

TITLE Driving alone versus riding together - How autonomous vehicles can change the way we travel

AUTHORS Peter Davidson, BE (Civil) (1<sup>st</sup> Hons)  
Director, TransPosition  
[peter@transposition.com.au](mailto:peter@transposition.com.au)

Anabelle Spinoulas, BSc(Physics, applied maths) (1<sup>st</sup> Hons), MPhys  
Associate Product Specialist, TSS-Transport Simulation Systems  
[anabelle.spinoulas@gmail.com](mailto:anabelle.spinoulas@gmail.com)

PRESENTER Peter Davidson

# DRIVING ALONE VERSUS RIDING TOGETHER - HOW SHARED AUTONOMOUS VEHICLES CAN CHANGE THE WAY WE DRIVE

Peter Davidson and Anabelle Spinoulas

Autonomous vehicles (AVs) are likely to have significant impacts on travel behaviour and road network operations in the medium to long term. Autonomous vehicles will improve safety on roads as they more closely and consistently observe their surroundings (using technologies such as radar, LIDAR, GPS, and computer vision) and react much more quickly. As a result, these driver-less cars will be able to travel closer together and operate at higher speeds, thus increasing capacity on roads. However, the improved comfort; ability to better use the time while travelling; and reduced complexity of parking will make road-based travel more attractive. This is likely to increase trip making and increase average trip lengths. The extra demand pressures could be exacerbated by the use of cars to auto-chauffeur people, reducing parking requirements but increasing demand in the direction opposite to peak traffic flows. The relative attractiveness of public transport will also be altered; improvements to car travel will make PT relatively less attractive, however autonomous vehicles could also improve connections to services and make PT more responsive and affordable.

This paper uses TransPosition's 4S model to evaluate the effects of AVs on mode share, congestion, safety, and environmental impacts of travel. It considers a number of scenarios, including ranges of AV uptake and different proportions of privately owned vs shared use vehicles. It shows that very different outcomes are possible, and that there will be significant problems if AVs are adopted as improved privately-owned cars. Finally the paper discusses implications for policy and transport strategy.

Note that an earlier version of this paper was presented at the Australian Institute of Traffic Planning and Management Conference in 2016, and then published in the Australian Road Research Board's (ARRB) Road & Transport Research Journal, September 2016.

## OBJECTIVES AND MOTIVATIONS

There have been many advances in Autonomous Vehicle (AV) technology over the past few years. Even though there are still significant technical, legal, liability and social obstacles that must be overcome, it now seems reasonable to consider AV in future planning, as they are likely to have significant impacts on travel behaviour and road network operations.

AVs will observe their surroundings using technologies such as radar, lidar, GPS, and computer vision. These technologies will be more reliable than the human eye and the system will not be subject to slow human reaction times. This technology will not only improve safety on roads, but also allow these driver-less cars to travel closer together and operate at higher speeds (Fagnant and Kockelman 2015). However, this increased capacity on roads might be counteracted by the likely increase in trip making and average trip lengths due to the improved comfort; ability to better use the time while travelling; and reduced complexity of parking. The extra demand pressures due to the increased attractiveness of road-based travel could be reduced by auto-chauffeur and reducing parking requirements. The relative attractiveness of public transport will also be altered; on the one hand the improvements to car travel will make PT relatively less attractive; on the other hand autonomous vehicles could make PT more responsive and affordable.

This paper will look at what the introduction of AVs could mean for the future of transport and includes some initial modelling of autonomous vehicle impacts in South East Queensland (Australia), using TransPosition's 4S Model — earlier work by the authors can be found in Davidson and Spinoulas (2015). The 4S model is particularly well suited to investigating changes such as AV, because it is based on a first-principles utility formulation where all parameters can be easily changed. This differs

from traditional transport models, which are calibrated with aggregate behavioural factors that are not easily amenable to fundamental changes. Both privately owned AVs and shared AVs are considered in this paper. This paper also addresses the use of AVs under a 'mobility-as-a-service' structure, with some final comments of possible safety implications of AVs. Much of this work has been done under the support of the Department of Transport and Main Roads (TMR) in Queensland.

## METHODOLOGY

### TransPosition's 4S Model

The analysis of the impact of Autonomous Vehicles has been done using TransPosition's 4S model (see Davidson 2011). This is a relatively new modelling approach developed by TransPosition that includes a very high level of spatial and behavioural detail, and is sensitive to a much wider range of system changes. Unlike other strategic models, the 4S model has a well-defined micro-economic basis and a relatively small number of parameters that are more regionally and temporally stable; this makes it particularly suitable for addressing system-wide change, such as that associated with the introduction of AV. This is done by modifying key behavioural variables, such as the perceived value of time, and vehicle operating costs, to reflect the AV scenarios. The model then works through the consequences of these through the modified behaviour of all travellers in the city.

### Description

The TransPosition 4S model has been developed over the last 7 years. The model is structured differently from the usual four-step-model; it is based on a micro-economic utility framework and has strong capabilities in modelling multi-modal systems, freight, pricing and regional analysis.

The Segmented Stochastic Slice Simulation (4S) model is named for the following features:

- **Segmented:** Uses a comprehensive breakdown of different travel markets, and allows all behavioural parameters to vary by market segment (value of time, tolls, destination utilities etc.)
- **Stochastic:** Uses Monte Carlo methods to draw values from probability distributions. Every parameter can be a random variable
- **Slice:** Takes very efficient slices (samples) of the travel market across the whole model area and through the distributions (the efficiency of this approach is demonstrated by the fact that large regional models can be run in an hour, and national models can be run overnight)
- **Simulation:** Uses a traveller/vehicle state-machine with very flexible transition rules to effectively simulate all aspects of travel choice (with every road, walking and cycling path, and timetabled public transport)

### High level assumptions

There are a number of key, high level assumptions that the model makes about travel behaviour.

- **Utility maximization** – People make decisions to maximize their overall net utility - that is the utility of the activity they can undertake at a destination minus the cost of travel to that destination.
- **Random utility theory** – People make different assessments of utility, so utility can be described by a random variable. In practice, this means that variables like walking speeds, wages, preferred arrival time, and perceptions of different destinations are all described with random variables.

- Generalized cost – People assess costs by adding up all of the components of their travel, including the weighted value of time spent travelling, vehicle operating costs, tolls, fares and parking charges.
- Behavioural factors constant over time – The determination of the key parameters that describe behaviour is done using current and historical surveys, and calibration against observed travel. In preparing forecasts, we change only those variables that are intended to change (such as population, employment and network characteristics). The behavioural parameters are assumed to carry forward into the future. This assumption can be relaxed in scenarios, but is implicit in the use of a current model to make predictions.
- Demand determined by land use – The main locational factor that determines travel demand is classified population and employment.

In addition to these high level assumptions, there are a large number of model specific assumptions; covering the form of utility functions and the probability distributions that describe each random variable. See Davidson 2011 for a full discussion of the detail of the model and its calibration.

## **Modelling Autonomous Vehicles in TransPosition's 4S Model**

To test the impact of autonomous vehicles, a number of scenarios have been tested using TransPosition's 4S model for South East Queensland. By focusing on a particular region, the interaction between the multiple changing elements can be considered. In particular, because the 4S model is multi-modal, it can investigate the interaction between car demand and other modes. Although the work has been done in a particular region, many overall conclusions should be transferable to other cities.

Note that there are two separate innovations that are likely to occur - connected vehicle technology, and vehicle automation. It is possible to have Connected Vehicles (CV) that are not Autonomous Vehicles, and vice versa. It seems likely that (in the longer term scenarios being considered in this paper) most autonomous vehicles will also be connected, giving Connected Autonomous Vehicles (CAV). For the bulk of this work we have assumed that all AV's are CAV's. Only the shorter term safety analysis looks specifically at CV and non-connected AV.

## **AUTONOMOUS VEHICLE MARKET SHARE**

There is no consensus on how quickly the market will adopt Autonomous Vehicles, but there are some natural constraints. To begin with, AVs will likely cost significantly more than similarly sized non-AV. This will limit the proportion of the market that will be willing to buy them. While the rapid rise of smart phones has shown that people are willing to spend reasonably large amounts of money on things that they previously spent much less on, the high cost of early AV will be impossible for most people to afford.

The best understanding of how much people are willing to pay for vehicles comes from looking at what people are currently spending on vehicles. Looking at the quantity of new vehicle sales also gives a good indication on how quickly the fleet turns over - a critical issue when determining how quickly AV technology will spread through the fleet.

Note that the issue of differential uptake of AV is complex - it is likely that it will be related to income (increased uptake with income), but also to age (perhaps reduced uptake by age). For this analysis we simply assume uniform adoption rate across the region.

The AV market share model began with data on new vehicle sales, broken down by 28 categories as shown in the attached figure below. For each vehicle type, we assume that the proportion of new vehicles that would be AV will remain at zero until a critical year - the year in which an AV can be built to that price point. The proportion of new AV vehicles will then grow linearly until it reaches 100% at another nominated year. Three cases were considered - conservative, moderate and aggressive.

The total number of new autonomous vehicles sold each year is estimated by assuming the proportion of new sales by type stays constant in the future; that total sales grow with population; and that the AV proportion follows the linear growth model described above. The size of the fleet in any year can then be determined by combining these new vehicle sales with data on the existing vehicle fleet in Australia, and removing vehicles from the fleet according to a simple vehicle lifetime model.

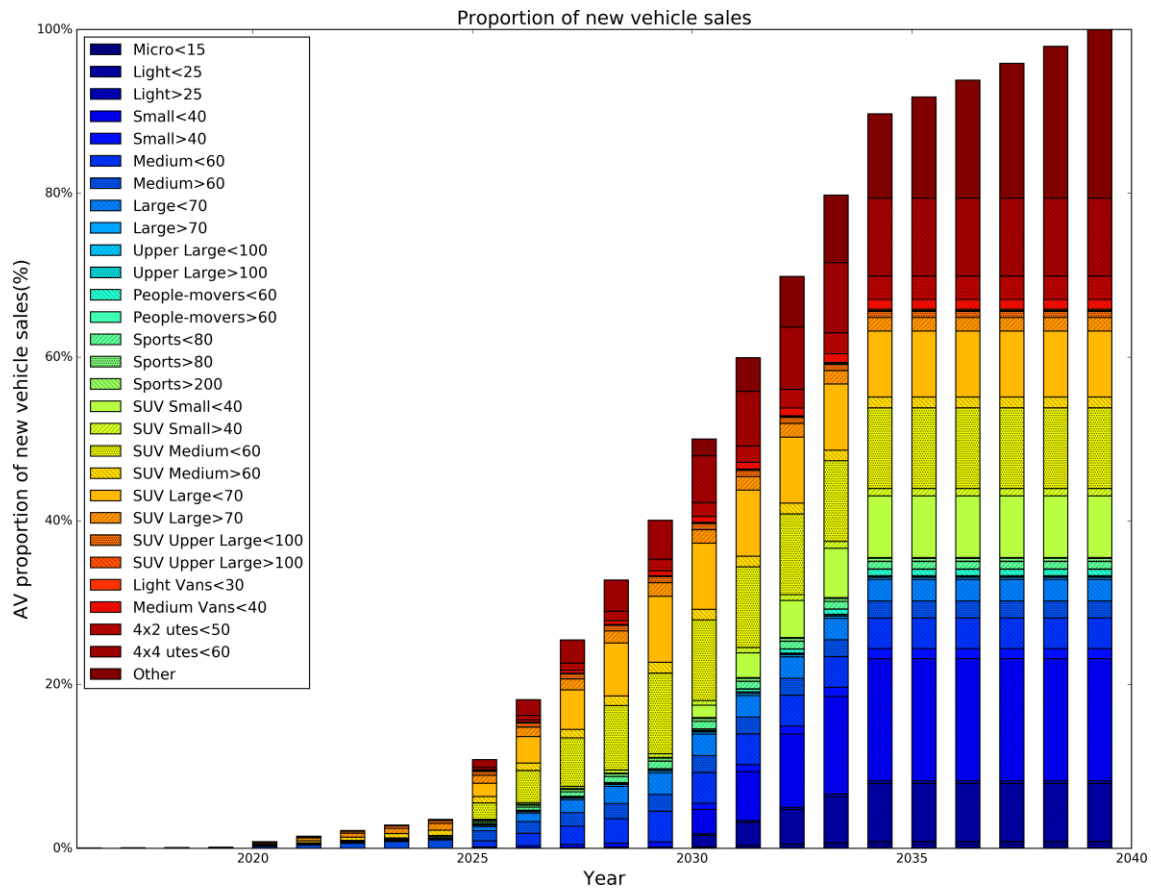


Figure 1: AV % of new sales (Aggressive case)

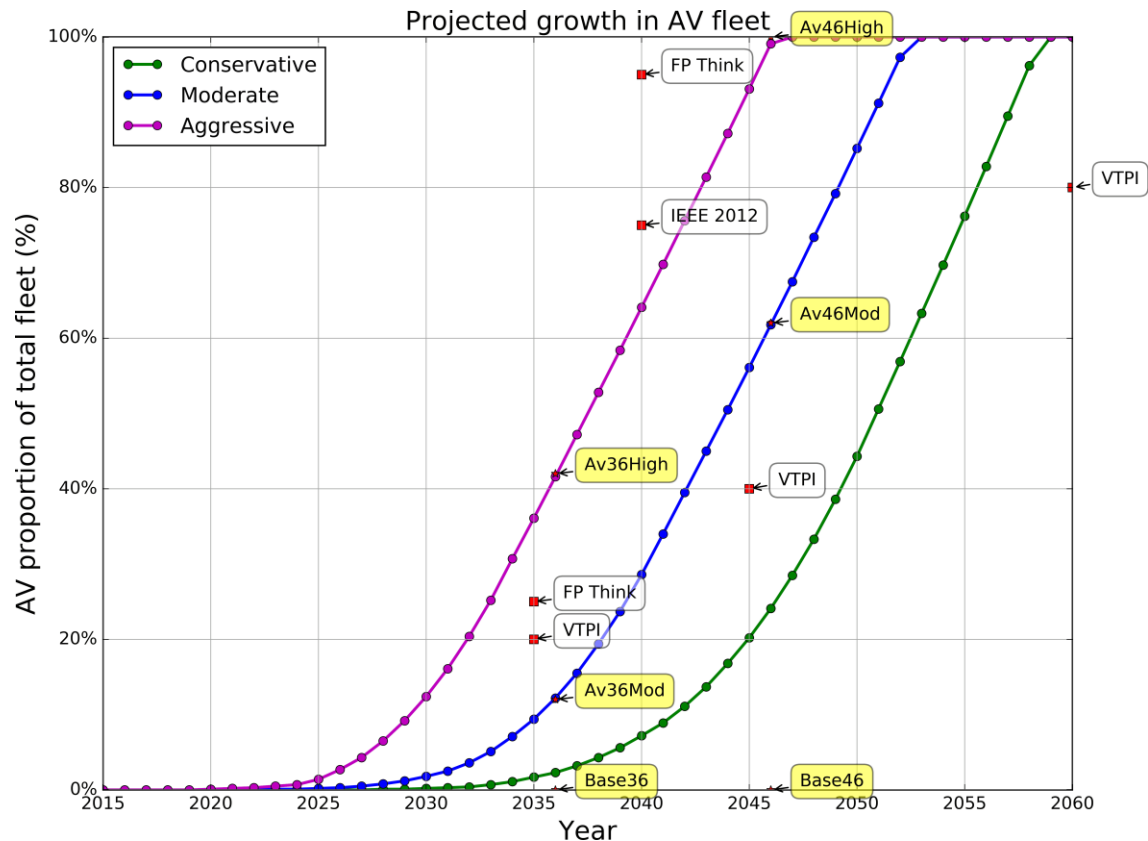


Figure 2: AV Fleet Proportion

The AV fleet can now be calculated by adding the new AV sales to the previous year's AV fleet (obviously this is 0 in 2015). In the aggressive case, we estimated a total of 14,598,602 AVs in 2041. Taking the stock of vehicles into account, this means that 65% of the fleet will be autonomous by 2041. This increases further to 95% by 2046. The conservative case estimates only 26% AV fleet in 2046, with 62% in the moderate case. All cases are assumed to reach 100% AV; this is partly an artificial construct of the model formulation, since manually driven cars are likely to remain in small numbers into the foreseeable future, even if they are only allowed limited use on the network. Thus the sharp edges at the top of the fleet proportion curves should almost certainly be rounded, with a residual non-AV fleet. In any case, the model projects a saturation of AVs by 2048 in the aggressive case; 2053 in the moderate case; and 2058 in the conservative case.

The chart above shows a sample of forecasts made by other researchers demonstrating that our projections are generally consistent with the literature (IEEE 2012; Litman 2015; Bierstedt 2014).

## Assumptions regarding autonomous vehicles

Autonomous vehicles will differ from current manually driven vehicles in a number of key ways

- Time spent in an AV will be more easily used for other activities - this will lower the cost of this time
- The likely linkage between AV technology and plug-in-electric means that AV will likely cost less to run

- Lower costs and simplified parking will make it more attractive for people to make more trips, and reduced requirements on drivers will eventually open up new travel markets (children, people without licenses etc.)
- Faster response time, uninterrupted attention, and vehicle-vehicle and vehicle-infrastructure communications will eventually allow AV to travel faster, and at a higher density.
- When vehicles can operate without a driver, there will be a new type of travel, as vehicles are sent back home, or between family members.
- If the development of mobility-as-a-service becomes popular, then the structure of people paying for transport will change. The cost of owning a vehicle will be included in every trip, rather than paid as once-off and intermittent payments. This will change the marginal cost of each car trip.

We have assumed that AVs share the roads with manually driven cars for most of the scenarios. This limits some of the performance improvements possible from AV technology. In the high cases in 2046 the network is assumed to be 100% autonomous, allowing greater increases in speed and capacity. See Section 4.1 for the description of the scenario assumptions.

### **Value of time**

Autonomous vehicles have the potential to improve the driver's experience. The degree to which the experience will be improved will depend on the Autonomous Level (defined by the National Highway Traffic Safety Administration 2013). Adaptive cruise control and lane following (Level 2) will make long distance driving a bit more pleasant, but the real benefits will come with partial or complete automation (Levels 3 and 4). Once drivers can take their hands off the wheel, and safely turn their attention to their computer or phone, then the experience of driving will be much less onerous. Things will become even better once the vehicle is completely autonomous; in this case the seats could be more comfortable and people may even sleep while they are travelling. For many people it will also be possible to work. These changes will allow this time to be used more effectively, reducing the perceived cost of this time.

For the purposes of modelling, we have assumed that the autonomous portion of the travelling fleet will enjoy some improvement in their perceived time-cost of travelling, implemented by a reduced weight for time spent in cars. We have assumed that this reduction in VOT will not apply to everyone - the model assumes that the reduction in weighting is uniformly distributed with an upper limit of 1, meaning no change. For all scenarios we have adopted a range of values, with lower limits and upper limits as given in the description of scenarios section below.

### **Increased trip rates**

The widespread use of autonomous vehicles will increase the number of trips for a few reasons

- They have lower costs (both real and perceived), and so some trips that have marginal net benefits at the moment will become more attractive.
- Parking will become easier, due to autonomous parking at nearby parking stations or autonomous chauffeuring
- It will become easier for a vehicle to be shared amongst family members, making it possible to make some trips that are currently impossible, or forced onto other modes.
- People will be able to drive at times that they currently cannot - for example, when they are drinking or too tired to drive. Some of these trips will change over from taxis, but the high cost and limited availability of taxis at peak times means that some of these trips will be new
- There will be new travel by people who currently cannot drive, including children; the elderly; people without licenses; and those with disabilities that preclude driving.

We have assumed that all of these factors combined will increase overall trip rates by 10% in 2036 and 15% in 2046.

### **Reduced operating costs for AV**

Autonomous vehicle technology and plug-in-electric technology are natural allies; they are coming to market at similar times and each one supports the other. AV needs a range of electrically powered sensors and actuators, and the system is more easily controlled with electric motors. Plug-in-electric vehicles need smarter controls, and a better understanding of travel patterns, due to their relatively smaller energy capacity and longer recharge times. The fact that AV is coming to market at the same time that the world is trying to decarbonize only makes the case more compelling. Electric vehicles should have a much lower vehicle operating cost than standard internal combustion engine vehicles, particularly in traffic. Electric vehicles currently cost more, but costs are likely to reduce over time as technology improves and economies of scale are realised.

It is difficult to predict the relative cost of electrical energy vs fuel energy in the future, but based on 2014 prices, electric vehicles give energy cost savings of approximately 50% compared with an internal combustion engine (ICE). Guterres (2014) discusses the cost differences.

We have again assumed a range for this impact - we have assumed a reduction to 50%-75% of the current vehicle operating costs for all scenarios except the high 2046 cases where we assumed a fixed 50% reduction for electric AVs.

Note that battery limitations and the lack of recharging facilities may limit the adoption of plug-in-electric vehicles in rural areas. This study has focused on urban demand impacts, and so the slower adoption of EVs in rural areas is unlikely to have much impact on the results. Analysis of wider, non-urban impacts would need to consider this issue more closely.

### **Increased speeds and capacities**

Autonomous connected vehicles have the potential to significantly improve the operational efficiency of our roads, with higher speeds and higher capacities. Some microsimulation modelling has indicated that the capacity of roads could double (from 2000 veh/lane/h up to 4000 veh/lane/h) (see Shladover, Su, and Lu 2012 for an example). However these results must be read with some caution, since they can overstate the impact. The aforementioned paper, for example, only considers a single freeway lane in isolation, despite the fact that most delays are due to intersections. It also assumes a much lower inter-vehicle gap than people may be comfortable with - some experimental results show that people are only comfortable using the adaptive cruise control system at gap settings similar to those they choose when driving manually. There is some research on autonomous intersection management that show significant reductions in intersection delays (more than 50%) due to smart scheduling of intersection space with connected autonomous vehicles (Dresner and Stone 2008; Au, Zhang, and Stone 2014). However it is likely that there will need to be significant cultural change, and very mature technology, before people will be comfortable with the very efficient autonomous intersections.

Finally, much of the analysis on this issue neglects other road users, such as buses, cyclists and pedestrians. It is difficult to see how these can be incorporated without significantly reducing the theoretical limits.

Given the uncertainty of these issues, we have been somewhat conservative on the speed and capacity improvements. In the transition years, the increased use of connected vehicle technology, and the reduction in the incidence of crashes due to the rising proportion of safer AV vehicles leads to a marginal (5%) increase in roadway capacity (in 2036). A network with 100% AV (high case in 2046) allows for significant increases in speed, capacity and intersection operations. The model assumes



that roadway capacities are 20% higher; posted speeds are increased by 20%; and intersection delays are reduced by 25%.

## **Unoccupied vehicles**

Once autonomous vehicles can travel without a driver, there will be scope for a whole new class of travel - manoeuvring of unoccupied vehicles. Rather than paying for parking, people may drive into work and then send their vehicle home for the day. When it is time to go home, the vehicle will have returned ready for the homeward trip. If they are running late at work they may send their vehicle back to pick up their children from school, and then return back to work to bring them home. In the extreme case, people may decide to have their vehicle drive around the city streets for an hour while they do their shopping.

Modelling this behaviour is very complex, and has not been done at this stage. Furthermore, there would be good reasons to introduce regulations to limit at least the most egregious cases. This could be done using additional charges for specific behaviour, or by a more general road pricing approach.

## **Mobility-as-a-Service (MaaS)**

We are used to the idea of private car use and public transport for travel. However, emerging technology allows private and public transport services to be packaged into transport plans. This idea has been termed 'Mobility-as-a-Service (MaaS)'. MaaS supports a shift away from privately owned modes and the idea of shared AVs are a crucial element of this. Rather than buying expensive vehicles, that are not in use 95% of the time, a full door-to-door transport service could be obtained simply by booking through a smartphone. For example, a MaaS app could suggest using Uber to get to the train station and then riding the train for the majority of the journey and then switching to another Uber for the 'last mile' section of your trip. On top of creating and managing trips, the app could also take care of payment automatically. It would effectively combine the Uber booking and payment process but with all modes available. In cases where people do not own a smartphone, transit cards might also be used. It is hard to know exactly how MaaS providers will set up their service and what type of payment plans they may use. Different providers might have different payment plans such as pay-as-you-go or a monthly fee.

In some literature the term 'Mobility-as-a-Utility' has taken over from MaaS, emphasising that fact that you have a right to this service. This would be analogous to paying for your electricity bill; it is a fee for service but there are rights associated with its use, including constraints on having the service removed for late payment. Once it is fully developed, a MaaS provider could be similarly constrained to ensure that people maintain their ability to travel. There could also be other consumer protections, such as a transport ombudsman, similar to those that exist for telecommunications and banking.

MaaS has huge potential to reduce car ownership and could also increase the efficiency and utilisation of transport providers. It may even be that public transport becomes more competitive and affordable under MaaS due to increase efficiency of the network and the use of AVs.

The model used in this analysis considers fully multi-modal travel so in effect we already consider a basic model for MaaS. We have incorporated the use of multiple modes in one journey including the use of active transport; public transport; private car use; private AVs; single-occupant shared AVs (autonomous taxis); and also multi-occupant shared AVs (car-sharing). However, currently we do not model taxis, existing ride-sharing services, public transport AVs and the ability for AVs to pick up others along the way. This last issue is a difficult one we hope to tackle in future papers. We have also not incorporated price packages for say unlimited transport use using multiple modes making some options cheaper than others.

## Shared AV (Autonomous Taxi)

Shared AV is a more socially beneficial option that becomes available once AV can travel without a driver. In this option people would make serial use of a shared autonomous vehicle under a mobility-as-a-service arrangement. In the simplest case these would still be single passenger vehicles (like an autonomous taxi), but a more efficient network could also have multi-occupant shared vehicles. Note that this option could be an early adopter of autonomous technology - the shared use would mean a much higher utilization than privately owned vehicles, making the high capital cost of AV technology much easier to sustain.

The modelling of shared AV is very complex, since it will depend on many aspects of the system that are completely unknown at this point. For example, the usability of the system and the amount of manoeuvring traffic will depend on the market penetration of the system; how far ahead people will need to book; where and how many depots will exist; what pricing model the operators will adopt; whether they have increased fees at peak times; how well integrated the AV system is with public transport; and what the vehicle charging/down time/duty cycle will be. Since this work is focused on the behavioural impacts of AV we are more interested in what the system looks like to users than how it might be run by operators. For users, the key question is how much will they be charged for each trip, so we need some way of estimating the likely costs for shared AV.

At its simplest level, the shared AV will look like a taxi, or a ride-sharing service, but with much lower rates due to the lack of a driver and (presumably) minimal licensing costs. So the best approach is to look at the cost structure for existing taxi and ride-sharing services and work from there. This exercise was done using detailed data collected from taxi drivers in Sydney (The Centre for International Economics (2014)). The AV service was assumed to run more efficiently than taxi services, due to higher usage and better systems. It was also assumed to have minimal licensing costs, but higher capital costs than taxis. The resulting fare structure for an AV service was estimated as \$0.10/min + \$0.40/km + \$1.20 flag-fall.

It is certainly possible that the fares could be lower once the capital costs of AV are reduced, and as the system operates more efficiently. However, there are reasons for caution on this as the unsupervised vehicles may have higher incidence of vandalism, and people may expect a high standard of cleanliness and amenity before they are happy to depend on the service.

## Shared AV (Multi-Occupant)

Modelling shared AVs (autonomous taxis) is difficult, however modelling car-sharing AVs (multi-occupant) adds an extra level of complexity. For the purposes of this paper, we have made some basic assumptions to perform an initial assessment of this type of travel. These assumptions include increasing the vehicle occupancy rate; reducing the cost of travel to the individual; and increasing the perceived value of time since people might find it less pleasant to travel with other passengers. It should be noted that although we consider car-sharing, we do not explicitly model picking up other people along a journey.

This category of travel could significantly increase the efficiency of the road network. With autonomous taxis the marginal cost of travel becomes much higher than when using a privately owned vehicle. Many of the expenses associated with vehicle ownership are capital or annual and so artificially lower the marginal cost of private travel. This could make some people travel slightly less as they would feel the financial impact of each trip. However, car-sharing will be much more affordable in aggregate, and so in conjunction with all the other benefits of AVs this could cause people to travel more often. However, since people are car-sharing this does not necessarily mean more cars on the network. Further discussions on this topic is in the results section below.

## RESULTS

### Description of Scenarios

The scenarios focus on the moderate and aggressive AV cases in 2036 and 2046. The aggressive AV growth profile does not quite reach 100% by 2046, but a set of scenarios with 100% AV were included so that the capacity improvements of this case could be considered. In each of the AV scenarios there are a number of changes; a reduction in the value of time spent in-vehicle; an increase in the rate of trip making; a reduction in the per-km vehicle operating cost; an increase in average speed; an increase in capacity; and a reduction in intersection delays. The size of these effects varies by scenario according to the assumptions in the table below. Note that all AV scenarios assume plug-in-electric vehicles.

Table 1: AV Scenarios (factors applied to base assumptions)

Name	AV Share	Value of Time	Trips	Vehicle operating cost	Speed	Capacity	Intersection Delays	Shared AV	Multi Shared
Base 11	0%	-	-	-	-	-	-	-	-
Base 36	0%	-	-	-	-	-	-	-	-
Av36 Mod	12%	75% - 100%	110%	50% - 75%	-	105%	-	-	-
Av36 High	42%	75% - 100%	110%	50% - 75%	-	105%	94%	-	-
Base 46	0%	-	-	-	-	-	-	-	-
Av46 Mod	62%	60% - 100%	115%	50% - 75%	112%	112%	90%	-	-
Av46 High	100%	60% - 100%	115%	50%	120%	120%	75%	-	-
Av46 High Shared	100%	60% - 100%	110%	50%	120%	120%	75%	70%	-
Av46 High MultiShared	100%	75% - 125% <sup>1</sup>	115%	50%	120%	120%	75%	40%	30%

### The impact of private AV

#### Impact on mode share

The model shows that in the absence of AV, the general trend is for more active transport, more public transport and declining car mode share. The introduction of AV changes this; the higher the proportion of AV in the fleet the higher the car mode share. This is because the AV vehicles are more attractive, and generally have lower cost than most other options.

<sup>1</sup> This only applies to the multi-shared AV component. The regular shared and private AVs use 60%-100%. The reason the VOT goes above 1 for MOSAV is because some people may find it more unpleasant to travel in a multi-shared AV than by themselves in a private AV.

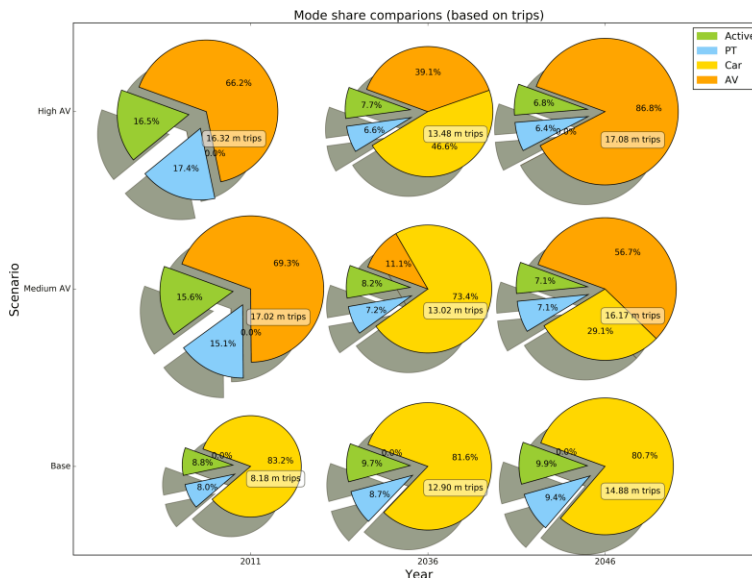


Figure 3: Mode share results by scenario

### Impact on generalised costs, time and distances

While preliminary, the modelling in this paper shows that AVs have the potential to lead to very large increases in both average trip length and in total travel time. The reason for this is that the increased comfort associated with automatic driving make travellers less sensitive to travel times - they will travel more often and will be willing to stay in their vehicles longer. This is compounded further if the shift to electric vehicles leads to big drops in vehicle operating costs - this will reduce travellers' sensitivity to travel distances. Both of these effects are important, and their impact on total travel times is similar. The table also shows increases in net utility. Net utility is the dollar value of the benefits of travelling to the selected destination, minus the cost of getting there. The figures show that the perceived improvements are more than the extra costs, that is, people are better off overall with an AV network. There are differential effects, and there are winners and losers, however the majority of the people benefit.

Table 2: System-wide, and per capita generalised costs, times, distances and net utility by scenario (daily)

Scenario	$\Sigma$ Cost \$m	$\Sigma$ Hours m hr	$\Sigma$ PKT m km	$\Sigma$ VKT m km	$\Sigma$ NetU \$m	Cost \$	Hours h	PKT km	VKT km	NetU \$	Driving Speed km/h
Base11	74.5	3.7	101.6	78.0	103.4	23.1	1.15	31.5	24.1	32.0	32.9
Base36	122.1	6.3	163.3	125.3	173.1	23.4	1.21	31.3	24.0	33.2	30.9
Av36Mod	116.4	7.3	202.7	153.2	194.4	22.3	1.39	38.8	29.3	37.2	31.8
Av36High	120.7	7.6	209.9	158.9	201.3	23.1	1.45	40.2	30.4	38.6	31.2
Base46	141.5	7.4	185.2	142.7	204.2	23.6	1.24	30.9	23.8	34.0	29.8
Av46Mod	142.1	9.4	256.9	194.1	249.9	23.7	1.57	42.8	32.3	41.7	30.5
Av46High	149.5	10.3	291.1	219.8	268.2	24.9	1.71	48.5	36.6	44.7	31.3

While autonomous vehicles share the road with manually driven cars, and are required to have a licensed driver at all times, they will have a negative effect on congestion, travel times and (probably)

total productivity. This could lead to a reinforcing cycle, where those using AVs will increase congestion for everyone but experience the impacts less themselves; they will be more relaxed in their vehicles, and their electric batteries will use little power when idling. The extra congestion will be suffered more acutely by those in traditional vehicles; they will have the frustration of more frequent stop-start conditions, and pay the extra price of running engines on idle while they wait in queues. This could increase the uptake of autonomous vehicles. Nonetheless, the delays will be unavoidable and will also have an impact on commercial, freight and emergency traffic for whom more pleasant driving experiences account for little.

The effect of increasing AV on average speeds is mixed; the impact of AV is strongest in longer distance trips, and so there is a tendency to differentially increase demand for these trips. Since they involve more travel on higher speed interurban roads they can lead to an increase in average speeds. However more of the road network is congested. Even under cases where the AV adds extra capacity and higher speeds, most of these benefits are more than captured by increased demand on busy roads.

## **The impact of shared AV**

Two scenarios were explored for the shared AV case. Both scenarios have a fully AV fleet, with only a minority of privately owned AVs. The bulk of the fleet (70%) is assumed to be owned by transport operators, and made available to travellers with a per-trip charge. The first scenario assumes 70% of the fleet is shared with only a single booking at any time. The second scenario assumes 40% single-occupant shared AVs (SOSAV) and also 30% multi-occupant shared AVs (MOSAV) allowing multiple simultaneous bookings.

### **Impact on mode share**

The extra charge associated with the use of a shared vehicle is added directly to the cost, which is why this scenario has higher per capita costs, and lower per capita net utility than the standard 2046 High AV scenario. The relatively high marginal cost of shared AV reduces the attractiveness of cars, increasing share in the other modes. This is somewhat misleading, though, since it ignores the savings associated with not having to own a vehicle - these costs are equivalent to per capita costs of \$14 - \$24/day. If these costs are added to all of the other scenarios, then the shared AV case is much cheaper, with a saving in cost of at least \$10/day and an increase in utility of at least \$4.60. The MOSAV has lower dollar costs than the SOSAV but higher perceived value of time; this makes it attractive for people with lower values of time and lower income. This is the market that is particularly served by existing public transport operations. The net result is lower public transport use; similar per capita costs; but higher per capita net utility than the 2046 High Shared AV scenario.

However, the MOSAV still has higher per capita costs, and lower per capita net utility than the standard 2046 High AV scenario since the marginal cost of MOSAV is still higher than owning a private vehicle. As for the previous SOSAV case, the relatively high marginal cost of MOSAV reduces the attractiveness of cars, increasing share in the other modes. Note again that this analysis ignores the savings associated with not having to own a vehicle. Therefore, if these costs were added to all of the other scenarios, then the multi-occupant shared AV case would be the cheapest option.

### **Impact on generalised costs, time and distances**

The per capita distances travelled for both shared scenarios are lower than all other scenarios; even lower than the 2011 base case. This is due to the higher marginal cost of travel; at the moment long car trips are effectively subsidized by annual car ownership. This is because one must buy a car; insure it; register it; and service it; whether or not it is used. This artificially lowers the cost of car

travel; since most of the fixed costs have already been paid, the marginal cost is just the fuel cost and perhaps some wear and tear on tires. One way of looking at this is to consider that some trips are valuable and others are less so. We buy a car because we need to make the valuable trips; once we own it we may as well use it even for less valuable trips, as long as the benefits are higher than the marginal (fuel) cost. In a sense, the high value trips are cross-subsidizing the lower value trips. Under the shared AV case, these cross subsidies are removed; every trip must pay the full cost of travel, including a pro-rata amount for the ownership of the vehicle. This leads to a focusing of travel; the high value trips will still occur but the lower value ones will not. Similar arguments may be made about mode choice; once people are charged the full cost of car travel the other modes look more attractive (hence an increase in PT and active transport in the shared AV cases).

*Table 3: System-wide, and per capita generalised costs, times, distances and net utility by scenario (daily) for the single-occupant and multi-occupant shared 2046 High AV case*

Scenario	$\Sigma$ Cost \$m	$\Sigma$ Hour s m hr	$\Sigma$ PKT m km	$\Sigma$ VKT m km	$\Sigma$ NetU \$m	Cos t \$	Hour s h	PK T km	VK T km	Net U \$	Drivin g Speed km/h
Av46High	149. 5	10.3	291. 1	219. 8	268. 2	24.9	1.71	48. 5	36. 6	44.7	31.3
Av46HighShared	181. 1	7.3	155. 2	130. 6	182. 8	30.2	1.22	25. 9	21. 8	30.5	30.3
Av46HighMultiShare d	182. 3	7.7	176. 2	131. 2	204. 7	30.4	1.28	29. 4	21. 9	34.1	31.2

There is a difference between passenger kilometres travelled (PKT) and vehicle kilometres travelled (VKT). This difference is due to vehicle occupancy; because cars sometimes have multiple occupants there are fewer VKT than PKT. In most scenarios the patterns of vehicle occupancy are largely unaltered so VKT and PKT move together. The MOSAV option increases average vehicle occupancy meaning that more PKT can occur with only marginal increases in VKT. Furthermore, the increased occupancy can lead to lower levels of congestion on key corridors. Moving from a SOSAV scenario to a MOSAV scenario has the following effects:

- reduced monetary costs lead to increased car demand and increases in trip length
- increased occupancy leads to reduced congestion and increased average speeds
- the net effect is to increase car travel with negligible impact on system-wide cost and VKT which results in an increase in net utility

When the ownership costs of private AV is taken into account, the mixed fleet with high proportion of single- and multi-occupant shared AVs leads to the best overall travel outcomes.

## Mobility-as-a-Service (MaaS)

The model used in this analysis considers fully multi-modal travel. MaaS supports a shift away from privately owned vehicles using single- and multi-occupant shared AVs. Public transport services are also a key part of this system; where they cannot be easily accessed by walking, the shared AV can make the use of PT possible. Although without AVs it is possible to drive to PT services, parking is often constrained and the car can only be used at the home end. Privately owned AVs can eliminate the issues with parking but they can still only be used at the home end. Shared AVs allow PT and AV to be used in any combination; in the extreme case travellers may make multiple shifts between AV and PT in a single journey.

The table below de-constructs the use of car and AV to access PT services. It is clear that privately owned AVs reduce the use of PT but the area that is most strongly impacted is long distance travel where many of the services are too far to walk to. The percentage of PT accessed by car (either AV or manually driven) is reduced under the privately owned AV scenarios.

Shared AVs increase overall PT mode share due to the high marginal cost of travel. In addition to this, by incorporating shared AVs within a multi-modal trip PT becomes more attractive. This indicates that increasing use of MaaS can increase PT mode share and lead to better use of line haul PT than a privately owned AV fleet.

*Table 4: Mode share results, including access mode to public transport*

Scenario	Mode share (% of all trips)			PT access mode (% of all trips)		PT Access Mode (% of PT Trips)	
	All Car	All AV	All PT	PT by Car	PT by AV	PT by Car	PT by AV
Base11	81.5%	-	7.8%	2.0%	-	25.2%	-
Base36	79.9%	-	8.6%	2.7%	-	31.1%	-
Av36Mod	71.9%	10.9%	7.1%	1.7%	0.2%	23.6%	3.0%
Av36High	45.7%	38.3%	6.4%	1.0%	0.7%	15.8%	11.5%
Base46	79.1%	-	9.2%	3.1%	-	33.6%	-
Av46Mod	28.6%	55.6%	7.0%	0.8%	1.4%	11.2%	20.6%
Av46High	-	85.2%	6.3%	-	2.1%	-	33.1%
Av46HighShared	-	65.0%	17.0%	-	5.9%	-	34.7%
Av46HighMultiShared	-	68.9%	14.3%	-	5.0%	-	35.3%

## Safety Implications

As a part of the work undertaken for the Department of Transport and Main Roads (TMR), we also looked at the potential safety impacts of connected and autonomous vehicles. It should be noted that throughout this document when we refer to AVs we mean connected autonomous vehicles (CAVs) which will be the focus of this section.

In order to make a preliminary assessment of the likely safety impacts of connected autonomous vehicles, a simple road crash model was prepared. This model used 2009 crash data for Queensland (The Department of Transport and Main Roads 2012) and assumed percentage reductions for each crash type upon the introduction of AVs. The total impact of fatalities and other crash types was calculated by combining the VKT values with the reduction in fatalities/hospitalisations for each scenario. These figures are shown in the table below. There is an increase in fatalities in the base case from 2011 to 2036 and 2046 due to increases in VKT. The moderate 2036 AV case also has increases in fatalities due to increases in VKT. This is partly due to the lower vehicle operating costs that come with electric vehicles and also the low market penetration rates of AV in 2036. In 2046 there is a significant reduction in fatalities due to a higher market penetration of AVs which lead to greater reduction in crashes. Please note that the same factors have been applied for crashes leading to hospitalisation, medical treatment, minor injury and property damage which we have termed 'other crashes' in the above table. However, the proportion of these crash types will be different.

Table 5: Impact of AVs on fatalities and other crash severity types, and total change in crash costs

Scenario	Compared with	Change in Fatalities	Change in Other Crashes	Total cost change (\$m)
Base36	Base_11	58%	58%	\$2,280
Av36Mod	Base_36	16%	16%	\$644
Av36High	Base_36	-14%	-17%	- \$635
Base46	Base_11	78%	78%	\$3,056
Av46Mod	Base_46	-33%	-38%	- \$1,457
Av46High	Base_46	-67%	-74%	- \$2,872
Av46HighShared	Base_46	-88%	-91%	- \$3,538
Av46HighMultiShared	Base_46	-87%	-90%	- \$3,499

We then multiplied the total number of crashes for each crash severity by the estimated average crash costs by severity category from the Austroads Guide to Project Evaluation Part 4: Project Evaluation Data (Austroads 2012) to come up with the total risk cost for each crash type. From there we calculated the total crash cost change for each scenario by applying the change in hospitalisations/fatalities percentage shown above. As shown in the table below there is an increase in crash cost for the base cases and the moderate 2036 AV case due to increases in VKT, as mentioned above. It is not until there is a high market penetration of AVs that we see significant reductions in crash costs. This is because the higher penetration rates lead to a greater reduction in crashes which outweighs the increase in VKT.

## CONCLUSIONS

The initial adoption of autonomous vehicles will increase travel times, increase distances and increase congestion. There will be an increase in car mode share, with reduction in active and PT use. This stage is still associated with a net improvement in perceived costs, however there are many losers (especially those still in manual vehicles). The safety impacts are mixed. The small AV portion of the fleet improves overall network operations which increases overall car demand. Although the AVs are safer, during the transition their benefits are outweighed by the increased risk associated with increased travel in manually driven cars. The net effect is a slight worsening of safety outcomes when AV penetration is low.

A 100% AV fleet running on the current model of private ownership will further decrease active and PT share, and increase overall travel. The congestion impacts of this extra demand are mitigated by capacity improvements made possible by eliminating manual vehicles. The AV fleet increases car demand but this is outweighed by the large safety improvements assumed for the AVs. The net effect is a large improvement in safety outcomes.

Part of the increased demand for car travel comes from the lower operating cost of electric vehicles. AVs based on internal combustion engines would have reduced behavioural impacts due to higher costs, but worse environmental outcomes and lower utility.

Shared AVs change the way that we pay for travel - pay-as-you-go rather than all-you-can-eat. The behavioural impacts for shared AVs are uncertain - we have assumed that people make choices based on the marginal cost of travel. Shared AV will have a lower annual cost than private car ownership, even allowing for high cost vehicles in the shared AV fleet. They will be cheaper for users than even the smallest car - much cheaper if parking is involved. However, the marginal cost of a trip



will be much higher - for local trips it may be 3-4 times as high. Therefore, the higher marginal costs felt by users of a shared AV service leads to lower car demand, more PT and active transport and less congestion. Shared AV would have further benefits for congestion management and effectively provides a proxy for road pricing. Significant safety improvements are derived from the reduced car demand and the much safer vehicles.

Multi-occupant shared AVs allow for more car travel than the single-occupant shared AVs due to their lower dollar cost. The growth in demand is limited to some degree by the higher perceived value of time spent in the company of strangers and the slight operational losses associated with picking up and dropping off the other passengers. Nonetheless, the higher vehicle occupancy allows greater mobility without any significant increase in system cost and safety outcomes.

A mixed fleet with a high proportion of single- and multi-occupant shared AVs leads to the best overall travel outcomes with improved safety; increased mobility; reduced annual cost; and improved synergies with the existing PT system.

The results imply that infrastructure requirements will be somewhat reduced in the long term, however there will be significant congestion in the short to medium term. Therefore, we will need to justify infrastructure spending based on much shorter projected benefit streams. The best approach (as usual) would be to implement road pricing - it could take us over the hump associated with the transition.

The results have shown that things will get worse before they get better. If we operate autonomous vehicles as just improved private cars then we will have significant problems with increased demand and increased congestion. The full benefits of autonomy will not be realised until manual vehicles are removed from most roads. Any a privately owned autonomous fleet would be much less efficient than one with a majority of shared vehicles. We need policies that allow us to move as quickly as possible to a fully autonomous fleet and to shared vehicles/mobility-as-a-service.

## REFERENCES

- Au, Tsz-Chiu, Shun Zhang, and Peter Stone. 2014. "Semi-Autonomous Intersection Management." In *Proceedings of the 2014 International Conference on Autonomous Agents and Multi-Agent Systems*, 1451–2. International Foundation for Autonomous Agents; Multiagent Systems.
- Austrorads. 2012. "Austrorads Guide to Project Evaluation Part 4: Project Evaluation Data."
- Bierstedt, J et al. 2014. "Effect of Next-Generation Vehicles on Travel Demand and Highway Capacity." FP Think Working Group.
- Davidson, Peter. 2011. "A New Approach to Transport Modelling-the Stochastic Segmented Slice Simulation (4S) Model and Its Recent Applications." In *Australian Transport Research Forum*.
- Davidson, Peter, and Anabelle Spinoulas. 2015. "Autonomous Vehicles: What Could This Mean for the Future of Transport?" In *Australian Institute of Traffic Planning and Management (AITPM) National Conference, 2015, Brisbane, Queensland, Australia*.
- Dresner, Kurt, and Peter Stone. 2008. "A Multiagent Approach to Autonomous Intersection Management." *Journal of Artificial Intelligence Research*, 591–656.
- Fagnant, Daniel J, and Kara Kockelman. 2015. "Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations." *Transportation Research Part A: Policy and Practice* 77. Elsevier: 167–81.
- Guterres, J. 2014. "Vehicle Fuel Cost Per Litre - Electricity Vs. Petrol." Nenergy. <http://nenergy.com.au/blogs/news-reviews/11530353-vehicle-fuel-cost-per-litre-electricity-vs-petrol>.

IEEE. 2012. "Look Ma, No Hands!, IEEE Advancing Technology for Humanity News Releases."  
[http://www.ieee.org/about/news/2012/5september\\_2\\_2012.html](http://www.ieee.org/about/news/2012/5september_2_2012.html).

Litman, T. 2015. "Autonomous Vehicle Implementation Predictions: Implications for Transport Planning." Victoria Transport Policy Institute. <http://www.vtpi.org/avip.pdf>.

National Highway Traffic Safety Administration. 2013. "U.S. Department of Transportation Releases Policy on Automated Vehicle Development."  
<http://www.nhtsa.gov/About+NHTSA/Press+Releases/U.S.+Department+of+Transportation+Releases+Policy+on+Automated+Vehicle+Development>.

Shladover, Steven, Dongyan Su, and Xiao-Yun Lu. 2012. "Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow." *Transportation Research Record: Journal of the Transportation Research Board*, no. 2324. Transportation Research Board of the National Academies: 63–70.

The Centre for International Economics. 2014. "2014 Survey of Taxi Drivers and Operators - Preliminary Survey Results for the Sydney Metropolitan Transport District."

The Department of Transport and Main Roads. 2012. "2009 Road Traffic Crashes in Queensland."