment mimicking the effect of autonomous vehicle ownership. As part of the study, private chauffeurs were provided to 43 households in the Sacramento, California region for one or two weeks. The private chauffeurs served as an "autonomous" vehicle by taking over driving duties for the household. All households participating in this study were recruited among previous participants in the 2018 regional household travel survey (HHTS) from the Sacramento Area Council of Governments (SACOG). In the study, we attempted to recruit a diverse sample of households in terms of key socio-demographics, household composition, and average weekly vehicle miles traveled (VMT) of the household members, among other aspects. Some of the households were given a two-week chauffeur period to explore whether changes in travel behavior persist as the treatment period is extended. We tracked household travel prior to, during, and after the week(s) with access to the chauffeur service. Another non-chauffeur week of travel diary was also available for each household from the SACOG's 2018 household travel survey data.

Key Research Findings

The number of trips and vehicle miles traveled of the household members substantially increased with access to an "autonomous" vehicle, primarily due to zero-occupancy trips. During the chauffeur week(s), the total number of trips increased on average by 25 percent, 85 percent of which were "zero-occupancy" (ZOV) trips (when the chauffeur is the only occupant). Households participating in the study experienced a 60% increase in vehicle miles traveled. Over half of this increase was due to zero-occupancy vehicle trips in which the "autonomous" vehicle (i.e., chauffeur) was sent on errands or sent home to avoid parking fees after dropping off household members or other family or friends.

Participating households became more auto-dominant and shifted away from other modes. The introduction of the "autonomous" vehicle led to shifts away from virtually all other travel modes, with transit use experiencing the largest drop. Households used "autonomous" vehicle trips to replace transit use both for commuting and longer trips, such as between Sacramento and San Francisco (an approximately 90-mile distance). Households with an “autonomous” vehicle also walked, bicycled, and used ridehailing services less often, particularly if they had frequently used these modes before having access to the “autonomous” vehicle.

Access to an “autonomous” vehicle provided significant benefits to households with seniors and people with disabilities. Households with retirees experienced the largest increase in vehicle miles traveled (121%) of any cohort. Elderly participants and those with disabilities reported substantial lifestyle improvements through the use of the “autonomous” vehicle, with greater freedom to travel at night, take longer distance trips, and, for those who were formerly transit dependent, travel without being tied to a fixed transit schedule.

Households that had been driving the least prior to the study experienced the greatest percent increase in vehicle miles traveled during the study period. Households that were less auto-dependent were taking more non-motorized and transit trips prior to gaining access to the “autonomous” vehicle. The replacement of these trips by the “autonomous” vehicle led to large increases in vehicle miles traveled (102%). Relatedly, households that belonged to the lowest VMT category observed the highest percent increase in VMT (137%). For this group, which was dominated by single occupancy households and the elderly, the advantage of having an AV was manifested in the ability to live a more active lifestyle.

Household travel shifted from personal vehicles to the “autonomous” vehicle. Households with access to a personal vehicle in addition to the “autonomous” vehicle showed a marked shift in vehicle use. Miles traveled in the non-autonomous vehicle(s) dropped by 53% even as overall household vehicle miles traveled increased. This shift was even more pronounced in households without children whose schedules were likely more flexible. This result points to the potential for autonomous vehicle ownership to allow households to reduce the number of vehicles owned.

Policy Considerations

The study underscores the potential for autonomous vehicles to radically increase accessibility for some users, particularly the elderly, people with disabilities, and those with lower incomes. As regulators craft legislation, incentives, and pricing programs to address the externalities of the deployment of autonomous vehicles, they should consider flexibility or allowances for specific user groups such as seniors, low-income households, and people with disabilities that arguably have the most to gain from having access to an autonomous vehicle.

The study results also suggest that the deployment of autonomous vehicles could lead to a large increase in the use of private vehicles, in particular due to zero-occupancy trips and associated vehicle miles traveled. While these trips can benefit the vehicle owner, they may exacerbate congestion and increase emissions (if the vehicles are not zero-emission). Regulators should consider disincentives or limits on zero-occupancy trips. These policies will be more successful if implemented proactively, before the adoption of autonomous vehicles becomes widespread.

Contents

Introduction

While the development of autonomous vehicle (AV) technology is well underway, governments are lagging behind in terms of planning and legislation. Guerra (*1*) reviewed the regional transportation plan (RTP) of the 25 most populous U.S. major cities and found that only one included any mention of AVs. Interviewing planners at the 25 metropolitan planning agencies (MPOs), he found that two of the main reasons for the lack of inclusion of AVs in RTPs are that planners do not believe the impact of AVs will be profound and that the impacts are not certain enough to make credible planning efforts. Relatedly, Wong & Shaheen (*2*) looked at the actions taken by states across the U.S. in response to AVs and found that policymakers have primarily focused on safety, testing, and infrastructure. However, the potential changes in travel-related behaviors, which is a critical factor in the technology's impact on the transportation system, has not received enough attention. In this study, we seek to improve the understanding of the impact of AVs on travel behavior, and consequently the transportation system, helping policymakers to be proactive with their policies.

The literature indicates that *existing* implementations of partially automated features that ease the burden of driving but still require constant attention from the driver (i.e., levels 2 and 3 of vehicle automation) are leading to more travel (see e.g., (*3*)). Our focus is on levels 4 and 5, where the AVs can operate without human presence or intervention in some (level 4) or all (level 5) conditions. Such AVs have the potential to result in the most radical shifts in travel behavior, albeit they are not currently available commercially for individual use.

The two methods used in the literature to explore travel behavior shifts relevant to our study are based on either (i) the analysis of survey data and/or (ii) the application of microsimulation and travel demand modeling approaches. In survey studies, participants are usually asked to indicate their preferences, decisions, and potential shifts in their travel behavior under hypothetical AV future scenarios. On the other hand, for studies based on microsimulations, researchers modify existing transportation models to incorporate AV options and simulate an AV future. This requires making assumptions about changes in travel behavior caused by the technology. The two methods have been used to explore long-term changes in travel related behavior such as residential and work location choices and short-term changes such as daily activity patterns. For instance, simulation studies consistently find that the introduction of AVs will lead to an increase in vehicle miles traveled (VMT) (see e.g., (*4*, *5*)), the number of vehicle trips (see e.g., (*6*, *7*)), and the average trip length (see e.g., (*8*, *9*)). Moreover, the literature indicates that AV options will likely cannibalize transit ridership (e.g., (*10*, *11*)), largely due assumptions about the reduction of AV riders' value of time (VOT), which are backed by findings from survey studies (see e.g., (*12*, *13*)).

We contribute to this literature by quantifying potential changes in short-term activity patterns and travel behavior choices using an experimental approach that is different from the standard surveys or microsimulations described above. We build and expand on our previous pilot study in the San Francisco Bay Area (*14*), administering a naturalistic experiment that utilizes professional drivers ("chauffeurs") to simulate life with a personally-owned AV. Just like an AV, a personal chauffeur takes over driving duties and can be sent out to run errands. The goal of the experiment was to enable participants to experience the more salient features of an AV, namely the driverless feature, and observe directly how their daily travel and activities may change in an AV future. This allows the quantification of potential travel and activity shifts, which can then be compared to results in the literature based on different approaches. The results can also inform assumptions being made in AV-focused microsimulations. We were able to highlight aspects of travel behavior that have received relatively less attention, such as the proportion and patterns of zero occupancy vehicle (ZOV) trips (when the chauffeur is the only occupant) and the potential benefits to less mobile groups such as the elderly and mobility impaired.

The remainder of the paper is organized as follows: first we outline the methodology, describing the experimental design and data collection process. Then we present the key findings, followed by a discussion and analysis of the potential biases in the results. We conclude by discussing the policy implications and point to future research directions.

Methodology

Building on our previous, smaller 13-household pilot study in the San Francisco Bay Area (*14*), we carried out an expanded study of 43 households in the Sacramento region. All households participating in this study were recruited among previous participants in the 2018 regional household travel survey (HHTS) from the Sacramento Area Council of Governments (SACOG).

The flow of the experiment is illustrated in Figure 1. First, participants were screened, recruited, and brought onboard. Next, households began recording their detailed travel diary using a smartphone app and a vehicle tracking GPS device. During the first (control) week, travel diaries were recorded under status quo conditions (no AV). Then, households received one or two weeks of the chauffeur service. In total, 34 households received 60-hours of chauffeur service for one week and nine households received 60 hours per week for two weeks. The two-week chauffeur period was intended to explore whether changes in travel behavior persist as the treatment period is extended. After the chauffeur week(s), travel diaries were recorded for a second control week. Travel diaries were therefore recorded for the chauffeur week(s), one week before, and one week after. A third non-chauffeur week of travel diary was also available for each household from the SACOG's 2018 household travel survey data (*15*) and was used as an additional control week. An online survey was administered before and after the three to four weeks of travel tracking to collect data on demographics, regular travel, attitudes and intentions regarding AVs, and (post-chauffeur) reflections on the experiment. The experiment started in August 2019 and was concluded in the beginning of March 2020. Periods with major holidays were avoided in order to focus on typical travel patterns.

This study incorporated several improvements over the pilot study. First, to obtain a more diverse sample in terms of demographics, modal preferences, and mobility barriers, we partnered with the Sacramento Area Council of Governments, which provided access to their travel survey data from 2018 and allowed us to recruit participants among the respondents from the survey who had agreed to be contacted again for follow-up studies. Second, to examine the impact of the treatment period, some households received one week of the chauffeur service and some received two weeks. Third, all adult members of the household and all vehicles in the household were tracked. Finally, a more advanced phone tracking app (rMoves) was used in order to record trip purpose and vehicle occupancy and to distinguish between personal and shared modes.

The experiment quantifies changes in travel behavior under status quo policy and travel conditions. There was no attempt to simulate future (potential) policies that could influence travel behavior (such as eventual modifications in travel costs, or policies restricting access to certain types of AV use), although we do discuss the policy implications of the results at the end of this report.

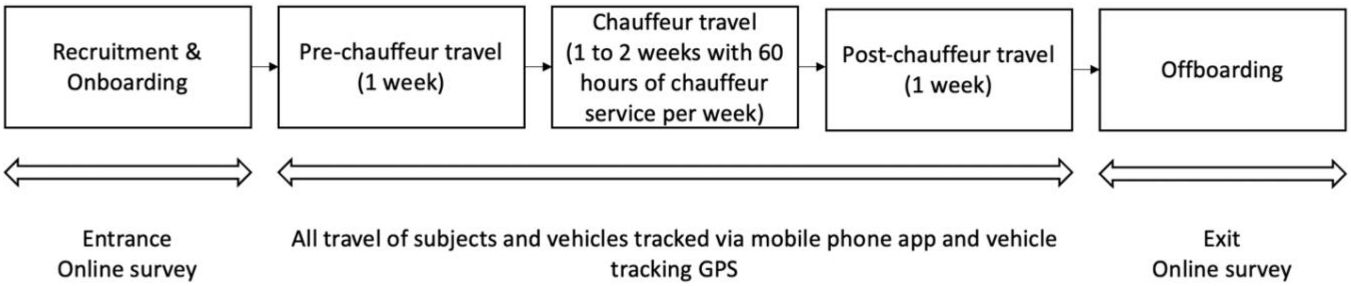

Figure 1. Flow of experiment and data collected

Sampling Strategy and Subject Recruitment

A wide array of dimensions related to household mobility and demographics were targeted in the sampling strategy. The sampling frame was the list of 4,010 households that participated in SACOG's 2018 household travel survey and agreed to be contacted for follow-up studies. This provided detailed demographic and travel diary data on which to draw the sample as well as a control travel week from the 2018 household travel survey for comparison. Vehicle ownership was a prerequisite to participate in the study. This group of potential participants was then stratified according to their household VMT, the amount of travel undertaken potentially reflects the general lifestyle and mode choices adopted by a household. Households were segmented by splitting the total VMT recorded in SACOG's household travel week into equal thirds: less than 127 miles, between 127 miles and 243 miles, and more than 243 miles. Within each of the three VMT levels, respondents were selected to obtain a diverse mix of participants based on demographics and lifestyles according to their household composition (non-family single and multiple occupancy, families with and without children, non-working elderly aged 60 and above), income, mode use, and residential location (urban, suburban, rural).

A total of 862 households were invited to participate in the study, and 50 households were successfully recruited. However, the experiment had to be cancelled for the last seven households due to the COVID-19 pandemic in early 2020, leaving us with a total sample of 43 households who completed the experiment. Households were recruited in the order of their response to the invitation while trying to maintain the diversity of the sample based on the demographic and travel characteristics highlighted above. Households interested in participating in the study took part in a 20–40-minute phone interview where we described the details of the experiment, what an AV is, and how a chauffeur can simulate owning one. They were informed that, during the chauffeur week(s), chauffeurs would take over driving duties of one household vehicle, and they could run errands that AVs will be able to perform. They would be provided 60 hours of chauffeur service per week that they could allocate based on their needs. The research budget was the limiting factor on the chauffeur hours provided, and 60 hours was determined based on experience from the pilot experiment. Hours were allocated by the household one week in advance and could be modified up to a day in advance (and even on the same day, based on the driver's availability). Households were asked to book all 60 hours even if they believed not all hours would be used to allow for spontaneous trips that were not pre-planned. However, detailed information on how many of the booked hours where in fact used was not recorded (as opposed to households sending the chauffeur home early since no trips were scheduled for the remainder of the day). Chauffeurs were assigned to a single household vehicle that was deemed the household "AV." Any "AV" trips, including lending the service to friends and family, were performed using the household "AV."

During the chauffeur week(s) households did not receive rides for "free;" even though participants did not pay for the professional driver service, they still paid for out-of-pocket costs they would incur in using their own household vehicle (and would be subject to the same comfort and other characteristics of that vehicle). Thus, this experiment simulates a future in which the driving task is replaced by the availability of automation, but costs remain similar to those of today in an AV future, including all marginal costs for parking, tolls, and gas, as well as the fixed costs of auto ownership. Implicit in the experiment is the assumption that AV costs will be comparable to conventional vehicle costs today. This assumption appears reasonable based on cost estimates in the literature (*16–18*), though the potential changes in future travel demand that could be associated with changes in those travel costs (including potential pricing policies) remains a topic for further consideration, which we briefly discuss in the policy implications portion of this paper, and could be a topic for future expansion of the research.

Data Collection

To understand changes in household travel behavior, we employed a detailed travel diary which tracked household members 18 years of age and older and all household vehicles. For vehicle tracking, the GPS device "Automatic" was installed on all household vehicles. All household vehicles were tracked in order to explore the changes in VMT for the entire household and the shift in vehicle usage between household vehicles (e.g., from other household vehicles to the "autonomous" vehicle) during the chauffeur week(s).

For tracking of the movement of household members, the GPS-based smartphone app "rMove" was used. This is the same app that was used for the SACOG household travel survey (see (*15*), for details). The app collected detailed information on every trip by passively collecting location information and nudging participants to answer a daily trip survey on mode choice, trip purpose, and the number of individuals traveling. All adult members in the household were asked to install the app on their phones. All adult members in 38 of the 43 households complied with this request. In the remaining five households, only one of the adult members installed the rMove app[1]. However, since all household vehicles were tracked, the household vehicle VMT for adults who did not install rMove was still captured. Moreover, since study participants were highly auto oriented (even more so for the households with a non-mobile phone tracked adult), the lack of rMove data for these adults does not significantly affect our conclusions.

[1] Four of the five households consisted of two adults, only one of whom installed the app. The last household consisted of a single parent, their two 18-year-old children, and two grandparents, where only the parent installed the app.

In addition to having household members install the rMove app, chauffeurs also installed the app and answered the survey questions for all trips made during their shifts, thus providing detailed information on trips where the chauffeur was the only individual in the car (identified herein as *zero occupancy vehicle*, or ZOV, trips).

Finally, to complement the travel diary data, participants filled entry and exit surveys that provided demographic information as well as information on lifestyle and perceptions of AVs that could help further explain changes in travel behavior. The exit survey had an extra section that asked participants about their "AV" experience during the experiment.

The average per household cost for a chauffeur week in this study was $2,500, almost double that of the pilot study ($1,400). The increase in cost was mainly due to the change in the chauffeur service provider (required by the University of California liability requirements), which increased the hourly cost from $20/hour in the earlier study (*14*) to $35/hour for this larger experiment. Tracking all household vehicles (requiring additional Automatic devices) and using the more comprehensive rMove app to collect a richer dataset also contributed to increased experiment costs.

Data Cleaning

With household vehicle data being recorded by Automatic and rMove, there were inconsistencies in some trips that had to be rectified. These were eliminated between the data sources by a process that (1) carefully investigated all trips recorded in order to add trips missed by one data source and captured by the other, (2) deleted trips made by chauffeurs using the household vehicle for purposes that were not related to the study (e.g., going on a break to grab lunch), and (3) combined data collected with the smartphone rMove data from the chauffeurs with those collected from the household members, namely adding "zero occupancy vehicle" trips and "friends and family" trips (see definition for the latter in the next section of this report).

Results

In this section, the key findings from the experiment are presented. Note these definitions that are used throughout:

- Primary (adult) household members are identified as all members who are at least 18 years old.
- Friends and family (FAF) are defined as household members that are younger than 18 or friends and family members that do not belong to the household (e.g., do not live in the same house as our participants).
- For every household, the travel behavior statistics that are reported are based on the changes in their travel behavior measures (e.g., VMT) between the chauffeur and non-chauffeur weeks. For instance, if a household traveled 100 and 120 miles in the first and second non-chauffeur week respectively, and 150 miles in the chauffeur week, then they traveled 150 – ((100+120)/2) = 40 more miles during the chauffeur week.
- All results are based on the sample and are not weighted to the population. (Discussed later in relation to self-selection bias.)

Sample Statistics

Table 1 summarizes the demographics of the population in the SACOG region, SACOG travel survey sample, the subset of vehicle owners in SACOG travel survey sample, households invited to participate in the study, and the final study participants. Summary statistics for all samples, except for the overall SACOG region and SACOG travel survey sample, are reported for car owners only, as this was a requirement for participating in the study.

Overall, the characteristics of the participating households are similar to those of the population in the SACOG region and HHTS respondents. The main difference is that our sample includes a higher proportion of females and is more educated and affluent. However, this was not the case for households invited to participate, indicating that these groups were more willing to participate in the study perhaps because they are more interested in the topic and had fewer reservation about the experiment and researchers. It is possible that these observable demographic characteristics might be correlated with other unobservable characteristics (e.g., lifestyles, attitudes towards the adoption of technology, and willingness to trust others), which influenced our decision not to weight the sample as discussed in more detail later in this report. We also note that, since investigating changes in mode choice was one of the primary objectives, households that rely on non-auto modes were oversampled. This is reflected by the (slightly) lower auto mode share and higher non-auto mode shares for the invited and participating samples compared to the remaining samples.

Table 1. Summary of the population demographics

	SACOG Region (*19*)	SACOG HHTS		Invited Sample	Study Sample
		Complete Dataset	Vehicle Owners		
Households	877,911	3,956	3,708	862	43
Persons	2,463,103	8,191	7,827	1,955	76
Gender					
Male	48.4%	45.3%	45.7%	46.7%	38.7%
Female	51.6%	54.7%	54.3%	53.3%	61.3%
Age					
Less than 34 yrs.	31.1%	24.5%	24.0%	30.7%	25.0%
35 yrs. to 54 yrs.	33.5%	31.5%	31.6%	38.1%	46.1%
More than 55 yrs.	35.4%	44.0%	44.3%	31.2%	28.9%
Race					
White alone	65.9%	71.7%	72.8%	71.1%	70.3%
Black or African American alone	6.8%	4.7%	4.0%	4.3%	6.3%
American Indian and Alaska Native alone	0.7%	2.3%	2.2%	2.0%	0.0%
Asian or Pacific Islander	13.8%	12.1%	12.2%	14.3%	18.8%
Some other race alone	6.4%	2.7%	2.7%	1.9%	0.0%
Two or more races	6.5%	6.4%	6.2%	6.5%	4.7%
Ethnicity					
Not Hispanic or Latino	78.0%	92.1%	92.2%	89.8%	92.1%
Hispanic or Latino	22.0%	7.9%	7.8%	10.2%	7.9%
Education					
Less Than Bachelors'	70.1%	66.4%	54.4%	50.2%	12.1%
Bachelors' or more	29.1%	33.6%	45.6%	49.8%	87.9%
Household Income					
Less than $75,000	54.6%	45.9%	43.3%	39.4%	25.6%
$75,000 - $150,000	29.4%	29.8%	31.5%	34.2%	41.0%
More than $150,000	15.9%	24.3%	25.2%	26.3%	33.3%
Vehicle Ownership					
No vehicle available	6.3%	6.3%	0.0%	0.0%	0.0%
1 vehicle available	31.2%	43.2%	46.1%	36.7%	39.5%
2 vehicles available or more	62.5%	50.5%	53.9%	63.3%	60.5%
Employment Status					
Employed	61.3%	66.4%	67.4%	24.6%	68.4%
Unemployed	38.7%	33.6%	32.6%	75.4%	31.6%
Household Size					
1-person household	25.2%	38.6%	36.3%	29.4%	23.3%
2-person household	33.1%	37.0%	38.4%	40.7%	44.2%
3 or more person household	41.7%	24.4%	25.3%	29.9%	32.6%
Number of household members under 18 yrs.					
One or more	33.7%	21.3%	22.1%	27.6%	27.9%
None	66.3%	78.7%	77.9%	72.4%	72.1%

	SACOG Region (*19*)	SACOG HHTS		Invited Sample	Study Sample
		Complete Dataset	Vehicle Owners		
Mode choice*					
Auto	-	84.1%	85.5%	81.1%	80.0%
Walk	-	11.5%	10.7%	12.9%	13.3%
Bike	-	2.8%	2.5%	3.9%	4.7%
Transit	-	1.6%	1.3%	2.1%	2.0%

** Mode choice for our sample was reported for the non-chauffeur weeks, while mode choice for the SACOG region was not reported since this information is only available for commute trips.*

Changes in Travel Behavior

Table 2 summarizes the quantitative results in terms of changes in average travel behavior due to simulating a personally-owned AVs from several sources: this experiment (in the first three columns), the previous pilot study (*14*) (in the fourth column), and the remaining literature (in columns 5 and 6). In the text that follows, we elaborate on the results from this experiment by discussing five general findings: findings 1-3 emphasize the average shifts in travel behavior observed in the sample as a whole, finding 4 investigates variation in travel behavior related to demographics and automobile availability, and finding 5 highlights evidence regarding potentially life-changing benefits of AVs for certain segments of society. Throughout, we draw on both the quantitative results from tracking the travel behavior as well as the insight gained from the more qualitative entry and exit surveys.

Table 2. Summary of results

	This Experiment			*Literature*		
	All trips	Excluding ZOV trips	Excluding ZOV & FAF trips	Pilot: (14)	Remaining Literature	Citations
Average change in VMT	+60% (0.00)	+33% (0.00)	+29% (0.00)	-	+1% to +79%	(4, 5, 20)
"AV" (chauffeur car) VMT change	+114%	+68%	+62%	+82%	-	(14)
% ZOV and FAF VMT of total VMT	20%	-	-	-	ZOVs account for 30% of vehicle trips	(6)
% ZOV and FAF VMT of induced VMT	54%	-	-	34%	-	(14)
Change in total miles traveled, by all modes	+44% (0.00)	+21% (0.01)	+17% (0.02)	-	-	-
Change in total number of trips, by all modes	+25% (0.00)	+3% (0.37)	0% (0.96)			
Change in average trip length (for household vehicles)	+14% (0.00)	+17% (0.00)	+18% (0.00)	-	+3% to +47%	(8, 21)
Change in number of vehicle trips	+39% (0.00)	+12% (0.02)	+8% (0.11)	+58%	+3% to +45%	(6, 14, 21)
Change in number of trips at night (after 6 pm)	+20% (0.07)	+5% (0.55)	+4% (0.64)	+88%	-	(14)
Change in 20+ mile trips	+75% (0.00)	+50% (0.00)	+45% (0.00)	+91%	-	(14)
Change in 50+ mile trips	+81% (0.02)	+40% (0.18)	+36% (0.22)	-	-	-
Change in transit mode share	-70% (0.03)	-	-	-	-9% to -70%	(22, 23)
Change in walking mode share	-10% (0.24)	-	-		-21%	(4)

Values in parentheses correspond to the p-value of a paired t-test that checks if the mean of the 43 households is equal during the chauffeur and non-chauffeur weeks

To check if the differences between the chauffeur and non-chauffeur weeks is statistically significant, paired t-tests were used to compare the means of the metric under study for all 43 households (p-values for that comparison are included in parentheses in the table). When all trips are considered, all differences are statistically significant at the five percent significance level, except for the difference in night trips which is significant at the 10 percent significance level, and the difference in walking mode share which is not statistically significant. However, when ZOV and FAF trips are excluded, the differences in the total number of trips via all modes, number of night trips, and number of trips over 50 miles become insignificant.

Finding 1: Overall, VMT increased by 60 percent (half of which came from ZOV trips) as did the number of trips: 39 percent more vehicle trips, 75 percent more trips between 20 and 50 miles, and 81 percent more trips longer than 50 miles.

The overall systemwide VMT increase during the chauffeur weeks was 60 percent, which includes all household vehicles trips as well as trips using non-household vehicles (e.g., Uber, car from work, friend's car). The increase ranged from a low of 3 percent for a family with no kids to a high of 700 percent for an elderly individual with another household member with a disability who usually commutes by transit.

ZOV and FAF trips made up 53.6 percent of the induced VMT (47.5 percent from ZOV and 6.1 percent from FAF trips). One source of ZOV trips was households switching their (commute) mode from transit or biking/walking to the "AV" and sending the car back home when parking was an issue. The majority of ZOV trips (66.4 percent) and ZOV miles (78 percent) were pick-ups and return home trips. Running errands made up 17 percent of ZOV trips and 13 percent and ZOV miles respectively. Shopping was the lowest use case for ZOVs (7 percent and 4 percent of ZOV trips and miles, respectively).

Similar to ZOV trips, picking up and dropping off friends and family members constituted most of the FAF trips (67 percent) and miles (71 percent). Moreover, driving friends and family to run errands ranked second in terms of FAF trip purposes (19 percent) and miles (14 percent). Only one of the 11 households with children in the household recorded any trips with their minor alone in the car with the chauffeur.

Along with VMT impacts, Table 2 also summarizes the key changes in activity patterns. Interestingly, during the chauffeur weeks, person trips only increased by 4 percent and miles by 21 percent, compared to 25 percent growth in system wide trips and 44 percent in miles (i.e., if ZOV trips are considered). Similarly, system wide, there was a 20 percent increase in evening trips (trips where the start or end time is after 6 pm), 76 percent more trips between 20 and 50 miles, and 81 percent more trips over 50 miles. However, if only person trips are considered (i.e., ZOV trips are excluded), these numbers drop to 5 percent, 50 percent and 61 percent respectively. These results indicate that ZOVs were a primary source of travel behavior change as they constituted the majority of the additional trips generated.

Moreover, during the chauffeur weeks, there was a 17 percent increase in the average length of person trips (1 mile) and a 23 percent (0.5 miles) increase in the median length, indicating a greater willingness to travel to farther locations. Looking at trip purpose, social and recreation trips had the lowest percent increase in the number of trips (5 percent), but the highest increase in the average trip length (46 percent), and these results are not affected by the exclusion of ZOVs. On the other hand, pick-up and drop-off trips had the highest percentage increase in number of trips (180 percent) and a 37 percent increase in average trip length. These numbers drop to 45 percent more trips and 35 percent longer average trips if ZOV trips are excluded.

The entry and exit surveys provide further insight into the changes in participants' travel behavior. Answers to the open-ended questions regarding their chauffeur experience, as well as questions regarding their opinions on AVs, revealed several factors that contributed to changes in the participants' travel behavior:

1) more relaxed travel, with 90 percent of respondents indicating that they would enjoy their travel more in an AV;
2) increased productivity during travel with 75 percent of participants indicating that their travel would be more productive in an AV;
3) time savings by sending out AVs to run errands with 91 percent of participants agreeing with the statement that they would be more productive during an average week if AVs can run errands for them;
4) traveling when tired or under the influence of alcohol, and
5) safety.

Finding 2: Households shifted their vehicle usage away from the non-AV household vehicles (53 percent decrease in VMT) and non-household vehicles (11 percent decrease in VMT) to the AV vehicle (114 percent increase in VMT), compared to the non-chauffer weeks.

During the chauffeur weeks, there was a shift away from non-household vehicles (e.g., ridehailing, car from work, friend's car, etc.) and more dependency on household vehicles. For household vehicles, VMT increased by 66 percent, while it decreased for non-household vehicles by 11 percent. Moreover, there was a 114 percent increase in VMT for the "AV" and a 53 percent drop in VMT for secondary vehicles, with some households completely forgoing the use of non-AV vehicles. This was possible because the chauffeur could autonomously shuttle between trips to serve multiple household members. Elderly persons and families without kids had a much higher drop in non-AV use (62 percent for both) as compared to families with kids (19 percent).

The shift in the usage of household vehicles indicates the potential reduction of car ownership in households where members can coordinate their schedules. In their exit survey, one subject indicated that this is how they envision their future: "We also only used one car the entire week as the chauffeur made it easier for both my husband and I to use the car separately during the day, therefore I would envision owning only one car instead of two if in the future we had a driverless car."

Finding 3: Participants shifted away from transit, ridehailing, biking, and walking trips which dropped by 71 percent, 58 percent, 37 percent, and 13 percent, respectively.

One of the most important questions regarding an AV future is the impact on mode choice. To address this, an effort was made to recruit multimodal households and detailed data were collected on mode choices. However, households in the study area were highly auto-oriented, which was reflected by their mode choice during the non-chauffeur weeks, where 80 percent of trips were auto-trips, and 13 percent were walking, five percent biking, and two percent transit trips.

During the chauffeur week, households became more auto oriented and shifted away from other modes. Transit suffered the most during the chauffeur week, with transit trips and miles dropping by 71 percent and 90 percent respectively. During the non-chauffeur weeks, there were mostly two types of transit trips taken by nine of the 43 households—work trips and long-distance trips (e.g., to San Francisco), both of which were substituted for AV trips. For AV work trips, the chauffeur was often sent back home to avoid parking which was scarce and expensive in downtown Sacramento. Similar to transit, ridehailing trips and miles dropped by 58 percent and 63 percent respectively. Since AVs combine the attractive features of a personal car (e.g., privacy) and a ridehailing trip (e.g., no parking concerns), the latter loses much of its appeal. The same trend is observed for biking, as the number of trips and miles biked dropped by 37 percent and 38 percent, respectively.

For walking, even though the overall number of trips and miles decreased by 13 percent and 17 percent respectively, the change was not uniform across households: in particular, 58 percent of households exhibited a decrease in walking miles (by an average of 42 percent), 28 percent exhibited an increase (by an average of 92 percent), and 14 percent did not record walking trips during the study. For households that decreased walking, the average weekly miles walked during a non-chauffeur week was eight miles, double that of households that increased their walking trips. Moreover, those that decreased their walking had a much higher increase in VMT (80 percent) compared to those who walked more (40 percent). This indicates that households that walk more are likely to substitute walking trips with AV trips.

Finding 4: Variations in travel behavior were observed by age, household structure, income, residential location type, prior level of VMT, and auto dependency.

Even though we had a relatively small sample, it was interesting to see how the response to the chauffeur service differed across multiple dimensions and lifestyles. During the chauffeur week, elderly participants had the highest increase in VMT (121 percent; 101 percent if ZOV trips are excluded) followed by single occupancy households (113 percent; 58 percent if ZOVs trips are excluded). However, single occupancy households had the highest increase in night trips (93 percent; 41 percent if ZOVs trips are excluded), trips between 20 and 50 miles (153 percent; 50 percent if ZOVs trips are excluded), and trips longer than 50 miles (500 percent; 300 percent if ZOVs trips are excluded). On the other hand, families with kids had, by far, the lowest increase in VMT (18 percent; 10 percent decrease if ZOV trips are excluded) perhaps as these households were the least flexible in terms of adjusting their schedule.

Looking at heterogeneity by VMT category on which the sample was stratified (i.e., the terciles as calculated from the SACOG survey data), households that traveled less than 127 miles per week had the highest percent increase in VMT (137 percent; 110 percent if ZOV trips are excluded). Those in the medium VMT category (between 127 and 243 miles per week had the next highest increase (93 percent; 52 percent if ZOV trips are excluded), and the high VMT category (more than 243 miles per week) had the lowest increase (27 percent; 5 percent if ZOV trips are excluded). This is reasonable as the lowest VMT category is the least active in terms of overall miles and VMT. For this group, which is dominated by the elderly and single occupancy households, the advantage of having an AV is manifested in the ability to live a more active lifestyle. On the other hand, households in the high VMT category (dominated by families with and without kids) already spend a significant portion of their day on the road (on average 74 miles per day during a non-chauffeur week), so there is less room to add more travel.

To explore income effects, the sample was split into 13 high-income households (>$150,000), 16 medium-income households ($75,000 - $150,000), and 10 low-income households (<$75,000). Four households declined to provide income information. Low-income households had the highest increase in VMT (63 percent; 28 percent if ZOV trips are excluded) followed by medium-income households (54 percent; 33 percent) and high-income households (36 percent; 13 percent). The results may be driven by the fact that the high-income category was dominated by six families with kids and four without kids leaving only one elderly household and two single-occupant households.

As for any effects from residential location, each household was assigned to one of three location types based on the California tract classification adopted by Salon (*24*): urban (combined urban and central city from the original study from Salon), suburban, rural (combined rural and rural-in-urban from Salon). Suburban residents had the highest increase in VMT (75 percent; 48 percent if ZOV trips are excluded), followed by rural residents (47 percent; 21 percent if ZOV trips are excluded) and urban residents (34 percent; 9 percent if ZOV trips are excluded).

Finally, the data were analyzed based on auto-dependency, classifying non-auto dependent households as those that relied on a non-auto mode for commuting or used non-auto modes for at least 15 percent of their trips. This applied to 21 (about half) of the households. The rest (22 households) where classified as auto dependent. There was a substantial difference between the two groups in terms of VMT and total mile traveled via all modes with non-auto dependent households increasing their VMT by 102 percent (68 percent if ZOV trips are excluded) and total miles traveled 70 percent (42 percent if ZOV trips are excluded) compared to a 27 percent increase in trips (7 percent if ZOV trips are excluded) and a 20 percent increase in miles (1 percent if ZOV trips are excluded) for auto dependent households. However, the difference in total number of trips added is less than 5 percent (27 percent and 23 percent for the two groups respectively and 5 percent and 2 percent respectively if ZOV trips are excluded). This further highlights the impact owning an AV will have on travel behavior, particularly for households that are multimodal. These households not only became more auto-oriented, but the average trip length also increased by 35 percent as they switched to AV trips whereas there was no change in the average trip length for auto dependent households.

Finding 5: The experiment underscores the potential life-changing benefits of AVs for the elderly and individuals with mobility barriers.

A benefit of AVs is their potential value for individuals with mobility barriers. In the entrance survey, five elderly individuals indicated that they have a condition or anxiety that limits how often or how long they can drive at night or on a highway. This was reflected in the fact that the elderly cohort had the highest percent increase in VMT (121 percent; 101 percent if ZOV trips are excluded). Moreover, the chauffeur service also gave this cohort the freedom to travel more at night (74 percent increase; 50 percent increase if ZOV trips are excluded) and on trips between 20 and 50 miles (165 percent; 218 percent if ZOV trips are excluded) and longer than 50 miles (267 percent increase; 167 percent if ZOV trips are excluded). Two days after starting the chauffeur service, one elderly participant emailed the research team to express her enthusiasm about the service: “I love the chauffeur service. I’ve already gone to two places I would never have driven to on my own and it’s been wonderful.” Similarly, in their exit survey, when asked, after participating in the experiment, how they believe their life will change when AVs are the norm, all the elderly participants shared one of three advantages of AVs—safety, the ability to explore new places, and going out at night:

- “I would be more inclined to go out at night as well as more distant locations.”
- “I like the idea of picking up out of town friends, doing an activity and returning them safely home.”
- “If I had a self-driving car, I would go more places, spend more time with friends, and participate in more activities. I often pass up opportunities now because I don’t feel comfortable driving in heavy traffic or at night or in unfamiliar places.”

Our sample also included a particularly interesting household consisting of an elderly member and another member with a disability that prevented them from driving a car. The chauffeur service opened up a new world for this household increasing their VMT by 700 percent. They also traveled more at night, making on average two evening trips during the chauffeur week compared to 0.5 trips in a non-chauffeur week. Similarly, they made an average of five trips longer than 20 miles and 1.5 trips longer than 50 miles during a chauffeur week, compared to 2.5 trips longer than 20 miles and no trips longer than 50 miles during a non-chauffeur week.

The elderly household member exhibited a similar behavior to other elderly participants described above and increased their VMT by about 350 percent. However, the service was particularly life changing for the individual with the disability who went from being a captive transit rider to having the freedom to travel anywhere and anytime via their personal car. During non-chauffeur weeks, the individual relied on transit for all trips (~200 miles per week), namely for commuting, and had virtually zero VMT. During the chauffeur weeks, they switched to traveling via their AV, cutting their one-hour commute by half and raising their VMT to about 350 miles per week. They also traveled 156 miles (via all modes) for social activities during an average chauffeur week compared to 74 miles for an average non-chauffeur week. To this individual, an important advantage of the AV was not being tied to the transit schedule. In their exit survey, they highlighted this by mentioning that an AV will change their lives by allowing them to “go more places and go at different times.”

It is challenging to objectively measure quality of life and how having access to an AV affects it. However, the increase in VMT, average trip length, and night trips highlight how AVs would allow retirees and individuals with mobility barriers the freedom to travel and explore new and farther locations, and at more flexible times of day without having to compromise their safety. These results, supported by participants’ exit survey responses highlighting the benefits of AVs, suggest that the greater accessibility provided by the chauffeur service (i.e., “AV”), could lead to an enhanced quality of life.

Discussion of Potential Biases

In this section, we discuss and analyze potential sources of bias in our results, especially in terms of observed increases in VMT, by examining responses from the exit survey (both closed and open-ended questions). Since our study was only designed to compare adopting an AV to current conditions, we do not consider any potential sources of bias that might to due to future changes to structural aspects of the transportation system (e.g., higher levels of congestion and introduction of other new technologies, modes, business models, and policies).

Sources of downward bias

Human Driver Instead of a Real AV

The impact of the presence of the chauffeur was pointed out by many participants in their exit surveys. In response to being asked "whether they would have used the car more often if it were a real AV," 70 percent of participants somewhat/strongly agreed, 23 percent somewhat/strongly disagreed, and 7 percent were neutral. In explaining their responses, 52 percent somewhat/strongly agreed that the presence of the chauffeur made them, or other passengers, feel uncomfortable. Some reported avoiding trips in an attempt to limit interactions with the driver or to avoid "inconveniencing" the driver. Others reported feeling guilty about ignoring the driver or uncomfortable having private conversations in their presence.

- "It was very hard NOT to become personally involved with the chauffeur, especially since mine was a young woman. I even canceled one late-night trip because I wanted her early the next morning."
- "I definitely decided not to use the service at night when I get home from work around 3:00 AM. I probably would have used the service for more tasks such as picking up small items from the store etc."
- "It [the chauffeur] just didn't seem like a self-driving car to me. I wasn't comfortable talking to other people in the car or on the phone about personal topics, which I do often."

It is interesting to note that while 70 percent of the participants believed they would have traveled more often if it were a real AV as compared to having the chauffeur, the literature indicates that people in the U.S. are still skeptical of AV technology (*25*). One reason for this discrepancy may be that the study participants tended to be AV enthusiasts. In response to the question whether they "can't wait for AVs to be available," 67 percent somewhat/strongly agreed with the statement, 22 percent were neutral, and only 11 percent somewhat/strongly disagreed. Another reason could be that the lack of trust in the technology is likely to influences the decision to purchase an AV, but not how often to use it once it is adopted. Further, awareness about AVs is still generally low in society. However, once individuals are exposed to the idea (as participants were in this study) they start elaborating the potential benefits they could get from this new technology, and how their use could be even higher in a real world with automated vehicles, compared to the experiment with the chauffeur.

The 60-hour Chauffeur Limit

Limiting the chauffeur service to 60-hours per week takes away from the spontaneity a true AV, a sentiment many participants highlighted. For example, some participants mentioned not being able to make spontaneous last-minute trips because they did not have the chauffeur booked.

- “I feel I would be more inclined to constantly run small errands using a self-driving car, i.e., picking up ice cream at the last minute etc.”
- “The time restriction may have impacted our results a little bit, only because with an active teenager and our busy lives it's hard to fully predict when we'll need access to a car.”
- “In a few instances, we sent the driver away only to realize we wanted to go somewhere shortly after.”

The Novelty Factor

The novelty factor can produce both upward and downward biases. In terms of downward bias (upward bias is discussed in the next section), there is a learning curve for getting used to using the chauffeur. In response to the statement “one (two) week(s) with a chauffeur was not enough to get into a routine and adjust to a life where I own a self-driving car,” 66 percent agreed/strongly agreed, 17 percent disagreed/strongly disagreed, and 17 percent were neutral.

- “I understand it had to be limited to one week, but it takes a couple of days to get used to it [the chauffeur service].”
- “A week wasn’t enough for me to feel like the chauffeur setup was an autonomous vehicle.”

Exclusion of Zero Vehicle Households from the Study

As owning at least one vehicle was a prerequisite to participation, the study did not include zero vehicle households. Therefore, we excluded those with limiting factors to car-ownership such as financial constraints or inability to drive. As participants with lower income or mobility impairments had among the highest increases in VMT, this may lead to an underestimate of the average VMT increase.

Sources of upward bias

Shifting Activities to the Chauffeur Week(s)

To ensure that any changes in travel behavior were the result of having a chauffeur during an otherwise typical week and not affected by scheduling the experiment to coincide with an unusual travel period, participants were asked to select a three-week (up to four-week) period with no special events such as holidays or extended travel. At the conclusion of the-experiment, the condition was tested using a Paired t-test and a Wilcoxon signed rank test (the non-parametric version of the Paired t-test) comparing the total miles traveled via all modes in the pre-chauffeur week and the post-chauffer week. The difference was not statistically significant (p-values of 0.33 and 0.15, respectively) and therefore the assumption of randomness was assumed to be valid.

Another potential bias is participants shifting activities from the non-chauffeur weeks to the chauffeur week. When asked directly if they "rescheduled some of my activities from the non-chauffeur weeks to the chauffeur week," 52 percent disagreed/strongly disagreed, 14 percent were neutral, and 34 percent agreed/strongly agreed. As the difference between the non-chauffeur weeks is not statistically significant, any shifts that did occur happened equally in drawing from the pre- and post-chauffeur weeks. Moreover, running the same hypothesis tests above but between the non-chauffeur weeks and the survey week from the 2018 SACOG survey, the difference was not statistically significant (p-values of 0.40 for the Paired t-test and 0.37 for the Wilcoxon signed rank test). This gives some confidence that, while one third of households stated they shifted activities to the chauffeur week, this did not have a significant impact on the change in VMT.

The Novelty Factor

The novelty factor may bias results upward as households have the unique opportunity of using a chauffeur service, thus opting to take advantage of it to the fullest: "I think I was trying to imagine ways to make use of the time that I otherwise wouldn't have done this week even if it were a self-driving car simply because I only had the service for one week." The novelty factor was investigated first by comparing effects on the one chauffeur versus two chauffeur week households and then by examining non-typical trips and extreme behavior.

If the novelty factor results in more travel, then one would expect participants who had one week of chauffeur service to have a higher per week increase in VMT compared to those who received two weeks (as two chauffeur week households can spread additional activities over the two weeks). Comparing the two treatment groups, households who received two weeks of the chauffeur service actually had a higher percent increase in VMT (80 percent) compared to the one-week households (56 percent). However, a confounding factor is that the two-week households were dominated by low VMT households. There is also evidence of a fading effect from the two-week chauffeur households, because six households decreased their VMT during the second week relative to the first (ranging from -6 percent to -55 percent), two households increased their VMT (by 15 percent and 44 percent), and one had virtually no change in VMT across weeks (-2 percent). That said, closer examination shows that the main difference between the two weeks comes primarily from a single outlier event (such as a trip to San Francisco). Outlier events for the sample as a whole is considered next.

An aspect of "taking advantage of the chauffeur service to the fullest" is making long-distance trips. While these trips will likely be more frequent during an AV era, perhaps not as frequent as observed in this sample. To explore the impact of "non-typical" trips, a sensitivity analysis on the increase in VMT was performed along several dimensions. Compared to the 60 percent overall increase in VMT, this figure drops to a 44 percent increase if trips that start or end outside the Sacramento region are excluded, and drops to 55 percent without trips longer than 50 miles, and to 47 percent by eliminating trips longer than 25 miles. These results indicate that at most one quarter of the overall increase in VMT is coming from "outlier" trips that may be driven by the nature of the experiment.

Extreme ZOV behaviors were also observed, including an 83-mile airport pickup at SFO, a 120-mile round trip package delivery, and a 45-mile round trip for food pickup. Excluding these extreme ZOV trips reduces the percentage of ZOV miles making up part of the total VMT from 18 percent to 16 percent. As the individual with the disability showed the highest percent increase in VMT and largest shift from transit to car, excluding this household from the analysis results in a total VMT increase of 56 percent (relative to 60 percent) and a reduction in transit mileage of 86 percent rather than 90 percent.

It cannot be determined whether the extreme behaviors outlined in this section were simply the result of the novelty factor or if these habits will persist in an AV future. Nevertheless, the sensitivity analysis indicated that even ignoring the more extreme responses the presence of the chauffer still resulted in substantial change in travel behavior.

Self-selection Bias (and Decision Not to Weight Results)

Since the participants in our study were not randomly selected from the general population, it is possible that their personal attitudes about driving, new technologies, etc. likely played a role in not only their choice to participate in the study, but also how they adjusted their behavior during the chauffeur week(s), both sources of "self-selection bias" which could potentially skew the outcome of the study, making it harder to generalize the results to the public at large. As noted in Table 1, our study sample included a higher proportion of individuals who are women, more educated, or more affluent compared to the general population of the Sacramento region. It is likely that these demographic factors are related to higher propensity to use AVs, such as more positive attitudes towards adopting new technologies and negative preferences for driving. This suggests that the study might overestimate the increase in VMT from AVs in the general population. However, these individuals would likely be among the first adopters of AVs, so their behaviors will likely drive the initial impacts of AVs in the future. For example, Daziano et al. (*26*) found that individuals with higher incomes and higher levels of education are more likely to be early adopters of AV technology. We observe such correlations in our sample, for example half of the participants who do *not* have a Bachelors' degree agreed with the statement that "*Learning how to use new technologies is often frustrating for me,*" whereas only 9 percent of the respondents who have a Bachelors' degree or higher education agreed with that statement. Similarly, half of the women agreed with the statement "*I'd usually rather have someone else (trustworthy) do the driving,*" whereas only one-fourth of men in the sample agreed with the statement.

There is, however, reason to believe that the correlation between sociodemographic characteristics and self-selection bias and behavioral change is spurious (or a partial correlation at best). For this reason, we do not attempt to weight our sample based on sociodemographic characteristics to generalize the results to the larger population, as this would assume the observed behaviors to be representative of those in the larger SACOG region—an assumption that is unlikely to hold for the reasons discussed above. In addition, our relatively small sample exacerbates the issue as applying weights would assume that a small number of households in our sample would be highly representative of their respective demographics.

Conclusion and Policy Implications

This study presents results from an experiment designed to explore potential changes in travel-related behaviors induced by personally-owned AVs. Life with an AV was simulated by providing participating households with a personal chauffeur that, like an AV, took over driving duties and could drive by itself. For our sample of 43 households in the Sacramento region, actual travel behavior changes were quantified, including changes in VMT, mode choice, participation in activities, and timing of activities. The results are summarized in Table 2 and discussed throughout this report. Here we shift the focus to policy implications, drawing on statistics generated from the study. A major caveat is that all these statistics are for this specific sample (not weighted for reasons explained above), however the numbers do provide helpful context regarding possible effects of more widespread adoption of AVs in the future among the population generally.

The experiment highlighted many of the potential changes that AVs may bring to society, and to travel demand in particular, with many of the participants in the experiment making substantial changes to their activity schedules and travel patterns. The study highlights potential social benefits that could derive from the deployment of privately-owned AVs such as improved access to places for those who have driving limitations, such as the elderly (demonstrated by the 150 percent increase in VMT among this group during the chauffeur week), but also potential drawbacks in terms of greater traffic congestion and more negative environmental impacts. Our study shows that, if personally-owned AVs are widely adopted without proper regulations to limit some of their negative externalities, this could lead to substantially increased car travel, as reflected by the 60 percent increase in the overall VMT recorded in the experiment during the chauffeur weeks (results in the highest range of previous estimates reported in the literature). Further, 70 percent of the respondents reported that their increase in car travel would have been even higher if real AVs were available, compared to the experimental settings with the chauffeur. This, together with the other potential biases affecting the results in the study (as discussed in the previous section), highlights how the very substantial increases in VMT measured in this study might even underestimate the true impacts of AVs on travel demand.

Other undesirable consequences of AV adoption could include switching away from public transit and active modes of travel and the extreme reliance on ZOVs (also known as “ghost” trips). The use of public transportation and active modes dropped significantly during the chauffeur week(s) as transit, biking, and walking trips decreased by 71 percent, 37 percent, and 13 percent respectively, partly due to participants’ ability to avoid the cost and hassle of parking by sending ZOVs home.

As rising fuel costs (and other operational costs) alone are not substantially lowering VMT, road user charges, or other policies will be required to reduce induced travel. These should be designed in a progressive and flexible way to curb specific components of VMT and travel demand, potentially based on location, time of day, congestion level and vehicle type. This might mean adopting pricing mechanisms prohibiting (or strongly limiting), empty “ghost” vehicle trips, at least in central, more congested locations, and when traffic congestion is high. This is critical as ZOVs made up half of the induced auto demand in this study. Such policies should be coordinated with incentives and fees to avoid mode shifts from public transit or active travel We recommend such policies should be combined with more accommodating policy frameworks for the mobility impaired to balance societal benefits while meeting environmental and transport efficiency goals. While this will lead to impacts on travel demand, as shown by the results from this study, it would allow redistribution of the benefits from increased mobility and accessibility among those that are currently most disadvantaged. It will continue to be critical to further understand how different groups of people will respond to the availability of AVs in crafting thoughtful policies that maintain an equitable transportation system and do not impose added burdens on underprivileged households.

Though this study has not explored the potential impacts on land use, AVs could encourage shifts in residential location, by reducing the travel burden on households, possibly leading toward further suburbanization. Accordingly, regional long-range planning will need to consider AV deployment in developing land use development and transportation strategies. Finally, state and federal agencies should consider these findings as they consider electric vehicle (EV) targets as a way to contain tailpipe emissions from AV deployment.

This study has shown the need for proactive regulations for future AV use, to mitigate the potentially large impacts on travel demand that could result from the deployment of privately-owned AVs. Changing people's behavior through legislation will take time as behavior change is slow, especially when faced with resistance from users and when involving medium/longer-term decisions such as vehicle purchase and the decision to eventually adopt an automated vehicle in the household.

Data from this study could be used to develop better travel demand models for use in urban microsimulators. This includes updating parameters related to auto preferences and values of time, reformulating inter-regional trip models, and developing new models for ZOV behavior. This study is uniquely positioned to inform such modeling and microsimulation studies with empirical data (revealed preferences). Insights gained from a naturalistic experiment such as conducted in this study can provide more realistic estimates of the travel behavior impacts associated with AV deployment than those obtained from studies based on stated preferences involving hypothetical scenarios. Hence, we believe this study does an important service to the transportation planning community, and it contributes to informing decision-makers in this field on how society can get ready for a future dominated by automated vehicles, whenever they become commercially available.

References

1. Guerra, E. Planning for Cars That Drive Themselves. *Journal of Planning Education and Research*, Vol. 36, No. 2, 2016, pp. 210–224. https://doi.org/10.1177/0739456X15613591.

2. Wong, A., and S. Shaheen. *Synthesis of State-Level Planning and Strategic Actions on Automated Vehicles: Lessons and Policy Guidance for California*. Sacramento, 2020.

3. Hardman, S., J. H. Lee, and G. Tal. How Do Drivers Use Automation? Insights from a Survey of Partially Automated Vehicle Owners in the United States. *Transportation Research Part A: Policy and Practice*, Vol. 129, 2019, pp. 246–256. https://doi.org/10.1016/j.tra.2019.08.008.

4. Childress, S., B. Nichols, B. Charlton, and S. Coe. Using an Activity-Based Model to Explore the Potential Impacts of Automated Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2493, No. 1, 2015, pp. 99–106. https://doi.org/10.3141/2493-11.

5. Taiebat, M., S. Stolper, and M. Xu. Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound. *Applied Energy*, Vol. 247, 2019, pp. 297–308. https://doi.org/10.1016/j.apenergy.2019.03.174.

6. Bernardin, V. L., T. Mansfield, B. Swanson, H. Sadrsadat, and S. Bindra. Scenario Modeling of Autonomous Vehicles with Trip-Based Models. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2673, No. 10, 2019, pp. 261–270. https://doi.org/10.1177/0361198119846478.

7. Vyas, G., P. Famili, P. Vovsha, D. Fay, A. Kulshrestha, G. Giaimo, and R. Anderson. Incorporating Features of Autonomous Vehicles in Activity-Based Travel Demand Model for Columbus, OH. *Transportation*, Vol. 46, No. 6, 2019, pp. 2081–2102. https://doi.org/10.1007/s11116-019-10030-w.

8. Auld, J., O. Verbas, M. Javanmardi, and A. Rousseau. Impact of Privately-Owned Level 4 CAV Technologies on Travel Demand and Energy. No. 130, 2018, pp. 914–919.

9. Thakur, P., R. Kinghorn, and R. Grace. Urban Form and Function in The Autonomous Era. *Australasian Transport Research Forum (ATRF), 38th, Melbourne, Victoria, Australia*.

10. Kröger, L., T. Kuhnimhof, and S. Trommer. Does Context Matter? A Comparative Study Modelling Autonomous Vehicle Impact on Travel Behaviour for Germany and the USA. *Transportation Research Part A: Policy and Practice*, Vol. 122, 2019, pp. 146–161. https://doi.org/10.1016/j.tra.2018.03.033.

11. World Economic Forum. *System Initiative on Shaping the Future of Mobility Reshaping Urban Mobility with Autonomous Vehicles Lessons from the City of Boston*. 2018.

12. Malokin, A., G. Circella, and P. L. Mokhtarian. How Do Activities Conducted While Commuting Influence Mode Choice? Using Revealed Preference Models to Inform Public Transportation Advantage and Autonomous Vehicle Scenarios. *Transportation Research Part A: Policy and Practice*, Vol. 124, 2019, pp. 82–114. https://doi.org/10.1016/j.tra.2018.12.015.

13. Zhong, H., W. Li, M. W. Burris, A. Talebpour, and K. C. Sinha. Will Autonomous Vehicles Change Auto Commuters' Value of Travel Time? *Transportation Research Part D: Transport and Environment*, Vol. 83, 2020, p. 102303. https://doi.org/10.1016/j.trd.2020.102303.

14. Harb, M., Y. Xiao, G. Circella, P. L. Mokhtarian, and J. L. Walker. Projecting Travelers into a World of Self-Driving Vehicles: Estimating Travel Behavior Implications via a Naturalistic Experiment. *Transportation*, Vol. 45, No. 6, 2018, pp. 1671–1685. https://doi.org/10.1007/s11116-018-9937-9.

15. SACOG. 2018 SACOG REGIONAL HOUSEHOLD TRAVEL SURVEY - Sacramento Area Council of Governments. https://www.sacog.org/post/2018-sacog-regional-household-travel-survey. Accessed Jun. 17, 2020.

16. Bösch, P. M., F. Becker, H. Becker, and K. W. Axhausen. Cost-Based Analysis of Autonomous Mobility Services. *Transport Policy*, Vol. 64, 2018, pp. 76–91. https://doi.org/10.1016/j.tranpol.2017.09.005.

17. Becker, H., F. Becker, R. Abe, S. Bekhor, P. F. Belgiawan, J. Compostella, E. Frazzoli, L. M. Fulton, D. Guggisberg Bicudo, K. Murthy Gurumurthy, D. A. Hensher, J. W. Joubert, K. M. Kockelman, L. Kröger, S. Le Vine, J. Malik, K. Marczuk, R. Ashari Nasution, J. Rich, A. Papu Carrone, D. Shen, Y. Shiftan, A. Tirachini, Y. Z. Wong, M. Zhang, P. M. Bösch, and K. W. Axhausen. Impact of Vehicle Automation and Electric Propulsion on Production Costs for Mobility Services Worldwide. *Transportation Research Part A: Policy and Practice*, Vol. 138, 2020, pp. 105–126. https://doi.org/10.1016/j.tra.2020.04.021.

18. Compostella, J., L. M. Fulton, R. De Kleine, H. C. Kim, and T. J. Wallington. Near- (2020) and Long-Term (2030–2035) Costs of Automated, Electrified, and Shared Mobility in the United States. *Transport Policy*, Vol. 85, 2020, pp. 54–66. https://doi.org/10.1016/j.tranpol.2019.10.001.

19. American Community Survey: U.S Census Bureau, (2018). Selected Demographic Characteristics, 2014-2018, American Community Survey 5-year Estimates. Retrieved on May, 2019 from http://fact finder2.census.gov/.

20. Auld, J., V. Sokolov, and T. S. Stephens. Analysis of the Effects of Connected–Automated Vehicle Technologies on Travel Demand. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2625, No. 1, 2017, pp. 1–8. https://doi.org/10.3141/2625-01.

21. Auld, J., O. Verbas, M. Javanmardi, and A. Rousseau. Impact of Privately-Owned Level 4 CAV Technologies on Travel Demand and Energy. Procedia Computer Science, Vol. 130, 2018, pp. 914–919.

22. Huang, Y., K. M. Kockelman, and N. Quarles. How Will Self-Driving Vehicles Affect U.S. Megaregion Traffic? The Case of the Texas Triangle. *Research in Transportation Economics*, Vol. 84, 2020, p. 101003. https://doi.org/10.1016/j.retrec.2020.101003.

23. Levin, M. W., and S. D. Boyles. Effects of Autonomous Vehicle Ownership on Trip, Mode, and Route Choice. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2493, No. 1, 2015, pp. 29–38. https://doi.org/10.3141/2493-04.

24. Salon, D. Heterogeneity in the Relationship between the Built Environment and Driving: Focus on Neighborhood Type and Travel Purpose. *Research in Transportation Economics*, Vol. 52, 2015, pp. 34–45. https://doi.org/10.1016/J.RETREC.2015.10.008.

25. Harb, M., A. Stathopoulos, Y. Shiftan, and J. L. Walker. What Do We (Not) Know about Our Future with Automated Vehicles? *Transportation Research Part C: Emerging Technologies*, Vol. 123, 2021, p. 102948. https://doi.org/10.1016/j.trc.2020.102948.

26. Daziano, R. A., M. Sarrias, and B. Leard. Are Consumers Willing to Pay to Let Cars Drive for Them? Analyzing Response to Autonomous Vehicles. *Transportation Research Part C: Emerging Technologies*, Vol. 78, 2017, pp. 150–164. https://doi.org/10.1016/j.trc.2017.03.003.