Consideration of the Implications of Tech-enabled Transport on Infrastructure Investment

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EXECUTIVE SUMMARY

The purpose of this report is to identify specific considerations around transport technology enablement that stand to impact on business case development, risk assessment and economic modelling of transportation infrastructure, along with transport planning, design and operation. The findings provided in this report seek to provide guidance on such considerations based on national and international practices and research to identify specific areas where transport agency assumptions could be updated or amended to better reflect anticipated future conditions.

The investigation was undertaken in two parts. Part 1 focused on identifying a list of potential considerations of how greater levels of technology enablement of transport will influence long term infrastructure decision making, both strategic and technical. Part 2 then involved the research partners assessing this list through a 'Materiality Survey' to identify the five key themes for strategic consideration. On request from the project partners, Part 1 is structured in-line with the stated purpose of each of the SBEnrc Core Partner transport-related agencies, including:

- Main Roads Western Australia states its focus as being on delivering value for customers, sustainability, movement and safety, and provides services in the following six categories: Road Safety, Road Maintenance, Road Efficiency, State Development, Road Management and Community Access.
- The Western Australian Department of Transport has a stated purpose to '*provide and enable safe, accessible and efficient movement for the economic and social prosperity of Western Australia*'. As part of this purpose, the Department has the vision '*to have the best integrated and intelligent transport services and solutions in the State*'.
- Roads and Maritime Services NSW has a stated purpose to '*enable safe, efficient and reliable journeys on road and maritime networks to deliver on NSW Government priorities for the transport system*':
    a) *To build, manage and maintain state road and waterway networks and assets,*
    b) *To maximise the customer benefits and service potential of our networks,*
    c) *To seamlessly integrate our networks with private motorways, local roads, and urban and regional communities, and*
    d) *To use our networks to facilitate economic and social development and growth in NSW.*

Based on this the investigation was structured around the three main themes of: Safety and Accessibility; Efficient and Reliable Mobility; and Improved Economic Performance. For each of these themes, a set of considerations was identified as listed below and Part 1 provides a summary of such considerations with specific mention of the possible implications for infrastructure-related investment and ongoing costs.

Safety and Accessibility Considerations

1. Access to mobility services for those unable to drive
2. Increased vehicle occupancy rates
3. Interference from obsolete line marking

Efficient and Reliable Mobility Considerations

1. Traffic smoothing providing a more predictable flow
2. Reduced headway and line of sight requirements
3. Prolonging peak congestion from empty running vehicles
4. Shift to medium sized private and public vehicles (10-12 seats)

Economic Performance Considerations

1. Reduced revenue from Fuel Excise and Registration Fees
2. Impact on car parking space requirements
3. Greater accuracy in vehicle path control affecting lane design
4. Reduced need for signage and signalling
5. Increased reliance on interaction with the electricity grid

In Part 2 of the investigation, these considerations where then mapped to tangible implications for decisions related to long-term infrastructure investment. These implications where then investigated further through a 'Materiality Survey' of representatives from Project industry partners covering three State governments, to consider how material the implications are to investment decisions, with the findings shown in Table 1.

The findings of the investigation suggest that the following considerations stand to be material to such decisions, with the percentage of submissions indicating a 'High' level of materiality shown in brackets:

1. Increase in projected traffic volumes and total vehicle kilometers travelled.
2. Increased maximum highway capacity (from self-driving cars being closer together and better managed).
3. Extended periods of peak congestion from empty running (self-driving vehicles driving around after dropping people off).
4. Reduced need for car parking space in urban areas due to self-driving vehicles.
5. Increased viability and investment in rapid mass transit infrastructure from greater electrification and autonomy.

Part 2 provides a reminder of the context for each of the 5 themes, provides samples of survey responses from partners and then identifies initial areas of strategic consideration to inform infrastructure investment decisions.

Table 1: Summary of Findings from the Materiality Survey

Potential Implications from Tech-Enabled Transport	**High Materiality**	**Medium Materiality**	**Low Materiality**
Safety and Accessibility Considerations			
Access to mobility services for those unable to drive			
- *Increase in projected traffic volumes*	100%	0%	0%
- *Increase in total vehicle kilometre travelled*	71%	14%	14%
Increased vehicle occupancy rates			
- *Increased average occupancy rate of vehicles.*	50%	25%	25%
- *Increased average weight of passenger vehicles.*	0%	43%	57%
- *Reduction in projected traffic volumes.*	50%	17%	33%
Interference from obsolete line marking			
- *Increased requirement for appropriate line marking design, application and maintenance.*	29%	0%	71%
Efficient and Reliable Mobility Considerations			
Traffic smoothing providing a more predictable flow			
- *Less interruption of traffic flow from vehicle collisions.*	29%	43%	29%
- *Less overall speed and related wear on the road surface.*	14%	0%	86%
- *Reduced braking distances required at intersections*	14%	14%	71%
- *Reduced need for roadside barriers and physical safely equipment.*	29%	43%	29%
- *Potential for greater expense for signalling communications.*	29%	71%	0%
Reduced headway and line of sight requirements			
- *Increased maximum highway capacity.*	71%	29%	0%
- *Shorter line of sight distances ahead of signalling.*	0%	50%	50%
- *Shorter breaking distances.*	14%	14%	71%
Prolonging peak congestion from empty running vehicles			
- *Increased average vehicle numbers from empty running.*	100%	0%	0%
- *Extended periods of peak congestion from empty running*	86%	14%	0%
Shift to medium sized vehicles (private and public)			
- *Changes in average vehicle size and weight, a reduction on large busses, increase private vehicles.*	0%	29%	71%
- *Increased viability and investment in rapid mass transit infrastructure to be largely retrofitted into existing transport networks.*	57%	43%	0%
Economic Performance Considerations			
Reduced revenue from Fuel Excise and Registration Fees			
- *Reduced revenue for road agencies from electrification of vehicles.*	71%	29%	0%
- *The need to accurately charge vehicles for distance travelled on particular roads.*	43%	43%	14%
Impact on car parking space requirements			
- *Reduced width of car park spaces required for driverless vehicles.*	43%	29%	29%
- *Reduced need for car parking space in urban areas (vehicle pooling and driverless vehicles).*	57%	43%	0%
- *Increased need for pick-up/drop-off facilities for driverless vehicles.*	29%	43%	29%
Greater accuracy in vehicle path control affecting lane design			
- *Decreased lane width requirements.*	0%	57%	43%
Reduced need for signage and signalling			
- *Reduce need for signage and traffic signals.*	0%	71%	29%
Increased reliance on interaction with the electricity grid			
- *Increased call for vehicle charging equipment to be embedded into the transport network.*	43%	43%	14%
- *Potential for revenue generation by transport agencies from electricity sales.*	17%	33%	50%
- *Greater potential for electrified self-driving mass transit options.*	33%	67%	0%

INTRODUCTION

The development of technologies for both vehicles and transport infrastructure is suggested to be able to provide safer, cheaper, cleaner and faster personal mobility and freight services. However, given the rapid rate of change in this area, it stands to pose both opportunities and risks for transport agencies globally. SBEnrc Project P1.52 '*Tech-Enabled Transport: Informing the Transition to Technology Enabled Transport Vehicles and Infrastructure*'[1] seeks to provide guidance as to how to navigate the transition to technology-enabled vehicles and transportation infrastructure in a manner that maximises the utility of investments and best prepares for the future of mobility. The project focused firstly on identifying current assumptions in partner agencies around the scale and pace of technology enablement of vehicles and infrastructure across all modes. This work then informed consideration, with partners, of how the deployment of integrated technologies into transportation infrastructure is likely to unfold to support passenger, freight and mass transit vehicles of the future.

In particular, the shift to technology-enabled vehicles and transport infrastructure to allow vehicle-to-vehicle (V2V) and vehicle-to-infrastructure data transfer presents significant opportunities that will require a change in the assumptions around transport planning, design and network operation. Hence, the previous relative certainty around assumptions of vehicle use and the growth in number of vehicles are being challenged. There are growing risks that transport infrastructure may not keep pace with changing levels of technology enablement of vehicles, across all modes, and account for a mix of vehicles with differing levels of technology enablement; from those with little to no technology, to vehicles that can communicate with other vehicles and the transport infrastructure itself, to vehicles that do not require drivers or operators. Regulations will play an important role in the emergence and development of technology-enabled vehicles and infrastructure. Authorities around the world are now adapting and rethinking their approaches to regulating the use of technology in transportation in order to avoid conflicts without stifling the innovative uses of these technologies.

The objectives of the project were to:

1) *Identify and Recommend Updates to Assumptions to Inform Transport Planning*: The project identified specific assumptions held by partners around technology transitions (related to vehicles, infrastructure and user interactions) used in business case development, risk assessment and economic modelling of transportation infrastructure, along with transport planning, design and operation. The project interrogated such assumptions based on national and international practices and research to identify specific areas where partner assumptions could be updated or amended to better reflect anticipated future conditions to inform sensitivity testing and future planning.

2) *Identify Specific Recommendations to Support the Tech-enabled Transition:* This part of the project included a review of existing reports and studies related to the policy implications of the increase in technology enablement of vehicles and transport infrastructure, to identify those applicable to the project participants, informed by

[1] SBEnrc Project P1.52: http://sbenrc.com.au/research-programs/1-52/

updated assumptions from Objective 1. It provided guidance as to how specific policies and regulations may be renewed to better underpin the transition to technology-enabled vehicles and transport infrastructure.

3) *Provide Strategic Considerations for Investment*: The final part of the project drew on the findings of the previous two objectives to provide clear guidance on how technology enablement of vehicles and infrastructure is likely to transition in the coming decade and the implications for risk management and infrastructure investment.

In the last decade there has been a rapid increase in the level of technology embedded in both vehicles and transport infrastructure. This process began to pick up speed with innovations such as designing cars that can park themselves, freeway cameras that can detect vehicle types and speed, and greater computerisation of vehicles to assist with driving and detecting maintenance issues. Nowadays, the race is on to design a vehicle that is self-driving regardless of the interconnectivity of the transport network around it, by using extensive on-board sensors and computational capacity.

As this technology finds its way on to public roads it will begin to impact on the type of infrastructure that is needed in the future. On the one hand, such technology may mean we can remove signs, roadside barriers, stoplights, etc. and cars will optimise their travel pathways moving between lanes seamlessly, on the other hand we may have a fleet of empty cars (so-called 'zombie cars') protected from pedestrians and cyclists while they drive around filling up the road network and causing greater congestion and pollution issues.

PART 1: IMPLICATIONS FOR INFRASTRUCTURE INVESTMENT AND PLANNING

Given the level of technology enablement is increasing dramatically in vehicles with the promise of driverless vehicles, the state of road infrastructure will play a key role in their performance. According to Austroads, '*Existing road infrastructure will need to support a mixed fleet of vehicles with differing levels of automation across a range of vehicle classes'*.[2] The following considerations outline a number of areas where technology enablement of vehicles has implications for decisions around infrastructure investment, based on the three main themes described above.

Safety and Accessibility Considerations

Access to mobility services for those unable to drive

Greater levels of technology enablement of vehicles, in particular self-driving vehicles, will allow greater access to mobility services for those in the community that are unable to drive due to age, physical conditions, or level of intoxication. For example, according to a 2017 study in Victoria by the Monash Institute of Transport Studies, ridership in private vehicles of the 76+ year old age group would be expected to increase 18.5 percent if they were able to travel in autonomous vehicles. The study also found that the 18-24 year old age group could increase ridership by up to 14.6 percent and the 12-17 age group could increase by 11 percent.[3]

Potential implications for transport infrastructure investment decisions:

- *Increase in projected traffic volumes.*
- *Increase in total vehicle kilometres travelled.*

Increased vehicle occupancy rates

The potential for self-driving vehicles to reduce the cost of ride share services stands to increase the average vehicle occupancy rates of both mass transit and private mobility services. For instance, an early study in Singapore in 2014 suggested that self-driving vehicles offering ride sharing could cost effectively satisfy mobility needs of the city with a fleet a '*third of the size of the current vehicle fleet*'.[4] Results from a study in New Jersey in 2015 suggested that the implementation of self-driving taxis (called an 'aTaxi') could increase average occupancy rates especially during peak hours, if final destinations are close by, and to and from places such as railway stations.[5]

Potential implications for transport infrastructure investment decisions:

- *Increased average occupancy rate of vehicles.*
- *Increased average weight of passenger vehicles.*
- *Reduction in projected traffic volumes.*

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[2] Austroads (2017) *Assessment of Key Road Operator Actions to Support Automated Vehicles*, Austroads, AP-R543-17, May 2017.

[3] Truong, L., De Gruyter, C., Currie, G. and Delbosc, A. (2017) *Estimating the trip generation impacts of autonomous vehicles on car travel in Victoria, Australia*.

[4] Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., and Pavone, M. (2014) *Toward a Systematic Approach to the Design and Evaluation of Automated Mobility on-Demand Systems: A Case Study in Singapore*, *MIT Open Access Articles*, 2014.

[5] International Transport Forum (2015) *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic*, p 10.

Interference from obsolete line marking

Road marking must be visible for drivers in all weather during both day and night.[6] There are standards for a certain amount of luminance and retro-reflectivity for line markings in order for the road markings to be visible and stand out at night for human drivers. However, the requirement for technology-enabled vehicles is not clear, with multiple automakers designing vehicles with differing systems. If the locations of road markings are moved and the old markings are not completely blacked out, given that many vehicle road detection cameras are greyscale these faded markings could be misinterpreted by technology-enabled vehicles and could interfere with the direction of the vehicle, causing safety concerns.[7]

Potential implications for transport infrastructure investment decisions:

- *Increased requirement for appropriate line marking design, application and maintenance.[8]*
- *Identification of standards around the detection of line marking and other signage.*

Efficient and Reliable Mobility Considerations

Traffic smoothing providing a more predictable flow

Greater levels of technology enablement of vehicles and transport infrastructure will allow vehicles to match speeds with the timings of traffic signals to improve efficiency (however, this may require signalling infrastructure to be fitted with communications devices). This will both reduce energy use by vehicles, by travelling at speeds that have the vehicle arrive at or close to the green light, and improve safety due to lower average speeds and less variance in speeds. Further, this stands to reduce energy use and wear and tear on the vehicles associated with stop-starts at signals.[9] Estimates vary between studies, with some suggesting that even a 10 percent share of Adaptive Cruise Control (ACC), a relatively low-tech option, can significantly increase traffic flow stability.[10] Recent field experiments at the University of Illinois have shown the ability to calm traffic flows between signals can be achieved with a market penetration of only 5 percent of vehicles being technology-enabled.[11] However these findings needs to be balanced with other studies that suggest that even a 60 percent uptake would have little effect on traffic flow.[12]

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[6] King, B. (2013) *Roads that cars can read. A Quality Standard for Road Markings and Traffic Signs on Major Rural Roads, Proposals for Consultation*.

[7] Raposo, M., Ciuffo, B., Makridis, M. and Thiel, C. (2017) *The r-evolution of driving: from Connected Vehicles to Coordinated Automated Road Transport (C-ART).*

[8] Catbagan, J., Haratsis, B., Taperell, A., Mees, M. and Burrell, C. (2017) *Thought Leadership Paper Integrated Transport Planning, Australia & New Zealand Driverless Vehicle Initiative*.

[9] Orosz, G. and Stépán, G. (2006) *Subcritical Hopf bifurcations in a car-following model with reaction-time delay*. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 462(2073), pp.2643–2670: Zhang, L. and Orosz, G. (2013) *Designing network motifs in connected vehicle systems: delay effects and stability*. In Proceedings of the ASME 2013 Dynamic Systems and Control Conference. Palo Alto, California, USA: ASME - The American Society of Mechanical Engineers, pp. V003T042A006–V003T042A006.

[10] Kesting, A., Treiber, M., Schönhof, M., and Helbing, D. (2008) *Adaptive cruise control design for active congestion avoidance*. Transportation Research C, 16(6), pp.668–683.

[11] Work, D., Stern, R., Cui, S., Delle Monache, M., Piccoli, B., Seibold, B., and Sprinkle, J. (2017) *Dissipation of stop-and-go waves via control of autonomous vehicles*: Field experiments, 2017.

[12] VanderWerf, J., Shladover, S., Miller, M. and Kourjanskaia, N. (2003) *Evaluation of the Effects of Adaptive Cruise Control Systems on Highway Traffic Flow Capacity and Implications for Deployment of Future Automated Systems*. 81st Annual Meeting of the Transportation Research Board, Washington, DC, pp.78–84.

Potential implications for transport infrastructure investment decisions:

- *Less interruption of traffic flow from vehicle collisions.*
- *Less overall speed and related wear on the road surface.*
- *Reduced braking distances required at intersections.*
- *Reduced need for roadside barriers and physical safely equipment.*
- *Potential for greater expense for signalling communications equipment.*

Reduced headway and line of sight requirements

Greater levels of technology enablement of vehicles will allow vehicles to react faster to their surroundings, especially when receiving signals from the transport infrastructure, and in particular reduce the need for headway between vehicles, or ahead of signalling that is required to allow human reaction times. For instance, considering private vehicles in order to achieve the maximum highway capacities of around 2,200 vehicles/hour, drivers require an estimated 1.63 second headway to account for human reaction time, accounting for approximately 11 percent of the total longitudinal distance for vehicles travelling at 100km/hour.[13] This reaction time is factored into infrastructure design, with Queensland Government estimating a reaction distance of 42 meters, almost half the total stopping distance of 98 meters, for a passenger vehicle travelling at 100km/hour.[14] However, technology-enabled vehicles may have safe headways of as little as 0.5 seconds which will increase the maximum highway capacity.

The platooning, or virtual coupling of vehicles, has the potential to increase vehicle throughput density, traffic flow and lane capacity; however, research suggests this will require V2V communication to be effective[15] and may also present complications for the drivers of non-technologically-enabled vehicles on the road.[16] Estimates show that conservative platooning distances (accounting for an extra 25 percent spacing than required) could more than double normal lane capacity.[17] However, some simulations predict that increased roadway capacity obtained by lower headways will only be achieved when 75% of the cars on the road are autonomous, which is likely to be in the mid- to long-term future (after 2035).[18]

Potential implications for transport infrastructure investment decisions:

- *Increased maximum highway capacity.*
- *Shorter line of sight distances ahead of signalling.*
- *Shorter breaking distances.*

Prolonged peak congestion from empty running vehicles

A potential impact on the road network from greater technology enablement, in particular self-driving vehicles, is that they stand to create a 'secondary demand' on the road network when

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[13] Shladover, S. (2009) *Cooperative (rather than autonomous) vehicle-highway automation systems*. IEEE Intelligent Transportation Systems Magazine, 1(1), pp.10–19.

[14] Queensland Government (2016) *Stopping distances on wet and dry roads*, Queensland Government.

[15] Liang, C.. and Peng, H., (2000) *String stability analysis of adaptive cruise controlled vehicles*. JSME International Journal Series C, 43(3), pp.671–677: van Nunen, E., Kwakkernaat, M., Ploeg, J., and Netten, B. (2012) *Cooperative Competition for Future Mobility*. IEEE Transactions on Intelligent Transportation Systems, 13(3), pp.1018–1025.

[16] Gouy, M., Wiedemann, K., Stevens, A., Brunett, G., and Reed, N. (2014) *Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control?* Transportation Research Part F, 27(B), pp.264–273: Sun, Y. (2016) *Road to autonomous vehicles in Australia: A comparative literature review*.

[17] TECH-FAQ n.d, *Vehicle Platooning*, viewed 24 November 2017, www.tech-faq.com/vehicle-platooning.html

[18] Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L. and Walters, J. (2014) *Effects of Next-Generation Vehicles on Travel Demand and Highway Capacity,* op. cit.

they drive empty between trips. This impact may be mitigated to some extent if the vehicle travels empty only for a short period of time and then displaces the use of another vehicle (for instance if a private vehicle dropped children to school then picked up a customer to make a trip). However, it is also feasible that this may result in an overall increase in the number of vehicles on the road, thereby increasing and prolonging peak congestion. For instance, if a vehicle drives empty to avoid car parking charges by parking at home and then coming back to pick up the traveller, or a vehicle returns home for a cheaper recharging option. A study by the University of Western Australia in 2016 suggested that the number of empty running vehicles depends on the level of penetration of self-driving vehicles, estimating that an additional 20 percent of vehicle numbers can be expected with as little as a 10 percent self-driving vehicle fleet. The study also suggested, however, that this may reduce significantly to 10 percent when the self-driving fleet is at 90 percent.[19]

This finding is in alignment with the findings of a study by the University of Virginia in 2016 that suggested an additional 7 - 14 percent of vehicles can be expected with a 98 percent self-driving fleet.[20] According to a study by the University of Pennsylvania, '*vehicle pricing structures have had the biggest effect on reducing travel time*'.[21] Lawmakers in the State of Massachusetts have forwarded a bill to impose a fee on what they refer to as 'zero-occupancy cars', seeking to implement a per-mile fee of at least US2.5c.[22]

Potential implications for transport infrastructure investment decisions:

- *Increased average vehicle numbers from empty running.*
- *Extended periods of peak congestion from empty running.*

Shift to medium-sized vehicles (private and public)

Greater levels of technology enablement of vehicles leading to self-driving vehicles stands to create a new mode that can largely replace private vehicles and reconfigure mass transit routings and timetabling. Removing the driver from say a bus or a train will significantly reduce the running costs of public transport and allow for smaller more frequent services that stand to increase the use of mass transit.[23] Examples of such systems include the PostBus self-driving shuttle systems which have been tested on a 1.5km circuit since June 2016 in Sion, Switzerland[24] and NAVLY autonomous shuttle buses in Lyon, France.[25] Public perceptions have been positive as seen in a 2017 trial in Las Vegas of self-driving shuttle buses that in an 11 day period had over 3,000 users which deemed the service an overall success.[26]

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[19] Sun, Y. (2016) *Road to autonomous vehicles in Australia: A comparative literature review*. University of Western Australia.

[20] Chen, T., Kockelman, K., and Hanna, J. (2016) *Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions*, In Transportation Research Part A: Policy and Practice, Volume 94, 2016, Pages 243-254, ISSN 0965-8564.

[21]Duranton, G and Turner, M (2011) *The Fundamental Law of Road Congestion: Evidence from US Cities*.

[22]Muoio, D 2017, *Why self-driving cars could be terrible for traffic*, viewed 24 November 2017,

[23] International Transport Forum 2015, *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic*, p 37., viewed 24 November 2017, <https://www.itf-oecd.org/sites/default/files/docs/15cpb_self-drivingcars.pdf>

[24] Post Bus (2016) *Start of public testing of autonomous shuttles,* viewed 25 November 2017, www.postauto.ch/en/news/start-public-testing-autonomous-shuttles

[25] Keolis n.d., *Keolis Trialling Autonomous Shuttles in Lyon*, viewed 24 November 2017, www.keolismiddleeast.com/en/project-description/8/Keolis-trialling-autonomous-shuttles-in-Lyon

[26] Keolis n.d., *Unlimited Mobility,* p 15., viewed 25 November 2017, www.keolis.com/sites/default/files/atoms/files/keolis_autonomous_shuttles.pdf

The short term value of such services is to provide low cost demand responsive last/first mile services to existing public transport options.[27] Longer term, however, they may provide the catalyst that sees large scale investment in rapid mass transit corridors, which also capture land value benefits associated with stations, serviced with a seamless fleet of self-driving shuttles all but eliminating the need for private vehicle ownership in many parts of the world's cities. According to KPMG, the future may see, '*a fleet of compact electric modules capable of seating 10 passengers, which can adapt to the capacity and journey based on the passenger demands. These modules would have the ability to connect and disconnect to other modules as per requirement'*.[28] However, a 2016 survey by the Royal Automobile Club (RAC) found that 30% of commuters in Western Australia would be highly likely to use a private automated vehicle, while a significantly smaller proportion (18%) responded that they would use a shared service.[29]

Potential implications for transport infrastructure investment decisions:

- *Changes in average vehicle size and weight, a reduction on large busses and an increase on private vehicles.*
- *Increased viability and investment in rapid mass transit infrastructure to be largely retrofitted into existing transport networks.*

Economic Performance Considerations

Reduced revenue from Fuel Excise and Registration Fees

The shift to technology-enabled cars stands to reduce revenue for road agencies in two main ways. Firstly, the shift to electrification will see a reduction in fuel consumption that will result in reduced fuel excise revenue which is currently estimated to account for half of the road fees received by state and federal government. Secondly, the shift to hybrid vehicles with smaller internal combustion engines and fully electric vehicles stands to reduce registration revenue that is typically based on the capacity of the internal combustion engine.

Potential implications for transport infrastructure investment decisions:

- *Reduced revenue for road agencies from electrification of vehicles.*
- *The need to accurately charge vehicles for distance travelled on particular roads.*

Impact on car parking space requirements

It is typical for cities around the world to have between five and eight car parking spaces for every car in the city. In Perth, Western Australia for instance, there is on average four parking spaces per person in inner-city areas, and as much as 10 in outer suburb areas.[30] This means that a significant amount of the land in cities is being allocated to parking vehicles which could be used for other purposes.[31] Technology-enabled vehicles are very likely to impact future requirements for car parking. For instance, driverless vehicles will require less parking space for three main reasons. Firstly, driverless vehicles can be parked 15 percent closer together as

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[27] International Association of Public Transport (2017) *Autonomous Vehicles: A Potential Game Changer for Urban Mobility*.
[28] KPMG (2017) *Impact of Autonomous Vehicles on Public Transport Sector*, KPMG International, February 2017.
[29] RAC (2016) *Autonomous Vehicle Survey*, Royal Automobile Club of Western Australia, Perth.
[30] Newman, P., and Kenworthy, J. (1999). *Sustainability and Cities: Overcoming Automobile Dependence*. Island Press.
[31] Anderson, J., Nidhi, K., Stanley, K., Sorensen, P., Samaras, C., Oluwatola, O. (2014) *Autonomous Vehicle Technology: A guide for policymakers*, Rand Corporation, Santa Monica.

space is not required for the opening of doors.[32] Secondly, the vehicle can return to their owner's home or to parking areas outside densely urbanised areas. Thirdly, both driver operated and driverless vehicles may provide pooled mobility-as-a-service offerings meaning that parking may not be required unless the vehicle is out of service. However, in such a scenario there will be a need for pick-up/drop-off areas in urban areas that may require reallocation of parking space to avoid congestion issues.

Potential implications for transport infrastructure investment decisions:

- *Reduced width of car park spaces required for driverless vehicles.*
- *Reduced need for car parking space in urban areas (vehicle pooling and driverless vehicles).*
- *Increased need for pick-up/drop-off facilities for driverless vehicles.*

Greater accuracy in vehicle path control affecting lane design

Vehicles on the road that have higher levels of technology enablement are likely to allow narrower lanes due to greater precision in the vehicle's travel path compared to human drivers, which stands to reduce the cost of road construction and maintenance. A study commissioned by the State of Florida Department of Transportation in 2017 estimated that self-driving vehicles can operate safely in lanes that are as much as 20 percent narrower.[33] In addition, the width of emergency lanes, shoulders, median strips and clear zones could all be decreased (this is assuming complete uptake of automated or connected vehicles).[34] In addition, it is likely that the autonomous vehicles well in the future will be smaller than cars today, calling for even narrower lanes, even accommodating a single or single front and back configuration that halves the lane width requirements.

Potential implications for transport infrastructure investment decisions:

- *Decreased lane width requirements.*
- *Potential for greater vehicle density from single line vehicles utilising half of current lanes.*

Reduced need for signage and signalling

Greater levels of technology enablement of vehicles will mean a reduced need for visual communication, such as signs and signalling equipment, which may revolutionise the look and feel of streets and roads. For instance, navigation requirements will shift from providing street and destination signage to on-board computer navigation which could significantly reduce the amount of signs, delivering both an economic and aesthetic benefit. A study by Florida State University[35] identified a potential secondary benefit of '*decluttering of the streetscape due to signal removal allowing for better wayfinding*'.[36]

Given that vehicles will increasingly be aware of and even communicate directly with other vehicles, this may eliminate the need for intersection signalling with algorithms working out the best flow through the intersection from all directions and directing the vehicles through with

[32] Bertoncello, M. and Wee, D. (2015) *Ten ways autonomous driving could redefine the automotive world*, McKinsey&Company.
[33] Chapin, T., Stevens, L., Crute, J., Crandall, J., Rokyta, A. and Washington, A. (2016) *Envisioning Florida's Future: Transportation and Land Use in an Automated Vehicle World*, p 7. Florida State University Department of Urban & Regional Planning, USA.
[34] Hendrickson, C., Biehler, A. and Mashayekh, Y. (2014) *Connected and Autonomous Vehicles 2040 Vision*. Carnegie-Mellon University. Pennsylvania Department of Transportation, Bureau of Planning and Research, USA.
[35] Chapin, T., Stevens, L., Crute, J., Crandall, J., Rokyta, A. and Washington, A. (2016) *Envisioning Florida's Future: Transportation and Land Use in an Automated Vehicle World*, p 7. Florida State University Department of Urban & Regional Planning, USA.
[36] DeAngelis, J. (2016) *Planning for the Autonomous Vehicle Revolution,* American Planning Association.

minimal disruption to vehicle flow. There are a number of different methods of replacing visual signals in intersections and communicating directly with vehicles being investigated, such as a study at Massachusetts Institute of Technology (MIT) based on the slot-based system[37] used for air traffic landing control and landing. Many of these, however, rely on full saturation of technology-enabled vehicles; however, systems based on a mix of human-driven and self-driving vehicles may alter signal operation in the shorter term.[38]

Potential implications for transport infrastructure investment decisions:

- *Reduced need for signage and traffic signals.*

Increased reliance on interaction with the electricity grid

Along with an increase in the level of technology enablement of vehicles we are seeing an increase in the level of electrification of vehicles which will result in a shift away from fossil fuel based transport fuels. A 2017 study suggests that by 2030 there could be as many as 9 million electric vehicles on the road in the UK, resulting in an extra 8GW of demand at peak times. The report estimates that by 2030 the global energy demand from electric vehicles could be as much as 21 TWh, increasing to 88 TWh by 2050.[39] However, if the demand for transport energy shifts to the electricity grid and the grid is powered with other types of fossil fuels the reductions in greenhouse gas emissions may be reduced. Since the late 1990's, the Rocky Mountain Institute in Aspen Colorado has advocated for vehicles to be part of the urban energy network (vehicle-to-grid[40]) which done well can deliver substantial benefits, such as improved grid reliability. However, as a 2013 study by MIT suggests, if not managed well it could place additional pressure on the electricity grid.[41] To create an impactful benefit to the electricity grid the vast majority of electric vehicles must be simultaneously plugged in and operated as one decentralised storage system.[42] Initial charging data suggests that the majority of owners may not intend to charge vehicles during the day, but self-driving vehicles may charge or discharge intermittently at various locations across the day.[43]

Potential implications for transport infrastructure investment decisions:

- *Increased call for vehicle charging equipment to be embedded into the transport network.*
- *Potential for revenue generation by transport agencies from electricity sales.*
- *Greater potential for electrified self-driving mass transit options.*

[37] DeAngelis, J. (2016) *Planning for the Autonomous Vehicle Revolution,* American Planning Association.
[38] Ilgin Guler, S., Menendez, M. and Meier, L. (2014) *Using connected vehicle technology to improve the efficiency of intersections. Transportation Research Part C: Emerging Technologies*, 46, pp.121-131.
[39] Nationalgrid (2017) *Future Energy Scenarios*, July 2017.
[40] Kempton, W. and Tomić, J. (2005) *Vehicle-to-grid power fundamentals: Calculating capacity and net revenue*, Journal of Power Sources, vol. 144, Issue 1.
[41] Bullis, K 2013, *Could Electric Cars Threaten the Grid?*, viewed 25 November 2017,
[42] Patterson, B. (2015) *Electric Vehicles Drive to Back Up the Grid,* viewed 25 November 2017,
[43] Wood, E. (2017) *Microgrids and Electric Vehicles: How One Will Drive the Other,* viewed 25 November 2017,

PART 2: KEY FINDINGS AND STRATEGIC CONSIDERATIONS

There are many jurisdictions around the world currently updating legislation to allow for the testing and use of automated vehicles, some of these are discussed below.

Theme 1: Increase in projected traffic volumes and total vehicle kilometre travelled

Overview

Should an increase in projected traffic volumes and vehicle kilometres travelled (VKT) result from greater levels of technology enablement of vehicles, this will have a high materiality for transport infrastructure investment decisions. Such increased levels of traffic volume may come from both empty running vehicles, as described in the second theme, and greater access to mobility services for members of the community. Greater levels of technology enablement of vehicles, in particular self-driving vehicles, will allow greater access to mobility services for those in the community that are unable to drive due to age, physical conditions, level of intoxication or other reasons. For example, according to a 2017 study in Victoria by the Monash Institute of Transport Studies, ridership in private vehicles of the 76+ year old age group would be expected to increase 18.5 percent if they were able to travel in autonomous vehicles. The study also found that the 18-24 year old age group could increase ridership by up to 14.6 percent and the 12-17 age group could increase by 11 percent.[44]

Selection of Comments from Respondents

- *If drivers are removed from vehicles, the cost of transport should drop. This should lead to a great deal of induced traffic as many of those who were previously priced out could now afford access. For such improved access to occur, design of vehicles will have to be such that individuals with special needs could access the vehicles without driver assistance.*
- *Driverless vehicles may result in a greater preference for private vehicles and less patronage of public transport.*
- *If unbridled, then it could see 'zombie cars' overwhelming the network. Private driverless cars may lead to sprawl and two extra trips when sending the car home from work. If it is a shared AV this may affect this impact but there are social issues.*
- *There are questions about where empty vehicles are stored; if centrally then it may result in more congestion, if decentralised adjacent to demand points this may reduce the extra traffic… cars may be distributed around the city to reduce unneeded empty running… this is impacted by the ownership model, private owners might want to send it home where public or mobility-as-a-service vehicles (MaaS) could be aggregated and stored.*
- *The level of increase in VKT in an AV future may be dependent on the operating profile/ownership model of the vehicle fleet. For example, impact on VKT may be different depending on whether it is predominately privately owned and operated AVs, or a model where shared vehicles are popularised particularly for commuter trips.*
- *Depends on willingness to share. There is a dearth of data on willingness to share (small) vehicles. Potentially, depends on travel behaviour trends, uptake of MaaS and how the fleet and ride-sharing is 'optimised' to achieve the most efficient network performance and travel times for customers.*

[44] Truong, L., De Gruyter, C., Currie, G. and Delbosc, A. (2017) *Estimating the trip generation impacts of autonomous vehicles on car travel in Victoria, Australia*.

– *Vehicle occupancy is intrinsically linked to cultural preferences of an individual's propensity to share. Noting recent data from Uber suggested that 40% of all Uber trips in San Francisco are shared through UberPool.*

Strategic Considerations

It is recommended that consideration be given to:

1.1 Policy measures to prevent increased traffic volume from empty running.

1.2 Mechanisms to control the storage of vehicles used for multiple transport services.

1.3 How to utilise MaaS offerings to compliment various transit modes and distribute transport demand across the network.

1.4 Policies which promote self-driving vehicles for first and last mile trips to feed mass transit.

1.5 Incentives for shared occupancy and multiple trip vehicle use.

1.6 Better understanding of customer attitudes toward sharing and associated behaviour change mechanisms.

1.7 The relationship between vehicle sharing and trip cost and how to encourage greater use of shared vehicles.

Theme 2: Increased maximum highway capacity

Overview

Greater levels of technology enablement of vehicles will allow vehicles to react faster to their surroundings, especially when receiving signals from the transport infrastructure, and in particular reduce the need for headway between vehicles, or ahead of signalling that is currently required to allow human reaction times. For instance, considering private vehicles, in order to safely achieve the maximum highway capacities of around 2,200 vehicles/hour, drivers require an estimated 1.63 second headway to account for human reaction time, accounting for approximately 11 percent of the total longitudinal distance for vehicles travelling at 100km/hour.[45] This reaction time is factored into infrastructure design, with Queensland Government estimating a reaction distance of 42 meters, almost half the total stopping distance of 98 meters, for a passenger vehicle travelling at 100km/hour.[46] However, technology-enabled vehicles may have safe headways of as little as 0.5 seconds which will increase the maximum highway capacity.

The platooning, or virtual coupling of vehicles, has the potential to increase vehicle throughput density, traffic flow and lane capacity; however, research suggests this will require vehicle-to-vehicle (V2V) communication to be effective[47] and may also present complications for the

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[45] Shladover, S. (2009) *Cooperative (rather than autonomous) vehicle-highway automation systems*. IEEE Intelligent Transportation Systems Magazine, 1(1), pp.10–19.

[46] Queensland Government (2016) *Stopping distances on wet and dry roads*, Queensland Government.

[47] Liang, C.. and Peng, H., (2000) *String stability analysis of adaptive cruise controlled vehicles*. JSME International Journal Series C, 43(3), pp.671–677: van Nunen, E., Kwakkernaat, M., Ploeg, J., and Netten, B. (2012) *Cooperative Competition for Future Mobility*. IEEE Transactions on Intelligent Transportation Systems, 13(3), pp.1018–1025.

drivers of non-technology-enabled vehicles on the road.[48] Estimates show that conservative platooning distances (accounting for an extra 25 percent spacing than required) could more than double normal lane capacity.[49] However, some simulations predict that increased roadway capacity obtained by lower headways will only be achieved when 75% of the cars on the road are autonomous, which is likely to be in the mid- to long-term future (after 2035).[50]

Selection of Comments from Respondents

– *Can fit more cars on the road, but we need to focus on fitting more people on the road.*

Strategic Considerations

It is recommended that consideration be given to:

2.1 The timing of self-driving vehicle saturation on freeways to warrant assumptions around greater capacity.

Theme 3: Extended periods of peak congestion from driving empty

Overview

A potential impact on the road network from greater technology enablement, in particular self-driving vehicles, is that they stand to create a 'secondary demand' on the road network when they drive empty between trips. This impact may be mitigated to some extent if the vehicle travels empty only for a short period of time and then displaces the use of another vehicle (for instance if a private vehicle dropped children to school then picked up a customer to make a trip). However, it is also feasible that this may result in an overall increase in the number of vehicles on the road, thereby increasing and prolonging peak congestion. For instance, if a vehicle drives empty to avoid car parking charges by parking at home and then coming back to pick up the traveller, or a vehicle returns home for a cheaper recharging option. A study by the University of Western Australia in 2016 suggested that an additional 20 percent of vehicle numbers can be expected with as little as a 10 percent self-driving vehicle fleet. The study also suggested, however, that this may reduce significantly to 10 percent when the self-driving fleet is at 90 percent.[51] This finding is in alignment with the findings of a study by the University of Virginia in 2016 that suggested an additional 7 - 14 percent of vehicles can be expected with a 98 percent self-driving fleet.[52] According to a study by the University of Pennsylvania, '*vehicle pricing structures have had the biggest effect on reducing travel time*'.[53] Lawmakers in the State of Massachusetts have forwarded a bill to impose a fee on what they refer to as 'zero-occupancy cars', seeking to implement a per-mile fee of at least US2.5c.[54]

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[48] Gouy, M., Wiedemann, K., Stevens, A., Brunett, G., and Reed, N. (2014) *Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control?* Transportation Research Part F, 27(B), pp.264–273: Sun, Y. (2016) *Road to autonomous vehicles in Australia: A comparative literature review*.

[49] TECH-FAQ n.d, *Vehicle Platooning*, viewed 24 November 2017, www.tech-faq.com/vehicle-platooning.html

[50] Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L. and Walters, J. (2014) *Effects of Next-Generation Vehicles on Travel Demand and Highway Capacity,* op. cit.

[51] Sun, Y. (2016) *Road to autonomous vehicles in Australia: A comparative literature review*. University of Western Australia.

[52] Chen, T., Kockelman, K., and Hanna, J. (2016) *Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions*, In Transportation Research Part A: Policy and Practice, Volume 94, 2016, Pages 243-254, ISSN 0965-8564.

[53] Duranton, G and Turner, M (2011) *The Fundamental Law of Road Congestion: Evidence from US Cities*.

[54] Muoio, D 2017, *Why self-driving cars could be terrible for traffic*, viewed 24 November 2017,

Selection of Comments from Respondents

- *Self-driving vehicles may encourage greater sprawl given that passengers do not need to pay attention to the road and will be open to travelling longer distances.*
- *This may mean more cars on local streets avoiding peak conditions.*
- *This is one of the biggest unknown impacts, what does a car do when it drops someone off at work? This will need to be considered when designing road pricing mechanisms as charging per distance and route choice may the influence empty running.*
- *This calls for prevention through policy measures that are responded to early to avoid large future risk.*

Strategic Considerations

It is recommended that consideration be given to:

3.1 The implications for self-driving vehicles to encourage greater urban sprawl.

3.2 The design of road-pricing mechanisms to discourage empty running vehicles either driving around between 'trips' or temporarily parking in various locations.

Theme 4: Reduced need for car parking space in urban areas

Overview

It is typical for cities around the world to have between five and eight car parking spaces for every car in the city. In Perth, Western Australia for instance, there is on average four parking spaces per person in inner-city areas, and as much as 10 in outer suburb areas.[55] This means that a significant amount of the land in cities is being allocated to parking vehicles which could be used for other purposes.[56] Technology-enabled vehicles are very likely to impact future requirements for car parking. For instance, driverless vehicles will require less parking space for three main reasons. Firstly, driverless vehicles can be parked 15 percent closer together as space is not required for the opening of doors.[57] Secondly, the vehicle can return to their owner's home or to parking areas outside densely urbanised areas. Thirdly, both driver operated and driverless vehicles may provide pooled mobility-as-a-service offerings meaning that parking may not be required unless the vehicle is out of service. However, in such a scenario there will be a need for pick-up/drop-off areas in urban areas that may require reallocation of parking space to avoid congestion issues.

Selection of Comments from Respondents

- *Space can be repurposed for other uses, but linked with a plan for where cars will go on the fringe and how to bring people and goods in and out.*

Strategic Considerations

It is recommended that consideration be given to:

4.1 The revision of mandatory parking requirements and provision for transitioning to lower parking capacity.

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[55] Newman, P., and Kenworthy, J. (1999). *Sustainability and Cities: Overcoming Automobile Dependence*. Island Press.
[56] Anderson, J., Nidhi, K., Stanley, K., Sorensen, P., Samaras, C., Oluwatola, O. (2014) *Autonomous Vehicle Technology: A guide for policymakers*, Rand Corporation, Santa Monica.
[57] Bertoncello, M. and Wee, D. (2015) *Ten ways autonomous driving could redefine the automotive world*, McKinsey&Company.

Theme 5: Increased viability and investment in rapid mass transit infrastructure

Overview

Greater levels of technology enablement of vehicles leading to self-driving vehicles stands to create a new mode that can largely replace private vehicles and reconfigure mass transit routings and timetabling. Removing the driver from say a bus or a train will significantly reduce the running costs of public transport and allow for smaller more frequent services that stand to increase the use of mass transit.[58] Examples of such systems include the PostBus self-driving shuttle systems which have been tested on a 1.5km circuit since June 2016 in Sion, Switzerland[59] and NAVYA autonomous shuttle buses in Lyon, France.[60] Public perceptions have been positive, as seen in a 2017 trial in Las Vegas of self-driving shuttle buses that in an 11 day period had over 3,000 users which deemed the service an overall success.[61]

The short term value of such services is to provide low cost demand responsive last/first mile services to existing public transport options.[62] Longer term, however, they may provide the catalyst that sees large scale investment in rapid mass transit corridors, which also capture land value benefits associated with stations, serviced with a seamless fleet of self-driving shuttles all but eliminating the need for private vehicle ownership in many parts of the world's cities. According to KPMG, the future may see, '*a fleet of compact electric modules capable of seating 10 passengers, which can adapt to the capacity and journey based on the passenger demands. These modules would have the ability to connect and disconnect to other modules as per requirement'*.[63] However, a 2016 survey by the Royal Automobile Club (RAC) found that 30% of commuters in WA would be highly likely to use a private automated vehicle, while a significantly smaller proportion (18%) responded that they would use a shared service.[64]

Strategic Considerations

It is recommended that consideration be given to:

5.1 The potential for mass transit options to compliment road transport and provide seamless journey management that alleviates road user demand and ensures capital deferment in road expansion.

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[58] International Transport Forum 2015, *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic*, p 37., viewed 24 November 2017, <https://www.itf-oecd.org/sites/default/files/docs/15cpb_self-drivingcars.pdf>

[59] Post Bus (2016) *Start of public testing of autonomous shuttles,* viewed 25 November 2017, www.postauto.ch/en/news/start-public-testing-autonomous-shuttles

[60] Keolis n.d., *Keolis Trialling Autonomous Shuttles in Lyon*, viewed 24 November 2017, www.keolismiddleeast.com/en/project-description/8/Keolis-trialling-autonomous-shuttles-in-Lyon

[61] Keolis n.d., *Unlimited Mobility,* p 15., viewed 25 November 2017, www.keolis.com/sites/default/files/atoms/files/keolis_autonomous_shuttles.pdf

[62] International Association of Public Transport (2017) *Autonomous Vehicles: A Potential Game Changer for Urban Mobility*.

[63] KPMG (2017) *Impact of Autonomous Vehicles on Public Transport Sector*, KPMG International, February 2017.

[64] RAC (2016) *Autonomous Vehicle Survey*, Royal Automobile Club of Western Australia, Perth.

CONCLUSION

As this report has shown, the development of technologies for both vehicles and transport infrastructure to provide safer, cheaper, cleaner and faster personal mobility and freight services stands to pose both opportunities and risks for transport agencies in relation to infrastructure investment. Given the range of potential areas of impact outlined in this report, it is clear that greater consideration needs to be given to the implications of such technology. The findings of the 'Materiality Survey' have identified the perceived level of materiality to transport agencies of each of the items and provided a clear mandate for further investigation.