Title page

Estimating the Trip Generation Impacts of Autonomous Vehicles on Car Travel in Victoria, Australia

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ABSTRACT

Autonomous vehicles (AVs) potentially increase vehicle travel by reducing travel and parking costs and by providing improved mobility to those who are too young to drive or older people. The increase in vehicle travel could be generated by both trip diversion from other modes and entirely new trips. Existing studies however tend to overlook AVs' impacts on entirely new trips. There is a need to develop a methodology for estimating possible impacts of AVs on entirely new trips across all age groups. This paper explores the impacts of AVs on car trips using a case study of Victoria, Australia. A new methodology for estimating entirely new trips associated with AVs is proposed by measuring gaps in travel need at different life stages. Results show that AVs would increase daily trips by 4.14% on average. The 76+ age group would have the largest increase of 18.5%, followed by the 18-24 age group and the 12-17 age group with 14.6% and 11.1% respectively. If car occupancy remains constant in AV scenarios, entirely new trips and trip diversions from public transport and active modes would lead to a 7.31% increase in car trips. However increases in car travel are substantially magnified by reduced car occupancy rates, a trend evidenced throughout the world. Car occupancy would need to increase by at least 5.3% to 7.3% to keep car trips unchanged in AV scenarios.

Keywords: Autonomous vehicles; driverless; induced demand; car trips; life stages

Abstract = 229 words (limit = 250 words)

INTRODUCTION

Autonomous Vehicles (AVs), also called as automated or self-driving vehicles, are a potentially disruptive technology *(1-3)*, with claimed benefits such as crash reduction, reduced traffic congestion, enhanced productive use of travel time, fewer emissions, better fuel efficiency and parking benefits *(4-10)*. AV technology has rapidly advanced in recent years. Vehicles with some automation features such as automated braking and self-parking have already been available on the market. Google and many automakers plan to commercialise AVs by the end of this decade *(11)*. In the US, AV testing on roadways was legalised in four states and Washington DC as of 2014 *(12)*. In 2016, South Australia became the first state in Australia allowing AV testing on roadways *(13)*.

Recent surveys suggest a diverse pattern of public opinions on AVs where people have high expectations of the benefits of AVs such as crash reduction, but are highly concerned about equipment failure and hacking issues *(14-16)*. Apparently, it will take time for AVs to achieve a major market share. For example, Litman *(17)* used the adoption patterns of previous vehicle technologies to estimate that AVs will represent 10%-20% and then 20%-40% of the vehicle fleet by 2030 and 2040 respectively. Using a survey about preferences for connected and automated vehicle technologies in the US, Bansal and Kockelman *(18)* predicted that the share of fully AVs in 2045 would vary between 25% and 87%, depending on willingness to pay and technology prices.

Much is still unknown about the impacts of AVs on travel behaviour. Although AVs have been estimated to reduce travel times due to platooning *(19)*, these benefits may be offset if AVs also result in increases in car trips. AVs could increase vehicle travel by reducing travel and parking costs and by providing improved mobility to those who are too young to drive and older people *(7, 10, 20-23)*. The increase in vehicle travel may be generated by mode shift from public transport and active modes and by entirely new trips. However, existing travel demand modelling studies tend to overlook AVs' impacts on entirely new trips *(6, 24, 25)*. There is a need to develop a methodology for predicting possible impacts of AVs, including the generation of entirely new trips, across all age groups.

This paper aims to explore the impacts of AVs on car trips by age group using a case study of Victoria, Australia. A new method for estimating entirely new trips associated with AVs across all age groups is proposed. Mode shift from public transport and active modes such as walking and cycling are also considered. The remainder of this paper is structured as follows: a review of previous studies on travel behaviour impacts of AVs is presented in the next section. The methodology is then described, followed by results and discussion. This paper concludes with a summary of key findings.

LITERATURE REVIEW

AVs have great potential to reduce crashes, considering that the majority of crashes are attributed to driver errors, fatigue, alcohol, or drugs *(2, 7, 12)*. Since AVs are safer, it is expected that they will be able to travel with shorter gaps between vehicles. Thus, AVs will be able to utilise road and intersection capacity more efficiently *(3)*. It has been speculated that automated driving can reduce traffic congestion by up to 50%, and that connected vehicle technology would reduce this even further *(19)*. AVs are also expected to reduce parking costs as they can drop off passengers and self-park in cheaper locations *(17)*. Further, parking demand could be significantly reduced with shared autonomous vehicles (SAVs) *(5)*. AVs could also offer travellers a meaningful use of time, which is previously lost to driving in conventionally driven vehicles (CDVs) *(7, 10)*.

All these benefits are expected to have significant impact on travel behaviour. AVs could encourage longer distance travel and increase total vehicle kilometre travelled (VKT) by reducing travel and parking costs and by providing improved mobility to those who are too young to drive, older people, and the disabled *(7, 10, 20)*. The increase in VKT could be associated with trip diversions from public transport and active modes as well as entirely new trips. For example, multitasking ability when riding in AVs could be attributed to a one percentage point increases in driving alone and shared ride mode shares *(26)*. In addition, as SAVs could be used for feeder trips to public transport systems *(27)*, they may reduce the shares of active modes such as walking and cycling. SAVs however may increase VKT due to empty vehicle travel for relocation or passenger pick up *(5)*. On the other hand, safety benefits of AVs may also lead to improved cycling safety perceptions, which could potentially influence the use of bicycles, particularly among vulnerable groups *(28)*. AVs could also have impacts on mode choice for long distance travel *(29)*.

Several studies have estimated travel behaviour impacts of AVs by varying assumptions on AV market penetration rates and impacts on road capacity, value of time, and operating and parking costs. For example, Gucwa *(30)* used an activity-based model to estimate AVs' impact on VKT in the San Francisco Bay Area with different assumptions on road capacity and value of time. This study assumed there was no SAVs. It was found that changes in users' value of time has a significantly higher impact on VKT compared to changes in road capacity. Depending on assumptions on value of time, VKT could increase by between 8% and 24%. Using an activity-based model of Metro Atlanta, Kim et al. *(25)* tested AVs' travel impact with different scenarios based on the increase in road capacity, reduction in travel time disutility, reduction in vehicle operating cost, and reduction in parking cost. Results suggested that total daily vehicle trips could increase by between 0.8% and 2.6% while VKT could increase by between 4% and 24%. This study did not consider other potential impacts such as empty vehicle travel for self-parking and AV availability for non-driving groups and zero-car households, and changes in vehicle ownership. An agent-based simulation study for Lisbon, Portugal suggested that the increase in VKT could vary substantially depending on types of SAVs, penetration rate, and the availability of high capacity public transport *(24)*. For example, SAVs that can be shared by multiple passengers with and without high capacity public transport could lead to a 6% and 89% increase in VKT respectively.

Few studies have further considered AVs' travel behaviour impacts with assumptions on induced travel demand or entirely new trips associated with AVs. Childress et al. *(6)* investigated AVs' travel demand impacts using an activity-based model of Puget Sound region, Washington. Several scenarios were designed with regards to AV penetration rate, road capacity, value of time, operating and parking costs. When road capacity was assumed to increase by 30%, VKT could increase between 4% and 20%. In addition, transit and walk shares could be reduced by up to 9% and 21% respectively. In their model, slight increases in person trip rates were modelled with the reduction in actual and perceived travel time. In another study, Davidson and Spinoulas *(31)* used a stochastic simulation model to estimate AVs' travel demand impacts in Brisbane, Australia, with different assumptions on penetration rate, value of time, and operating costs. In this study, trip increase levels were assumed to be between 10 and 20%. Results indicated that VKT could increase by between 4% and 41%. In addition, the mode share for public transport could decrease by between 2% and 14% while walking and cycling could reduce by up to 11% when AV penetration rates are high.

Increased travel due to AVs is often estimated by quantifying AVs' improved mobility to those who are non-drivers, older people, and the disabled. For example, Harper et al. *(23)* assumed that with AVs, non-drivers aged 19 and above and drivers with travel restricted medical conditions would travel as much as those of the same age and healthy drivers. In addition, healthy older drivers were assumed to travel as much as the 19-64 population. Using data from the 2009 National Household Transportation Survey (NHTS), they predicted that increased travel demand from the non-driving younger people, older adults, and the disabled as a result of AVs could alone lead to a 12% increase in VKT in the US. Similarly, using a survey with information about reasons for not having a driver's license, Sivak and Schoettle *(22)* identified reasons that would be no longer applicable with AVs and estimated that VKT for young adults aged 18-39 could increase by 11% in the US. Investigating the distribution of daily driving distances by age with NHTS data, Wadud et al. *(21)* found a steady declining trend in driving between the age of 44 and 62 and argued that this trend represents a natural decline in driving. Thus, the gap between actual driving among those aged 62+ years and this natural declining trend, which is associated with declined driving abilities, could be filled by AVs. As a result, AVs could lead to a 2-10% increase in vehicle travel. It is noted that increased vehicle travel estimated in these studies may include a shift from car passenger, public transport, walking and cycling trips. Therefore, entirely new travel demand associated with AVs was not explicitly considered.

Overall, existing studies on AVs' travel behaviour effects tend to overlook their impacts on entirely new travel demand or new trips associated with improved mobility to young people and older people. It is essential to distinguish between increased vehicle travel from mode shift and from entirely new trips. There is a need to develop a method for estimating possible impacts of AVs on entirely new trips across all age groups.

METHOD

General assumptions

In this paper, AV scenarios are modelled with the base case (without AVs) obtained from Victorian Integrated Survey of Travel and Activity (VISTA) 2007-2010 data. With this base case selection, the analysis in this paper can ignore uncertainties associated with future traffic growth and infrastructure changes and hence focus on AVs' impacts. The following assumptions are made for AV scenarios:

- All cars are fully AVs with level 4 automation *(32)*. In addition, AVs are affordable.
- There is a pool of SAVs that do not require a driver's license to use.
- Children age 12-17 are legally able to use AVs unsupervised by adults.
- Conventional public transport systems still exist.

Car trip model

To investigate potential impacts of AVs on car trips, a car trip model is proposed. In the car trip model, the total daily car trips can be formulated as follows:

$$CT_{AV} = \frac{(CT_{base} + CPT_{base}) + NPT + \alpha_{pt}PT_{base}^{pt} + \alpha_{w\&c}PT_{base}^{w\&c}}{(1+\alpha_{occ})OCC_{base}} \tag{1}$$

where CT_{AV} = total daily car trips in AV scenarios, CT_{base} = total daily car trips (or total person trips as car driver) in the base case, CPT_{base} = total daily person trips as car passenger in the base case, NPT = entirely new daily person trips associated with AVs, PT^{pt}_{base} = total daily person trips by public transport in the base case, α_{pt} = percentage shift from public transport to AVs, $PT^{w\&c}_{base}$ = total daily person trips by walking and cycling in the base case, $\alpha_{w\&c}$ = percentage shift from walking and cycling to AVs, OCC_{base} = the average car occupancy rate in the base case (person/car), and α_{occ} = percentage change in the average car occupancy rate in AV scenarios compared to the base case.

The numerator in Eq. (1) represents the total daily person trips by AVs under the AV scenarios, which can be expressed as the sum of total person-car trips in the base case (car drivers and passengers in the base case would continue to use AVs), entirely new daily person trips due to the availability of AVs, and daily person trips shifted from public transport, and waking and cycling to AVs. Note that empty car trips for relocation or passenger pick-up are not considered as this paper only focuses on the travel behaviour impacts of people. The denominator shows the average car occupancy rate in the AV scenarios. Hence, the total daily car trips in AV scenarios is estimated as the total daily person trips by AVs divided by the average car occupancy rate. TABLE 1 summarises total daily person trips, trip rates, and mode shares in the base case, obtained from VISTA data. As the share of taxi and other trips are negligible, they are assumed to be constant and ignored in the analysis.

TABLE 1 Trip making and mode shares in the base case

Mode	Total daily person trips	Daily trip rate	Share
Car driver	8,187,221	1.53	51.0%
Car passenger	4,494,906	0.84	28.0%
Public transport	1,087,666	0.20	6.8%
Walking & Cycling	2,168,276	0.40	13.5%
Other (taxi and other trip)	119,862	0.02	0.7%
Total	16,057,931	3.00	100.0%

The percentage change in car trips due to AVs can therefore be expressed as follows:

$$\frac{CT_{AV} - CT_{Base}}{CT_{Base}} 100\% \tag{2}$$

As indicated in Eq. (1), four parameters are needed to estimate the impacts of AVs on car trips. To determine entirely new trips associated with AVs, an estimation method is proposed in the next section using actual travel patterns from VISTA data. In addition, different settings of mode shift from public transport and active modes, and average vehicle occupancy rates, are considered various AV scenarios.

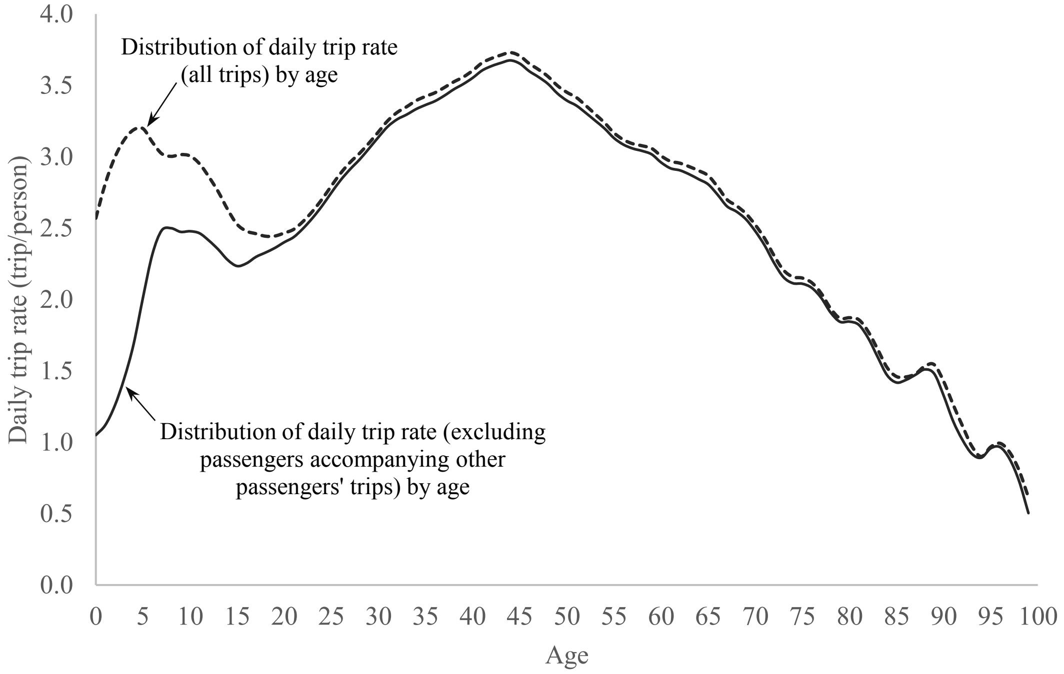
Estimates of entirely new trips associated with AVs

AVs may generate entirely new travel as they can fill gaps in travel need of road users at different life stages, such as those aged 12-17 who are too young to drive, those aged 18-24 who still do not have a driver's license *(33)*, or older people aged 65+ who have driving-restricted disabilities. In this analysis, seven life stages, ranging from infancy and childhood to late adulthood, are considered. Descriptions of life stages and corresponding driver's license rates obtained from VISTA data are presented in TABLE 2. License rate increases with age, peaks at the 30-65 age group with 94%, and then decreases after that.

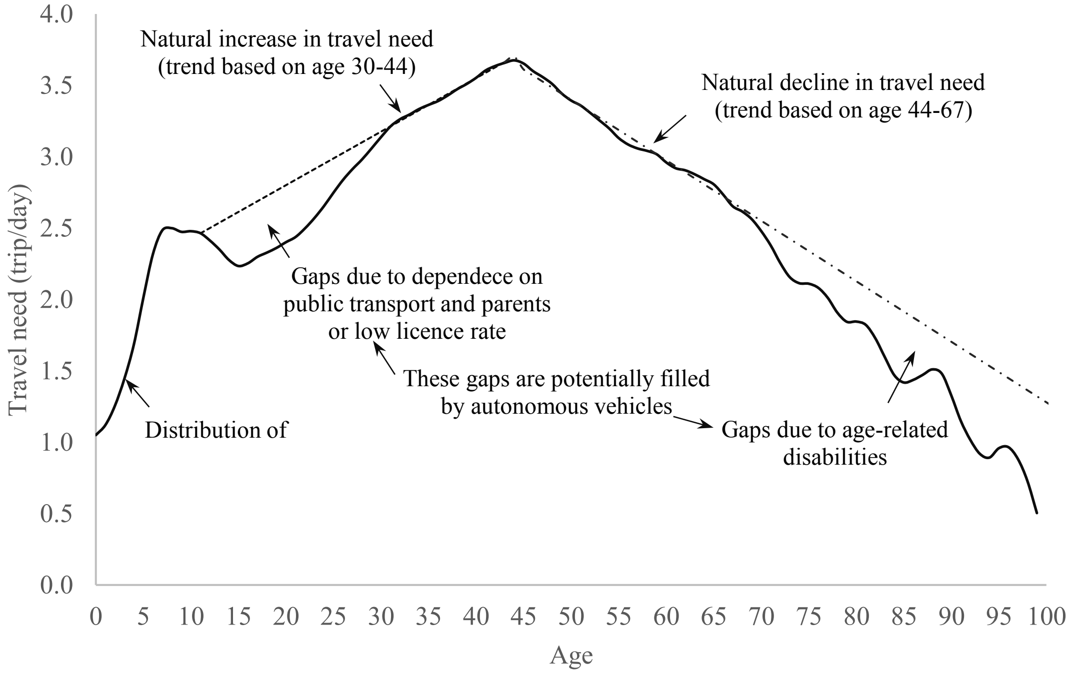
TABLE 2 Summary of Life Stages and Driver's License Rate

Age group	Life stage	Life stage description	Driver's license rate
0-11 years	Infancy & childhood	Up to end of primary school	0%
12-17 years	Adolescence	High school students	0%
18-24 years	Early adulthood	Workers and students	71%
25-29 years	Adulthood	Workers and parents with lower licence rates	85%
30-65 years	Adulthood	Workers and parents	94%
66-75 years	Mature adulthood	Retirees	87%
76+ years	Late adulthood	Elderly	68%

FIGURE 1a shows the distribution of daily trip rates by age obtained from VISTA data. Trip rates considering all modes and trip purposes among infants are surprisingly high with above 2.5 trips per day, which are even higher than trip rates among teenagers. An explanation is that infants tend to travel with their parents as they could not be left at home on their own, leading to passengers accompanying other passengers trips *(34)*. For example, a parent who drives a child to school also needs to bring his/her infant as a car passenger. As a result, the purpose of the infant's trip is to accompany passengers. Hence, this trip can be termed as a passenger accompanying another passenger's trip. Another example is that two children need to be dropped off at two different schools. The second child would undertake an accompanying trip as a car passenger before being dropped off at his/her school. Thus, the second child's trip to the first child's school is also a passengers accompanying other passengers' trip. It can be seen that although passengers accompanying other passengers' trips occur for all age groups, they are much more significant for young age groups. In fact, 36% and 12% of daily trips among the 0-11 and 12-17 age groups are passengers accompanying other passengers' trips respectively. These passengers accompanying other passengers' trips arguably should be excluded from actual travel need.



a) Distribution of daily trip rates by age



b) Distribution of travel need (daily trip rate excluding passengers accompanying other passengers' trips) by age and gaps in travel need to be filled by AVs

FIGURE 1 Distribution of trip rates by age and new trips generated by AVs

FIGURE 1b depicts the distribution of travel need, which is represented by daily trip rates excluding passengers accompanying other passengers' trips, by age. It shows that travel need increases considerably from newborn to seven years old and then levels off until 12 years old. After the age of 12, travel need slightly decreases until the age of 15 and then increases again after that. Travel need increases almost linearly between the ages of 30 and 44, then decreases steadily between the ages of 44 and 67, and decreases much faster after that. This finding is consistent with a previous study which also found that VKT per driver peaks at the age of 44 using NHTS data in the US *(21)*. Given a very high license rate for the 30-65 age group (94%), it is reasonable to assume that the increasing trend between the age of 30 and 44 represents a natural increase in travel need and the decreasing trend between the age of 44 and 67 represents a natural decline in travel need due to life stages.

Gaps in travel need for the 12-17 age group due to their dependence on public transport and parents, and for the 18-24 and 25-29 age groups due to low driver's license rates, can therefore be measured by the differences between the actual travel need curve and the linear extrapolation of the natural increase trend based on the 30-44 age group. Similarly, gaps in travel need for the 66-75 and 76+ age groups, due to low driver's license rates and age-related disabilities, can be measured by the differences between the actual travel need curve and the linear extrapolation of the natural decline trend based on the 44-67 age group. It is assumed that these gaps can be filled by AVs and SAVs, leading to entirely new trips. Travel need for the 0-11 age group is assumed to remain the same in AV scenarios.

Let α_i denote the percentage of entirely new trips among age group i, P_i denote the population of the age group i, and PT_{base} denote total daily person trips by all modes in the base case. The overall percentage of entirely new trips compared to PT_{base} is calculated as:

$$\alpha_{NPT} = \frac{\sum \alpha_i P_i}{\sum P_i} \tag{3}$$

Hence, entirely new daily person trips due to AVs can be estimated as follows:

$$NPT = \alpha_{NPT} PT_{base} \tag{4}$$

Mode shift to AVs

It is feasible that the benefits of AVs' might act to generate mode shifts from public transport and active modes to AV travel. For example, previous research has suggested that public transport and walking shares might decline by 9% and 21% respectively with a 30% increase in road capacity, 35% reduction in perceived travel time cost, and 50% reduction in parking cost *(6)*. In addition, public transport and walking and cycling shares is estimated to decrease by 14% and 11% respective if operating costs decrease by 50% and perceived travel time costs decrease by 10%-50% *(31)*. Based on the findings of these prior studies, this analysis assumes that up to 10% of travellers switch from walking and cycling to AVs ($\alpha_{w\&c}$ would be up to 10%).

This study also assumes that mode shift from public transport to AVs is influenced by the level of household car ownership. Public transport trips made by members of saturated-car households, where the motor vehicle count equals or exceeds the number of people of driving age (arbitrarily defined as 18-80), are unlikely to switch to AVs and therefore are assumed to continue making those trips by public transport. In addition, 10% of public transport trips made by members of limited-car households, where there are less motor vehicles than people of driving age, are assumed to switch to AVs. Finally, 20% of public transport trips by members of no car households are assumed to switch to AVs given the availability of affordable SAVs. Based on VISTA data, this would lead to an overall 4.18% decline in public transport share (α_{pt} would be up to 4.18%), which is within the range suggested in previous studies *(6, 31)*.

Car occupancy

There is much speculation in the research literature that AVs will encourage more sharing of cars. This theory is entirely in conflict with actual trends in sharing of cars in practice. Car occupancy rates on arterials and freeways in Melbourne have decreased by approximately 4% over the last 10 years *(35)*. FIGURE 2 suggests that the decline in car occupancy rates on arterials and freeways will tend to continue in future. Using VISTA data, the average car occupancy rate of Victoria's network in the base case (OCC_{base}) can be estimated as the sum of total daily person trips as driver and as car passenger divided by total daily person trip as drivers, which is 1.55 persons per car. The average car occupancy rate of the whole network can be assumed to follow the same decline pattern of car occupancy rate on arterials and freeways. Hence, by 2050, when AVs are predicted to have a major market share *(17)*, the average car occupancy rate would decrease by up to 16% to 1.30 persons per car. In AV scenarios, ride-sharing coupled with SAVs may lead to higher car occupancy rates, particularly among younger age groups. On the other hand, empty trips from relocation and passenger pickup of SAVs may reduce car occupancy rates. In this analysis therefore, various average car occupancy rates will be tested in AV scenarios, with the percentage change in the average car occupancy rate compared to the base case (α_{occ}) ranging between -16% and 10%.

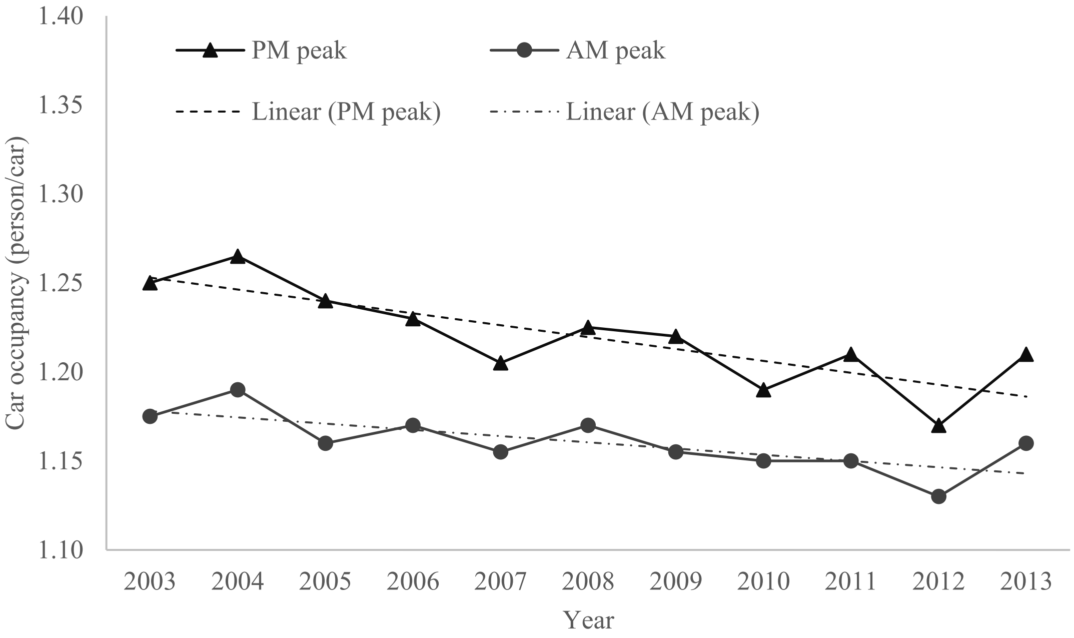


FIGURE 2 Car occupancy rates on arterials and freeways in Melbourne adopted from Vicroads *(35)*

Scenarios

Three sets of scenarios are designed to explore how AVs would affect car trips with variations in mode shifts and car occupancy rates. A summary of scenarios is presented in TABLE 3. The first set of scenarios considers impacts of entirely new trips, the second set additionally accounts for mode shift from public transport, and the third set further includes mode shift from walking and cycling. Given the uncertainty in car occupancy rates, all sets are investigated under various assumptions on car occupancy ranging from a reduction of 16% to an increase of 10%.

TABLE 3 Scenario Descriptions

Scenarios sets	Descriptions	Parameters		
		α_{pt}	$\alpha_{w\&c}$	α_{occ}
Set 1	AVs generate entirely new trips under various car occupancy rates	0%	0%	-16% to 10%
Set 2	AVs generate entirely new trips and shift from public transport under various car occupancy rates	4.18%	0%	-16% to 10%
Set 3	AVs generate entirely new trips and shifts from public transport and walking and cycling under various car occupancy rates	4.18%	10%	-16% to 10%

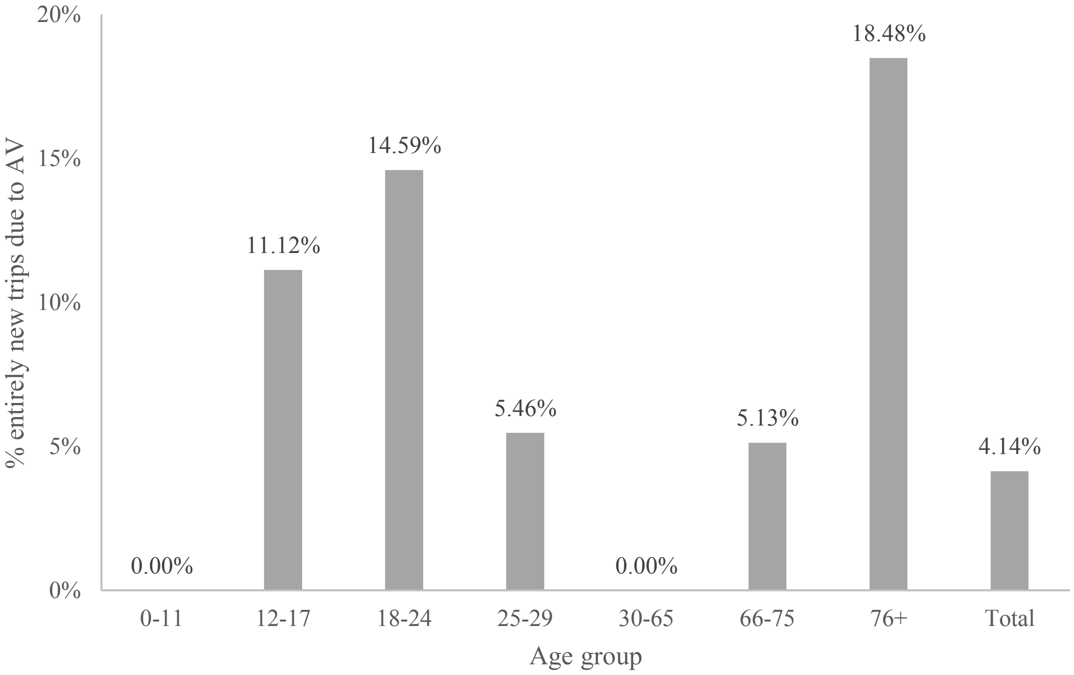
RESULTS AND DISCUSSION

Entirely new trips

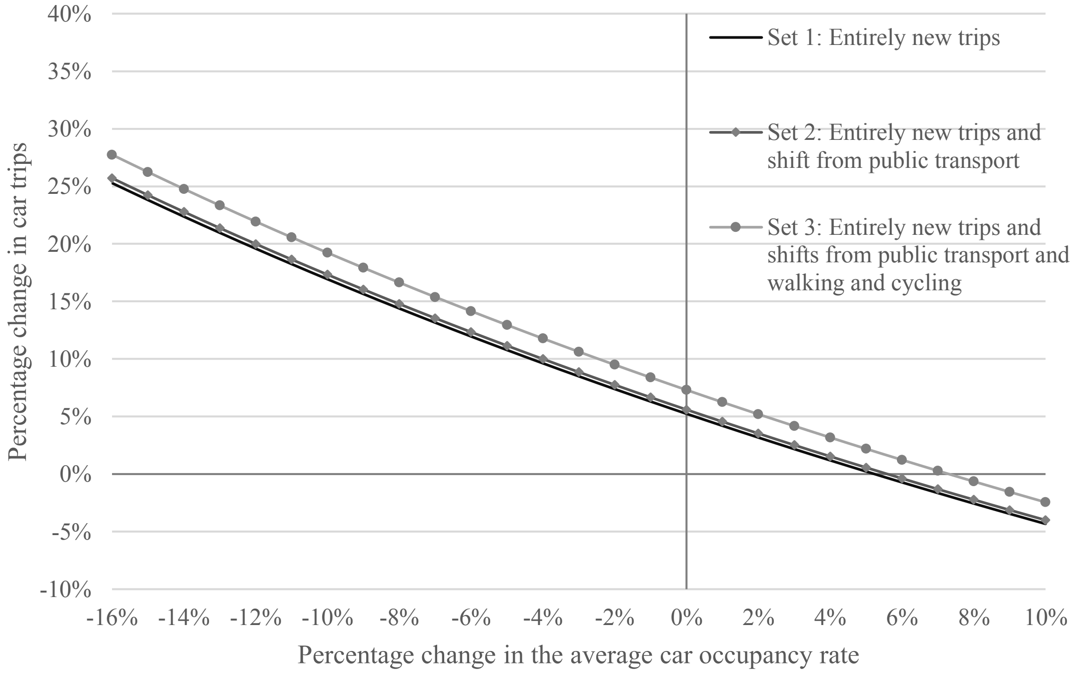
FIGURE 3a presents the percentage of entirely new trips generated by AVs compared to total daily trips in the base case by age group. The 76+ age group has the largest increase of 18.5%, followed by the 18-24 age group and the 12-17 age group with 14.6% and 11.1% respectively. The 25-29 and 66-75 age groups have much lower increases of around 5%, which could be attributed to their relatively higher license rates. Overall, AVs may lead to an increase of 4.14% in daily trips compared to the base case (α_{NPT} = 4.14%). The gaps in travel need among young people, particularly the 18-24 age group, are mainly associated with low driver's license rates and a lack of transport alternatives, especially in rural and regional areas *(33)*. A contributing factor to the decline in youth licensing could be the implementation of graduated driver licensing in Victoria *(36)*. Hence, the introduction of AVs would potentially fill these gaps, generating new trips.

Car trips

Percentage changes in car trips of various AV scenarios are summarised in FIGURE 3b. If the car occupancy rate remains unchanged, entirely new trips generated by AVs contribute to a 5.24% increase in car trips. Trip diversions from public transport and walking and cycling create 0.36% and 1.71% additional increases in car trips respectively. This suggests increased car travel in AV scenarios would be dominated by new trips rather than by mode shift. This can be explained by small shares of public transport and active modes in Victoria, which are 6.8% and 13.5% respectively. Even when AVs cannot attract mode shift from public transport and active modes, the improved mobility that AVs provide to those who are too young to drive, who do not have a driver's license and older people would still lead to a noticeable increase in car travel. Overall, this finding highlights the importance of exploring the increase in vehicle travel both from mode shift and from entirely new trips.



a) Percentage of entirely new daily trips generated by AVs compared to total daily trips in the base case by age group



b) Percentage change in car trips compared to the base case by various AV scenarios

FIGURE 3 Entirely new trips and car trips in AV scenarios

The impact of car occupancy on changes in car trips is clearly a major factor affecting AV travel. Car trips increase almost linearly with decreasing car occupancy rates. For example, if the average car occupancy rate is reduced by 16%, car trips increase by 25.29% if only entirely new trips associated with AVs is considered. In addition, car trips further increase by 0.43% and 2.04% if trip diversions from public transport and active modes are included respectively. Given the declining trend in car occupancy rates in Victoria plus possible empty trips related to AVs and SAVs' self-parking, relocation and passengers pick up, car occupancy is expected to decrease in future. Thus, it is likely that car trips would increase substantially as increased car travel due to AVs is magnified by reduced car occupancy rates.

Results also indicate that to keep car trips unchanged, the average car occupancy rate would need to increase by at least 5.3% to 7.3%, depending on whether only entirely new trips or both entirely new trips and mode shift are considered. Moreover, if the average car occupancy rate increases by 10%, car trips in AV scenarios would decrease by 2.5% to 4.3%. Increasing car occupancy in AV scenarios is however challenging even when SAVs are coupled with ride-sharing, considering associated empty trips that may occur due to self-parking, relocation, and passenger pick up activities. Overall, results show that a 1% increase in the average car occupancy rate would lead to 1.15% decrease in car trips on average. This suggests that investigations of ride-sharing behaviour and car occupancy rates are needed to provide a further understanding of AVs' impact on car travel.

CONCLUSIONS

This paper has explored the impacts of AVs on car trips using a case study of Victoria, Australia. A new method for estimating entirely new trips associated with AVs across all age groups was proposed. In the proposed method, entirely new trips are estimated by measuring gaps in the travel needs of road users at different life stages. Various AV scenarios were designed with mode shifts from public transport and active modes, and car occupancy rates.

Results showed that AVs would lead to an overall increase of 4.14% in daily trips in Victoria. The 76+ age group would have the largest increase of 18.5%, followed by the 18-24 age group and the 12-17 age group with 14.6% and 11.1% respectively. Providing that the car occupancy rate remains unchanged, entirely new trips generated by AVs could create a 5.24% increase in car trips. Car trips would increase by 7.31% if mode shifts from public transport and active modes to AVs are also included. Analysis showed that despite much speculation that AV's might encourage car sharing, actual trends show a decline in sharing of cars. Modelling results suggested that a 1% decrease in the average car occupancy rate would lead to an average of 1.15% increase in car trips. Hence, increases in AV travel will be significantly magnified by continued reductions in car occupancy rates that we consider likely in the future. The average car occupancy rate would need to increase by at least 5.3% to 7.3% so that car trips would not increase in the AV scenarios modelled. This is however challenging even with SAVs and ride-sharing due to associated empty trips and the decline in car occupancy rates in Victoria.

The analysis in this paper has been limited to AVs' impacts on car trips. AVs' possible impacts on VKT are also of importance, but have not been addressed in this paper. However, it is likely that the increase in car trips will also lead to more VKT. When estimating entirely new trips generated by AVs, possible new trips from those who have driving-restricted conditions among the 30-65 age group was not considered. This can be addressed in future work by assuming that they would travel with AVs as much as healthy drivers of same age. It can be argued that the natural decline in travel need for the 67+ age group could potentially be faster than the assumed linear relationship due to full retirement and physical and financial limitations. Thus, entirely new trips generated by AVs for this older age group could be lower than that estimated by this research.

This analysis made assumptions on mode shift due to AVs, which should be improved in future research by incorporating AVs' benefits into a behavioural framework. AVs' market penetration rate was strictly assumed to be 100% in this paper. However, lower market penetration rates could also be considered by scaling down the impacts of AVs on new trips and mode shifts accordingly. Potentially lower costs of AV travel in future could generate greater mode shift to AVs, compared to values assumed in the analysis based on previous studies. Benefits of AVs, such as increased road capacity, might further generate demand, in addition to filling the gaps in travel need. These factors should be considered in future research, in addition to empty AV trips and traffic growth. Nevertheless, this paper provides a new method to estimate entirely new trips generated by AVs and highlights the importance of car occupancy in understanding travel behaviour impacts of AVs.

REFERENCES

1. Morrow, W. R., Greenblatt, J. B., Sturges, A., Saxena, S., Gopal, A., Millstein, D., Shah, N., and Gilmore, E. A., Key Factors Influencing Autonomous Vehicles' Energy and Environmental Outcome, *Road Vehicle Automation*, G. Meyer and S. Beiker, eds.: Springer, 2014.
2. Fagnant, D. J., and Kockelman, K. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice,* Vol. 77, 2015, pp. 167-181.

3. Levinson, D. Climbing Mount Next: The Effects of Autonomous Vehicles on Society. *Minnesota Journal of Law Science and Technology,* Vol. 16, No. 2, 2015, pp. 787-809.
4. Greenblatt, J. B., and Saxena, S. Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nature Clim. Change,* Vol. 5, No. 9, 2015, pp. 860-863.
5. Fagnant, D. J., and Kockelman, K. M. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies,* Vol. 40, 2014, pp. 1-13.
6. Childress, S., Nichols, B., Charlton, B., and Coe, S. Using an Activity-Based Model to Explore the Potential Impacts of Automated Vehicles. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 2493, 2015, pp. 99-106.
7. KPMG. *Self-driving cars: The next revolution.* 2012.
8. Shladover, S. E. Cooperative (rather than autonomous) vehicle-highway automation systems. *IEEE Intelligent Transportation Systems Magazine,* Vol. 1, No. 1, 2009, pp. 10-19.
9. Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., and Pavone, M., Toward a systematic approach to the design and evaluation of automated mobility-on-demand systems: A case study in Singapore, *Road Vehicle Automation*, G. Meyer and S. Beiker, eds., pp. 229-245: Springer, 2014.
10. Heinrichs, D., and Cyganski, R. Automated Driving: How It Could Enter Our Cities and How This Might Affect Our Mobility Decisions. *disP - The Planning Review,* Vol. 51, No. 2, 2015, pp. 74-79.
11. Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L., and Walters, J. *Effects of Next-Generation Vehicles on Travel Demand and Highway Capacity.* FP Think, 2014.
12. Anderson, J. M., Kalra, N., Stanley, K. D., Paul Sorensen, Samaras, C., and Oluwatola, O. A. *Autonomous Vehicle Technology A Guide for Policymakers.* RAND Corporation, 2014.
13. DPTI. *SA becomes first Australian jurisdiction to allow on-road driverless car trials.* Department of Planning, Transport and Infrastructure, 2016.
14. Schoettle, B., and Sivak, M. *A Survey of Public Opinion about Autonomous and Self-driving Vehicles in the US, the UK, and Australia.* The University of Michigan, Transportation Research Institute, Ann Arbor, Michigan, 2014.
15. Kyriakidis, M., Happee, R., and de Winter, J. C. F. Public opinion on automated driving: Results of an international questionnaire among 5000 respondents. *Transportation Research Part F: Traffic Psychology and Behaviour,* Vol. 32, 2015, pp. 127-140.
16. Bansal, P., Kockelman, K. M., and Singh, A. Assessing public opinions of and interest in new vehicle technologies: An Austin perspective. *Transportation Research Part C: Emerging Technologies,* Vol. 67, 2016, pp. 1-14.
17. Litman, T. *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning.* Victoria Transport Policy Institute, 2015.
18. Bansal, P., and Kockelman, K. M. Forecasting Americans' Long-Term Adoption of Connected and Autonomous Vehicle Technologies. *Transportation Research Board 95th Annual Meeting*, Washington DC, 2016.
19. Hoogendoorn, R., Arem, B. v., and Hoogendoorn, S. Automated Driving, Traffic Flow Efficiency, and Human Factors. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 2422, 2014, pp. 113-120.
20. Guerra, E. Planning for Cars That Drive Themselves: Metropolitan Planning Organizations, Regional Transportation Plans, and Autonomous Vehicles. *Journal of Planning Education and Research,* Vol. 36, No. 2, 2016, pp. 210-224.
21. Wadud, Z., MacKenzie, D., and Leiby, P. Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice,* Vol. 86, 2016, pp. 1-18.
22. Sivak, M., and Schoettle, B. *Influence of current nondrivers on the amount of travel and trip patterns with self-driving vehicles.* The University of Michigan, Transportation Research Institute, Ann Arbor, Michigan, 2015.
23. Harper, C., Mangones, S., Hendrickson, C. T., and Samaras, C. Bounding the Potential Increases in Vehicles Miles Traveled for the Non-Driving and Elderly Populations and People with Travel-Restrictive Medical Conditions in an Automated Vehicle Environment. *Transportation Research Board 94th Annual Meeting*, Washington DC, 2015.
24. ITF. *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic.* International Transport Forum, 2015.
25. Kim, K., Rousseau, G., Freedman, J., and Nicholson, J. The Travel Impact of Autonomous Vehicles in Metro Atlanta through Activity-Based Modeling. *The 15th TRB National Transportation Planning Applications Conference*, 2015.

26. Malokin, A., Circella, G., and Mokhtarian, P. L. How Do Activities Conducted while Commuting Influence Mode Choice? Testing Public Transportation Advantage and Autonomous Vehicle Scenarios. *Transportation Research Board 94th Annual Meeting*, Washington DC, 2015.
27. Liang, X., Correia, G. H. d. A., and van Arem, B. Optimizing the service area and trip selection of an electric automated taxi system used for the last mile of train trips. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 93, 2016, pp. 115-129.
28. Milakis, D., Van Arem, B., and Van Wee, G. *Policy and society related implications of automated driving: a review of literature and directions for future research.* Delft University of Technology, 2015.
29. LaMondia, J. J., Fagnant, D. J., Qu, H., Barrett, J., and Kockelman, K. Long-Distance Travel Mode-Shifts Due to Automated Vehicles: A Statewide Mode-Shift Simulation Experiment and Travel Survey Analysis. *Transportation Research Board 95th Annual Meeting*, Washington DC, 2016.
30. Gucwa, M. The Mobility and Energy Impacts of Automated Cars. *Automated Vehicles Symposium*, San Francisco, CA, 2014.
31. Davidson, P., and Spinoulas, A. Autonomous vehicles: what could this mean for the future of transport? *Australian Institute of Traffic Planning and Management (AITPM) National Conference*, Brisbane, Queensland, 2015.
32. NHTSA. *U.S. Department of Transportation Releases Policy on Automated Vehicle Development.* National Highway Traffic Safety Administration, U.S. Department of Transportation, 2013.
33. Currie, G., Gammie, F., Waingold, C., Paterson, D., and Vandersar, D. *Rural and Regional Young People and Transport: Improving Access to Transport for Young People in Rural and Regional Australia.* National Youth Affairs Research Scheme, 2005.
34. Shaz, K., and Corpuz, G. Serving Passengers – Are You Being Served? *4th Annual PATREC Research Forum*, 2008.
35. Vicroads. *Traffic Monitor 2012-13.* VicRoads, 2015.
36. Delbosc, A., and Currie, G. Changing demographics and young adult driver license decline in Melbourne, Australia (1994–2009). *Transportation,* Vol. 41, No. 3, 2014, pp. 529-542.