Australasian Transport Research Forum 2016 Proceedings
16 November -18 November 2016, Melbourne, Australia
Publication website: http://www.atrf.info/papers/index.aspx

Urban form and function in the autonomous era

Praveen Thakur[1], Robert Kinghorn[1], Renan Grace[1]

[1]KPMG, 147 Collins Street Melbourne VIC 3000

Email for correspondence: thakurp@kpmg.com.au

Abstract

A new era in transport is imminent. A step change in transport technologies will change citizens' decisions about where to live, work and play, and how they move around. The 'autonomous era' will be shaped by two competing dynamics. Reduced perceived costs of travel are likely to encourage citizens to accept longer travel times, exacerbating the existing problems of congestion and urban sprawl. On the other hand, new autonomous ride-sourcing services may catalyse a move away from private vehicle ownership. This would increase the marginal cost of travel, encouraging urban consolidation and regeneration. The transport policy and infrastructure decisions we make now will affect the trajectory our cities take with respect to these dynamics. This paper uses a bespoke strategic Land Use and Transport Interaction (LUTI) model for Melbourne to explore the potential impacts of the autonomous era on transport infrastructure demand and urban form. Policy implications of the autonomous era are also considered.

1. Introduction

Fully autonomous vehicles are no longer simply a concept. Many of the world's largest companies, including Google, Apple, Tesla, Nissan and Ford are involved in a race to develop mass market autonomous vehicles (AVs) (InformationWeek, 2016). These technologies are likely to be available in the market by the early 2020s (Stoll, 2016; Lambert, 2016). Notwithstanding regulatory hurdles and the time lag for AVs to penetrate the existing vehicle fleet, AVs could plausibly be the dominant mode of transport in Australian cities within two to three decades. This timeframe falls within the current planning horizon for our cities and regions.

The literature on urban planning and economic geography suggests that urban areas have historically been shaped by transport accessibility (Hansen, 1959; McFadden, 1978; Waddell, 1996). Transport accessibility in turn is largely determined by the characteristics of the dominant mode of transport. Until the middle of the 19th century, urban form was dictated by walking travel time, leading to dense inner cores and mixed uses. From the 1860s, our cities expanded outwards along electric train and tram corridors creating the 'spider-web' urban form in industrial cities. The post war period led to the rise of the private car, and sprawling cities characterised by large plots in outer suburbs (Newman & Kenworthy, 1999).

In the same way that our cities were reshaped by railways and trams in the 19th century and the mass adoption of private cars in the mid-20th century; the rise of autonomous vehicles has the potential to shape our urban form in the 21st century and shift the role that transport infrastructure plays in our economy. By not considering these factors in our infrastructure planning and prioritisation processes, we risk sub-optimal allocation of infrastructure funding, potentially compromising the living standards of future generations.

Following this introductory section, the remainder of this paper is structured as follows:

- Section 2 summarises the literature of factors that affect urban form
- Section 3 considers the potential impacts of AVs on travel behaviour
- Section 4 considers the potential impacts of AVs on travel demand and urban form
- Section 5 summarises the key findings and presents a discussion and a set of recommendations to government.

2. What shapes cities?

Throughout history, the engine of social and economic development has been located in the dense inner cores of major cities. This can be partially explained by the theory of *agglomeration economies*, which posits that productivity growth is driven by positive externalities enabled by clustering of economic activity (Krugman, 1991). In addition, humans have a basic need for social interaction which is also facilitated by clustering of activities.

As a result, our cities are shaped predominantly by a general societal preference to live within a half hour commute from the inner cores of major cities (Newman & Kenworthy, 1999), a trend that has persisted throughout all of the major technological revolutions and is commonly known as Marchetti's constant (Marchetti, 1994).

As transport technology evolved and mobility increased, cities responded by increasing the distance and altering the spatial distribution in which economic and social activity orbits these centres.

Newman and Kenworthy (1999) identify three eras in the evolution of cities:

1) The ***Walking City.*** For most of human history, and until the middle of the 19th century, daily tasks were undertaken on foot. This led to urban activities being clustered within a 2.5 kilometre (30 minute walk) radius. Few areas retain these characteristics in Australian cities, with The Rocks in Sydney and the West End in Fremantle being rare examples.

2) The ***Transit City***. From the 1860s, urban activity pushed outwards along linear corridors as trains and trams became viable means of daily transport. This created smaller sub-centres around transit nodes, allowing people to live at lower densities and increasing the radius of cities to 10 or 15 kilometres. Melbourne's inner suburbs retain this characteristic to some extent, with economic and social activity concentrating linearly along tram corridors.

3) The ***Automobile City***. From around the time of the World War II, the rise of the private car led to new possibilities for urban development. First, the areas between linear transit corridors were developed, followed by the outward expansion of the city boundaries. With new freeway corridors, city radii was able to extend up to 50 kilometres, and activities were able to disperse and segregate throughout the enlarged urban area. This dynamic has defined the character of Australian cities as we know them today.

As we move deeper into the 21st century, a new era in transport is imminent. The introduction of AVs has the potential to catalyse a transition into what we refer to as the *autonomous era*. Where previous shifts were enabled by increases in the speed and scope of daily travel, the coming era will be shaped by changes in the perceived marginal cost of travel and changes in car ownership norms induced by the availability of AVs.

3. Effects of AVs on travel behaviour

This paper identifies two key impacts that AVs are likely to have on travel behaviour:

1) A willingness to accept longer travel times.
2) A shift from the existing norm of private vehicle ownership to the use of autonomous ride-sourcing services for daily travel.

3.1 Willingness to accept longer travel times

Travel demand is principally a derived demand, and is therefore contingent on demand for access to activities. As such, travellers weigh up the perceived benefit of participating in an activity against the perceived costs of travel to access that activity. Benefits of a trip may include wages for a commuting trip, enjoyment for a social trip or any other perceived benefits derived from participating in activities. For a trip undertaken by private car, the major perceived cost is the travellers' time. Travellers also perceive the cost of fuel. For each half hour of private travel, a typical traveller perceives approximately $7.80 of travel time cost[1] and $2.10 of fuel cost[2].

AVs have the potential to improve travel times in cities by increasing the capacity of urban roadways through "shorter headways, coordinated platoons, and more efficient route choices" (Eno Centre for Transportation, 2013). However, these benefits are expected to occur largely on freeways, and are likely to be partly eroded by induced demand as users take advantage of increased roadway capacity and make more frequent and/or longer trips. In addition, research has shown that AVs in mixed traffic can actually reduce the capacity of intersections if occupants choose low acceleration and deceleration settings for passenger comfort (Le Vine, et al., 2015). As such, the impacts that AVs will have on urban travel times is uncertain.

However, AVs may impact the willingness of consumers to accept longer travel times by reducing the typical value of travel time savings (VTT) for road users. VTT refers to a traveller's willingness to pay to avoid a given duration of travel and represents how aversive a trip is. For example, an uncomfortable or inconvenient trip (eg. walking in heavy rain) would attract a high VTT. Conversely, a comfortable trip (eg. in the back of a chauffeured car) would attract a lower VTT.

The introduction of autonomous vehicles is likely to reduce the VTT for a typical traveller. This is because riding in AVs is more comfortable and convenient than having to focus on driving. AVs free up travellers to converse with each other, sleep, read or use mobile devices or computers. Due to the increased comfort and convenience of AVs, travellers may be willing to accept longer travel times. As a result, urban residents with a low VTT may choose to make more frequent and/or longer trips, and may choose to live further away from major centres than would otherwise be the case.

3.1.1 Potential quantum of impact

The extent of VTT reductions that may be attributable to AVs remains unknown. This paper assumes that VTT could reduce by up to 50% for AV road users. This is equivalent to assuming that people will accept up to double the travel time in an AV relative to today's technology.

3.2 Shift to autonomous ride-sourcing for daily travel

As noted in the previous section, travellers typically perceive time and fuel costs when considering trip-making decisions. While other costs are incurred, including finance, depreciation, registration, insurance, tyres and maintenance costs, these are not typically perceived by the user on a per trip basis. Rather, they are perceived as 'sunk' costs associated with the decision to own a private vehicle.

For taxi or ride-sourcing trips, users perceive the costs of their own time as well as a fare set by the operator. This fare includes all associated costs, including the sunk costs noted above, as well as administration/IT costs, a profit margin, the driver's time as well as relevant regulatory costs and taxes such as taxi licence fees and GST. The marginal cost of using taxis or shared cars is therefore greater than the marginal cost of using private vehicles. The share of travel undertaken by taxi in Australian cities in turn is low, with taxis predominantly used for high-value business trips, airport trips or attending social events (DEDJTR, 2016)[3].

---

[1] Assuming a private value of time of 40% of Average Weekly Earnings (AWE) (Transport and Infrastructure Council, 2014), Full Time Adult Ordinary Time Earnings (Victoria) of $1481.60 in November 2015 dollars (ABS, 2016) and a 38 hour work week.
[2] Based on the RACV car owning and operating costs guide (RACV, 2015), medium car, Toyota Camry Atara S, fuel cost of 10.49 cents per km with an assumed trip length of 20 km and an average speed of 40 km/h.
[3] Based on an analysis of taxi trip purposes using Victorian Integrated Survey of Travel and Activity (VISTA) data.

Driver earnings and other driver costs account for more than 50% of a fare paid by taxi passengers in New South Wales (CIE, 2012)[4]. Removing the costs of drivers from a taxi or ride-sourcing[5] fare has the potential to bring the annual cost of ride-sourcing for daily travel below the annual cost of owning a private vehicle for most urban residents.

In the event that a significant proportion of urban residents were to abandon car ownership and shift to using ride-sourced AVs, fares could fall even further due to efficiencies associated with greater utilisation of the fleet, and further still if consumers were inclined to take advantage of discounted fares in exchange for allowing the ride-sourced vehicle to pick up other customers en route (i.e. car-pooling).

If this scenario were to eventuate, the total annual cost of travel would decrease, but the perceived cost on a per trip basis would *increase*, as full operating costs of travel (and a profit margin) become perceived by users on a per trip basis in the form of a ride-sourced AV fare. This is demonstrated in the following section.

3.2.1 Potential quantum of impact

The future cost to users of ride-sourced AVs is dependent on a number of factors, many of which are subject to considerable uncertainty. Select factors include take-up rate, regulations, taxes, registration and insurance costs, road pricing, energy prices and business operating models. For the purposes of this paper, we assume a widespread take-up and related economies of scale to demonstrate the potential impact of ride-sourced AVs.

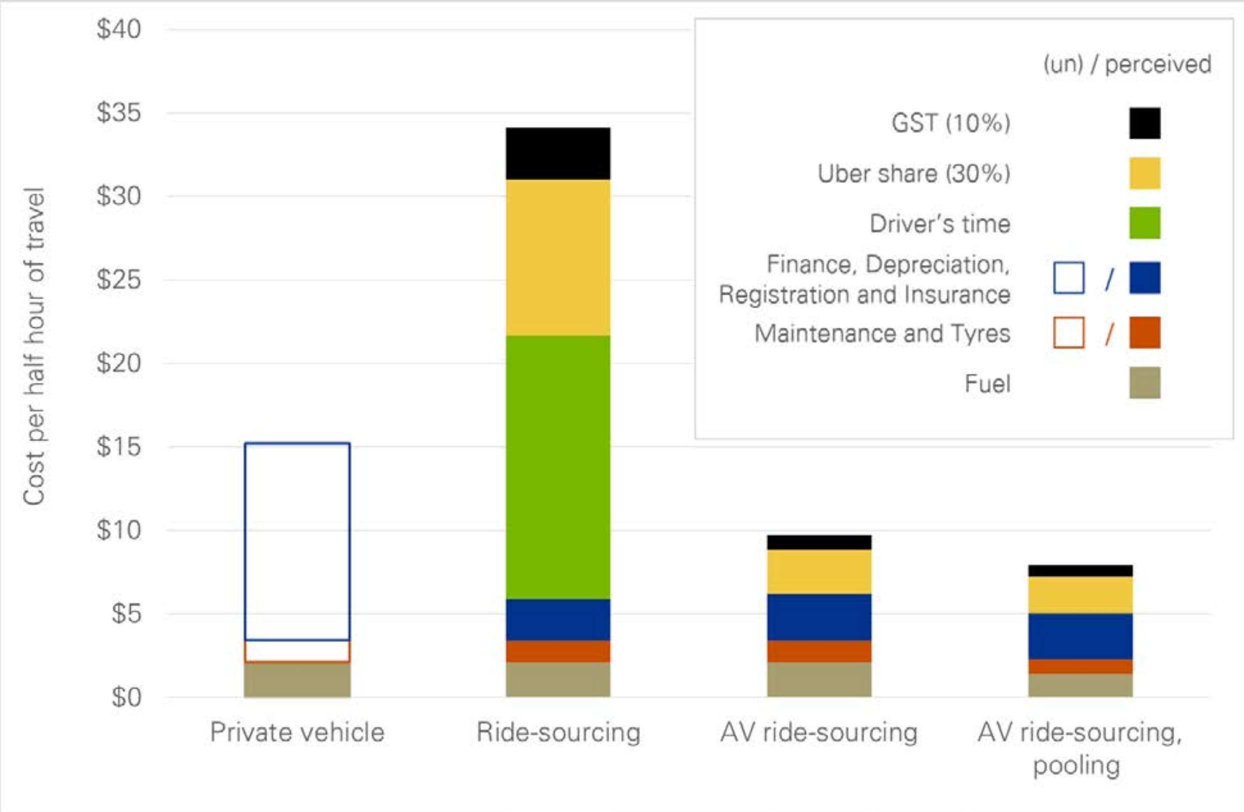
A comparative analysis was undertaken to assess the vehicle operating cost (VOC) of owning a single private vehicle against the cost of using a ride-sourcing AV service (i.e. the potential fares for these services). Costs are estimated on an annual basis and represented as the average cost per half hour of travel. Driver costs are estimated as the remaining component of Uber's current rates after accounting for all other costs[6]. Figure 1 shows costs perceived on a per trip basis in solid colour and costs perceived as sunk as transparent with a solid border. For more detail regarding the assumptions of this analysis, please refer to the Appendix.

[4] See chart 7.1, page 60 of CIE (2012).

[5] Ride-sourcing refers to paid private mobility services such as Uber, Lyft and taxis.

[6] Uber's rates are $2 per trip, $0.32 per minute and $1 per kilometre at the time of writing in June 2016. It is assumed than no surge pricing is applicable.

Figure 1: Vehicle operating costs and fare components for ride-sourcing



Source: Authors' analysis

As demonstrated in Figure 1, the cost per half hour of private vehicle travel is estimated at approximately $15.20, with $2.10 or 14% of this cost perceived on a marginal basis. The cost of ride-sourcing per half hour is estimated at $34.10, 220% higher than the cost of using private vehicles on a total cost basis, and some 1620% higher on a perceived marginal basis. However, by removing the cost of the driver, a ride-sourced AV falls below the cost of private ownership. The cost of using AV ride-sourcing varies between $7.90[7] and $9.70[8]. These annual cost savings could appeal to consumers when considering car ownership decisions and catalyse a mass shift away from private vehicle ownership[9]. Importantly, if this were to occur, it would be accompanied by an estimated increase in perceived marginal costs of car travel by a factor of 380% to 460%, while saving consumers money on an annual basis. If this scenario were to eventuate, it would likely dampen travel demand, increase public transport mode share and encourage urban consolidation and regeneration.

In the analysis presented in the following section, we assume that no increase in vehicle occupancy (car-pooling) is applicable.

4. Effects of AVs on urban form and function

If the effects of AVs on travel costs outlined in the previous section are to occur, they are likely to have major flow-on effects for infrastructure demand and urban form. In order to test the potential magnitude and direction of these impacts, a LUTI analysis was undertaken using the morning peak period of a typical weekday in Greater Melbourne in 2046.

---

[7] Assuming an increase in vehicle occupancy of 50% due to pooling.

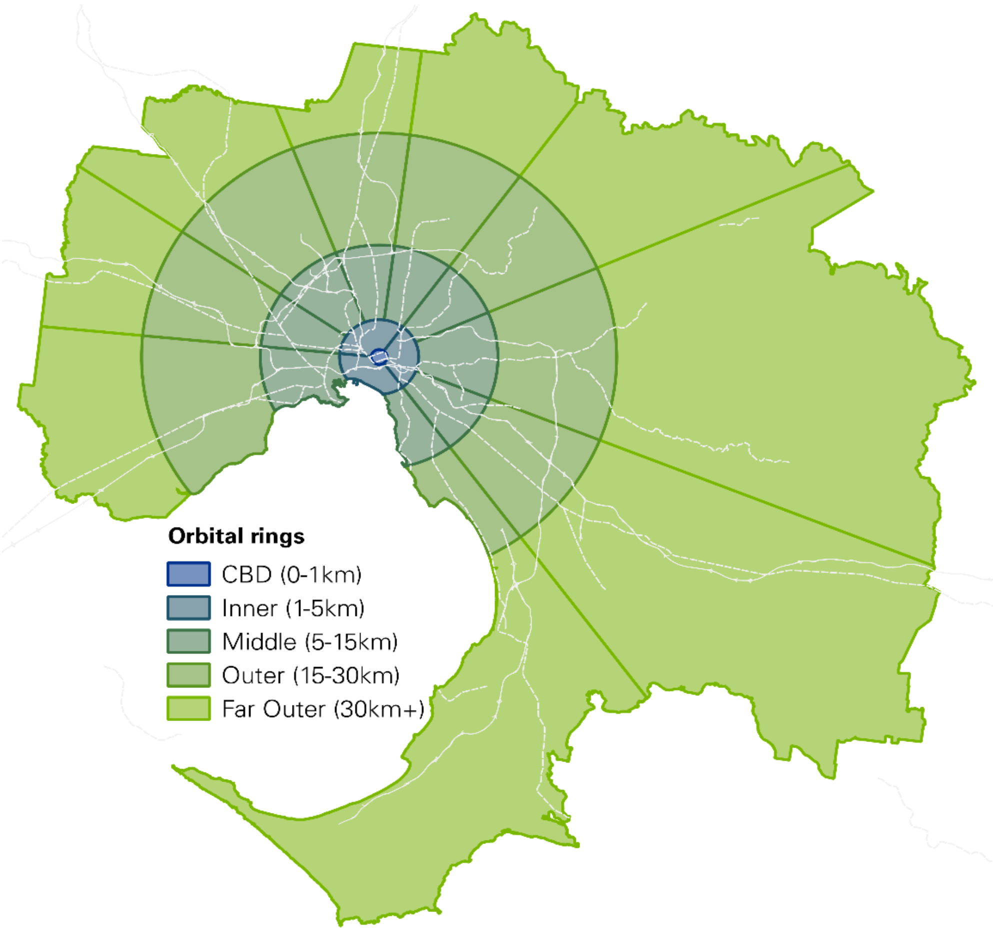
[8] Assuming no change in vehicle occupancy.

[9] This is a stated intention of Uber: *"Our intention is to make Uber so efficient, cars so highly utilised that for most people it is cheaper than owning a car."* - CEO of Uber Travis Kalanick, 8 February 2015.

4.1 Model description

The KPMG LUTI model used for this analysis divides Greater Melbourne into 31 zones, including five orbital rings representing the CBD, Inner Suburbs, Middle Suburbs, Outer Suburbs and Far Outer Suburbs respectively. The geographical zone system is shown in Figure 2.

Figure 2: LUTI zone system



Source: Authors' analysis

The KPMG LUTI model incorporates a four-step transport model which is calibrated to the 2046 Reference Case forecast of the Victorian Integrated Transport Model (VITM). The transport component of the LUTI model performs similarly to VITM in terms of travel demand forecasting, albeit at a more aggregated level of detail. The land use module of the LUTI model re-distributes population according to a discrete choice (multinomial logit) model with accessibility to employment as an explanatory variable of residential location decisions. The logit model is calibrated to the reference case land use forecasts applied in VITM and accessibility metrics estimated using the transport component of the LUTI model.

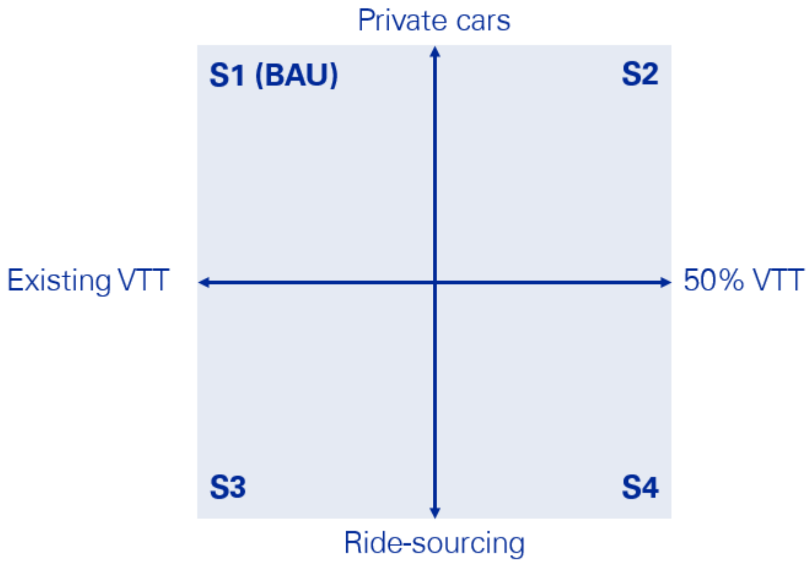
4.2 Scenario definitions

Four scenarios were constructed for input into the LUTI model. The scenarios are not intended to represent 'most likely' outcomes, but rather are proposed to be extreme scenarios to illustrate the potential direction and magnitude of impact.

Each of the four scenarios is based on the 2046 VITM reference case for Melbourne, with individual variables altered to reflect the travel behaviour impacts described in Section 3. The scenario definitions are summarised in Figure 3 and described below.

- Scenario 1 (S1) assumes no change in VTT and no shift to ride-sourcing AVs. In this sense, it is identical to the 2046 reference case and may be considered a Business As Usual (BAU) scenario for 2046.
- Scenario 2 (S2) assumes no shift to autonomous ride-sourcing, but a 50% reduction in VTT due to the comfort and convenience of autonomous vehicles.
- Scenario 3 (S3) assumes no change in VTT and a 100% shift to autonomous ride-sourcing for daily travel, leading to an increase in perceived per trip costs.
- Scenario 4 (S4) assumes both a 50% reduction in VTT and a 100% shift to autonomous ride-sourcing for daily travel.

Figure 3: Scenario definitions



Source: Authors' analysis

4.3 Results - infrastructure demand

The key model indicators for changes in infrastructure demand are shown in Table 1. Each scenario assumes a population of 7.2M (as per the VITM 2046 Reference Case). As demonstrated, the scenarios identified in this paper have a significant impact on infrastructure demand. The results are discussed further in Section 5.

Table 1: Changes in infrastructure demand by scenario, typical weekday AM peak

	S1	S2	S3	S4
	BAU	50% VTT, Private cars	Ride-sourcing	50% VTT, ride-sourcing
Trips ('000s)	3,746	3,746	3,746	3,746
Car mode share	83%	86%	80%	82%
Public transport mode share	17%	14%	20%	18%
Car person-km ('000s)	23,702	30,836	18,161	21,478
Car person-hr ('000s)	699	904	550	651
Public transport person-hr ('00s)	605	511	713	632
Car average speed (km/h)	33.9	34.1	33.0	33.0
Car average trip length (km)	7.6	9.6	6.1	7.0
Car average trip time (min)	13.5	16.8	11.0	12.7

Source: Authors' analysis

4.4 Results – land use

An important driver of residential location choice is accessibility to employment. As such, changes in perceived transport costs would be expected to alter the spatial distribution of Melbourne's population[10]. The modelled change in usual resident population by distance from the CBD is shown in Table 2. Results for S1 (BAU) are shown as per the VITM 2046 Reference Case forecasts. Results for S2, S3 and S4 are shown relative to the BAU scenario. The results are discussed further in Section 5. The residential location choice model is driven by accessibility to employment during the AM peak (relative to the inner suburbs). A visual representation of the relative accessibilities is shown in the Appendix.

Table 2: Change in population relative to BAU by distance from CBD

	S1	S2	S3	S4
	BAU	50% VTT, Private cars	Ride-sourcing	50% VTT, ride-sourcing
Inner Suburbs (1-5km)	556,851	-22,900	21,000	11,600
Middle Suburbs (5-15km)	1,887,786	-19,900	33,000	41,800
Outer Suburbs (15-30km)	2,635,319	-6,700	5,600	2,100
Far Outer Suburbs (30km+)	2,006,025	49,500	-59,600	-55,600

Source: Authors' analysis

5. Discussion and conclusions

5.1 Summary of key findings

Relative to the BAU scenario (S1), a reduction in VTT due to autonomous vehicles (S2) significantly increased demand for road infrastructure, with a 30% increase in car person kilometres during the morning peak, driven by increasing trip lengths and a mode shift away from public transport. S2 also had significant land use impacts, reducing population in the

[10] It is assumed that the total population in metropolitan Melbourne is unchanged between scenarios, with only the spatial distribution of the population varying between scenarios.

inner and middle suburbs by 42,800 residents relative to the Reference Case, with a corresponding 49,500 increase in population in the far outer suburbs.

Conversely, a shift to ride-sourcing AVs (S3) reduced car person kilometres by 23%, driven by a reduction in average trip length and a mode shift towards public transport. S3 also increased population in the inner and middle suburbs by 54,000 residents and reduced population in the far outer suburbs by 59,600 relative to the Reference Case.

A combination of a reduction in VTT and a shift to ride-sourcing AVs (S4) decreased car person kilometres by 9%, driven by a reduction in average trip length and a mode shift towards public transport. S4 had the largest impacts on population in the middle suburbs, with an increase of 41,800 residents.

A key finding of this analysis is that the increase in perceived travel cost due to the mass take-up of shared AVs is likely to be greater than the decrease in perceived travel cost due to the increased comfort and convenience of riding in AVs. This is despite assuming a significant decrease in VTT (by a factor of two) and conservative assumptions for the cost of using shared AV services. This finding can be confirmed with a rough calculation, as follows.

The perceived cost of travel time per half hour of travel is estimated to be $7.80 (refer to Section 3.1). If VTT is halved, perceived cost of travel time could decrease by $3.90. The perceived vehicle operating cost per half hour for a private vehicle is estimated to be $2.10 (refer to Section 3.2.1), increasing to $9.70 for the fare of a ride-sourced AV, an increase of $7.60. The net effect of both is an increase in perceived cost of travel by $3.70 per half hour of travel.

5.2 Discussion

The advent of autonomous vehicle technology will require a proactive approach towards transport policy, legislation and infrastructure planning. As AV take-up becomes more prevalent, governments will need to anticipate and plan for changing infrastructure demand and urbanisation patterns and associated energy use and sustainability effects.

Governments across Australia face some key barriers to facilitating autonomous vehicle take up in cities (both shared and private). These include a number of factors such as liability for accidents, liability in the event of malfunction, setting of performance and testing standards, as well as issues of cyber security and technological protections. Analysis of these issues are beyond the scope of this paper.

The analysis presented in this paper demonstrates that impacts of AVs on infrastructure demand will be significant. By not considering the effects of AVs in infrastructure planning and prioritisation, governments risk under or over provision of transport infrastructure. While the impacts of AVs remain uncertain, the findings of this analysis underscore the necessity to include explicit consideration of potential AV scenarios as well as robust treatment of risk and uncertainty in infrastructure demand in infrastructure business cases and strategies. These factors may be considered through the lens of scenario analysis and real options analysis.

While the analysis assessed extreme scenarios, the real world effects of AVs are likely to be more nuanced. It is expected that some residents will prefer to use a combination of ride-sourcing AVs, public transport and active modes, leading to urban consolidation and regeneration. Other sub-sections of the population will prefer to own their private vehicles, leading to a trend of increased demand for road infrastructure, congestion and urban sprawl. As a result, we are likely to see a combination of denser inner cores and sprawling development on the urban fringes.

The literature suggests that AVs are likely to provide the greatest benefits to users for freeways, where the ride will be smooth and comfortable, and large capacity gains may be available with vehicle-to-vehicle and vehicle-to-infrastructure communications technology. One study estimates that these technologies could increase roadway capacity by up to 60%

on freeways, but only by 15% on arterial roads (Eno Centre for Transportation, 2013)[11]. This trend is likely to encourage a certain subset of the population to live long distances from the city in areas with good access to freeways and with private ownership of AVs (and associated low perceived marginal costs of travel). If electric vehicles become widespread, this could further stoke that trend due to the significant savings on vehicle operating costs available for electric vehicles relative to petrol vehicles. The estimated perceived marginal cost of an electric vehicle (based on 2015 retail electricity prices and electric vehicle power consumption) is 4.6 c/km[12] compared to 10.5 c/km for a petrol vehicle, representing a 56% reduction in energy costs even with today's technology[13]. With advances in electric vehicle technology, rooftop solar and battery storage technology, this value could reduce even further. In addition, private AVs would obviate the need to pay high parking costs in the CBD and inner areas, as AVs could drop the passenger off and continue on to park in another location or service customers as a temporary ride-sourcing service.

If this is to occur, it is likely that an area-based road user charge (similar to London's congestion charge) would need to be imposed to avoid crippling inner city congestion. A distance based charge will also be necessary to manage demand for arterial and freeway travel if VTT and the perceived marginal cost of energy for private vehicles decrease significantly. Such an approach will not only help manage demand, but will also provide a revenue source to compensate for the loss of vehicle related taxes such as fuel excise and registration fees, and also for loss of revenue from traffic infringements. Improvements in telematics technology could open up the potential of efficient variable and dynamic distance, location and time of day charging to manage demand in real time.

Access to CBDs is governed by the capacity of arterial roads and trunk public transport infrastructure servicing them. In Australia's largest cities, inner city arterial roads are already at capacity, and widening these roads is not a viable option. Growth in passenger volumes entering the CBD will be governed by the provision of high-capacity trunk public transport infrastructure, and to a lesser extent, peak spreading. This growth is critical for Australian cities to maintain national and international competitiveness and for the realisation of agglomeration economies and other wider economic benefits. High-capacity public transport services could be complemented by AV ride-sourcing services delivering passengers to stations.

With the advent of high quality, relatively inexpensive and convenient AV ride-sourcing services with short wait times, living in vibrant inner city areas without the need to own and park a private vehicle will be attractive to many residents. This, combined with the release of large amounts of inner city floor space that is no longer required for car parking, is likely to lead to increasing densification of inner city areas. These trends may lead to positive externalities, such as agglomeration economies, labour market deepening benefits and urban consolidation benefits. An increase in demand for inner city real estate will also pose increasing challenges for state and local government planning authorities.

The shift to AVs as the dominant mode of transport in Australian cities will have many flow-on effects, some of which have been considered in this paper. Many of these effects are likely to lead to negative externalities, such as increasing congestion, pollution and urban sprawl. On the other hand, the effects of AV ride-sourcing services has the potential to lead to urban consolidation and regeneration, with associated positive externalities. The transport policy and infrastructure decisions we make now will affect the trajectory our cities will take with respect to these dynamics.

---

[11] Assuming 90% of vehicles on the road are AVs.

[12] This paper uses a figure of 10.49 c/km for perceived marginal cost (fuel cost), as shown in Table 3.

[13] Authors' analysis based upon (Australian Energy Council, 2016; Australian Energy Market Commission, 2015)

5.3 Recommendations for governments

In light of the key findings of this paper and related research, the following recommendations for governments have been identified.

- In the preparation of infrastructure strategies and prioritisation for transport policy and infrastructure, scenarios related to AVs and mass uptake of AV ride-sourcing services should be considered.
- Robust modelling efforts should be undertaken to understand the land use impacts of new transport policy and infrastructure with consideration given to the above scenarios. This may be conducted through the use of LUTI models, such as the one presented in this paper.
- Efforts should be taken to prepare for the introduction of road pricing regimes in light of the potential effects of AVs.
- In light of the high degree of uncertainty of the impacts of AVs on infrastructure demand, an increased focus should be placed on robust treatment of risk and uncertainty in infrastructure business cases, including scenario analysis and the use of tools such as real options analysis.

6. References

ABS, 2016. *6302.0 - Average Weekly Earnings, Australia, Nov 2015.* [Online]
Available at: http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/6302.0Nov%202015
[Accessed 2 June 2016].

Australian Energy Council, 2016. *E-litre comparison tool.* [Online]
Available at: http://www.energycouncil.com.au/energy_you/elitre_comparison_tool
[Accessed 16 June 2016].

Australian Energy Market Commission, 2015. *2015 Residential Electricity Price Trends.* [Online]
Available at: http://www.aemc.gov.au/getattachment/02490709-1a3d-445d-89cd-4d405b246860/2015-Residential-Electricity-Price-Trends-report.aspx
[Accessed 16 June 2016].

Bates, J. & Leibling, D., 2012. *Spaced out: perspectives on parking policy,* London: RAC Foundation.

Burns, L. D., Jordan, W. C. & Scarborough, B. A., 2013. *Transforming Personal Mobility,* New York: The Earth Institute - Columbia University.

CIE, 2012. *Reweighting of the taxi cost,* Sydney: NSW Independent Pricing and Regulatory Tribunal .

DEDJTR, 2016. *Victorian Integrated Survey of Travel and Activity (VISTA).* [Online]
Available at: http://economicdevelopment.vic.gov.au/transport/research-and-data/vista
[Accessed 20 June 2016].

Eno Centre for Transportation, 2013. *Preparing a Nation for Autonomous Vehicles - opportunities, barriers and policy recommendations,* Washington D.C.: Eno Centre for Transportation.

Fagnant, D. J. & Kockelman, K. M., 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C,* Volume 40, pp. 1-13.

Hansen, W. G., 1959. How Accessibility Shapes Land Use. *Journal of the American Institute of Planners,* 25(2), pp. 73-76.

InformationWeek, 2016. *Google, Tesla And Apple Race For Electric, Autonomous Vehicle Talent.* [Online]
Available at: http://www.informationweek.com/it-life/google-tesla-and-apple-race-for-electric-autonomous-vehicle-talent/d/d-id/1324351
[Accessed 2 June 2016].

Krugman, P., 1991. Increasing Returns and Economic Geography. *Journal of Political Economy,* 99(31), pp. 483-499.

Lambert, F., 2016. *BMW will launch the electric and autonomous iNext in 2021, new i8 in 2018 and not much in-between.* [Online]
Available at: http://electrek.co/2016/05/12/bmw-electric-autonomous-inext-2021
[Accessed 20 June 2016].

Le Vine, S., Zolfaghari, A. & Polak, J., 2015. Autonomous cars: The tension between occupant experience and intersection capacity. *Transportation Research Part C,* Volume 52, pp. 1-14.

Marchetti, C., 1994. *Anthropological Invariants in Travel Behavior, Technological Forecasting and Social Change,* Laxenburg, Austria: Internal Publication, International Institute for Applied Systems Analysis.

McFadden, D., 1978. Modelling the choice of residential location. In: A. Karqlvist, L. Lundqvist, F. Snickers & J. W. Weibull, eds. *Spatial Interaction Theory and Land Use Models.* Amsterdam: North-Holland Publishing Company, pp. 75-96.

Newman, P. & Kenworthy, J., 1999. *Sustainability and Cities: Overcoming Automobile Dependence.* Washington DC: Island Press.

Ozcabbie, 2012. *The great Taxi Insurance Rip-off.* [Online]
Available at: http://www.ozcabbie.com/the-great-taxi-insurance-rip-off
[Accessed 20 June 2016].

RACV, 2015. *RACV's car owning and operating costs guide.* [Online]
Available at:
http://www.racv.com.au/wps/wcm/connect/racv/internet/primary/my+car/Operating+Costs
[Accessed 2 June 2016].

The Boston Consulting Group, 2015. *Revolution in the Driver's Seat - the road to autonomous vehicles.* Boston: The Boston Consulting Program.

The Wall Street Journal, 2016. *GM Executive Credits Silicon Valley for Accelerating Development of Self-Driving Cars.* [Online]
Available at: http://www.wsj.com/articles/gm-executive-credits-silicon-valley-for-accelerating-development-of-self-driving-cars-1462910491
[Accessed 20 June 2016].

Transport and Infrastructure Council, 2014. *2014 National Guidelines for Transport System Management in Australia - environmental parameter values [PV4],* Canberra: Commonwealth Department of Infrastructure and Regional Development.

VicRoads, 2016. *Vehicle registration & TAC fees.* [Online]
Available at: https://www.vicroads.vic.gov.au/registration/registration-fees/vehicle-registration-fees
[Accessed 20 June 2016].

Waddell, P., 1996. *Accessibility and Residential Location: The Interaction of Workplace, Residential Mobility, Tenure, and Location Choices.* s.l., Lincoln Land Institute TRED Conference.

Appendix

Assumptions for VOC estimations

The assumptions of this analysis are described in Table 3.

Table 3: Assumptions for vehicle operating costs

	Private vehicle	Ride-sourced AV
Global assumptions		
Annual vehicle kilometres	15,000 km	16,500 km[14]
Average trip length	8.9 km[15]	9.8 km[14]
Average speed	40 km/h	
Fleet multiplier	1	0.1[16]
Fixed costs		
Cost of vehicle	$30,000	$40,000[17]
Loan term	5 years	5 years
Vehicle effective life	10 years	5 years
Trade-in value at end of life	$10,000	$0
Registration	$270 / year[18]	$2700 / year[19]
Injury insurance	$494 / year[20]	$2000 / year[19]
Vehicle insurance	$1000 / year	$2700 / year[19]
Variable costs		
Fuel	10.49 c/km[21]	
Tyres	1.39 c/km[21]	
Maintenance	5.28 c/km[21]	

Source: Authors' analysis and assumptions

An agent-based simulation of a shared AV scenario estimated 'empty running' arising from additional distance travelled for repositioning of AVs between servicing customers at 10% (Fagnant & Kockelman, 2014). A separate simulation estimated the equivalent value for a shared AV fleet undertaking Manhattan's yellow taxicab task at 11% (Burns, et al., 2013).

For this study, we therefore assume that ride-sourced AVs travel 10% further relative to private vehicles serving an equivalent passenger task.

The above noted studies also estimated the number of shared AVs that would be required to serve the same transport task as the current fleet of private vehicles. The analysis found that one shared AV would replace 9-13 private vehicles (Fagnant & Kockelman, 2014). Burns et

14 Includes 10% allowance for empty running (Fagnant & Kockelman, 2014), (Burns, et al., 2013).
15 Estimated average trip distance for Melbourne residents in 2013 (DEDJTR, 2016).
16 Assuming one shared AV would replace 10 private vehicles.
17 Assuming a $10,000 premium for autonomous vehicles (The Boston Consulting Group, 2015).
18 Cost of registering a vehicle in Victoria (VicRoads, 2016).
19 Estimated cost of registration and insurance of a taxi in Victoria (Ozcabbie, 2012).
20 Transport Accident Commission charge in Victoria (VicRoads, 2016).
21 Operating costs for a Toyota Camry Atara S according to RACV (RACV, 2015).

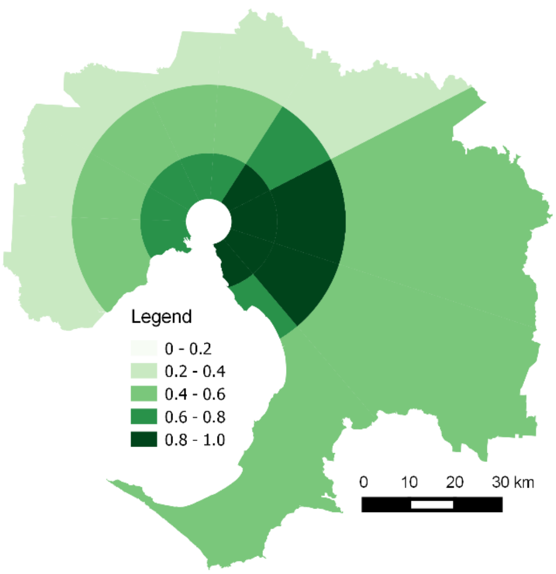
al. found that one shared AV would replace seven private vehicles, however this assumed low average wait times in a city with a relatively small population of 285,000. This replacement of the existing fleet represents the major efficiency dividend of ride-sourcing AVs, allowing high sunk costs of vehicle transport (finance, depreciation, registration and insurance costs) to be shared among a larger pool of users. This is in contrast to the inefficient use of vehicles under the existing private ownership model, as vehicles sit idle for 96% of their effective lives (Bates & Leibling, 2012; Burns, et al., 2013). In addition, AVs will also be able to undertake tasks while no-one is in the vehicle, such as picking up shopping.

It is also assumed that autonomous vehicles would command a $10,000 purchase premium relative to today's technology (The Boston Consulting Group, 2015). It is further assumed that future ride-sourced AVs would have a shorter effective life than today's private vehicles due to high utilisation (as is currently the case with standard taxis). Finally, it is assumed that registration and insurance costs of future ride-sourced AVs as roughly equivalent to those costs for today's taxis.

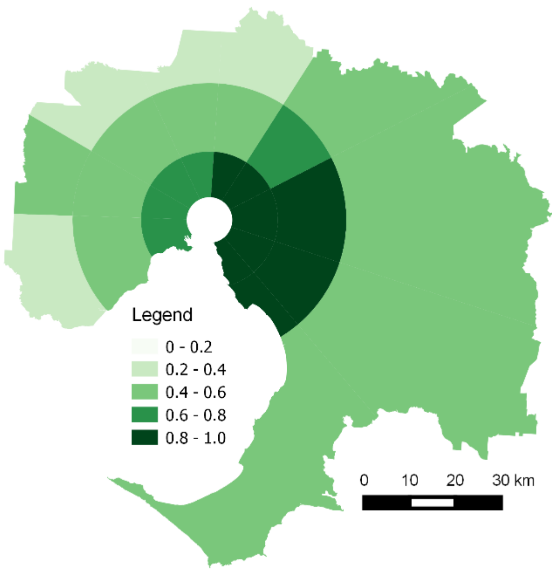
The analysis assumes that ride-sourcing business models are similar to the current Uber business model, which divides the fare between Uber and the driver. Future ride-sourcing AV services are assumed to work in a similar manner, with the fare covering the cost of the vehicle (and associated taxes) with 30% of the fare going to the operator for administration and IT costs and a profit margin.

Accessibility to jobs relative to inner suburbs

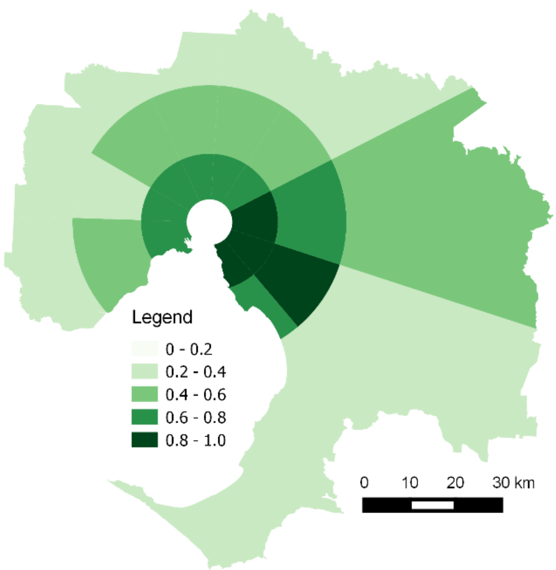
S1 (BAU)



S2 (50% VTT)



S3 (Ride-sourcing)



S4 (Ride-sourcing and 50% VTT)