AUTONOMOUS VEHICLES - WHAT COULD THIS MEAN FOR THE FUTURE OF TRANSPORT?

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Autonomous vehicles are an emerging technology that is 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 observe their surroundings using technologies such as radar, lidar, GPS, and computer vision; these will be more reliable than the human eye and the system will not be subject to slow human reaction times. 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 counter peak traffic flows. 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. All of these effects are explored in the TransPosition model, and the overall impact on Brisbane's traffic assessed.

1. INTRODUCTION

Autonomous vehicles have long been in the realm, of science fiction, however recent progress means that these driver-less cars will be on our streets in the relatively near future. There is strong competition between newer technology companies (such as Google, Uber and Tesla) and established car companies (such as Mercedes Benz, General Motors, Nissan and many others). Some have been working on autonomous vehicles for years, and there are many working prototypes and trial programs. Obviously there are still aspects of the driver-less car that still need to be refined, and there are many legal, liability, technical and social problems that must be overcome. However, in terms of transport planning into the future, autonomous vehicles should be considered, as they are likely to have significant impacts on travel behaviour and road network operations. This paper will address current progress and direction for autonomous vehicles, what this could mean for the future of transport and the possible analytical approaches to addressing these impacts. It will also include some initial modelling of autonomous vehicle impacts in Brisbane, using TransPosition's 4S Model to see the traffic impacts that could occur. Finally, some comments are made on the likely long term impacts on urban form.

2. BACKGROUND

2.1. History of Autonomous Vehicles

Ever since vehicles were first invented, futurists have been thinking about taking humans out of the drivers seat. Between 1920 and 1980 many efforts had been made by various car companies and Universities to pioneer autonomous vehicles. One of the first demonstrations was a radio-controlled driver-less car in the 1920's. This still required a second car behind to send out radio signals to the transmitting antennae that was installed in the 'driver-less' vehicle in front (The Milwaukee Sentinel 1926). A few decades later, people considered driver-less cars that could be activated by electronic devices embedded in the roadway. This would mean construction of new electronically controlled streets; these were considered in the UK and parts of the US. After early enthusiasm, the funding was withdrawn in both cases.

Since re-designing roads to include electronic railings was expensive, the focus shifted from cars that would operate autonomously on tracks, and on to getting fully automated cars to drive on the existing streets. A mere 20 years later, in the 1980's, Ernst Dickmanns of Bundeswehr University Munich in Germany made this vision seem possible. He and his team at the University managed to alter a Mercedes Benz van to drive autonomously over more than 20 km with top speeds of 96 km/h on an empty highway. By 1989, the robotic van was able to recognise obstacles (limited number detected) and in the 1990's it could perform lane changes autonomously. (Weber, 2014)

Many projects sparked from this first demonstration of a real robotic car able to drive autonomously on ordinary roads. One such event was the famous U.S Defense Advanced Research Projects Administration (DARPA) Grand Challenge held in the desert in 2004, where many teams who were working on autonomous vehicles fought for the $1 million prize. The first year of the DARPA Challenge was not successful for its contenders, with vehicles only travelling a few miles before crashing (Weber, 2014). There was no entrant that could complete the course through the desert with pre-positioned obstacles. The following year, DARPA held another Grand Challenge with more turns and obstacles and were offering double the prize money. This time, five out of the twenty-three entrants made the finish line (Vanderbilt, 2012). DARPA then held the Grand Challenge III in 2007 where they made autonomous vehicles drive through a mock urban environment. Out of the eighty-nine entrants, thirty-five teams were picked to compete in the National Qualification Event. Eleven teams were then picked to compete in the final event, where only six of these teams had vehicles that actually finished the course (DARPA, 2007).

Since the early 2000's, many universities and car companies have been working on improving vehicle autonomy. Although they worked most of the time, sometimes a human driver had to intervene and navigating intersections was difficult (see the next section for discussion on the levels of autonomy). Google is one among many companies that have had success with autonomous vehicles. Improvements are still being made today to get vehicles to operate fully autonomously, whilst making sure safety is maintained, and improved where possible.

2.2. Levels of Vehicle Automation

There are different levels of vehicle autonomy - from complete driver control to completely automated with no driver input. The National Highway Traffic Safety Administration (NHTSA) in America have put forward the following classification for autonomous vehicles (taken directly from NHTSA, 2013).

- **Level 0** (No-Automation): The driver is in complete and sole control of the primary vehicle controls - brake, steering, throttle, and motive power - at all times.
- **Level 1** (Function-specific Automation): Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
- **Level 2** (Combined Function Automation): This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.
- **Level 3** (Limited Self-Driving Automation): Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.
- **Level 4** (Full Self-Driving Automation): The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

In this study we will only be modelling the Levels 3 and 4, where there is little or no input from the human driver. We consider the short to medium term introduction of autonomous vehicles where there will be a mixture of manually driven cars (with increasing degrees of limited autonomy) as we have today, and fully autonomous vehicles.

2.3. Issues still to be addressed

2.3.1. Laws

Currently, trials are underway in a range of jurisdictions - at least 4 states in the U.S. (California, Michigan, Florida, Nevada); a number of European countries (including the UK, Germany, Spain, France, Italy and Belgium); and in Japan and China. In all of these, the laws require a particular application for testing of autonomous vehicles and the vehicles must have a demonstrated operational history and safety plans. Most also require two persons physically present in the vehicle, one of whom is an operator and must be instantly available to take over complete operation of the vehicle if necessary. The insurance and liability issues are reasonably straightforward for this testing phase - the vehicles are generally owned and tested by the company developing the technology, and at all times there is a nominated operator who is responsible for the vehicle.

In order for autonomous cars to be available for general use on public roads, there may need to be some reconsideration of a broad range of laws. The full potential of autonomous vehicles will not be realised until the driver does not need to constantly monitor the operation of the vehicle and take over when necessary. However this will lead to difficulties in defining who is responsible under these conditions, and who is liable for any accidents or injuries. The legal position is even more complicated for vehicles without any driver at all - either unoccupied vehicles, vehicles carrying children, or vehicles where the driver is asleep. Allowing unoccupied autonomous vehicles would give a wide range of benefits, as discussed below, but the social, legislative and insurance changes will be significant.

2.3.2. Technology

Although the technology currently undergoing trials is quite advanced, there is still much to work on. One of the biggest constraints at the moment is the mapping system. For example, Google has mapped approximately 2,000 miles where the autonomous vehicles operates - this mapping is at a much higher level of detail than is used for GPS guidance or other mapping products. The cars have performed so well over this area partly due to the car already having detailed knowledge of its position and surroundings and hence makes only partial real time sensing of external objects. The ability of the Google car to respond to stimuli outside of these already mapped environments has not yet been tested. (Clark, 2015) There is over 6-million km of road across the US, 800,000km in Australia, and 65-million worldwide, and so this mapping would take a lot more work. However, since the vehicles create 3D maps using LIDAR technology, then cars may be able to upload the data to a cloud-service and build an updated database for roads they have not driven on yet.

There are also other problems that the current prototype Autonomous Vehicles face; the Google car cannot yet drive in snow, heavy rain or on ice. It also has trouble with glare from the sun when detecting what colour the traffic lights are. Another problem is that currently the sensors detect external objects just as pixelated shapes and so whether there is a person or a newspaper in front of the vehicle on the road, the car will swerve to miss it. (Clark, 2015)

Finally, an ongoing problem with all technology products is security breaches. There would be significant advantages in allowing over-the-air updates to control systems, so that vehicles can improve their behaviour over time. As discussed above, the system would also want to connect to cloud services to update mapping and current conditions. Both of these have risks, as hackers could cause not just economic damage, but significant loss of life. It may be that the systems will need a locked-down core that can only be updated during servicing, and internal firewalls will be needed to ensure that the core system cannot be externally accessed. Real time mapping updates may be an acceptable risk, as long as the system is intelligent enough to realise that the stored map does not match the sensors. In this case, if the maps are changed maliciously, it would perhaps cause vehicles to stop or drive slowly but not cause unsafe situations. It will be important that the system be intrinsically safe.

2.3.3. Marketability

The main concerns for consumers today are cost, comfort and safety. Obviously for the driver-less cars to be obtainable to the public, costs will have to come down. This will presumably happen once there are many competitors selling autonomous cars, and the manufacturing enjoys economies of scale. Also, people are concerned with the safety of these autonomous cars. Even though computers should prove to be much safer than human drivers, it is likely that people will be much less forgiving of machine error over human error. Obviously it would be near impossible to have no crashes what-so-ever, but the first marketable vehicles will need to be very conservative with their safety decisions to reduce these concerns to the public. This may lead to some reduction in performance, as the early vehicles will probably choose to travel at lower speeds and at higher vehicle spacings than would be achievable with the rapid reaction times of a computer-controlled driver. The manufacturers may have a somewhat nuanced marketing approach, as the early adopters will probably place a higher premium on speed and comfort, but the wider market will need to be convinced of the safety of the vehicles.

2.3.4. Plug-in electric vehicles

There is no reason why autonomous vehicles could not be deployed with a traditional internal combustion engine, but it is likely that the majority of AVs will also be electric vehicles. The reason for this is partly just good timing; autonomous vehicle technology is coming to fruition at the same time as major improvements to battery technology and the first practical fully electric vehicles. But the technologies are also complementary - plug in electric vehicles need more intelligence and higher integration with monitoring and route planning. The need to reduce carbon emissions will also be a key factor, along with a likely disruption to the traditional vehicle manufacturing and distribution chain that may make it easier for new competitors. An example of this is Tesla Motors, which is both an automotive and energy storage company; selling electric cars, electric powertrains and battery products. They plan for all of their models being fully autonomous within 10 years.

There are also possibilities that fully-electric autonomous vehicles could become an important element of an integrated smart electricity grid, where plugged-in vehicles could be used as a temporary storage facility to smooth fluctuations in supply and demand.

In the modelling described later in this paper we will consider both the traditional, and the fully electric case.

2.3.5. Employment impacts

There are many jobs associated with transportation, including truck drivers, taxi drivers and bus drivers. It is likely that at some stage all of these jobs could be eliminated with suitable autonomous vehicles. With some vehicle improvements this could include garbage collectors, postal workers, home delivery drivers, earth movers and mining trucks. Together these account for a huge number of jobs, all of which could be displaced in a fairly short time span.

However the impacts do not stop there. Autonomous vehicles promise to be safe and lawful, with minimal crashes and negligible infringements. This will reduce insurance costs, but also largely eliminate the car insurance and crash repair industries. Along with this will be reduced need for traffic police, parking inspectors, magistrates and lawyers. Once shared autonomous vehicles become widespread, the total size of the vehicle fleet can be massively reduced - some estimate a drop of 90% (PWC, 2015). This will cause huge jobs losses in car manufacturing, car rental, car finance, car retail, petrol stations and all of the other industries that support road transportation. By eliminating the cost of drivers, the economics of transportation change as well - it may be that the shift to larger freight vehicles, for example, could be reversed, with smaller, targeted end-end transport of just-in-time goods. This would lead to reduced road maintenance costs and a potential reduction in wholesaling and storage jobs. Finally, the improvements to road speed, capacity and efficiency are likely to lead to less need for transport infrastructure going forward

- this will mean fewer jobs in road construction, road engineering and (dare I say it) transport planning and modelling!

All of these changes are likely to occur alongside technological disruption in other industries - this is a very pressing question on how we will structure work and society, but it is beyond the scope of this paper. Suffice it to say, that alongside the upsides that are discussed in the rest of this paper, there will certainly be downsides that must be planned for and mitigated.

2.4. How quickly will it happen

The question of how quickly Autonomous vehicles will establish market dominance is difficult, and a range of opinions have been offered. A number of car companies have predicted the fully autonomous vehicles will be on the market within the next 5-10 years - this includes Audi in 2017 (Torr, 2014), Ford in 2020 (Su, 2015), Nissan in 2020 (Nissan, 2013) and Tesla in 2023 (Kaufman, 2014). Google is probably most most advanced, and they plan to have a driverless car in the market by 2018 (Tam, 2012).

How quickly the market will take up these vehicles is unknown, and most projections are done by looking at the growth rate of previous technologies. In 2012, a panel of IEEE members predicted that 75% of the fleet would be autonomous by 2040 (IEEE, 2012). The Victoria Transport Policy Institute (Litman, 2015) predicts a slower uptake - with the 75% market being achieved by 2060. This was based on comparisons with other vehicle technologies, such as automatic transmission, on-board navigation and hybrid vehicles, all of which took several decades to reach significant market capture.

The FP Think Working Group (Bierstedt et al, 2014) acknowledges that there will be a number of factors that will accelerate the market penetration of AV - including very high rewards to the first movers, and the significant improvements to road safety. This leads them to predict that 25% of the fleet will be autonomous by 2035, with 95% penetration by 2040 when possible government mandates, or subscription based transport services are established. They predict that vehicles without a legal driver will be possible by 2050.

These projections are based on the assumption that autonomous vehicles will grow similarly to other vehicle technologies. But there is an argument that they could be more like technology products, which tend to have a much faster uptake profile; Personal Computers took only 20 years to go from first product to 80% coverage (in developed countries). Mobile phones were faster than this at only 15 years, and smartphone are almost at 80% after only 10 years (comScore, 2015). Admittedly these are cheaper devices than cars and generally have a higher turnover rate. But the average age of an Australian car is only 10 years, 40% of cars in Australia are less than 5 years old, and the number of new sales each year is almost 9% of the fleet (based on ABS Motor Vehicle Census and Sales of New Motor Vehicles). If autonomous cars can be made safely and affordably, there is no reason that they could not be taken up at a very fast rate.

Finally, there is good evidence that the rate of new technology adoption is still increasing. The following chart (Felton, 2008) shows the percentage of US houses owning various technological products over the last 100 years. It can be seen that all of the newer products have been taken up at a much faster rate than the older ones. It is at least possible that autonomous vehicles could follow this trend.

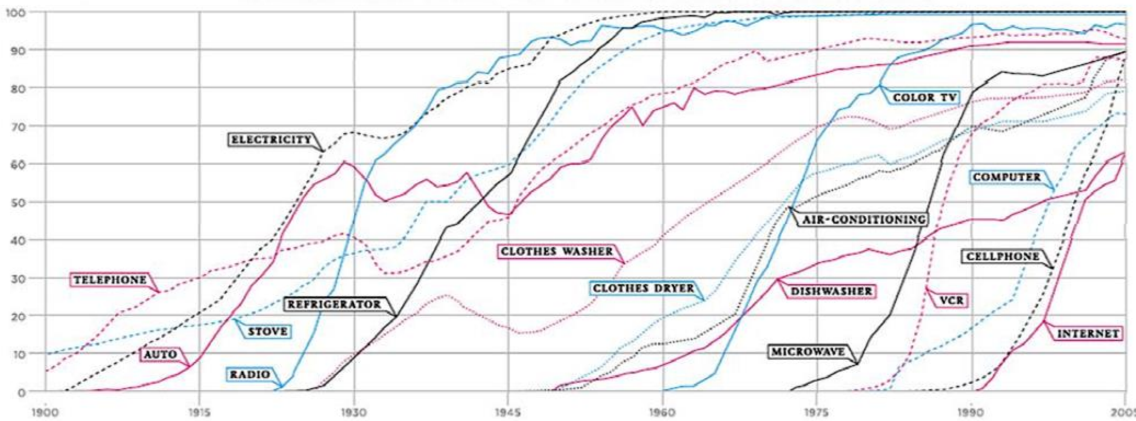

Figure 2.1: The accelerating rate of technology adoption

3. INTRODUCING AUTONOMOUS VEHICLES IN STAGES

When planning for future infrastructure developments, it is common to look 30-50 years ahead, with some projects considered even further into the future. Therefore, although autonomous vehicles are still in the design and testing stages, this advancement in technology cannot be ignored when undertaking infrastructure planning for the future.

This section outlines a possible sequence of stages for the introduction of autonomous vehicles onto our roads, and also the implications each stage has on modelling. All of these stages are concerned with fully autonomous vehicles, so the partial autonomy (adapative cruise control etc) are all assumed to occur before Stage 1. Three stages have been proposed, and are described in more detail in the following sections.

- Stage 1: Mixed vehicles - Fully autonomous vehicles and driver-operated vehicles sharing the road; all vehicles have a dedicated driver who can take manual control
- Stage 2: Mixed vehicles and driverless vehicles - Higher percentage of fully autonomous vehicles than in stage 1; vehicles can travel without drivers
- Stage 3: All vehicles on the road are fully autonomous - manually driven vehicles are excluded

Stage 1 will be the focus of this paper, where all autonomous vehicles introduced onto roads will be privately owned and will not be allowed to drive unoccupied. Modelling work for Stages 2 and 3 is underway, and the authors intend to present the results in subsequent papers.

3.1. Stage 1: Mixed vehicles - Fully autonomous vehicles and driver-operated vehicles sharing the road

In stage 1, there will be a mixture of privately owned Level 3/4 autonomous vehicles and the current privately owned driver-operated vehicles sharing the road. This stage assumes that the autonomous vehicles will be the responsibility of a licensed driver who may take manual control if necessary; this does not consider the case where children, intoxicated people, or unlicensed adults can use the vehicle without a licensed driver. In this stage it is also assumed that the vehicles will not be able to drive without an occupant; thus automated chauffeuring will not be possible, nor will shared vehicles.

The implications of Stage 1 include

- Reduced value of time (VOT) for car travel, due to increased comfort in driving
- Higher trip rates
- Lower vehicle operating costs (for electric vehicles)
- More travel and longer travel, since people place a lower cost on driving time
- Increased congestion due to all of the above

Only a portion of the fleet will be autonomous in Stage 1.

3.2. Stage 2: Mixed vehicles - Higher percentage of fully autonomous vehicles than in stage 1 and also these vehicles

Stage 2 considers a higher percentage of autonomous vehicles on the roads, with the majority of these vehicles privately owned. The key difference in this stage is that the vehicles are not required to have a licensed driver; they can travel unoccupied, or with passengers who previously could not drive independently such as children or those with disabilities that prevent them driving. It will probably also be possible for people to travel in these vehicles whilst intoxicated, or even while sleeping.

Since the vehicles can travel without an occupant, it will be possible for the vehicles to cheauffer passengers to their destination, and then either drive home, or drive to a parking area. It will also allow shared vehicles to operate, where the vehicle will serve multiple passengers, much like an automated taxi.

There will be a mixture of privately owned and shared autonomous vehicles and also still some privately owned driver-operated vehicles on the road at this stage.

At this stage it may also be possible to have autonomous buses, which could allow smaller vehicles and reduce the cost of providing public transport. In fact there could be a continuous spectrum of public transport, ranging from shared cars through to autonomous buses, right up to traditional mass transit.

Possible implications of Stage 2 on modelling are given below.

- Reduced value of time for car travel
- Higher trip rates and and trip length
- Reduced cost of parking
- Re-work parking in the city centre - more parking on the fringe of the city
- More counter-peak-direction traffic
- Increased use of Taxi/Uber etc.
- Increase number of PT services
- More chauffeuring
- Selected autonomous roads with improved capacity

3.3. Stage 3: All vehicles on the road are fully autonomous

Stage 3 considers the time when all vehicles on the road are autonomous. This will occur partly through market forces, including improved comfort, increase safety and reduced insurance costs. But it will also require legislation - to move to a complete AV network it will be necessary to forbid people from driving non-autonomous vehicles.

The benefits from this would be very significant. Assuming that the technology lives up to its promised, a fully autonomous network should have very few crashes. With instance communication and reliable protocols, the vehicles should be able to travel at a higher speed and with increase density (reduced vehicle headway). Better lane tracking could also allow narrower roads, or more lanes on existing roads. It should be possible to eliminate most traffic signals, relying on the vehicles to communicate and provide high throughput with minimal stopping. These changes would lead to vast improvements in road capacity, and reductions in congestion.

Pedestrians will still be an issue, but at high traffic intersections, the pedestrians could still have traditional signals. At other locations, it should be possible for pedestrians to notify their intention to cross the road, either with their mobile phone or with suitable stance and gestures. The vehicles can then allow the pedestrians to cross - vehicle to vehicle communication will ensure that all approaching vehicles are aware of the pedestrian.

A fully autonomous network could also lead to a fully shared autonomous network. This is where huge savings could emerge, with very large reductions in the cost of travel, and with a significant portion of the land area of the city being released for other uses. The savings would come from eliminating most driveways, garages, and car parks, as well as the need for individual capital investment in a vehicle that is unused for most of the time.

In summary, this stage would lead to the following.

- Capacity and speed improvements
- More travel, but less congestion
- Reduced private ownership, with commensurate decrease in costs
- Improved road safety, leading to reduced insurance cost, and savings in medical costs
- Free up road space - narrow lanes, bike lanes, boulevard
- Increase general productivity

4. PREVIOUS ATTEMPTS AT MODELLING AUTONOMOUS VEHICLES

The modelling of autonomous vehicles is a fairly new field of study. Most of the modelling that has been undertaken are micro-simulation type models that look at specific operational questions such as the function of an intersection. Some have looked at the longer term; when all vehicles are autonomous then it may be possible to do away with traffic signals (Au 2014). Other modelling has been done that looks specifically at the impacts of shared autonomous vehicles (SAVs) on a city. Questions such as how many SAVs are needed to fulfil the level of service requirements, and how this might impact on the travel patterns in the city. (Rigole 2014, Spieser 2014)

Some attempts have been made to quantify the impact on total travel patterns, but most of these have been based on simple estimates rather than modelling. An example of this is in Bierstedt (2014), where the overall impact is done by applying assumed market penetration numbers to assumed VKT per capita changes. This was done in a generic fashion, without reference to any specific city.

As far as we can see, there has been little work done at modelling the specific impacts of autonomous vehicles with reference to a full transport model for a particular city. Part of the reason for this is the nature of most transport models, which are calibrated with aggregate behavioural factors that are not easily amenable to fundamental changes. As described in the next section, the 4S model is particularly well suited to investigating changes such as AV, because it is based on a first-principals utility formulation where all parameters can be easily changed.

5. TRANSPOSITION'S 4S MODEL

5.1. Model 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

- Simulation: Uses a traveller/vehicle state-machine with very flexible transition rules to effectively simulate all aspects of travel choice

It differs in many ways from the traditional Four Step Model, and has many compelling advantages over many of the newer models as well.

- It has an elegant, theoretically sound basis that allows for realistic modelling of a very wide range of issues. This includes active transport, mode choice, toll modelling, behaviour change, induced demand and time-of-day analysis.
- Models can be prepared with much less effort and arbitrary coding - by eliminating zones, centroids, and centroid connectors the manual effort in putting networks together is vastly reduced. Also these aspects (zones, centroids and centroid connectors) are somewhat arbitrary abstractions that make the model highly dependent on manual inputs and individual assumptions.
- It is very computationally efficient - by focusing all of the computational effort on tasks that are likely to contribute to the final outcome, and by having a single iterative structure (rather than traditional models' use of a whole range of separate iterations for convergence) complex models can be run with practical run times. As an example of this, TransPosition has applied models of the whole of Queensland at the lot/local street level, and the whole of Australia at the Collection District (CD) and collector road level. A full integrated, multi-modal toll choice model for South East Queensland can be run in around 5 hours.
- Its simple core allows it to be extended to include time choice models, tour-based models, activity models, links to micro-simulation, latent class models and land-use/transport interaction.

More details on the theoretical Basis to the 4S Model, the background and benefits to this approach can be found in a paper presented by Peter Davidson to the Australian Transport Research Forum in 2011 - "A new approach to transport modelling - the Stochastic Segmented Slice Simulation (4S) model and its recent applications."

5.2. Behavioural Assumptions

The 4S model uses a similar approach for modelling both personal travel and commercial travel. In each case the model is based on travellers making decisions that maximise their net utility. The net utility is the utility of their chosen activity at their chosen destination (attraction utility), minus the cost of travelling to that destination. For private travel the attraction utility reflects the satisfaction that people get from being able to undertake an activity at a suitable location; for freight the attraction utility reflects the underlying value of delivering the freight to the destination.

As is usual for utility models, a generalised cost approach is used. A generalised cost approach endeavours to convert all components of travel impedance into dollar cost values. There are three main components of generalised cost; the value of the time spent travelling (including time weights for user preferences and also the time value of freight); the costs of operating the vehicle (including fuel cost, maintenance etc); and any other costs (including fares, tolls, parking etc).

The 4S model allows for taste variation through Monte Carlo simulation. All behavioural parameters, such as value of time, vehicle operating cost, and congestion sensitivity, are specified with random distributions, and the model considers how people will make choices under a range of specific values. The Monte Carlo approach makes it easy to test ranges of values, and to vary some costs for only a portion of the travel market. For the testing of Autonomous Vehicles, this flexibility makes it possible to test a range of assumptions for market penetration and behavioural responses.

6. MODELLING STAGE 1 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 Brisbane. By focusing on a particular city, 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. The 4S model also allows for variable demand, and includes an implicit induced demand component, so changes to transport costs can lead to changes in the overall demand for travel.

Only Stage 1 is considered in this report - it is the easiest to model because it is the most like today. The modelling of driverless cars has some additional complexities, due to the breakdown in the relationship between person trips and vehicle trips. In the existing models this is fairly simple, as one only needs to consider vehicle occupancy and possibly parking locations. Once the vehicle can drop people off, and then continue to a parking location, or return home for other activities, the model needs to consider the vehicle movements separately from the person movements. This becomes even more difficult under a shared vehicle scenario. We are working on extending the 4S model to consider these later stages of development.

The following sections outline the key assumptions made in modelling the impacts of autonomous vehicles.

6.1. Autonomous vehicle market share

For modelling we have assumed a market penetration of 25% in 2021 and 75% in 2031. This is at the higher end of the projected market growth, particularly in the early years, but provides a useful basis for considering the impacts.

6.2. Value of Time

The value of time attempts to include all factors that influence traveller's perception of time - including the opportunity costs (foregone wages or the utility of other ways of spending time) and the desirability of spending time on different travel options. This is implemented in the model by determining a basic value of time, and then multiplying time in different travel stages/modes by varying weights. For example, many people would rather spend 10 minutes driving a car than spend 10 minutes walking so, in general, walking is given a higher cost weight than driving. Because it is the dominant mode, driving is given a weight of 1, and the basic value of time is thus the value of time spent driving.

Autonomous vehicles have the potential to improve the driver's experience. This degree to which the experience will be improved will depend on the Autonomous Level (as defined above). 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 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. For all scenarios we have adopted a range of values, with lower limits and upper limits as given in the scenario table below.

6.3. Trip Rates and Lengths

The model uses a fairly detailed trip purpose breakdown, including highly segmented non-home-based travel. Travel is trip based, with separate trips for the forward and return journeys, and for any substantial stops in multi-stop tours. Trip production is based on trip rates for each market segment - the rates give people's average desired number of trips in a day. If the circumstances are not amenable for the trip (either the costs are too high or the Monte-Carlo selected utility is too low) then travel will not occur. Thus the model has some degree of accessibility-responsive trip rate; strictly it is based on relaxation of suppressed demand rather than induced demand but the overall effect is very similar.

It is assumed that the lower costs associated with autonomous vehicles, along wit improved comfort and reduced stress, will encourage people to travel more often. Under the Stage 1 scenarios being condsidered here, the increase trip rate will be relatively small - we have assumed 10% in 2021. Once the vehicles achieve higher levels of autonomy the impact is likely to be greater - we have assumed 20% in the high case in 2031.

6.4. Vehicle operating costs

As well as testing the impact of autonomous vehicles, we have also considered the likely shift to electric vehicles that will happen alongside automation. Electric vehicles should have a much lower vehicle operating cost than standard internal combustion engine vehicles, particularly in traffic. The reduction is somewhat less when compared with hybrid vehicles, although this could change if carbon pricing returns, or renewable energy costs decrease. Electric vehicles currently have a significant capital cost premium compared with traditional cars, but this is likely to reduce over time as technology improves and economies of scale kick in. Furthermore, there is some evidence that people discount capital costs when making their travel decisions and consider only marginal operating costs. For this reason we have assumed a reduction of 50% in vehicle operating costs for the electric AV scenarios (see Guterres, 2014 for some discussion of the cost differences).

6.5. Capacity

In the early stages, it is possible that the improved reaction time and better tracking could lead to higher speeds and higher traffic densities for autonomous vehicles. However it is unlikely that there would be much improvement when there are still unpredictable and slow manual drivers sharing the road. In fact, there will be some motivation for manufacturers to place a higher premium on safety than human drivers, and so travel slower and further apart. This could be particularly marked on freeways, where much of the traffic operates in a super-critical state, with high speeds and high densities. In the early stages the AVs could actually lower effective capacity on these roads.

For this modelling we have assumed that the capacity remains unchanged.

6.6. Description of Scenarios

Four AV scenarios/years have been considered, along with a do-nothing case for 2011, 2021 and 2031.

Table 6.1: Description of Scenarios

Scenario	AV Share	VoT Range	Trip Increase	VOC Reduction
BS_21_AV1	25%	75% - 95%	10%	None
BS_21_AV1_LowVoc	25%	75% - 95%	10%	50%
BS_31_AV1	75%	50% - 90%	10%	None
BS_31_AV1c_LowVoc	75%	50% - 90%	20%	50%

For simplicity, the do nothing case has an identical network to the 2011 case - this means that it does not include planned improvements, or even under-construction projects like the Legacy Way tunnel. This is clearly not realistic, but keeps the focus of the analysis on the AV impacts. The 2021 and 2031 cases are based on standard population and employment forecasts developed by the Queensland Government.

The lower VOT factor in Elec AV in 2031 to Elec AV in 2021 is to reflect that by the time autonomous vehicles have been on the market for 10 years, it assumed that technology will catch up and drivers will not need to take control of the wheel at any stage during their journey. Elec AV 2031 still assumes that the driver must be present, however they can now multi-task during their entire journey, with only a moderate supervision of the vehicle. Therefore, Stage 1 Elec AV in 2021 assumes Level 3 autonomy and Stage 1 Elec AV in 2031 assumes Level 4 autonomy (these scenarios are still Stage 1 because the driver is assumed to be required still for legal reasons).

7. RESULTS

This section shows outputs for the modelling of stage 1 of autonomous vehicles in TransPosition's 4S Model. These outputs include plots and tabulated data.

The table below shows various output comparisons for each scenario tested in the model. Each scenario listed in the first column has been compared with their respective base cases, mentioned in the second column. The table shows the percentage change in trips, vehicle kilometres travelled (VKT), trip length, vehicle hours travelled (VHT), speed, public transport (PT) and walking/cycling (W/C) mode share.

Table 7.1 Changes in Car travel, and non-car mode shares

Scenario	Comparison	Trips	VKT	Length	VHT	Speed	PT share	W/C share
Base 2021	Base 2011	21.2%	19.8%	-1.2%	27.5%	-6.1%	0.0%	5.9%
AV 2021	Base 2021	2.5%	3.6%	1.1%	4.7%	-1.0%	1.2%	-0.1%
Elec AV 2021	Base 2021	3.1%	15.1%	11.7%	15.1%	0.0%	-2.1%	-3.7%
Base 2031	Base 2011	43.1%	41.4%	-1.2%	60%	-11.7%	3.3%	12.4%
AV 2031	Base 2031	8.1%	14.5%	5.9%	24.1%	-7.8%	-1.6%	-3.3%
Elec AV 2031	Base 2031	-1.9%	31.5%	34%	43.4%	-8.3%	-13.6%	-11%

The table shows that traffic growth due to underlying population employment growth will be strong - without autonomous vehicles the total number of trips network will grow by over 20% to 2021 and 40% to 2031 compared with 2011. These trips are added to the network with only a slight increase in average length so the VKT grows accordingly. Congestion grows at a faster rate than trips or trip length; by 2021 speeds are 6% lower and by 2031 they are almost 12% lower - this ensures that total hours on the network grow very strongly - up by almost 30% in 2021 and 60% in 2031. These increases in congestion shift some demand away from cars - by 2031 the PT mode share has increased by 3.3% and the walk/cycle mode share has increase by over 12% (note that these are percentage increases in the proportions, not absolute percentage point increases).

Once AV are added to the mix, the total car demand increases roughly in proportion to the increase in trip rate and the assumed AV share - with 25% of the fleet being autonomous and a 10% increase in trip rates for AV this leads to a 2.5% increase in car trips. This neat relationship does not hold with the electric autonomous vehicles, as discussed below. While the AVs lead to only a modest increase in trip numbers, they have a more pronounced impact on VKT, and a much more pronounced impact on VHT - although only 8% of trips are added in 2031, the total time on the network increases by 24%. The reason for this is partly that the autonomous vehicle drivers are less concerned with travel times due to their improved comfort, and partly due to the nonlinear congestion response. The PT and active transport mode shares are only slightly changed in 2021, but by 2031 the high penetration rate of AV's has reduced both shares.

Making the AVs electric pushes most of these trends even further - now the drivers are not only less concerned about travel time, but they are also less concerned with travel distance. This leads to very high levels of growth in trip length and thus average VKT - 15% more than the 2021 base case, and 30% more than the 2031 base case. This shows that the electric vehicle effect on trip lengths is of a simililar magnitude to the autonomous vehicle effect. The impact on speeds is less dramatic - the average network speeds under the electric AV case is not much more than the non-electric case. One reason for this could be that the lower vehicle operating costs tends to favour longer distance trips, and these are generally high speed trips on highways. The other reason is that the model is showing that the electric AV case actually leads to a reduction in total car trips, despite the increases in VKT and VHT. This is because the increase in longer distance trips worsens congestion near centres - such as Brisbane's CBD. These shorter trips get a big increase in cost, due to congestion, but only slight reduction in vehicle operating costs since the trips are so short. The response to this is some supression of demand for these shorter, slower trips.

7.1. Volume Differences

This section aims to outline the differences between the base case with no AVs in 2021 and 2031 to the introduction of AVs in 2021 and 2031. This will be represented in the following volume difference plots. These plots show the difference in traffic between two scenarios. They clearly show the way in which traffic has changed due to the introduction of AVs. Red indicates an increase in traffic and blue represents a decrease in these plots. Due to the limited space in this paper only a sample plot is shown here.

The first figure below shows the volume differences for all vehicles between the base case in 2021 and stage 1 of the introduction of electric AVs in 2021 (Elec AV 2021). Recall that here Stage 1 Elec AV 2021 had 25% market penetration of AVs, a range of 5-25% lower VOT than the base case and also a 10% increase in trip rate over the base case. Stage 1 Elec AV 2021 also assumes that all AVs are electric and so a 50% reduction in VOT has been applied (Guterres, 2014). As shown in the plot, generally the traffic is increasing everywhere which is expected given driving has now become more attractive for the 25% of the vehicles that are electric AVs. There seem to be more long distance trips to/from the Gold Coast, Sunshine Coast and Toowoomba since people's VOT has dropped. Roads where there is a decrease in traffic could be due to people switching modes for shorter distance trips when roads become congested, as well as some overall supression of demand for these trips. The biggest increases are on the main long distance highways - the Pacific Motorway, the Bruce Highway, the Gateway Motorway, the Western Freeway/Centenary Highway and the Ipswich Motorway.

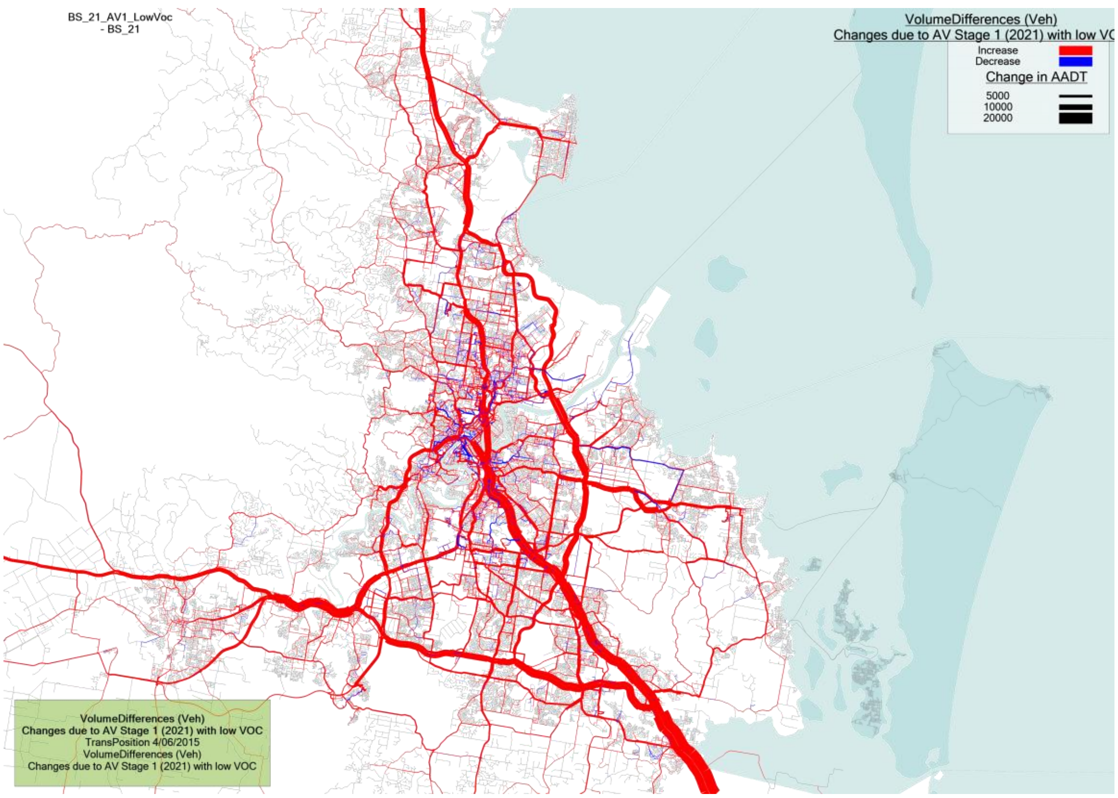

Figure 7.1: Base Case compared with Stage 1 AV in 2021

7.2. Desire Line Differences

The desire line plots show the key demand movements in the model; where traffic is generated and where it is being attracted to. For the purposes of this paper it is useful to compare the differences in demand patterns between the scenarios and so the desire line difference plots have been focused on here. The plots have been broken down into individual market segments. The main ones presented here include desire lines difference plots for cars (commercial and private) and public transport (PT). Note that the desire lines are directional, and show demand from the source to their attractor. The value of the desire lines is that it is easier to understand the key drivers of demand.

Note that the desire lines show demand movements between major urban areas. For demand within an area (intra-urban or intra-regional demand) the plot shows circles whose radius grows with the level of internal demand. In order to avoid unreadable plots, the small level of demand that occurs from place to place is excluded; any demand lower than a threshold is ignored.

The figure below shows the desire line differences for cars between the base case with no AVs compared with Stage 1 electric AV introduction in 2021 (Elec AV 2021). Internal demand has decreased within some centres whereas external demand between centres is generally increasing everywhere. This could indicate that some local trips are getting substituted by longer distance trips to better destinations. That is, people driving AVs no longer care so much about being in the car for a longer period of time to reach a better destination now that driving has become more attractive for them.

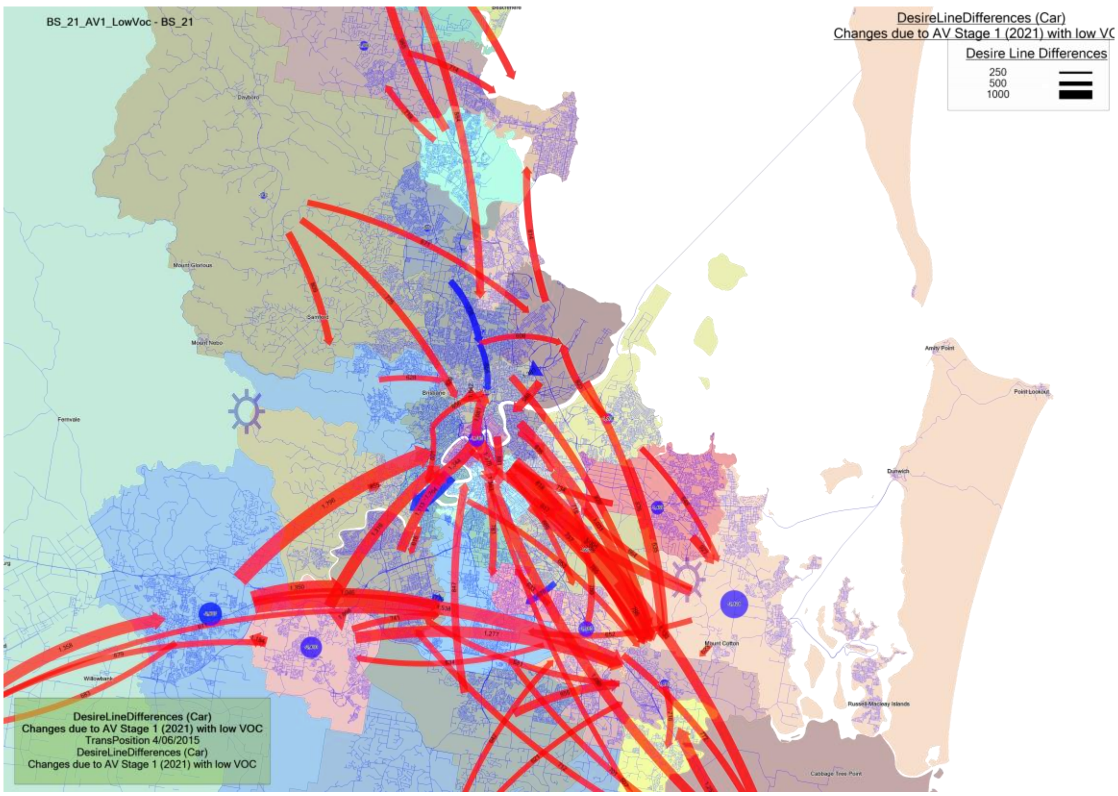

Figure 7.2: Desire line differences for the base case compared with Stage 1 AV in 2021 for cars

8. CONCLUSION

While preliminary, the modelling in this paper shows that Autonomous Vehicles 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 level of impact can be equated with years of growth - the shift to 25% electric AVs is similar to 5 years of population growth, and the shift to 75% is equivalent to around 15 years of population growth.

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 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 accutely by those in tradional 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. These negative impacts will be somewhat offset by the anticipated improvements in road safety.

The big gains in autonomous vehicles will come in the later stages - when they can operate without occupants, allowing automatic chauffering and shared vehicles; and when they can rely on instant communications with a fully autonomous vehicle fleet to increase speeds and reduce vehicle spacing. Although it has not been addresses in this paper, it is likely that the long term picture for a shared, fully autonomous fleet, is very good - with very low congestion, minimal new infrastructure and high productivity. A fully shared fleet could completely transform our cities, allowing both higher densities and improved mobility, and freeing up a huge amount of space in our houses, our yards, our streets, and in our urban centres. It could also significantly reduce resource usage, and the environmental impacts of travel.

The difficulty with this is that things will get much worse before they get better. There will be strong demand for new infrastructure to deal with the large growth in travel demand, and the likely increased mode share to car. However the economic lifetime of much of the new infrastructure will be limited, as the new world of shared autonomous vehicles will not require it. This is an important planning challenge, and clear insight into the likely trajectory of change is crucial.

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