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Parliamentary Inquiry

Monash University Submission 1

Current and future developments in the use of automation and new energy sources in land-based mass transit

December 2018

SUMMARY

The following contribution from Monash University seeks to address the parliamentary inquiry related to the current and future developments of automation of land-based mass-transit vehicles.

The submission has been drawn from relevant literature and the professional knowledge of our cross disciplinary experts and should be read in conjunction with the submission from the Monash University Accident Research Centre (Monash University Submission 2), which focuses on safety concerns related to passengers aboard autonomous mass-transit buses and shuttles and the interaction these autonomous vehicles will have with conventional road users.

The submission begins by considering the extent to which automated trains are currently used and the associated benefits and challenges. In general, the continued growth of driverless trains should be encouraged since there are strong cost reduction and rider service benefits resulting from this technology.

The submission calls for a nationally coordinated approach for the use of automated trains through policy, regulation and standards to encourage mass transit as a response to Australia's booming urban population growth.

The submission then considers the use of driverless buses. In practice few, if any, large scale mass transit services have been provided using this technology. Noting the infeasibility of current battery electric bus systems at present; it seems likely that future technology improvements could reduce recharge time and range capabilities and make battery electric buses feasible. If driverless buses do become feasible in future it might be possible to improve service frequencies in Australia by providing more buses at the same cost due to driver savings.

A major challenge for mass transit automation is the quality and age of Australia's rail and bus infrastructure; Australia's larger cities typically have old legacy railways and unreliable infrastructure. This will have to be renewed to make automation possible.

A further barrier to the effective use of autonomous small buses is the degree to which passengers will share these vehicles with strangers. If sharing does not occur this would be problematic since single occupancy cars are a major cause of congestion in cities.

An overview of the use and cost of alternative fuel options for deployment in buses, including an assessment of capital and operating costs and pollutant impacts, is then provided.

The submission then considers point-to-point transport using autonomous vehicles. Autonomous vehicles may help to alleviate congestion by reducing the overall number of vehicles on roads and parking spaces, however their use will likely increase the number of kilometres driven.

Fixed-route mass transport (bus and train-like services) will remain critical for major corridors, with small autonomous vehicles potentially able to serve as feeder services that cover the first and last miles.

About Monash

As the largest and most innovative university in Australia, Monash University is globally recognised for excellence in teaching and research.

An Australian leader in infrastructure and transport research and policy development, Monash University has a range of world-leading facilities and institutions that drive cross disciplinary research that leads to innovative rail system and public transport solutions both domestically and internationally.

The experts that contributed to this submission are:

- Professor Graham Currie - Chair of Public Transport and Director, Public Transport Research Group, Institute of Transport Studies
- Mr Ravi Ravitharan - Director, Institute of Railway Technology
- Professor Mark Wallace - Distinguished Professor, Faculty of Information Technology

RAIL MASS TRANSIT

Autonomous railways (driverless trains) in cities are now quite common. At the 2018 Singapore International Transport Conference and Exhibition it was claimed that 40% of passenger services in Asian cities use driverless trains. This share has grown considerably over the last decade; the International Association of Public Transport noted a 14% growth in automated metros between 2014 and 2016 in its review of the growth of rail automation (UITP, 2016).

There are a number of benefits of passenger rail automation (sources below cited in Currie G, 2018):

- Lower operating costs - Paris Metro 30% reduction; (Ossent T, 2010)
- Increased capacity:
  - shorter headways - half-length trains running twice the frequency; (Wang et al., 2016)
  - higher speed - shorter terminus turnaround, meticulous speed adherence
  - tighter dwell time
  - Increased vehicle capacity - no driver cabins and associated space, 6% increase; (Ossent T, 2010)
- More reliable and robust - 33% of 5-min delay incidents removed and availability 99-99.9% vs 96-98%; (Melo PC et al. 2011) and (Mohan S, Morrison S, 2013)
- Lower energy use - 30% reduction; (Cox CJ, 2011)
- Increased ridership due to higher frequency; (Graham DJ et al., 2009)
- General safety improvement.

In general, the continued growth of driverless trains should be encouraged since there are strong cost reduction and rider service benefits resulting from this technology.

There are some critical lessons to be learned about the design and management of passengers in driverless urban railways which are important to note for running driverless vehicles on streets:

- Driverless trains adopt platform doors to meticulously manage human interaction with entry/exit to vehicles
- Rail platforms are generally underground or raised; and platforms do not permit any other vehicle of pedestrian interaction with trains
- Streets where driverless buses or cars might operate have none of these protections and are far more complex locations; it is thus far more difficult to operate buses/cars without drivers' safety in these places without a considerable degree of management of passenger interaction.

Opportunities

A national coordinated approach to policy, regulation and standards for the use of automated vehicles in rail

There is an opportunity for a nationally coordinated approach to enhance Australian cities through policy, regulation and standards to encourage mass transit as a response to Australia's urban population growth.

Cities are complex, dynamic and always regenerating. Transport is a critical component of a city's ability to function. Metro rail systems have been the backbone for most smart cities. A bus can take up to 60 passengers. To replace a bus with cars, autonomous or not, it would require additional space on our roads. However, if you substitute cars with a metro rail system, it will be significantly more efficient and more effective in reducing congestion.

Research, Development and Innovation into the use of Autonomous Rail Vehicles in Australia

Automated driverless trains are becoming common in various countries. In Australia, the Office of the National Rail Safety Regulator recently approved Rio Tinto's auto haul of 240 car heavy haul cars. There are a number of opportunities for Australia to lead in the development and implementation of new technologies that will assist operators where automated driverless trains are used, create greater efficiencies and improve safety. The scope includes light rail, passenger rail networks and in the heavy haul freight rail industry.

The opportunities are as follows:

a) Real Time Monitoring of Track Condition and Rollingstock Performance

Drivers have traditionally been the last line of defence to report any track faults. With the removal of drivers in automated driverless trains, continuous real time monitoring of the track infrastructure condition and the rollingstock performance becomes essential to preventing catastrophic incidents and faults from occurring.

Continuous real time condition monitoring, immediate reporting of any deterioration and forecasting of the track's condition before commencement of the service will significantly improve safety and mitigate risks. Proactive decision making related to maintenance requirements and oversight of the effectiveness of maintenance actions will also assist with the increasing passenger utilisation of the mass transit system i.e. throughput.

With developments in technology it is now possible to provide faster and more regular feedback on track condition, and reduce potential risks to railway operations through the use of instrumented revenue vehicles (IRV).

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IRV technology was developed and has been successfully implemented in various leading heavy haul railway operations by Monash University's Institute of Railway Technology. IRV technology is an automated measurement platform which is embedded on standard revenue vehicles. These vehicles are permanently equipped with advanced measuring systems including different types of sensors and logging units to provide continuous feedback on track condition, vehicle dynamics and train operation.

Some of the key features of IRV technology include:

- IRV is highly robust and is embedded in the operation; it is therefore treated as any other wagon in the network operating under harsh railway conditions, and is generally maintained as part of the standard schedules.
- Track condition is measured as part of normal railway operations. Accordingly, there is no downtime which would otherwise be required when dedicated track condition monitoring devices are used.
- Dynamic responses of standard vehicles are measured during normal operating environments including loaded and empty conditions. Track conditions and vehicle responses are correlated, and strategies can be developed to improve system performance.
- Continuous measurement during each loaded and empty run provides frequent information which can be utilised for various short and long term trending analysis, including identifying maintenance effectiveness.
- Accurate sub-metre (within one metre accuracy) track location identification of any track response.
- Additional measuring sensors can be easily added to the platform to monitor various component performances under normal operating conditions.
- The platform can be used to understand underlying system performance. For example, multiple IRV units can be installed on a train to assess the performance improvements after the introduction of new components.

b) Big Data Analysis to assist with planning infrastructure and train movements

Significant population growth in most metropolitan areas of Australia is putting pressure on existing transport infrastructure. In future, this is only likely to increase significantly with forecasts suggesting that Melbourne's population is predicted to almost double to 8 million by 2051 (6.5 million by 2036) and Sydney's population is predicted to grow to 6.4 million by 2036.

A recent study by Infrastructure Partners Australia that used Uber journey times found that the difference between peak and off-peak travel times were growing in most Australian cities. To cope with such challenges, significant planning and investment in public transport will be required to ensure that travel times do not deteriorate further.

An obvious solution is to increase the frequency of public transport, and while there are existing limitations on signalling and power systems that are being addressed, other constraints are likely come in the form of how long it takes for people to board and alight from services. This constraint will intensify as demographics change and the population ages.

Increasing and expanding the reach of services also has significant associated costs. The question then arises as to what activities are likely to give the best value for money across the entire network. This question is not always easy to answer given the data surrounding how passengers use the network is often quite limited.

While smart ticketing systems can provide valuable insight into the number of people using the network, they do not give the complete picture; what passengers do after they have touched-on is largely unknown. There are a number of considerations for planner trying to provision services or expand the network, including:

- Which route or platform do passengers use?
- Do they opt for the fastest path or do they select the one with the least changes?
- Do they take the first available train or do they wait for a less crowded one?
- Do passengers follow service announcements to change platforms for faster travel or do they stay and wait?

Traditionally, passenger counting at railway stations has been done using hand-held counters or via manual customer surveys once or twice a year. Such approaches are generally expensive and time consuming and only provide limited snapshots on the days that the counts/surveys are completed.

Monash's Institute of Railway Technology has developed technologies to use Wi-Fi based technologies to count the number and compute the flow of Wi-Fi enabled devices, and hence by inference people, through the transport system. Smart mobile devices with wireless networking are now ubiquitous. If switched on these devices will look for wireless access points in their immediate vicinity. When Wi-Fi capable devices search for Wi-Fi networks they send out probe requests that contains information specific to the device making the request.

By using sensors that listen for these probe requests, it is then possible to count the number of devices in the immediate vicinity. By extending the system to include a number of sensors it is then possible to measure how people move between them.

c) Simulation modelling

Simulation modelling is one of the most cost effective ways of assessing various operational scenarios. The approach for an automated metro system's vehicle dynamics should be based on the development, validation and application of a vehicle-track interaction model using a Multi-Body Dynamic Simulation (MBDS) software. Monash's Institute of Railway Technology has completed several Metro Rail projects to simulate various scenarios to minimise unexpected behaviour of automated metro trains in the network.

A comprehensive MBDS model should be developed based on design data which would include the following vehicle design characteristics (suspension parameters, dimensions etc.) and the following details:

- Wheel and rail profiles
- Vehicle speed
- Vehicle mass (usually gross condition, but tare may be used if required)
- Track curvature and superelevation
- Track geometry
- Wheel/rail friction conditions (including portions of lubricated, partially lubricated and unlubricated rail section)
- Vehicle traction characteristics.

MBDS simulations will also evaluate traction and friction related concerns and strategies which are critical for automated metro systems. Highly developed agent based passenger flow simulations and the MDDS simulation using seat surface and feet level acceleration values to evaluate human exposure to whole-body vibration will further enhance the understanding of automated metro trains operations.

d) Improved communication with automated train systems using up-to-date communication networks

The ability to directly communicate over 3G/4G mobile and satellite networks greatly increases the defect detection to response time of any infrastructure or rollingstock defects and passenger related issues. Field recordings can be automatically downloaded to the main logging units mounted on the automated metro train, and the data is then remotely transmitted to the remote control centres for decision making.

ROAD MASS TRANSIT

Although there is much media attention and marketing regarding driverless buses, in practice few, if any, large scale mass transit services have been provided using this technology; there may be exceptions including bespoke monorail systems and a few metro based driverless light rail trains which are effectively railways. A number of small buses operate without a dedicated driver in cities; one of the longest running is the Rotterdam Rivium Bus which has been operating since 1999. This vehicle operates in a dedicated managed right of way. More recently a number of very small autonomous buses have been deployed in Australia including the Navya and Easy Mile technologies. These are very low capacity buses operating at very slow speeds almost always with an on-board supervisor who can drive the vehicle if necessary.

An important truth about current deployment of driverless buses is that they not very practical:

- Capacity is too low
- Speeds are too slow to enable an effective mass transit operation (in practice rarely above 10 kph).

A major barrier to addressing these constraints is safety; the vehicles have to drive slowly to avoid unexpected collisions with other users of roads. The answer can be segregation of the right of way of the vehicles or closer management of the road space (as in the Rivium Bus or in all applications of driverless trains).

With the current deployment of low capacity and slow speed buses, the only realistic application is bespoke local access services in low demand areas.

A major benefit of automation for buses/trams is that costs can be reduced without a driver. Driver labour costs typically represent over 60% of all costs of running buses. In Australia public transport bus services rarely cover more than 40% of costs via fare box revenue and hence are subsidised by government. Thus driverless buses, if they could become feasible, might considerably reduce government subsidies. Alternatively, government might decide to reinvest savings into more and better bus services. Currently Australian bus services have very poor service frequencies; in Melbourne the average frequency of service of a bus route is one bus every 30 minutes or so. If driverless buses become feasible it might be possible to improve frequencies by providing more buses at the same cost due to driver savings.

Cost savings resulting from mass transit automation mainly come from removing driver labour. The major implication is redundancies in the public transport workforce. This will need to be managed to ensure the wellbeing and future employment of this workforce in other areas.

Another major concern for automation is the quality and age of Australia's rail and bus infrastructure; the larger Australian cities have very old legacy railways and unreliable infrastructure. This will have to be renewed to make automation possible.

Finally a major barrier to effective use of small bus deployments of autonomous technologies is the degree to which passengers will share these vehicles with strangers. These buses have very small interiors and any sharing would be quite 'intimate', much like the size of a shared maxi-taxi. It is unclear if passengers would share such a vehicle with strangers without the presence of a driver. If sharing does not occur this is a major concern since single occupancy cars are a major cause of congestion in cities; sharing needs to be encouraged not discouraged.

Alternative fuels

The major world trend in mass transit is the consideration of battery electric bus propulsion; however this is by no means a common feature of current world services; rather a number of trials have been in operation. In general current battery electric bus technology is not practical for day to day mass transit operations because:

- Battery recharge times are too long
- The range of distance provided by battery electric power are too short for typical day operations of buses.

There are many deployments of electric buses; notably the vehicles at Schiphol Airport in the Netherlands. However, all these deployments are demonstration services provided at considerably high costs to illustrate the feasibility of electric bus operation. In general, Monash University's Public Transport Research Group (PTRG) research suggests common deployment of even the most advanced current electric bus designs would roughly double the bus fleet requirements in cities to provide the same service levels, largely because two buses are required to replace a current diesel bus.

There is widespread deployment of electric buses in China, however as in the Netherlands, these deployments are supported by very large government subsidies to cover the high costs of electric buses. Recent data suggests electric bus deployment is declining in China as the government has grown concerned about the high and rising costs of subsidies to support them; these subsidies are being reduced affecting demand for electric buses in China.

Having noted the infeasibility of current battery electric bus systems at present, it seems likely that technology improvements can act to reduce recharge time and range capabilities into the future thus making battery electric buses feasible. This is clearly an area the Australian Government should monitor carefully.

PTRG recently reviewed current literature on alternative fuel options for deployment in buses including an assessment of capital and operating costs and pollutant impacts. Here are the major findings:

Cost implications

Santarelli et al. (2003) undertook a comprehensive comparison of four different bus fuel technologies (diesel, natural gas, fuel cell methanol, fuel cell hydrogen) in terms of their energy, social, environmental and economic impacts. Table 1 provides a summary of capital costs for each bus type. The capital cost of fuel cell buses is considerably higher than diesel and natural gas powered buses. Santarelli et al. (2003) note that the first three commercialised Ballard fuel cell buses in 1997 had a capital cost of €1.291 million, but that this cost came down over time as more fuel cell buses were built.

Table 1: Capital cost of different bus types (€ '000)

Bus	Total cost of the bus (k€, 2000)
Compression ignition bus fuelled with Diesel oil	235
Spark ignition bus fuelled with natural gas	264
Bus FC TBB II	467
Bus FC Nebus	362

Source: Santarelli et al. (2003)
Note: Bus FC TBB II = fuel cell methanol; Bus FC Nebus = fuel cell hydrogen

Table 2 provides a summary of operating and maintenance costs for each bus type, excluding fuel costs. The operating and maintenance cost of fuel cell methanol buses is considerably higher than that of other bus types (€20,103/year vs. €11,727 – €13,318/year).

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Table 2: Operation and maintenance costs of different bus types (€/year)

Bus	O&M cost (€/yr)
Compression ignition engine bus fuelled with Diesel oil	13.318
Spark ignition engine bus fuelled with natural gas	13.083
Bus FC TBB II	20.103
Bus FC Nebus	11.727

Source: Santarelli et al. (2003)
Note: Bus FC TBB II = fuel cell methanol; Bus FC Nebus = fuel cell hydrogen

Table 3 provides a summary of fuel consumption costs for each bus type. Fuel consumption costs for natural buses is comparable to that of fuel cell buses (ranging from approximately €12,000 – €23,000/year), while diesel buses have much higher fuel consumption costs (approximately €38,000/year).

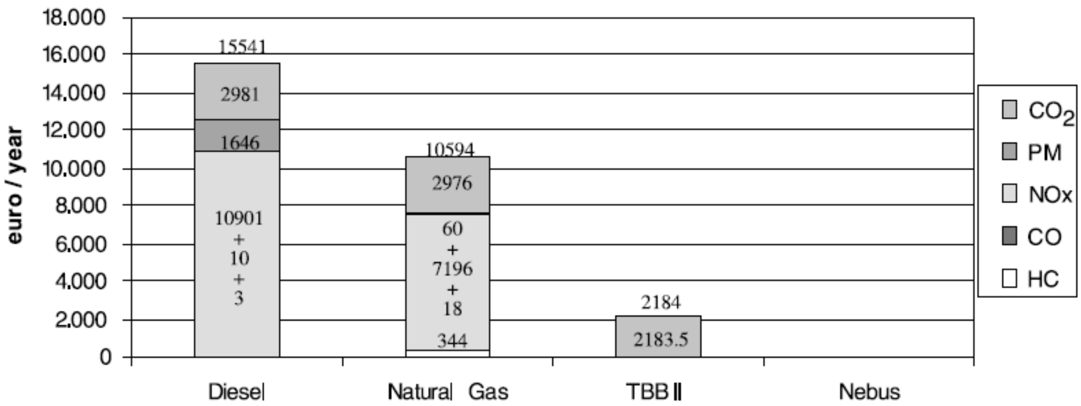
Table 3: Fuel consumption costs of different bus types

Bus	Fuel consumption	Fuel cost	Annual cost increase	Total cost in 12 years	Annual cost
Compression ignition engine bus fuelled with Diesel oil	1.45 km/l	0.832 €/l	5%	460 310 €	38 359 €/yr
Spark ignition engine bus fuelled with natural gas	1.16 km/N m^3	0.378 €/N m^3	3%	228 445 €	19 037 €/yr
TBB II	1.181 km/kg	0.25 €/kg	3%	148 530 €	12 377 €/yr
NEBUS H1	8.842 km/kg	5.67 €/kg	5%	274 471 €	22 873 €/yr
NEBUS H2	8.842 km/kg	7.16 €/kg	0%	248 599 €	20 717 €/yr
NEBUS H3	8.842 km/kg	2.41 €/kg	3%	191 245 €	15 937 €/yr

Source: Santarelli et al. (2003)
Note: TBB II = fuel cell methanol; NEBUS = fuel cell hydrogen

Figure 1 provides a summary of pollutant emission costs, termed 'social costs' by the authors, for each bus type. As can be seen, diesel and natural gas buses have much higher social costs than fuel cell buses, with fuel cell hydrogen buses having zero pollutant emissions.

Figure 1: Pollutant emission costs (social costs) of different bus types (€/year)



Source: Santarelli et al. (2003)
Note: TBB II = fuel cell methanol; Nebus = fuel cell hydrogen

Table 4 provides a summary of total annual costs for each bus type. Overall, natural gas buses have the lowest total annual cost (€76,835/year), followed by fuel cell hydrogen buses (€80,176/year), fuel cell methanol buses (€93,587/year), and then diesel buses (€96,805/year).

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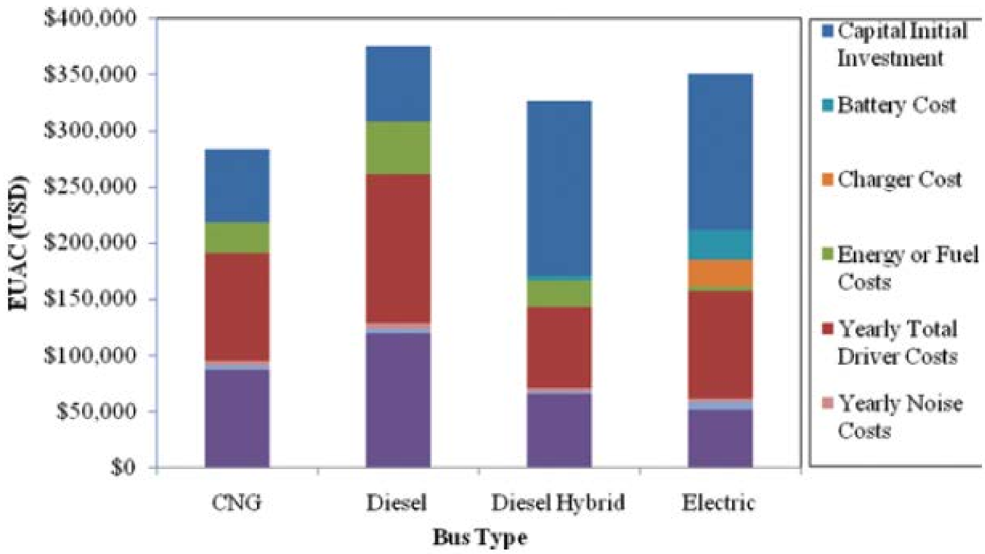
Table 4: Total annual costs of different bus types (€/year)

Base case	Compression ignition Diesel oil	Spark ignition Natural gas	FC TBB II	FC NEBUS
Bus cost (€)	235.000, 0	271.000, 0	468.000, 0	362.000, 0
Life (year)	12	12	12	12
Tax of interest	0.070	0.070	0.070	0.070
Capital recovery (€/year)	29.587, 0	34.119, 4	58.922, 1	45.576, 5
Maintenance cost (€)	13.318, 3	13.083, 7	20.103, 0	11.726, 8
Annual fuel consumption (l,N m^3, kg)	33.103, 4	41.343, 7	40.643, 5	32.520, 0
Fuel unit cost (€)	0.832	0.378	0.250	0.505
Annual increase tax for fuel	0.050	0.030	0.030	0.050
Fuel cost (€/year)	38.359, 2	19.037, 1	12.377, 5	22.872, 6
Partial cost (€/year)	81.264, 4	66.240, 3	91.402, 6	80.175, 9
Social cost (€/year)	15.540, 9	10.594, 2	2.184, 4	0, 0
Total cost (€/year)	96.805, 3	76.834, 5	93.587, 0	80.175, 9

Source: Santarelli et al. (2003)
Note: FC TBB II = fuel cell methanol; FC NEBUS = fuel cell hydrogen

Similar to Santarelli et al. (2003), Wang and Gonzalez (2013) undertook a comprehensive assessment of average annual total costs for different bus fuel technologies, but focused instead on Compressed Natural Gas (CNG), diesel, diesel hybrid, and electric buses. Their results are illustrated in Figure 2 which shows that CNG buses have the lowest average annual total cost, consistent with Santarelli et al. (2003), followed by diesel hybrid, electric and then diesel buses.

Figure 2: Average annual total costs for different bus types



Source: Wang and Gonzalez (2013)

Metro (2010) found that hybrid drive systems can add US$150,000 to US$200,000 to the purchase price of a new bus, but did not find any difference in per-mile maintenance costs. Over a 13.5 year vehicle lifespan, they found that when the upfront purchase price of the vehicle is factored in, Gasoline-Electric Hybrid buses cost about US$230,000 more than Compressed Natural Gas (CNG) buses, or an average annual cost increment of about US$17,000.

Similarly, Lajunen (2014) found that the purchase price of hybrid buses consistently exceeds that of conventional diesel buses. A summary of purchase costs is provided in Table 5.

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Table 5: Comparison of purchase costs of diesel and hybrid buses

Reference	Year	Diesel bus cost	Hybrid bus cost	Data source
Lastauto Omnibus (2013)	2013	222,000€		Mercedes Integro Euro 6
Ahluwalia et al. (2012)	2012	$325,000	$550,000	The data are from a cost analysis by BAE Systems
Feng and Figliozzi (2013)	2012	$368,500	$479,000	New Flyer 60ft diesel and diesel-hybrid buses
Lastauto Omnibus (2012a)	2012		360,000€	MAN Lion's City Hybrid (series hybrid with ultracapacitors) (MAN, 2013)
Nylund and Koponen (2012)	2012	215,000€	330,000€	Cost are estimated
Williamson (2012)	2012	380,000€[a]	488 000€[a]	Diesel bus is Volvo B12 and hybrid bus a series hybrid technology developed by BAE Systems
Zaetta and Madden (2011)	2011	170,000€–250,000€	350,000€	No data source declared
Hallmark et al. (2012)	2010	$367,000	$522,000	Bus specifications from Gillig (parallel hybrid)
Croft McKenzie and Durango-Cohen (2012)	2008	$347,000	$460,000	The data are from National Renewable Energy Laboratory transit bus demonstration projects
Laver et al. (2007)	2007	$350,000	$500,000	Typical purchase costs for 40-foot buses
Clark et al. (2007)	2006	$319,700	$531,600	Costs are the average prices calculated from the 2006 Transit Vehicle Database
Foyt (2005)	2005	$320,000	$500,000	The data were provided by CTTransit
Barnitt (2008)	2004		$385,000	Actual costs at the time of purchase (BAE Systems HybriDrive Gen II)

[a] Original costs are in Australian dollars, an exchange rate of 0.8 was applied.

Source: Lajunen (2014)

Ranganathan (2007) provides a comparison of diesel and diesel-electric hybrid bus fuel and maintenance costs in King County, as shown in Table 6. This shows that while maintenance costs are similar (US$0.44 – 0.46/mi), consistent with findings of Metro (2010), fuel costs are around 20% lower with diesel-electric hybrid buses (US$0.62/mi compared to US$0.79/mi).

Table 6: Comparison of diesel and diesel-electric hybrid fuel and maintenance costs ($US)

King County Transit Parallel Hybrid Bus Operating Costs Comparison		
	Diesel (60-foot)	**Diesel-electric Hybrid** (60-foot)
Fuel ($1.98 per gallon)	$0.79/mi 2.50 mpg	$ 0.62/mi 3.17 mpg
Maintenance	$0.46/mi	$ 0.44/mi
Total	$1.25/mi	$1.06/mi

Source: Ranganathan (2007)

Noel and McCormack (2014) undertook a cost benefit analysis of an electric school buses by comparing it to a traditional diesel school bus. Elements included in the analysis were capital costs, diesel fuel costs, electricity costs and revenues, maintenance costs and health and environmental externalities. Their results suggest that an electric school bus saves $US6,070 per seat and becomes a net present benefit after five years of operation, when compared to a traditional diesel school bus.

In general these findings support the use of alternative fuel vehicles for bus transit but these costs are always changing as technology develops; much of the published literature is a number of years old.

A major flaw in world thinking about electric buses is that current practice is to adopt a diesel bus chassis, remove the diesel engine and replace the engine with an electric engine and battery. This is very short sighted. A more bespoke bus vehicle design is feasible and could have cost and ridership benefits. A recent research paper by PTRG (Currie et al. 2018) explored the impacts of converting part of the Melbourne bus fleet to alternative fuel vehicles. The research identified that:

- Current Conventional Electric Bus designs are impractical in cost-effectiveness terms compared to diesel buses; fleet size increases of 38-82% are found; these are not economically sustainable.
- An Advanced Electric Bus (AEB) design using a bespoke chassis represent a significantly better fleet resource impact but still incur fleet size increases of around 10% compared to diesel.
- Overall all Electric Bus (EB) designs improve ride/noise quality with benefits valued at 26c/passenger trip. Most EB options tested increase ridership; by 1.9% for CEB from ride/noise quality improvements over diesel buses. Most AEB options also have a net ridership increase but this is a net effect balancing ridership decline through in-route recharge delay balanced by ridership growth from ride/noise quality benefits.
- Air conditioning operation significantly increases energy requirements, reducing operating range and requiring greater en-route recharging.

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Overall the research finds significant problems with current investment in EB technologies; fleet impacts of current designs are not economically sustainable and practice needs to focus on new designs with integrated purpose-made chassis and fast-charging lightweight battery packs.

POINT-TO-POINT TRANSPORT USING AUTOMATED VEHICLES

Traffic authorities worldwide take a keen interest in the probable impact of autonomous vehicles, which are projected to have a profound impact on urban mobility. For example, Transport for NSW plans to foster demand-responsive shared services and enable connected automated vehicles in their 40-year plan (The Bureau of Infrastructure, Transport and Regional Economics, 2015).

Researchers and practitioners expect viable, truly autonomous vehicles to be widely available approximately ten years from now, with all major car manufacturers being involved in the development (Chan, 2017).

Congestion is a major problem in larger cities. According to the Bureau of Infrastructure, Transport and Regional Economics, its avoidable cost was $16B in 2015 (The Bureau of Infrastructure, Transport and Regional Economics, 2015). Autonomous vehicles are projected to help alleviate congestion by reducing the overall number of vehicles on roads and parking spaces. Opportunities for speeding up traffic arise from autonomous vehicles to moving in platoons, optimising routes ad hoc and navigating intersections without traffic lights, especially if human driving can be made obsolete.

Autonomous vehicles are already being used for special purposes, such as airport or business park shuttles (Alessandrini, 2015). A last-mile service of autonomous vehicles that mix with conventional traffic was trialled in a number of European cities (Christie et al., 2016). A number of simulation studies have explored the replacement of all privately owned cars, sometimes including bus trips, with a shared autonomous vehicle system (Dia et al., 2017; and Fagnant and Kockelman, 2014; and Martinez et al., 2015; and Martinez and Viegas, 2017; and Zachariah et al., 2014). The authors tend to report reduced congestion, cheaper and faster trips, emissions reductions, less space requirements for reduced parking, equitability of transport, although not necessarily a reduction in overall kilometres driven. The studies tend to report unequivocally positive changes in congestion levels.

Transportation Network Companies (TNCs) like Uber and Lyft allow a glimpse into the possible future of mobility in the age of fully autonomous vehicles, because the ride-hailing services they provide are similar to the ones projected to be serviced by autonomous vehicles. Point-to-point shared or dedicated trips with autonomous vehicles only add convenience and accessibility to the service level of TNCs: travellers do not have to pick up or drop off or drive a vehicle. Trip demand is then likely to increase beyond the mere replacement of trips made now by private car or public transport.

Moreover, the level of service provided by TNCs at present is already leading to an increase in traffic. A recent US study (Schaller, 2018) finds that TNCs have increased road usage by 9 billion kilometres in nine US cities. Shared rides increase the distance travelled by a factor of 2.6 for every kilometre that would otherwise have been covered by a private car. The study explains this by trips that would not have been made without the service and covering distances between lifts. In a survey in the greater Sydney area, 37% of respondents reported having used a ride-sharing service (IPART, 2017). Clewlow and Mishra (2017) reported that there is a strong correlation between the number of ride hails and the reduction of car ownership, but not necessarily a reduction in total kilometres travelled. Wadud et al. (2016) investigated the consequences of cost models and note that the per-trip costing of ride hailing acts as a deterrent but also predict that autonomous vehicle transport will be popular among people who cannot drive or will not drive, such as youngsters or elderly people. The absence of a driver can reduce trip costs by up to 80%, fuelling demand.

A study by the International Transport Forum (2016) demonstrated that replacing all privately owned cars in Lisbon with shared vehicles reduced the number of vehicles but increased the overall number of kilometres by 6.4%. They warn that this is likely to increase to 90% more kilometres if only 50% of all private cars are removed.

Gruel and Stanford (2016) interviewed 30 experts in transportation planning, automotive industry, sharing economy, urban planning and government policy in the US. They found that the attractiveness of not having to drive will likely lead to longer trips and more urban sprawl. The uptake of autonomous vehicles by people not currently driving, empty trips, autonomous vehicles running errands and people currently using public transport is likely to increase traffic loads.

To summarise, studies suggest fully automated self-driving point-to-point transport will increase the number of kilometres driven for the following reasons:

- Additional trips will be made by people unable to use existing transport
- Empty relocation trips have to be made
- The absence of a driver makes travel more affordable
- Removing the strain of driving frees up travellers to complete tasks during trips and makes longer trips more bearable
- Autonomous vehicles may also be used to run errands without passengers.

For point-to-point autonomous vehicle services to deliver on reducing congestion, trips have to be shared. Simulations by the International Transport Forum (2016) of 8-seat and 16-seat on-demand minibuses demonstrate that a reduction in traffic loads is only possible if more than 60% of all private vehicles are replaced by the shared mode. Declining car ownership and the resulting reduction in the need for parking space has no impact on the total travel distance but can improve traffic flow (Rantasila, 2015).

Gruel and Stanford's interviews also suggest that increased efficiency of operation and the opportunity to share autonomous vehicles in addition to using them as a feeder service will help reduce congestion (Gruel and Stanford, 2016). Alessandrini et al. report findings from European studies on urban mobility, most notably the realisation that shared fixed-route 4-seater autonomous vehicles are only likely to be effective inside local and city centres. For most other transits between different service centres, inner and outer suburbs, individual use autonomous vehicles are likely to be effective, as are fixed-route bus services.

Although most sources agree that sharing autonomous vehicles will have a positive effect on congestion and travel times, the extent of the benefit depends on the quality of the routing algorithm and the size of the autonomous vehicle. Assuming point-to-point transport and mobile-app-based ad-hoc as well as pre-booked service requests, additional kilometres arise from detours for pick-ups and drop-offs of new co-passengers.

Excellent routing algorithms for pre-booked services (Kelly et al., 2015; and Ioachim et al., 1995) and ad-hoc additions exist (Xiang et al., 2006), but the more passengers are combined, the larger the proportion of detours is likely to be compared to individual trips. Some trip demands will be common in terms of direction and others rare. Rare types of trip demands are likely best served by autonomous vehicles with small capacities.

In contemporary Australian cities, many people travel from the suburbs to the city for work and therefore share a large part of their routes to work with other people. Diversity of trip demands is likely greatest at the start and end of the journeys, suggesting fewer and smaller vehicles are needed in these parts.

Rather than covering the joint part in between start and end with large point-to-point autonomous vehicles, it appears meaningful to retain fixed-route transport (bus and train-like services) along major corridors, with small autonomous vehicles as feeder services that cover the first and last miles (Kelly et al., 2015).

Alternatively, very small 'stackable' individual-use vehicles that can be assembled into larger 'trains' are a conceivable if radical and expensive option. Travellers are averse to mid-trip mode changes, and this option would eliminate a need for relocation and possible wait times.

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