FINAL REPORT

The Economic Impacts of Connected and Automated Vehicles

Prepared for
Department of Infrastructure, Transport, Regional Development and Communications

2 December 2021

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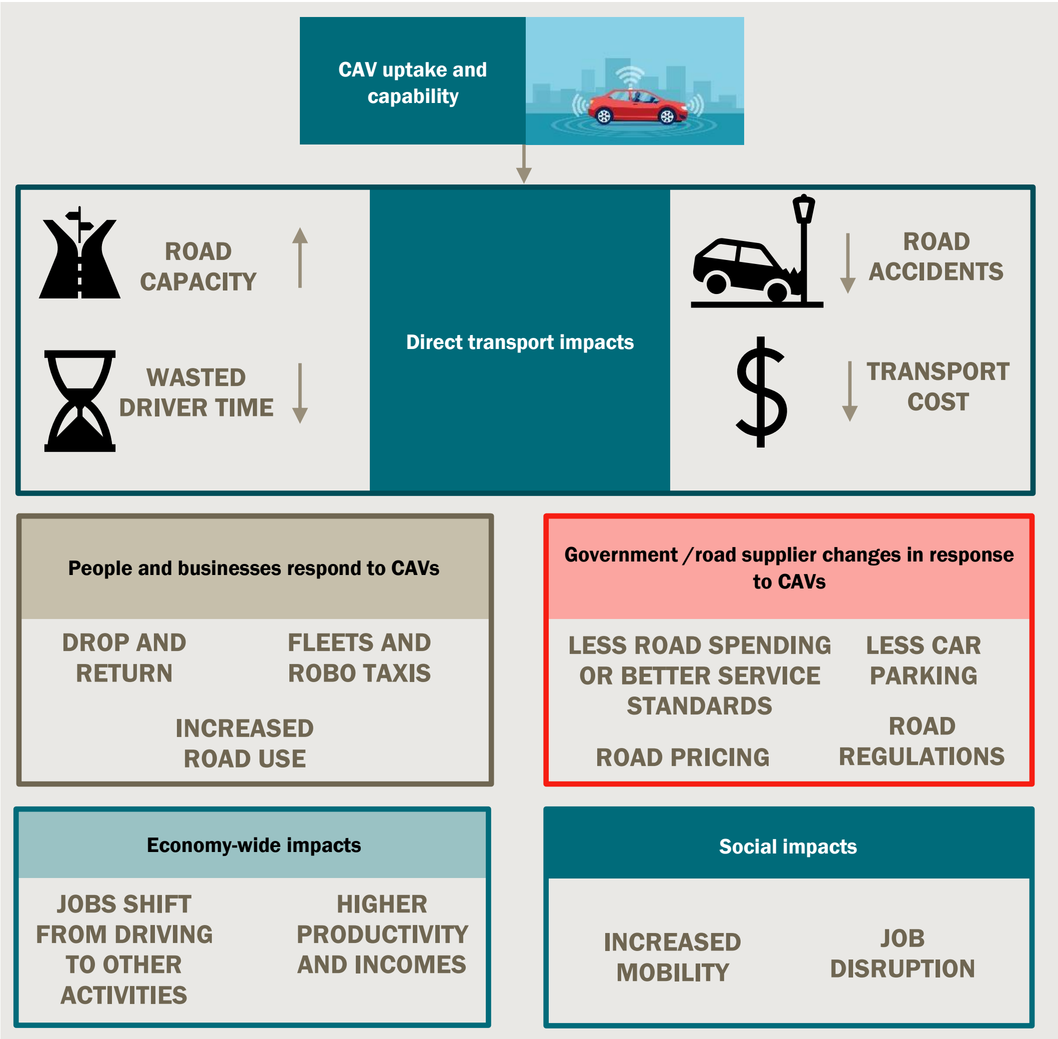
Executive summary

Uptake of connected and automated vehicles (CAVs) would have dramatic impacts on the road transport sector, and through this on the Australian economy and society. Directly, CAVs are expected to reduce road crashes, improve transport productivity through removing the need for a driver, allow people to do other activities instead of driving, (eventually) increase road capacity because more cars can fit on the same road, and improve accessibility for certain groups such as people with disability and elderly people. Indirectly, businesses, people and governments could respond to CAVs in many different ways. The overall picture of CAVs is shown in chart 1.

1 Economic and social impacts of CAVs



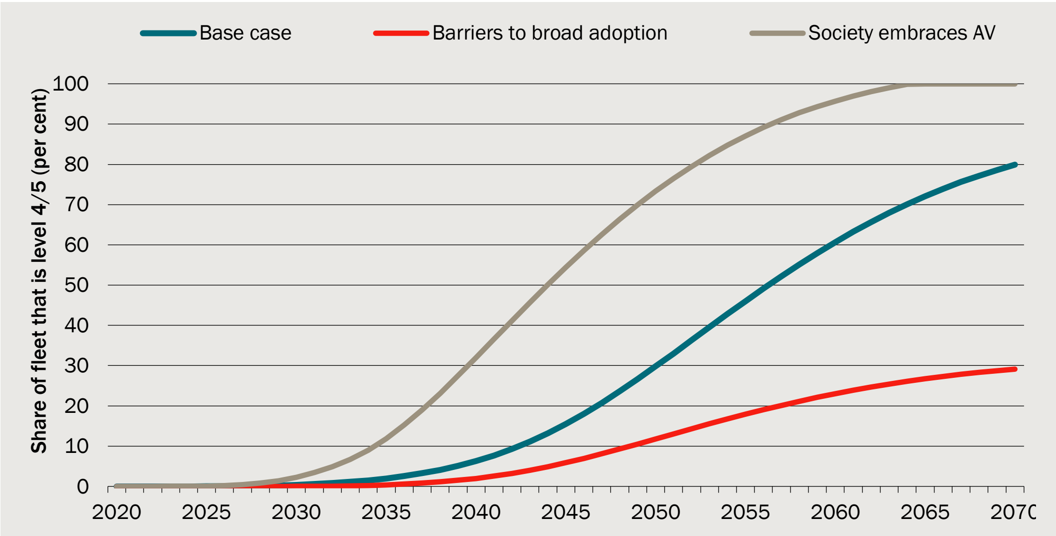
Data source: The CIE.

For this study, CAVs are defined as vehicles that can drive themselves, either completely, or under most circumstances. This aligns to Level 3, 4 and 5 from the Society of Automotive Engineers definitions of automation.[1] Automation and connectedness are expected to occur together for the purposes of this study. While Level 3 (conditional driving automation) forms part of the definition of CAVs, it is excluded from the scope of this study because its expected use case is limited.

Using Bureau of Infrastructure and Transport Research Economics (BITRE) scenarios[2] of possible uptake of CAVs, The CIE and WSP have drawn from the available evidence to quantify the impacts that CAVs could have. For central case estimates of impacts we apply the 'base case' BITRE uptake scenario. We also show results using the 'Society embraces AV' and 'Broad barriers to AV adoption' scenarios developed by BITRE. The expected share of the vehicle fleet that are CAVs under these three scenarios from now until 2070 is shown in chart 2.

- Uptake under all scenarios is low until 2030
- 30 per cent fleet penetration is reached by 2040 under the 'Society embraces AV' scenario, 2050 under the base case, and 2070 under the 'Broad barriers to AV adoption' scenario.

2 Projections of CAVs as a share of fleet under alternative BITRE scenarios



Data source: Bureau of Infrastructure and Transport Research Economics, 2021, *Forecasting uptake of driver assistance technologies in Australia*, advance draft (current as at 15 October 2021) provided by the Department of Infrastructure, Transport, Regional Development and Communications to CIE/WSP.

1 https://www.sae.org/standards/content/j3016_202104/

2 Bureau of Infrastructure and Transport Research Economics, forthcoming, *Forecasting uptake of driver assistance technologies in Australia*, advance draft (current as at 15 October 2021) provided by the Department of Infrastructure, Transport, Regional Development and Communications to CIE/WSP.

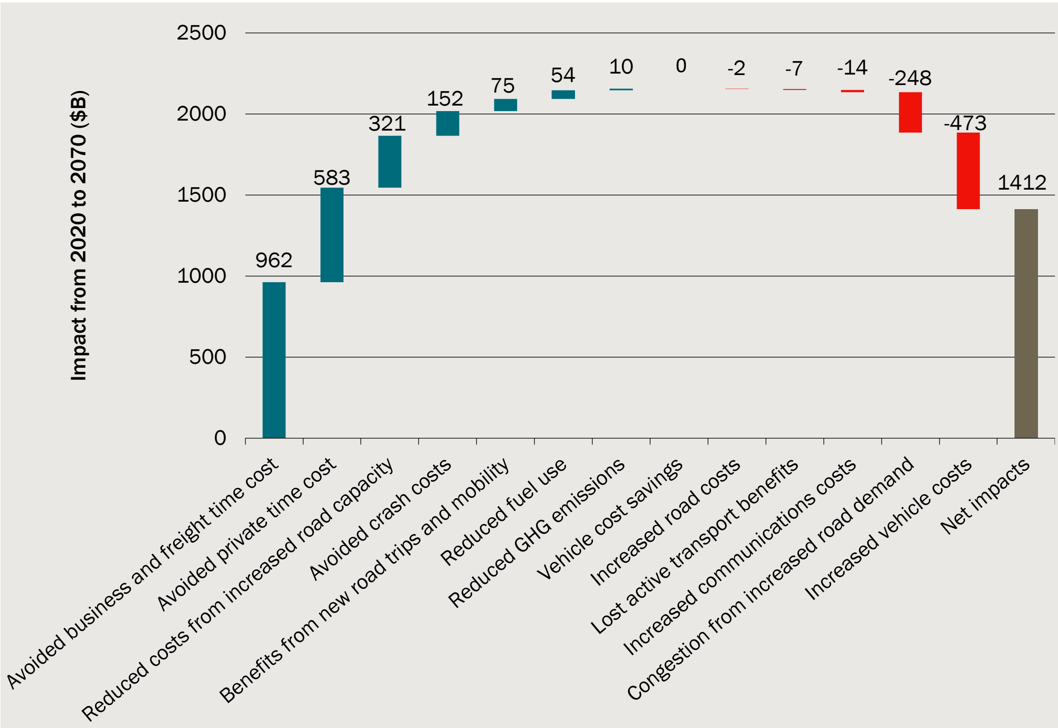
The **eventual impacts from CAVs are expected to be very large**.

- **From 2020 to 2070, CAVs would have a positive net value to the Australian community of $1.4 trillion under the base case uptake scenario. This includes all impacts on the Australian community, some of which would be reflected in Australia's economic performance (such as freight cost savings) and some of which would not (such as reduced road fatalities).**

The estimated impacts under the base case uptake scenario and central case expectations of the impacts of CAVs from 2020 to 2070 are shown in chart 3. From 2020 to 2070:

- reduced crash costs are worth $152 billion, with more than 8000 lives saved,
- reduced transport time costs for private car users as they no longer need to perform the driving task are valued at $583 billion,[3]
- reduced business time costs are almost $250 billion, along with reduced commercial vehicle (including light commercial) and bus time costs of more than $700 billion. Together, business and freight time cost savings are valued at $962 billion,
- reduced fuel use amounts to $54 billion due to smoother driving, and light and heavy vehicle platooning for regional and long distance and travel, and
- lower fuel use leads to less Greenhouse Gas (GHG) emissions worth $10 billion.

3 Benefits and costs from CAVs from 2020 to 2070



Data source: The CIE and WSP.

3 This is based on the number and distance of trips being the same as without CAVs. Benefits from new usage are considered separately.

Transport capacity impacts are also very large. Increased road capacity because CAVs can travel closer together has a benefit of $321 billion over the 50 year period. These impacts would dwarf the impacts of infrastructure investment aimed at increasing road capacity.[4] However, additional road transport demand offsets a large part of this, because with lower transport costs more vehicle demand is expected. This has a cost from re-congesting the road network of $248 billion. There are also some costs related to reduced active transport health externalities of $7 billion.

There are also benefits because of new usage of the road network. These are conservatively valued at $75 billion. This could be higher, particularly for groups with high levels of transport disadvantage, such as the elderly and people with disability.

The large benefits also require substantial costs, primarily for the CAVs themselves. Vehicle-related costs under the base case uptake scenario are $473 billion (above costs of non-CAV vehicles). A further $10-$20 billion is expected in communications infrastructure costs and $2.4 billion in additional road pavement costs.

The **benefits of CAVs are expected to occur towards the back end of the 50-year period considered**. By 2050, the net impacts are $13 billion. From 2051 to 2070, the net impacts are almost $1.4 trillion (table 4).

4 Summary of impacts of CAVs under the central case

Item	2020 to 2070	To 2030	2031 to 2050	2051 to 2070
	$b	$b	$b	$b
Avoided crash costs				
reduced fatal crash costs	43.2	0.0	4.5	38.7
reduced other crash costs	108.6	0.0	10.9	97.7
Transport benefits, CAV users				
reduced private vehicle time cost	583.2	0.0	47.5	535.7
reduced business time cost	251.7	0.0	19.0	232.7
reduced commercial vehicle and bus time cost	710.1	0.1	59.5	650.5
reduced fuel use	54.0	0.0	6.3	47.7
Transport system capacity benefits, current demand				
reduced congestion costs	320.5	-0.1	-55.0	375.6
Other benefits and costs				
changes in GHG emissions	9.8	0.0	1.1	8.6
vehicle cost savings from sharing/freight utilisation	0.0	0.0	0.0	0.0
Impacts of additional road demand				
benefits to new users	74.8	0.0	1.7	73.1

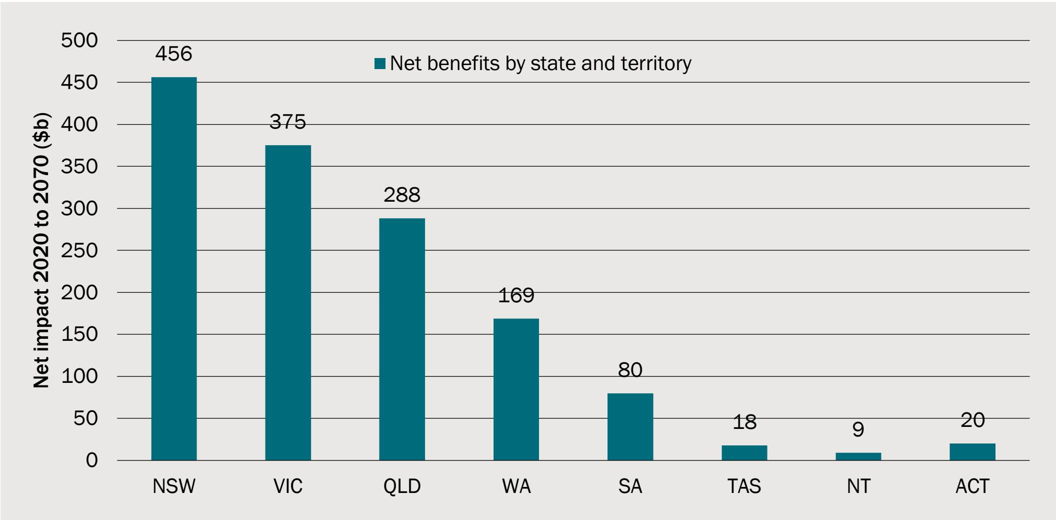
4 For example, WestConnex, one of the largest capacity expansion projects to a road network in an Australian city, was estimated to reduce road congestion costs in Sydney by $24 billion over a 30 year period. At high levels of uptake, CAVs would have this level of impact in a single year, albeit impacting across all Australian cities rather than only Sydney.

Item	2020 to 2070	To 2030	2031 to 2050	2051 to 2070
	$b	$b	$b	$b
additional congestion costs	-248.4	0.0	-5.2	-243.2
lost active transport benefits	-6.8	0.0	-0.4	-6.4
Costs of enabling CAVs				
additional vehicle costs	-473.0	-0.2	-62.8	-409.9
additional transport infrastructure costs	-2.4	0.0	-0.3	-2.0
additional communications costs	-13.5	-0.1	-13.5	0.0
Combined benefits and costs of CAVs	**1 412.0**	**-0.2**	**13.4**	**1 398.8**

Note: In 2020 dollars.
Source: The CIE and WSP.

The largest net benefit accrues to the largest states. This is because these states have more vehicle kilometres impacted, and because avoided congestion benefits are relatively higher in more populous states (chart 5).

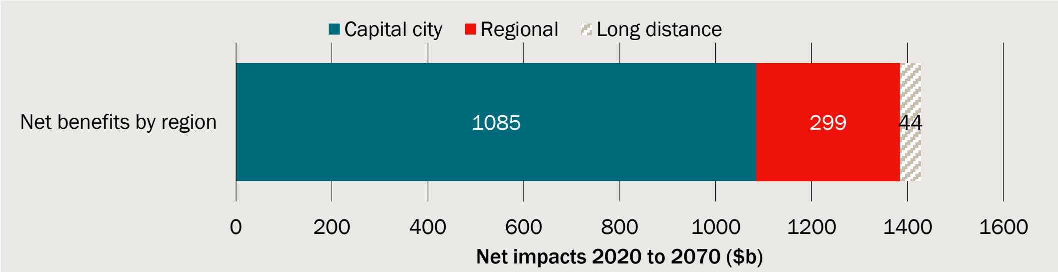
5 Net benefits by state and territory



Note: Measured from 2020 to 2070. Road infrastructure costs are not allocated to individual states and territories, so the sum of the states and territories is not equal to the Australia-wide impact.
Data source: The CIE and WSP.

Net benefits accrue most strongly for capital city travel, with $1085 billion of net benefit, followed by $299 billion for regional and $44 billion for long-distance inter-state freight (chart 6). This assumes that there is the same take up of CAVs across regions. If inter-state freight can achieve earlier take up on key freight routes, then this would increase the share of benefits from long distance road transport.

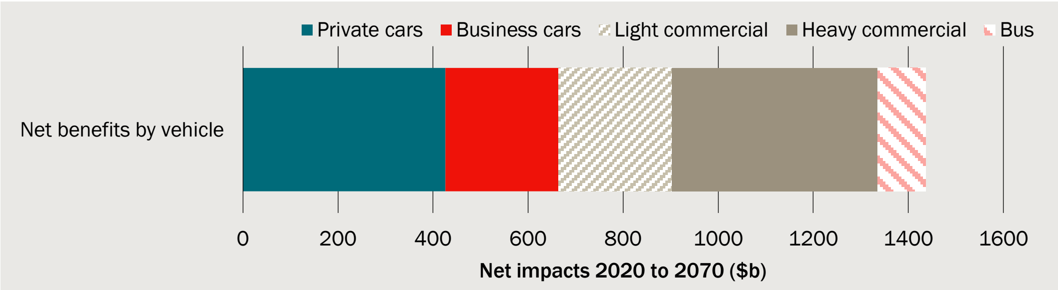
6 Net benefits by region



Note: Measured from 2020 to 2070. Net benefits in this chart do not include communications costs or road infrastructure costs.
Data source: The CIE and WSP.

The benefits accrue particularly strongly for private cars and heavy commercial vehicles (chart 7). Private cars are associated with large benefits because they represent a large share of road traffic. Heavy commercial vehicles are associated with benefits well in excess of their share of road traffic because heavy commercial vehicles (along with buses) are able to achieve travel with no driver.

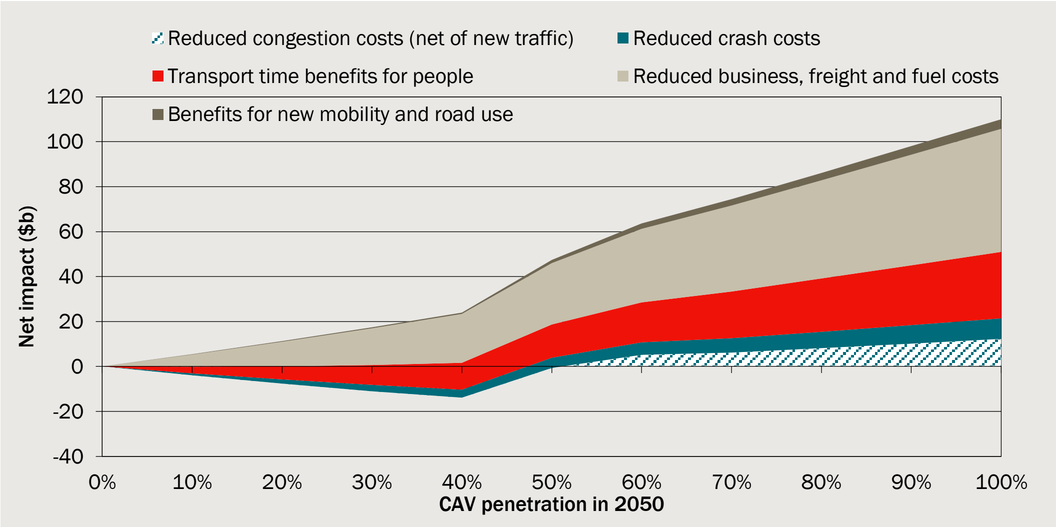
7 Net benefits by vehicle type



Note: Measured from 2020 to 2070. Net benefits in this chart do not include communications costs or road infrastructure costs.
Data source: The CIE and WSP.

To highlight the impacts of different levels of CAV penetration, in chart 8 we show benefits in a single year (2050) with different levels of CAV penetration. This does not include costs, such as the costs of buying vehicles and expanding communications networks. This is because the costs in one year, such as the cost of buying a CAV, are related to benefits across multiple years — i.e. all the years the CAV is then operated. Initially, there are negative congestion cost impacts. However, these are more than outweighed by other benefits. By the time penetration gets above 50 per cent, benefits are ~$40 billion per year, and capacity impacts begin to be positive as well. At 100 per cent penetration, benefits are over $100 billion per year.

8 Benefits with different levels of penetration 2050



Note: Measured at 2050.

Data source: The CIE and WSP.

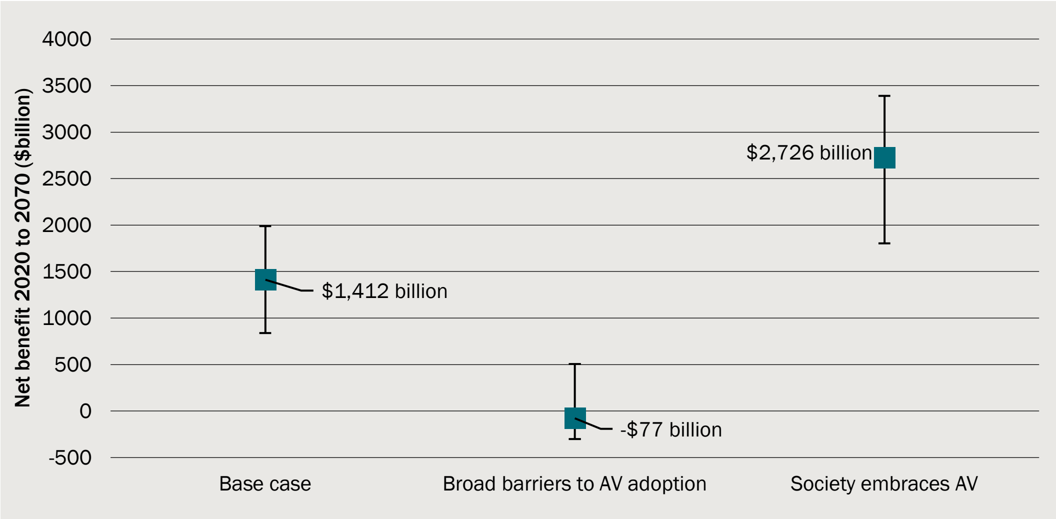
There is substantial uncertainty about the pathway for impacts of CAVs. A worst-case scenario would be both that CAVs are too expensive to generate mass market uptake and that the impacts of CAVs and mixed traffic lead to a less efficient road network. Under these circumstances, CAVs would be beneficial for much more selected uses, such as robo-taxis and other shared vehicle models and freight. In the worst-case uptake scenario (Broad barriers to AV adoption) and with high CAV costs and low benefits, overall impacts could be negative. On the other hand, under the best-case scenario (Society Embraces AV), where uptake occurs more rapidly, and where benefits are on the high side of the range expected, the net positive impacts could amount to over $3 trillion from 2020 to 2070.

In chart 9 we show the range of results from varying benefits within each uptake scenario. The base case scenario is linked to medium vehicle costs, Broad barriers to AV adoption is linked to high vehicle costs and Society embraces AV to low vehicle costs.

- For scenarios with low to medium vehicle costs and reasonable uptake, net benefits are always very large because the benefits of CAVs exceed these cost levels.
- For the Broad Barriers to AV adoption scenario, vehicle costs are high and uptake low, resulting in an expected net cost from CAVs. To the extent that high costs would reflect CAV manufacturers charging a price premium to recover costs of research, this would only be viable if there was a strong market for CAVs, suggesting a high cost but low uptake scenario may be less likely.

While some of the impacts of CAVs can be quantified, there are many impacts that are less tangible, as well as many ways in which responses to CAVs can change the level of benefits and costs and who the ultimate beneficiaries are. For example, governments may find that they can adjust their policies, programs and investment strategies in response to CAVs, to reduce costs and optimise benefits. The impacts of CAVs will also flow through economy and society, through reduced road freight costs and improved accessibility. For example, a 30 per cent reduction in road freight costs, which is approximately what would be expected with full CAV uptake, would boost Australia's GDP by 1 per cent.

9 Net impacts under different uptake and benefit assumptions



Data source: The CEI and WSP.

There are also a number of factors that will affect the extent to which the large potential benefits from CAVs are achieved:

- having fewer roads on which CAVs can be used autonomously would reduce uptake and benefits
- safety impacts may be proportionally smaller if CAVs struggle to drive safely in mixed settings or human drivers do not interact safely with CAVs
- travel time savings may not be fully achieved with mixed traffic if users do not feel trust and comfort in autonomous vehicles driving in mixed traffic
- fuel savings rely on platooning and smooth travel through intersections, both of which are more difficult to achieve in mixed settings, and
- having more CAVs shared under subscription models (where multiple people pay to use but not own CAVs) would reduce vehicle costs. This would be a likely outcome where CAVs are expensive but have large benefits for users.

The estimates made in this study of the impacts of CAVs are based on the set of assumptions detailed within the report. Benefits and costs are dependent on key assumptions such as the path for uptake, which will likely be less smooth than the scenarios modelled, and the ability of CAVs to achieve the impacts outlined in the literature. Both uptake and impacts will also depend on costs of vehicles. The overall estimates of the impacts of CAVs covers factors that are of value (or cost) to people. Not all of these will lead to impacts in economic activity — but all will be important in understanding the overall contribution that CAVs can make to the Australian community.

1 Introduction

What are CAVs?

Connected and Automated Vehicles (CAVs) are a broad group of technologies which can be considered separately as:

- connected vehicles (utilising wireless technology to communicate between vehicles, potentially other road users and infrastructure), and
- automated vehicles or automated vehicle systems which utilise control systems in vehicles to automate driving tasks.

Vehicle connectivity and automation are often grouped together as both step towards a greater level of automated assistance for driving tasks. Vehicle manufacturers are already preparing for and deploying vehicles that are supportive of connected operations. In 2025, the Australasian New Car Assessment Program (ANCAP) will likely require connectivity (e.g. vehicle to vehicle and/or vehicle to infrastructure) in vehicles to achieve a five-star safety rating.[5] Internationally and across some states in Australia, connected vehicles (or Cooperative Intelligent Transport Systems [C-ITS]) are being widely trialled and deployed.

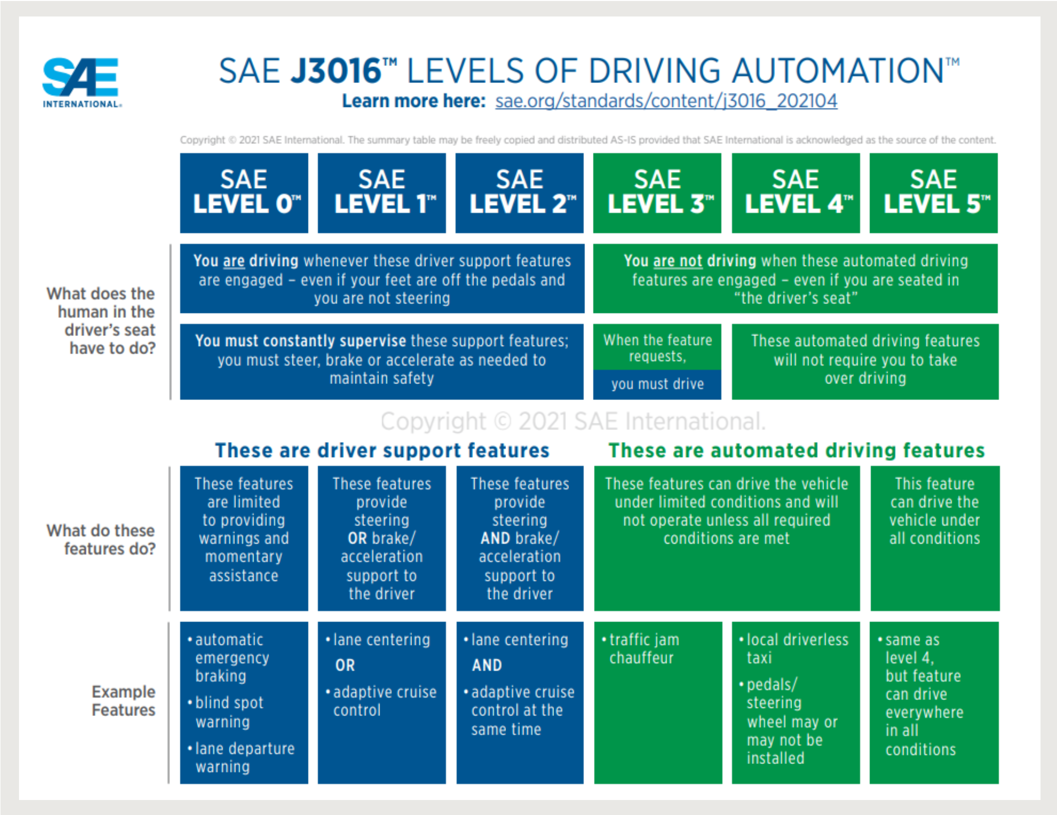
Because of the interconnectedness of connectivity and automation set out above, this project focuses on the economic value and impact of automation of the driving task. That is, the benefits of connected and automated vehicles are considered together. The level of automation of the driving task is discussed further below.

Level of Driving Task Automation

The National Transport Commission (NTC) recognises that manufacturers and industry use different terminology when referring to the level of automation of the driving task. To provide clarity and support enforcement guidelines for automated vehicles, the NTC has aligned its definitions to the SAE International Standard J3016 (SAE J3016), *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*. A summary of these definitions by as updated and issued by SAE in May 2021 is provided in chart 1.1.

5 ANCAP 2021, Submission to the Joint Select Committee on Road Safety, 23 August, https://www.ancap.com.au/publications/ancap-submission-joint-select-committee-on-road-safety-2021.pdf.

1.1 SAE J3016 Levels of Driving Automation



Data source: SAE International.

To support this assessment of economic impact we have sought to clearly define levels of automation in a practical manner that clearly aligns with expected benefits and costs.

Level 1 & 2

SAE levels 1 and 2 include low level automation, which is widely deployed in vehicles today. SAE defines these as driver assistance and partial driving automation respectively. Typical features that fall into this category are lane-keep assist, intelligent cruise control and automated braking. The defining factor being that the human driver must either remain in control of some driving functions or monitor and react to external events and conditions by taking over with manual operation. This report captures Level 1 and 2 automation as occurring in the no-CAV scenario, and is focused on the additional benefits that higher levels of automation provide.

Levels 3, 4 & 5

This report focuses on Levels 4 and 5 of driving task automation which bring increasing levels of automation and reduction/removal of the need for human monitoring or input. These levels refer to high driving automation and full driving automation respectively.

Level 3 (conditional driving automation) presents challenges in that the vehicle is expected to perform a full 'dynamic driving task' within a defined operational design domain (ODD), but if the vehicle cannot self-drive it will fall back to human control.

Therefore, human driver monitoring is always required. This use case is not likely to be considered safe for widespread deployment on the public road network unless there are significant safety mitigations in place. As a result, we note it is less likely to realise the potential benefits of highly automated driving in comparison to Level 4 and 5 which provide for a safe and graceful hand over of the driving task and do not require constant monitoring of the vehicle. As such, **Level 3 has been excluded from this analysis with the focus placed on SAE levels 4 and 5**.

Operational Design Domain

Alongside consideration of the levels of automation of the driving task, we must recognise the environment in which CAVs are able to operate with automated driving systems (ADS) engaged. This is referred to as the ODD. If a vehicle was to exit the ODD for highly automated features, human driver fallback would be required to continue safe operation, as the system would not be approved for use under other conditions. The ODD is an important consideration as the environment in which vehicles can operate will shape deployment use cases, business models and uptake.

The task

The CIE and WSP have been asked to measure the potential economic impacts of CAVs. To do this task we have defined 'economic' broadly to cover all types of impacts that people care about, which includes:

- impacts on costs related to road crashes, such as reduced mortality and morbidity, reduced property damage and reduced public health system costs,
- impacts on transport costs (e.g. travel time and reliability and operating costs such as fuel), which can include reduced costs for business (which is a productivity improvement) or reduced costs to people (for example, being able to use time driving for alternative activities), and
- impacts on the environment, such as changes to GHG emissions and air pollution, which in turn impact on people's health and quality of life.

'Economic' is not restricted to examining changes that impact the Australian economy. For example, substantial benefits are expected for reduced fatalities from road crashes. Beyond any economic impact from loss of lives, this has an impact on the quality of life of the community.

CAV technology is in its infancy, making uptake, benefits and costs highly uncertain. At one end, with close to universal uptake of CAVs very substantial benefits are expected. However, the path to getting there could be much slower if uptake of CAVs is slow. Since CAVs have reduced benefits in mixed traffic, this would decrease total benefits significantly.

This report sets out expectations of the size of benefits and costs related to CAVs and how these change under a variety of scenarios and responses. This information provides a perspective on the expected range and scale of the returns from CAVs and the conditions that are likely to maximise these returns.

Structure of this report

This report continues as follows:

- Chapter 2 sets out possible alternative scenarios for CAV uptake. There is a wide range for the uptake of CAVs, depending on factors such as costs and the use of subscription/sharing models.
- Chapter 3 identifies the overall projections of the road transport task from 2020 to 2070
- Chapter 4 identifies the impacts of CAVs from the literature, and what we are measuring in this study.
- Chapter 5 evaluates the safety impacts of CAVs.
- Chapter 6 evaluates the transport cost impacts of CAVs (not including vehicle costs, which are considered in chapter 9).
- Chapter 7 evaluates the impacts of CAVs on road transport capacity, which mainly relates to capital city road networks since roads outside capital cities experience far less congestion.
- Chapter 8 considers other impacts of CAVs, such as environmental impacts.
- Chapter 9 identifies the costs associated with enabling CAVs. This covers infrastructure costs and vehicle-related costs.
- Chapter 10 assesses how people may respond to CAVs, through changing road transport demand.
- Chapter 11 provides a summary of the impacts of CAVs, across Australia, and for particular regions and types of traffic.
- Chapter 12 provides sensitivity analysis of the estimates, highlighting the wide divergence of the impacts, depending on factors such as vehicle costs and uptake.
- Chapter 13 traces through some of the broader socio-economic implications of CAVs.

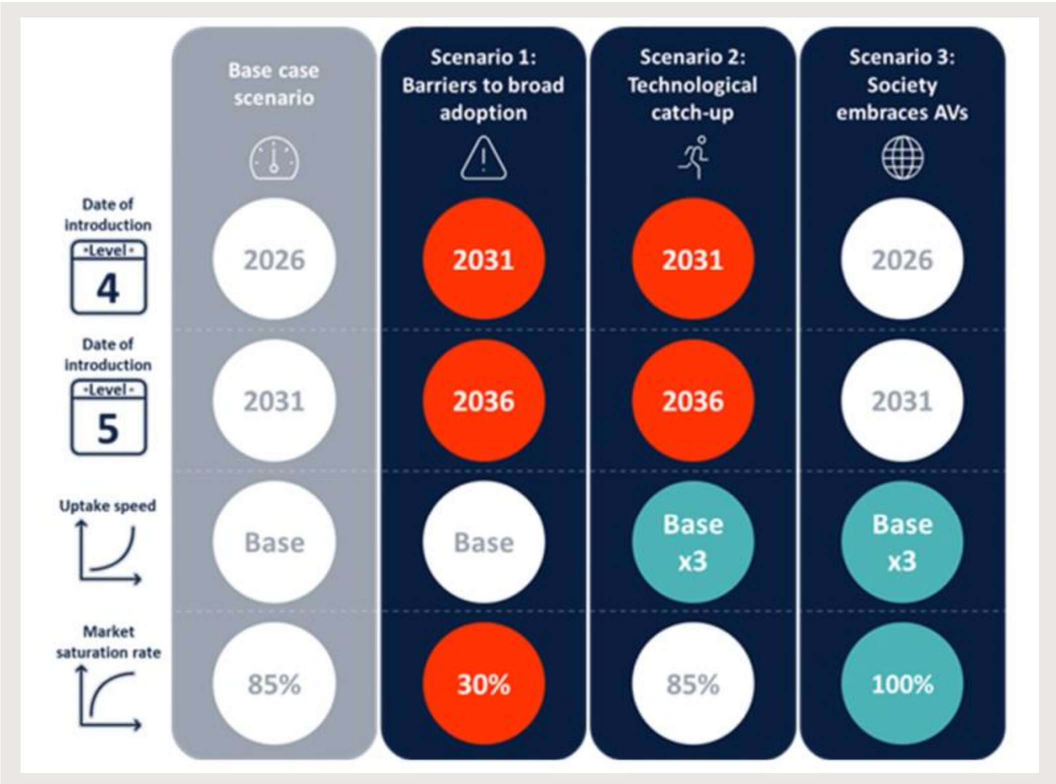
2 Scenarios for CAV uptake

Scenarios for CAV uptake are needed to simplify how we understand the economic impact of CAVs over a defined period of time. Scenarios need to be defined by the level of automation and consider the level of uptake and fleet penetration of CAVs over time. For the purposes of this report, scenarios are taken from other sources, rather than being based on the costs and benefits that CAVs deliver. However, these are clearly inter-related — if CAVs have high costs and deliver low benefits then uptake levels will be low.

Consideration of BITRE Scenarios

To determine scenarios of uptake for CAVs to use we have analysed and compared recent literature and projections. Scenarios developed by BITRE as part its draft Autonomous Vehicles (AV) forecast report were provided to CIE and WSP by the Department of Infrastructure, Transport, Regional Development and Communications (The Department). The scenarios used in this analysis are outlined in chart 2.1.

2.1 BITRE Scenarios



Source: Bureau of Infrastructure and Transport Research Economics, forthcoming, *Forecasting uptake of driver assistance technologies in Australia*, advance draft (current as at 15 October 2021) provided by the Department of Infrastructure, Transport, Regional Development and Communications to CIE/WSP, Figure 41: Key Parameters adopted in scenarios.

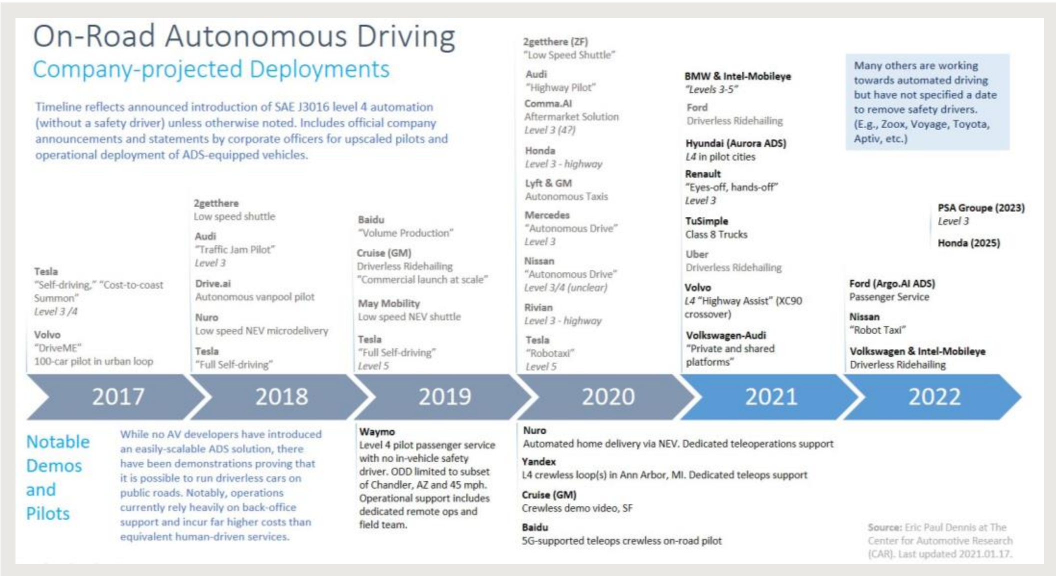
The variables used by BITRE to inform scenarios and assess the uptake and penetration of CAVs were:

- date of introduction
- uptake speed
- market saturation rate.

To understand the feasibility and likelihood of BITRE's forecasts we have compared its assumptions and data to that provided for the updated Austroads *Future Vehicles Forecasts Update 2031*.[6]

When the original Austroads *Future Vehicles 2030* forecast[7] was released it was more conservative than most other available research and literature. Since release, other forecasts have been revised down and are now more aligned to the Austroads 2030 work. Chart 2.2 below outlines how vehicle manufactures projected deployments have been shown to be overly optimistic in their promise of release dates and advancements in automated driving capabilities. This demonstrates that a more conservative forecast approach may be warranted.

2.2 On-road autonomous driving; company related deployments



Source: Centre for Automotive Research (CAR).

Table 2.3 compares the base trends identified in each report. These trend figures are from the 'high growth' or 'rapid' scenarios, as lower uptake scenarios do not show a meaningful trend until beyond 2031; beyond the scope of Austroads *Future Vehicles Forecasts Update 2031*. It is important to note the definitions provided for each trend forecast as they relate to SAE levels of automation.

The definitions as they relate to SAE levels of automation are:

- BITRE: share of light vehicles sold as SAE L4 and L5

6 https://austroads.com.au/projects/project?id=FCA6324

7 https://austroads.com.au/publications/connected-and-automated-vehicles/ap-r623-20

- Austroads *Future Vehicles Forecasts Update 2031*
  – highly automated driving early ODDs: covers full door to door urban journeys and urban and higher volume motorways. The minimum automation level is L4 – no fall-back ready driver
  – highly automated driving broader ODDs: extending beyond early ODD's to more urban and rural roads and conditions. The minimum automation level is SAE L4 – no fall-back ready driver.

2.3 BITRE and Austroads forecast trend comparison, share of vehicles sold

Year	BITRE Trend	FV2031 Early ODD	FV2031 Broad ODD
2025	0.12%	1%	<1%
2030	5.05%	8%	4%
2031	6.57%	12%	6%

Source: Bureau of Infrastructure and Transport Research Economics, forthcoming, *Forecasting uptake of driver assistance technologies in Australia*, advance draft (current as at 15 October 2021) provided by the Department of Infrastructure, Transport, Regional Development and Communications to CIE/WSP; Austroads 2031 draft provided by the Department.

Comparison of these trends goes some way to validating each other, with similar expected trends found before additional variables and assumptions are considered. For the purposes of reporting impacts of CAVs this study draws directly from the range of scenarios developed by BITRE.

Consideration of policy impacts

Emerging technologies that may impact on a significant portion of the population and/or government managed infrastructure will be influenced by the policy position of legislative authorities and road/telecommunications network operators. Attempting to predict and understand the impact of policy positions may be useful where seeking to develop and understand policy implications, however this analysis is focussed on understanding the potential economic impact of CAVs. Consideration of policy impacts has therefore been excluded from scope.

In developing scenarios to support this analysis we have examined existing literature to develop a clear understanding of trends in scenario development and the key assumptions associated with them.

Consideration of Vehicle Class

There is discussion regarding the relative impact and benefits relating to vehicle class throughout this report and some discussion of future business models. There is a lack of robust data to allow consideration of uptake scenario by class, such as for heavy commercial vehicles, light commercial vehicles, business vehicles and private vehicles. The assessment of impacts assumes that uptake is similar across vehicle classes. Given the pattern of costs and benefits, it is expected that this is somewhat conservative with regard to freight vehicles, as the benefits from driverless freight are higher relative to costs than for private vehicles.

Scenarios used in this report

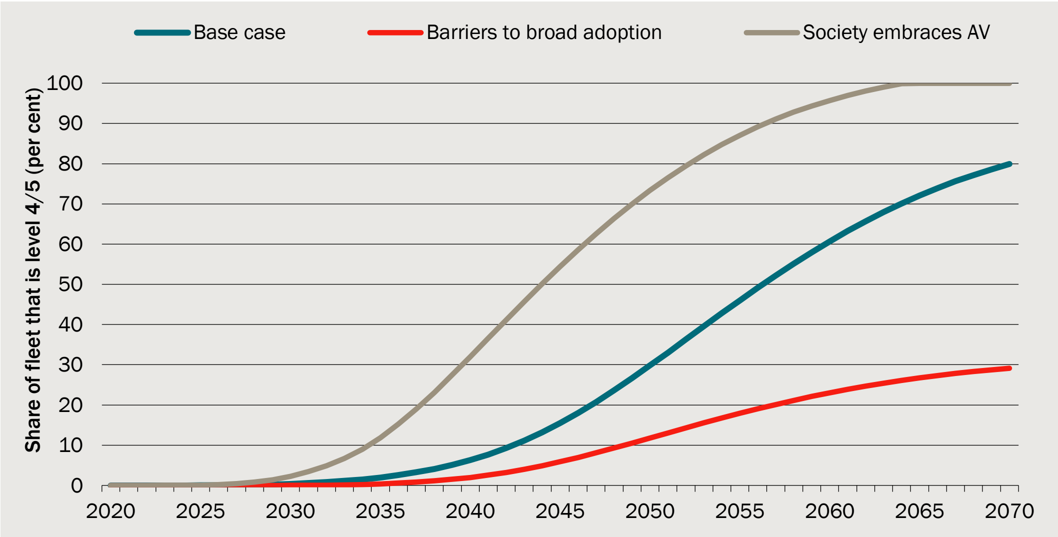
Fleet penetration rates

This report uses the scenarios developed by the BITRE as part of its draft AV forecast report, provided to CIE and WSP by the Department.[8] For the central case estimates of impacts we apply the base case uptake scenario. We also show results using the 'Society embraces AV' scenario and 'Broad barriers to AV' adoption scenario.

The expected shares of the vehicle fleet that are CAVs under these three scenarios from now until 2070 is shown in chart 2.4 and shows that:

- Uptake under all scenarios is low until 2030
- 30 per cent fleet penetration is reached by 2040 under the 'Society embraces AV' scenario, 2050 under the base case, and 2070 under the 'Broad barriers to AV adoption' scenario.

2.4 Projections of CAVs as a share of fleet under alternative BITRE scenarios



Data source: Bureau of Infrastructure and Transport Research Economics, 2021, *Forecasting uptake of driver assistance technologies in Australia*, advance draft (current as at 15 October 2021) provided by the Department of Infrastructure, Transport, Regional Development and Communications to CIE/WSP.BITRE 2021, draft AV forecast report, provided to CIE and WSP by the Department.

We apply these forecasts of penetration to all types of light vehicles, equally across capital cities and regions, and different types of light vehicle traffic (private, business and light commercial). We apply the same penetration rates to heavy commercial traffic in the absence of any other available projections. It is plausible that uptake may occur more rapidly for heavy commercial vehicles, because of the higher number of kilometres driven and the potentially higher driver cost savings from automation. This means that estimates for heavy commercial vehicles are likely to be conservative.

8 Bureau of Infrastructure and Transport Research Economics, forthcoming, *Forecasting uptake of driver assistance technologies in Australia*, advance draft (current as at 15 October 2021) provided by the Department of Infrastructure, Transport, Regional Development and Communications to CIE/WSP.

Vehicle kilometres travelled by CAVs and non-CAVs

The benefits of CAVs relate to the amount of vehicle kilometres and time driven, rather than the share of vehicles. We expect that there are two offsetting effects:

- CAVs will tend to be taken up by users who drive more, because they will see a more compelling case in terms of the potential savings. For example, an early use case may be long distance freight or robo-taxis. This could increase the share of kilometres driven by CAVs.
- CAVs will not be able to be operated autonomously on all roads and may initially be geo-limited or, require drivers (for freight) for some part of their journeys. This could reduce the share of kilometres driven by CAVs.

We have assumed that the CAVs would initially achieve benefits on only a share of the kilometres driven because automation would not be able to be used on all roads, and that this would gradually increase over time (table 2.5). For example, in 2050, we assume a light CAV can achieve benefits on 75 per cent of the kilometres of an average vehicle. That is, if an average vehicle travels 10 000 kilometres per year, then each CAV achieves benefits on 7500 kilometres per year. The kilometres per vehicle for which a CAV is expected to be able to achieve benefits increases because the operational design domain for CAVs gradually expands.

2.5 Average kilometres for CAV benefits as a share of average vehicle kilometres

Year	Light vehicles	Heavy vehicles
	Per cent	Per cent
2020	20%	20%
2030	20%	50%
2040	50%	50%
2050	75%	95%
2060	95%	99%
2070	95%	99%

Source: The CIE and WSP.

3 *Projections of the transport task*

The projected transport task consists of the number of vehicle kilometres travelled and number of hours spent travelling. It forms the backdrop to the types and magnitude of impacts that CAVs may have. Road transport projections indicate that:

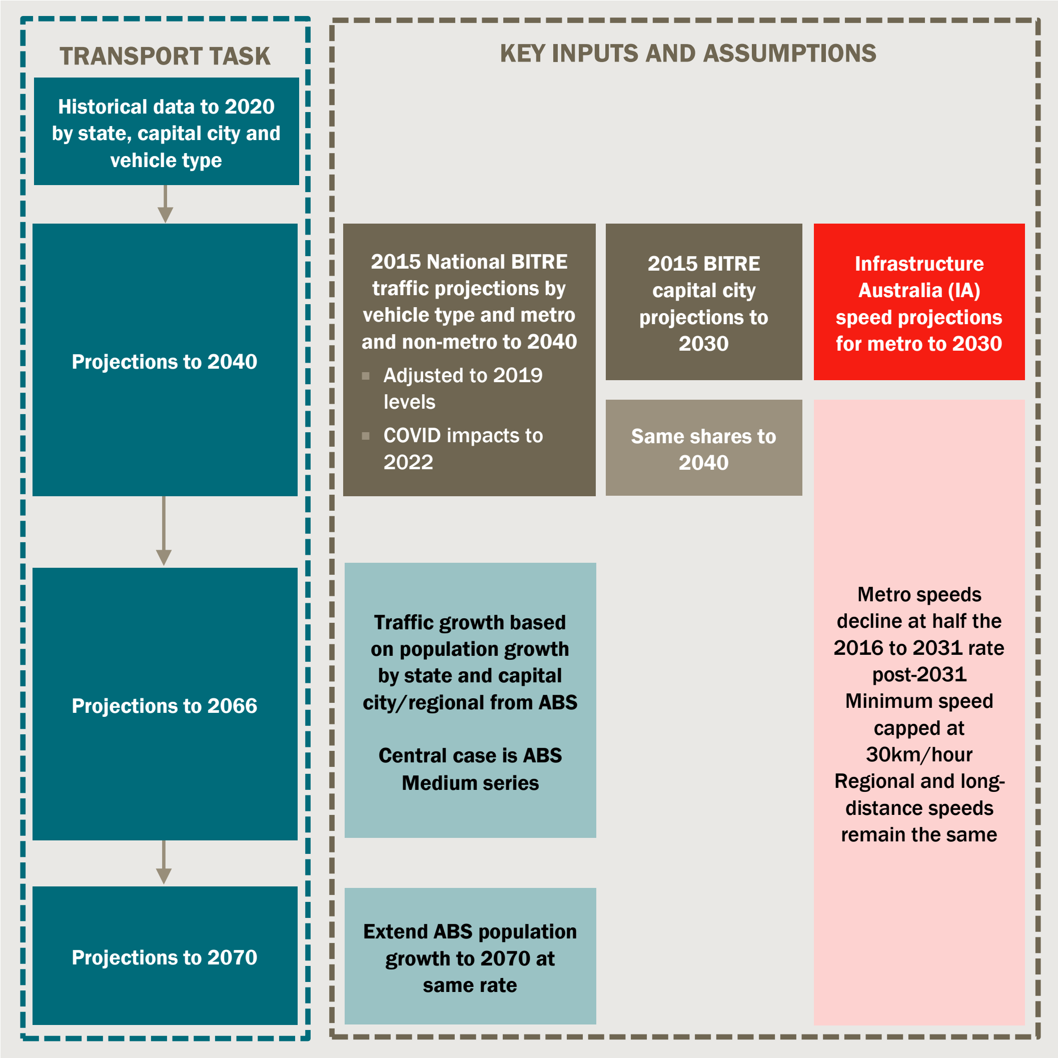
- the transport task is expected to increase over time, with more vehicle kilometres undertaken. The transport task is allowed to grow at rates expected by past BITRE work to 2040, and then in line with population growth forecasts, and
- the hours devoted to transportation are expected to increase more rapidly than the transport task, because of declining transport speeds due to congestion.

There are substantial uncertainties about the future road transport task related to population growth, COVID-19 impacts, working from home, the impacts of planned investments in public transport, and more. As a general rule, higher projections of the road transport task mean larger benefits from CAVs. The uncertainty about the transport task is much smaller than the level of uncertainty about the timing of uptake of CAVs due to the greater availability of historical data about the transport task to support projections.

Approach to constructing projections

To construct projections of vehicle kilometres travelled (VKT), we have extended existing forecasts, and then disaggregated where necessary to allocate the road transport task to particular vehicle types, states and regional versus capital city. To project vehicle hours travelled we apply projections of speeds to projected VKT. An overview of the key inputs for forecasts is shown in chart 3.1.

3.1 Approach to constructing transport forecasts



Data source: The CIE.

Vehicle kilometres travelled

The forecasts reflect:

- growth expected from BITRE from 2020 to 2040, from its forecasts made in 2015.[9]
  – We use the average of the Upper Baseline and Low VKT projection scenarios.
  – These forecasts have been very accurate for cars and light commercial vehicles (LCVs) until 2019, when COVID-19 substantially reduced traffic.
  – The forecasts have expected higher growth in rigid truck and bus vehicle kilometres than has occurred.
  – The forecasts expected substantially higher growth in articulated truck vehicle kilometres than has occurred.

9 BITRE 2015, *Traffic and congestion cost trends for Australian capital cities*, November, https://www.bitre.gov.au/publications/2015/is_074.

- We adjust forecast to start at actual 2020 (2019/20 financial year) traffic estimates from the BITRE Infrastructure Yearbook[10], and then apply the growth rates from BITRE 2015.
- Note that we also allow a recovery in road traffic volumes in relation to COVID-19.
  - COVID-19 impacts experienced in 2020 are assumed to continue to 2021 and 2022 before returning to normal in 2023.
  - COVID-19 impacts in 2021 and 2022 are maintained at the impact from 2021. In all likelihood these could be more severe for some types of traffic. This is not important for the impacts of CAVS, which do not eventuate over this period.

After 2040, we have allowed traffic trends to move in line with population growth estimates from the ABS for each state,[11] divided into capital city and regional travel. Inter-state freight growth is based on the entire state's population growth. For the central case estimates we use the ABS Medium series, which is based on medium fertility, medium levels of net overseas migration and the lower end of assumptions for life expectancy. The alternative series are high and low — these series are included in the impact model as sensitivities. This projection is from a base year of 2017 until 2066. We extend the trends from 2065-2066 to project 2067-2070.

Hours travelled

Hours of driving is important for the benefits of CAVs. Unlike for VKTs, there is no official dataset for hours spent driving. For capital cities, we have used modelling undertaken for Infrastructure Australia as part of its Infrastructure Audit.[12] This data was provided directly by Infrastructure Australia. It contains vehicle hours and vehicle kilometres from 2016 to 2031 for commercial and other vehicles for different time periods within a day. We have used this to construct estimates of the average speeds for each vehicle type and the trends in speeds. These are shown in table 3.2.

Speeds vary across capital city and are expected to decline from 2016 to 2031. The modelling accounts for projects that have been funded and would be completed over the time period. However, it does not account for all projects that may occur to 2031.

10 BITRE Infrastructure Yearbook 2020, Part T, https://www.bitre.gov.au/publications/2020/australian-infrastructure-statistics-yearbook-2020.

11 Available at: https://www.abs.gov.au/statistics/people/population/population-projections-australia/2017-base-2066

12 For example, the Sydney report is: Veitch Lister Consulting 2019, https://www.infrastructureaustralia.gov.au/sites/default/files/2019-08/Transport%20Modelling%20Report%20for%20Sydney.pdf.

3.2 Speeds for capital cities

Region	Cars			Commercial		
	2016	2031	Annual per cent change	2016	2031	Annual per cent change
	Km/hour	Km/hour	Per cent	Km/hour	Km/hour	Per cent
Sydney	42.2	37.2	-0.83	47.0	40.8	-0.94
Melbourne	45.0	42.6	-0.37	50.4	47.5	-0.40
Brisbane	52.3	44.3	-1.10	57.6	49.3	-1.03
Perth	54.7	49.1	-0.72	56.9	50.9	-0.74
Adelaide	45.5	42.6	-0.43	48.7	46.0	-0.38
Hobart	54.4	52.6	-0.22	60.8	58.6	-0.24
Darwin	54.4	52.6	-0.22	60.8	58.6	-0.24
ACT	54.4	52.6	-0.22	60.8	58.6	-0.24

Note: Modelling is not available for Hobart and Darwin and we have assumed the same speeds as for the ACT.

Source: CIE analysis based on data provided by Infrastructure Australia from its 2019 Infrastructure Audit.

After 2031, we have applied continued trends to capital city speeds, based on half of the trend from 2016 to 2031. The basis for reducing the decline in speeds is that there would be investments that will impact on performance of the road network.

For regional travel and inter-state freight, and buses, we do not have data on speeds. In the absence of such data, the assumptions made are that:

- regional cars and Light Commercial Vehicles (LCVs) will average 80 kilometres per hour,
- regional heavy commercial will average 80 kilometres per hour for intrastate regional travel, and 90 kilometres per hour for inter-state, and
- buses will average 30 kilometres per hour.

These assumptions are intended to approximate average speeds across lower-speed travel within regional cities and towns and high-speed travel on highways and main roads. Without data to inform the assumptions, we have chosen speed assumptions closer to the speed limit on highways/main roads, on the basis that this travel is expected to be responsible for a majority of vehicle kilometres. The exception for this is buses, which have a travel speed consistent with mostly travelling on town/city roads and more stop-start travel.

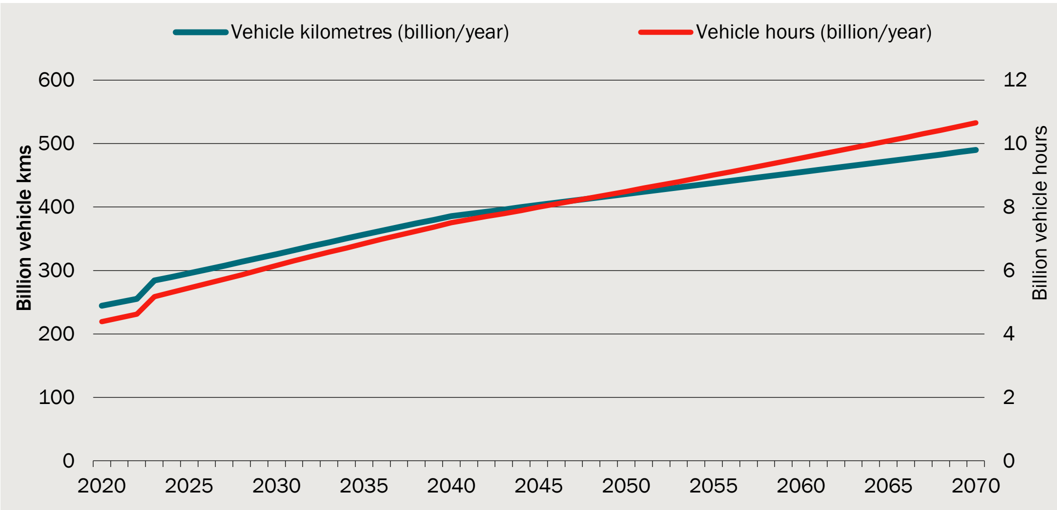
The projections of the transport task also involve projections of the cost of time, vehicle fuel use and emissions and safety. These are set out in the relevant chapters later in this report.

Central case projections without CAVs

The central case projections of vehicle demand nationally are shown in chart 3.3. These are the **baseline projections** before accounting for any impacts of CAVs on the amount of road traffic. The road transport task, covering all vehicles except motorbikes, is expected to double from 245 billion vehicle kilometres in 2020 to 490 billion vehicle kilometres by 2070. Growth is more rapid to 2040, based on BITRE growth rates, and then slows following this as growth is linked to population growth. Note that the initial uptick in growth reflects the recovery to pre-COVID-19 trends.

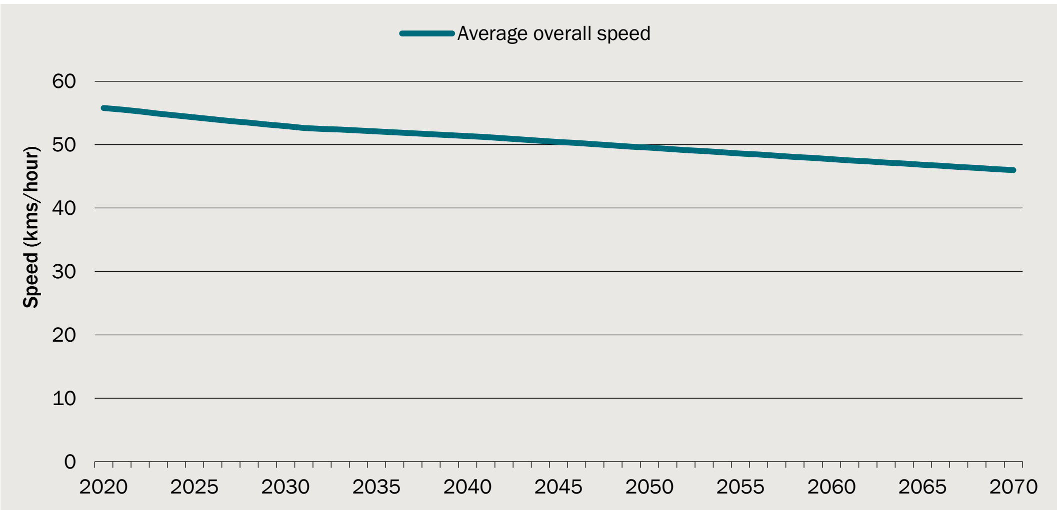
Vehicle hours grow more rapidly than vehicle kilometres because of a decline in speeds in capital cities. The projected speeds across all traffic is shown in chart 3.4, indicating a decline from an average speed of 56 kilometres per hour to 46 kilometres per hour in 2070.

3.3 Overall projections of road transport



Data source: The CIE.

3.4 Overall projections of speed



Data source: The CIE.

The majority of the transport task is private cars (61 per cent in 2020) and this remains relatively unchanged over the projection period (table 3.5). This reflects the assumptions made by BITRE to 2040 and the use of population projections for all traffic from 2040 to 2070. The overall shares remain fairly similar over time.

3.5 Transport task by vehicle type

By vehicle type	2020		2070	
	Vehicle kms	Share	Billion vkms	Share
	Billion	Per cent	Billion	Per cent
Private cars	148.8	61	299.1	61
Business cars	21.9	9	44.0	9
Light commercial	52.5	21	105.2	21
Heavy commercial	19.1	8	36.6	7
Bus	2.4	1	5.0	1
Total	**244.6**	**100**	**489.9**	**100**

Source: The CIE.

The share of the transport task in capital cities increases from 56 per cent in 2020 to 63 per cent in 2070 (table 3.6). Long distance transport, which is inter-state freight only, makes up a small share of the overall transport task, in terms of vehicle kilometres.

3.6 Transport task by type of travel

By vehicle type	2020		2070	
	Vehicle kms	Share	Billion vkms	Share
	Billion	Per cent	Billion	Per cent
Capital city	137.4	56	310.5	63
Regional	104.2	43	173.6	35
Long distance (inter-state freight)	3.0	1	5.8	1
Total	**244.6**	**100**	**489.9**	**100**

Source: The CIE.

The transport task is broadly reflective of population shares, with the largest task in NSW and Victoria (chart 3.7). This also does not change much over the projections, because population growth rates are relatively similar across areas.

3.7 Transport task by state and territory

By vehicle type	2020		2070	
	Vehicle kms	Share	Billion vkms	Share
	Billion	Per cent	Billion	Per cent
NSW	73.9	30	141.8	29
VIC	63.6	26	130.6	27
QLD	52.7	22	109.3	22
WA	27.0	11	61.1	12
SA	16.2	7	26.6	5
TAS	5.3	2	7.6	2
NT	2.1	1	4.5	1
ACT	3.9	2	8.4	2
Total	**244.6**	**100**	**489.9**	**100**

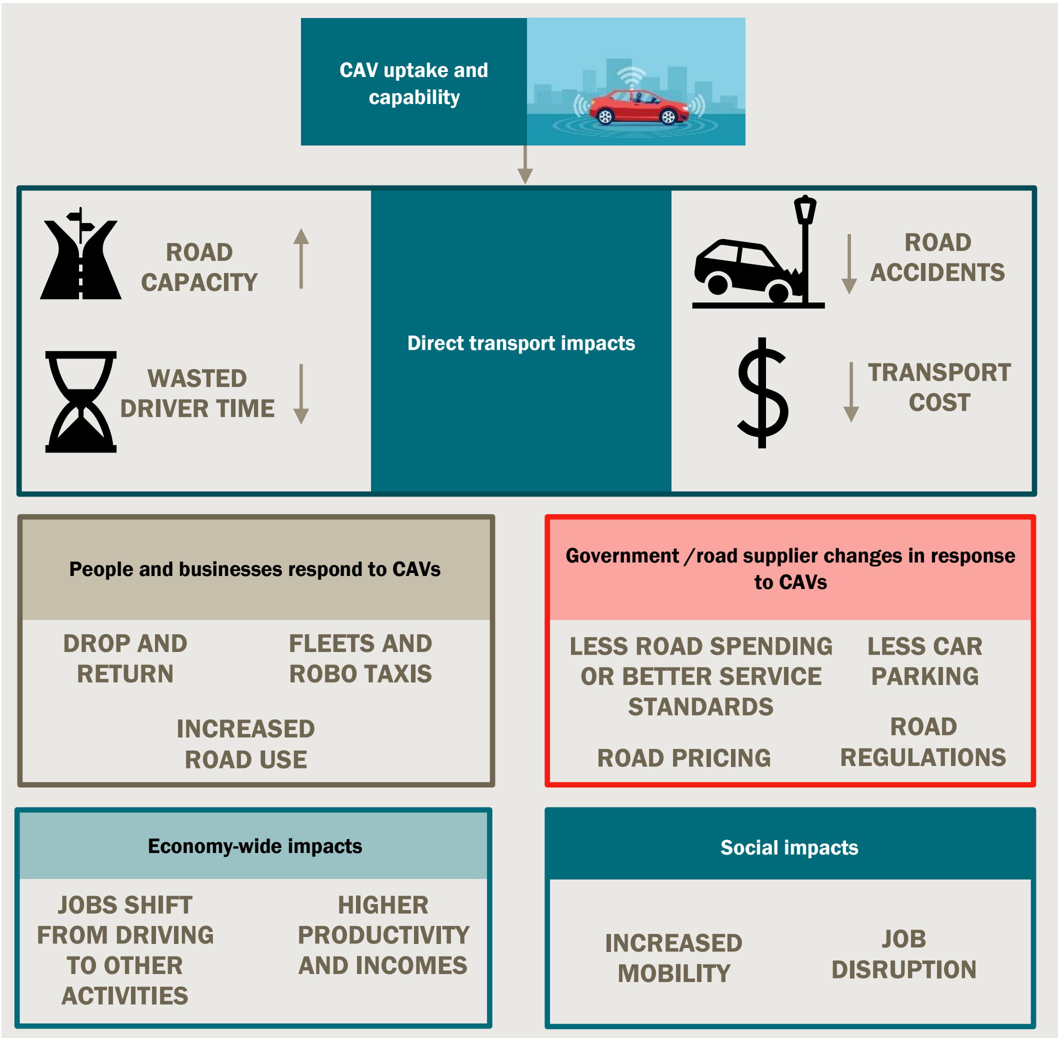
Source: The CIE.

Making long term projections of the transport task has substantial uncertainties. These include the basic drivers of demand, such as population growth and shifts in demand related to behavioural changes. Within the long timeframe considered there may also be other technological changes that influence road transport demand.

4 *What are the impacts of CAVs?*

CAVs could have dramatic impacts on the road transport sector. Directly, they are expected to reduce road crashes, improve transport productivity through removing the need for a driver, allow people to do other activities instead of driving and (eventually) increase road capacity because more cars can fit on the same road. Indirectly, businesses, people and governments could respond to CAVs in many different ways. A schematic of the overall picture of CAVs is shown in chart 4.1.

4.1 Economic and social impacts of CAVs



Data source: The CIE.

The broader impacts flow from the direct transport impacts of CAVs. Measurement of what CAVs do has to start with **understanding how CAVs impact on the transport system.** There are four key benefits that have been identified in the literature:

1. **Reduced road crashes** — CAVs should substantially reduce crashes because many crashes are caused by human mistakes.
2. **Reduced wasted driver time** — with CAVs, drivers will be able to undertake other activities while they are in a car, rather than focusing on driving. This could be activities that have economic implications, such as working during a commute, or could be simply doing other things such as consuming media and entertainment or resting.
3. **Reduced transport costs** — with CAVs, the cost of transport for goods and people can be reduced because a driver is no longer required. Furthermore, some other costs, such as fuel use are expected to fall. Of course, CAVs will also likely be more expensive in other ways, such as upfront vehicle costs and in ongoing maintenance.
4. **Increased road capacity** — with CAVs, more cars will eventually be able to move down the same road, which is an expansion of the effective capacity of the road network. This is because CAVs can move more closely together and respond more quickly to signals, allowing more vehicles to move through intersections and along roads. This means traffic can move faster, reducing the costs of congestion. Some evidence indicates in the early years of CAV uptake, this effect may actually be reversed because of cautious driving behaviour in mixed (i.e. CAV and non-CAV) traffic. On the other hand, at higher levels of uptake, roads will function more effectively.

These direct transport impacts could lead to many different possible social and economic impacts, as people, businesses and government respond to the opportunities presented. At the most basic level, if road transport becomes less expensive, then we would expect that there will be higher demand for it. This could come about because people make more trips, make trips by car instead of other modes, travel further than they otherwise would, choose to live further away from their place of work, or work further from where they live.

People may also decide to send their CAV home rather than parking at work. These changes have costs and benefits — costs because additional vehicle traffic may increase congestion and benefits because additional trips are made because they have value to those making them. Some additional trips may have a very high value, such as where CAVs enabled increased mobility for people who have difficulty travelling today.[13]

Businesses may also respond to CAVs through new models of providing goods or services. For example, on-demand transport provided through CAVs would be cheaper than current on-demand options and this model may provide a useful scenario where

13 For example, Harper et al (2016) focusses on increased travel among the non-driving, elderly and people with disability: Harper, C.D, Hendrickson, C.T., Mangones, S. and Samaras, C., 2016, 'Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions', *Transportation Research Part C: Emerging Technologies*, 72, 1-9, available at: https://doi.org/10.1016/j.trc.2016.09.003

CAVs are quite expensive to own for individuals. Businesses that provide car parking, or new developments that have parking, will also face changed demand for parking and may respond to use their assets in more efficient ways.

Finally, governments and road suppliers may respond to the uptake of CAVs in ways that change the level and pattern of benefits. This is in addition to the role government can play in influencing CAV uptake through the overall regulatory frameworks in place. Understanding the levers available to government to influence CAV uptake is a broader task than contemplated in this report. The ways in which governments and road suppliers may *respond* to the uptake of CAVs include:

- reduced expenditure on road capacity — because CAVs will eventually improve network capacity, this may reduce the need for government to invest in capacity enhancing projects. The amount spent specifically related to road capacity is not known. Road-related expenditure in total in 2018/19 was almost $29 billion[14]
- reduced expenditure on enforcement of road rules, such as speeding and drink driving — CAVs are unlikely to need the same level of enforcement of rules by police, because enforcement is related to humans breaking rules. Some rules may also no longer be relevant, such as drink driving
- reduced expenditure on education related to reducing road crash costs, such as drink driving, fatigue and speed reduction campaigns — for example, in Victoria, the largest government advertiser is the Transport Crash Commission — their expenditure in 2017/18 was $13 million.[15]
- segregating CAVs and other vehicles to optimise network performance — reduced travel time costs for CAVs rely on occupants trusting the safety of the vehicle and feeling comfortable, and some evidence suggests that these feelings are lower in mixed CAV/non-CAV settings.[16] Similarly, the benefits of CAVs in making intersections flow more smoothly and reducing fuel costs would be more achievable in a CAV-only environment
- increasing speed limits — where CAVs can operate much more safely then it may be possible to increase speed limits for some roads. This would depend on the level of penetration and mixing of CAVs and other vehicles. Increases in speed limits could have substantial benefits if they did not come with the same risk to life as currently is the case. For example, the cost of driver time is currently over $100 billion dollars, and is expected to rise to $400 billion by 2070 (without CAVs), because of an increasing value of time and increased time spent driving. Increased speeds could reduce the costs related to driver (and passenger) time. This would be most likely initially along routes where there are multiple lanes and a freeway environment

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14 BITRE 2021, *Australian infrastructure statistics yearbook 2020,* Table T 1.2d.

15 https://www.vic.gov.au/victorian-government-advertising-report-2017-18#expenditure-on-major-government-campaigns

16 Yap, M., Correia, G. and van Arem, B., 2016, 'Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips', *Transport Research Part A: Policy and Practice*, Volume 94, December 2016, pp.1-16, available at: https://www.sciencedirect.com/science/article/abs/pii/S0965856416307765

- removing car parking and reusing for alternative uses — the ability for a CAV to drop-off and then park elsewhere could see car parking relocated further from destinations. This could allow existing car parking to be repurposed for a higher value use.

The types of government changes would generally be anticipated to further increase the benefits related to CAVs, albeit not substantially. A positive impact is expected because government responses would tend to occur only where the change had a net benefit.

The one government change that could materially increase benefits is road pricing, which is not made possible by CAVs, but which could increase the benefits of CAVs. Road pricing would potentially produce very large increases in benefits through controlling the inducement effects of CAVs — in the central case estimates produced in this report, controlling inducement effects increases the benefits of CAVs by $180 billion, through reducing re-congestion of the road network, albeit also reducing the benefits for new road users.[17] However, some of the benefits of CAVs, such as reduced congestion, could be smaller if road pricing was already in place.[18] This is because the benefits of improving the effective road capacity would be reduced to some extent if road pricing was already mitigating congestion impacts.

More importantly, government responses could substantially alter the pattern of impacts of CAVs. For example, if governments responded by reducing their road investment, then the decongestion benefit from CAVs would instead become a government cost saving. Whether this translated through to lower taxes or increased expenditure on other activities would reflect the choices of government.

Many of these responses are longer term and would depend on specific business cases and policy analyses as to whether or not they occur as well as the practical considerations of implementation. Therefore, this analysis does not attempt to quantify these (see tables 4.2 and 4.3 below for the benefits and costs considered in this analysis).

Impacts examined in this study and in previous studies

Many of the impacts of CAVs have been examined in previous studies. A recent and comprehensive literature review covering mostly academic studies of benefits and costs is Andersson & Ivehammar (2019)[19]. Similarly, PwC (2020)[20] reviewed Australian and

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17 The specific mechanisms to minimise inducement would need to be investigated to achieve this in an efficient way.

18 BITRE 2015, *Traffic and congestion cost trends for Australian capital cities*, November, https://www.bitre.gov.au/publications/2015/is_074.

19 Andersson, P. and Ivehammar, P., 2019, 'Benefits and costs of autonomous trucks and cars', *Journal of Transportation Technologies*, 9(2) 2019, available at: https://file.scirp.org/Html/1-3500462_91048.htm

20 PwC, 2020, *Regulation of automated vehicles when in-service — Cost-benefit analysis*, prepared for the National Transport Commission, February 2020 available at: https://www.ntc.gov.au/sites/default/files/assets/files/PwC-CBA-In-service-safety-for-automated-vehicles.pdf

overseas studies that aimed to measure the benefits of automated vehicles. There are also non-academic publications that informally collate estimates from the literature.[21]

Across studies that seek to comprehensively measure benefits from connected and/or automated vehicles, the types of benefits and costs considered is mostly consistent. However, benefit categories are often named differently depending on how they are measured. That is, studies may capture the benefits of CAVs improving capacity of the road network through the benefit of reduced congestion, **or** increases in property prices that occur as a result, **or** reduced costs of infrastructure investment to deliver the original capacity level.

To address this, we have developed a single categorisation that includes all the types of benefits (table 4.2) and costs (table 4.3) described in the literature, in a way that does not double up estimates. There are a range of benefits and costs that are not estimated in this study, and the net effect of these exclusions on the estimated economic impact of CAVs is uncertain. Tables 4.2 and 4.3 also note the chapters that contain estimates of each benefit and cost category.

4.2 Types of benefits from CAVs

Benefit category in this study	Benefit names or subcategories of benefit in the literature	Discussion of inclusions/exclusions	Estimated in this study	Chapter in this report where this benefit is reported
Safety	▪ Safety benefits ▪ Crash avoidance and less severe crashes ▪ Reduced cost of loss of life/injury from crashes	Reduced crash costs relating to drivers, passengers, and pedestrians These safety changes can be measured net of any additional crashes caused by system failures, platooning, etc. Insurance costs would likely fall as a result of reduced crash costs — this is simply a different way of considering the same benefit, so including both would be double-counting.	✓	Chapter 5
Reduced cost of travel time	▪ Reduced cost/value of time for people using cars ▪ Productive use of travel time ▪ Reduced driver stress	Changes to the value of time assumed during travel depending on the degree to which drivers can do other things while driving. To the extent that drivers would work during this time, this can be considered a productivity-related benefit, particularly where related to business time.	✓	Chapter 6

21 See, for example, the list of benefits collated by Thales, available at: https://www.thalesgroup.com/en/markets/digital-identity-and-security/iot/magazine/7-benefits-autonomous-cars

Benefit category in this study	Benefit names or subcategories of benefit in the literature	Discussion of inclusions/exclusions	Estimated in this study	Chapter in this report where this benefit is reported
Reduced congestion	▪ Reduced congestion ▪ Increased network capacity ▪ Travel time savings ▪ Faster journeys ▪ Improved accessibility/mobility (including for non-drivers) ▪ Better asset utilisation	Changes in network capacity and congestion levels. This benefit stream should account for the extent to which this is mitigated by induced travel (as mentioned by, for example, Litman (2021). Induced travel refers to additional trips that are generated, in this case, because of reduced congestion or reduced travel time cost.	✓	Chapter 7
Reduced driver costs for freight, delivery and on-demand transport	▪ Reduced driver costs for freight and delivery ▪ Wage savings ▪ Freight productivity ▪ Industry impacts	Savings on driver wages or other freight transport-related costs associated with businesses that use drivers such as freight, delivery, and taxis.	✓	Chapter 6
Reduced vehicle operating costs	▪ Reduced vehicle operating costs ▪ Fuel cost savings ▪ Fuel efficiency benefits ▪ Energy management	Fuel impacts are very frequently measured in the literature and are sometimes more generically referred to as energy management benefits. Other changes in vehicle operating costs (such as tyre costs) are sometimes included under maintenance costs.	✓ (fuel only)	Chapter 6
Benefits from accessibility and new trips	▪ General value of new road trips ▪ Value of mobility for people such as the elderly and disadvantaged	Additional road travel is likely to occur as a result of CAVs, because it has a benefit to those people who now undertake it. This value may be high for particular disadvantaged groups that are now able to travel, and which are higher than typically measured using standard approaches for induced traffic. (e.g. Harper et al, [2016] focussed on this benefit stream)	✓ (except for higher value placed on travel by particular disadvantaged groups)	Chapter 6 and 7 (relates to both the reduced costs of travel time and reduced congestion)
Land use changes	▪ Parking benefits ▪ Impact on property values ▪ Increased sprawl and related costs	The key subcategory here is changes in use of land for parking, which translate into reduced parking revenue and/or substitution of land used for parking to other uses. Similarly, CAVs may also spur reallocation of road space for other uses. Changes in land use are highly uncertain, and not considered to be quantifiable with the available evidence by Andersson & Ivehammar (2019). We have not quantified reallocation of parking or road space because the amount of space reallocated is unknown.	×	N/A

Benefit category in this study	Benefit names or subcategories of benefit in the literature	Discussion of inclusions/exclusions	Estimated in this study	Chapter in this report where this benefit is reported
		Property value impacts are an alternative measure of other benefits such as reduced costs of travel time. This is because property values reflect the characteristics of the property, including the level of accessibility of that property. Therefore, reductions in the cost of travel time will be reflected in increases in property values. Measuring both property value uplift and other benefit categories will result in double-counting in most instances.		
Changes in emissions and energy use externalities	▪ Reduced emissions due to less fuel consumption ▪ Increased emissions due to induced travel	The two environmental externalities considered are those associated with energy use and emissions (including Greenhouse gases, Volatile Organic Compounds, Sulfur Dioxide, etc.) (see Fagnant & Kockelman, 2013). Emissions impacts are sometimes estimated including the effect of induced travel. That is what is done in this study.	✓	Chapter 8

Source: Litman (2021) available at: https://www.vtpi.org/avip.pdf, Andersson & Ivehammar (2019) available at: https://file.scirp.org/Html/1-3500462_91048.htm#ref9, Harper et al (2016), Anderson et al (2014) *Autonomous Vehicle Technology. A Guide for Policymakers*, Fagnant & Kockelman (2013) available at: https://www.caee.utexas.edu/prof/kockelman/public_html/TRB14SAVenergy_emissions.pdf CIE.

4.3 Types of costs from CAVs

Cost category	Issues relating to scope of what is included	Estimated in this study	Chapter of this report where this cost is reported
Higher vehicle costs	Andersson & Ivehammar (2019) note that some additional costs are more persistent (e.g. higher production costs) while others are transitory (e.g. development costs). Costs of vehicles would also include costs borne by the manufacturer in retraining staff involved in vehicle production. Vehicle cost savings would occur if autonomous vehicles result in the same transport task being delivered by fewer vehicles due to sharing/subscription models or utilisation of freight vehicles for more hours of the day.	✓	Chapter 9
Maintenance costs	Maintenance or ongoing costs for CAVs will potentially be higher than non-CAVs. This is included in estimates of higher overall vehicle costs.	✓ (included in vehicle cost estimates)	Chapter 9
Road infrastructure costs	There are road infrastructure costs associated with 'signs and lines' that would not be required for Level 1/2 CAVs, and hence additional costs would be incurred to facilitate Level 4/5 CAVs. In the very long term, there may be some savings on infrastructure costs associated with new streets being able to be narrower, reduced wear on road pavement due to changes in lane positioning, etc. These are not measured in this study.	✓	Chapter 9

Cost category	Issues relating to scope of what is included	Estimated in this study	Chapter of this report where this cost is reported
Infrastructure costs of other transport modes	To the extent that CAVs result in substitution from other modes of transport to private cars, this may drive reduced operational and capital expenditure on public transport, cycling, and other modes. We have not estimated these cost savings because reducing expenditure on public transport is one possible choice by government, with the alternative being to deliver superior service standards without reducing expenditure.	×	N/A
Communication infrastructure costs	Costs of upgrading telecommunications infrastructure to facilitate connectivity of vehicles, beyond what would occur anyway. The set of subcategories of telecommunications infrastructure required for CAVs is discussed in Infrastructure Australia (2017).	✓	Chapter 9
Increased public health costs	Substitution away from active transport (walking, cycling, etc.) to CAVs may have public health externalities. Litman (2021) also mentions that this shift would have social equity implications because these are affordable modes of transport.	✓	Chapter 10
Costs to retrain freight and delivery workers and job displacement	There are large numbers of people employed in the road transport sector. These people would instead undertake other jobs. If the transition to CAVs is more rapid, then there may be disruption and retraining costs, while if it is slow, as expected in the central case scenario, transitional costs would be less important. No studies appear to have quantified costs related to retraining.	×	N/A
Reduced security and privacy	Connectivity would be associated with some risk of hacking, location tracking, and related issues. No studies appear to have quantified such costs.	×	N/A

Source: Litman (2021) available at: https://www.vtpi.org/avip.pdf, Infrastructure Australia (2017) available at: https://infrastructure.org.au/wp-content/uploads/2017/09/AV-paper-FINAL.pdf, Andersson & Ivehammar (2019) available at: https://file.scirp.org/Html/1-3500462_91048.htm#ref9, CIE.

5 The safety impacts of CAVs

Road crashes impose substantial costs through loss of life, injury, costs to the public health system and damage to property. We estimate road crashes cost a total of $25 billion in 2020 and that this will gradually increase over time.[22]

A large share of road crashes is related to human error. It is expected that CAVs have the potential to substantially reduce crash rates — on top of the reductions expected from other features that are already being taken up by Level 1 and 2 automation that reduce safety costs, such as emergency automatic braking and lane-assist technology.

We estimate the safety benefits related to CAVs will be $152 billion over the period from 2020 to 2070. This includes saving over 8000 lives that would be lost in road crashes from 2020 to 2070. The benefits accrue mainly from 2050 to 2070 when there are higher levels of uptake of CAVs.

Road crashes in Australia

Road crashes in Australia are categorised by the severity of the injuries sustained by the occupant. Fatal crashes are the most severe, then crashes that lead to hospitalisation followed by crashes with minor injuries or only property damage. There are far fewer fatal crashes than other crash types, but their impact and costs are much larger. In the sections below we set out the evidence about the level and trends in crash rates. This evidence is used to extrapolate crash numbers for future years by assuming a constant rate of crashes per vehicle kilometre travelled.

Fatal crashes

The number of fatal crashes in Australia involving a car, truck or bus has steadily increased in recent years, from 1093 in 2016 to 1284 in 2019. The onset of the COVID-19 pandemic in 2020 resulted in less kilometres travelled and consequently less fatal crashes, with 1005 recorded in 2020.

For our analysis, road fatalities and fatal crashes were identified through the Australian Road Deaths Database[23]. The database provides an ongoing account of all road crash

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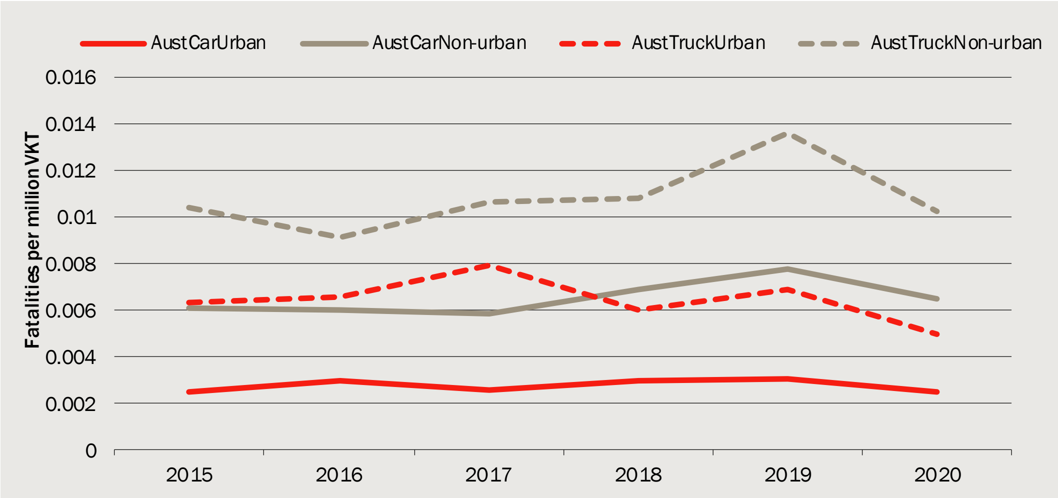
22 This increase will be steeper in the years following the COVID recovery, as road traffic demand increases back to pre-COVID-19 levels. No allowance has been made for other government policies that may be used to reduce the costs of road crashes outside of Level 1 and 2 automation and CAVS.

23 https://www.bitre.gov.au/statistics/safety/fatal_road_crash_database, accessed 7 September 2021

fatalities in Australia as reported by the police to each State and Territory road safety authority. Details for crashes indicated the number of fatalities, whether an articulated truck, heavy truck or bus was involved in the crash as well as the region of the crash. We combine these datapoints to determine for each region the number of crashes involving cars, trucks and buses.

To estimate the number of kilometres travelled per year per mode of transport, we refer to the ABS survey of Motor Vehicle Use[24]. The survey is conducted every 2 years and records detailed estimates of VKT in Australia during that year. We use the estimates of VKT for each vehicle type per region[25] per State. For each intermittent year the survey is not released (2015, 2017, 2019), we apply an average of the former and subsequent year. Applying the VKT estimates to the number of fatalities provides us a rate of fatalities per million VKT (chart 5.1). The rate of fatal crashes experienced an increase in 2019, followed by a decrease in 2020, which is likely due to the COVID-19 pandemic.

5.1 Fatal crashes per one million VKT for cars and trucks by region



Note: Any crash involving a truck is allocated as a truck crash, even if this also might involve a car.
Data source: The CIE, BITRE, ABS.

Crashes involving trucks have a higher rate of fatalities than cars (chart 5.2). Non-urban travel has a higher rate of fatalities compared with urban travel. The Northern Territory (NT) stands out for having a significantly high fatal crash rate. The high crash rate in the NT has been reported as systemic,[26] with such contributing factors as high alcohol consumption, low seatbelt usage, single lane roads of which many are unsealed, and extreme weather.

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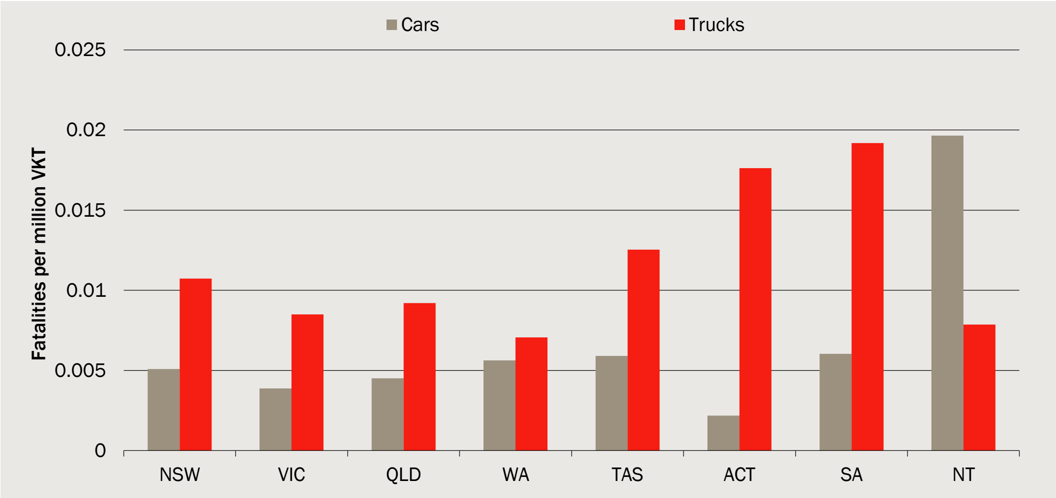
24 https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia, accessed 7 September 2021

25 There are 2 regions, capital cities and other areas.

26 Read (2015), Open speeds on Northern Territory roads: Not so fast, pp. 14-15 https://www.mja.com.au/journal/2015/203/1/open-speeds-northernterritory-roads-not-so-fast

5.2 Average fatalities per million VKT in 2018-2019 by state and territory



Note: Any crash involving a truck is allocated as a truck crash, even if this also might involve a car.
Data source: The CIE, BITRE, ABS.

Hospitalised crashes

Hospitalised crashes in Australia have remained relatively stable in recent years, with 38 129 recorded in 2016 and 38 582 in 2018.

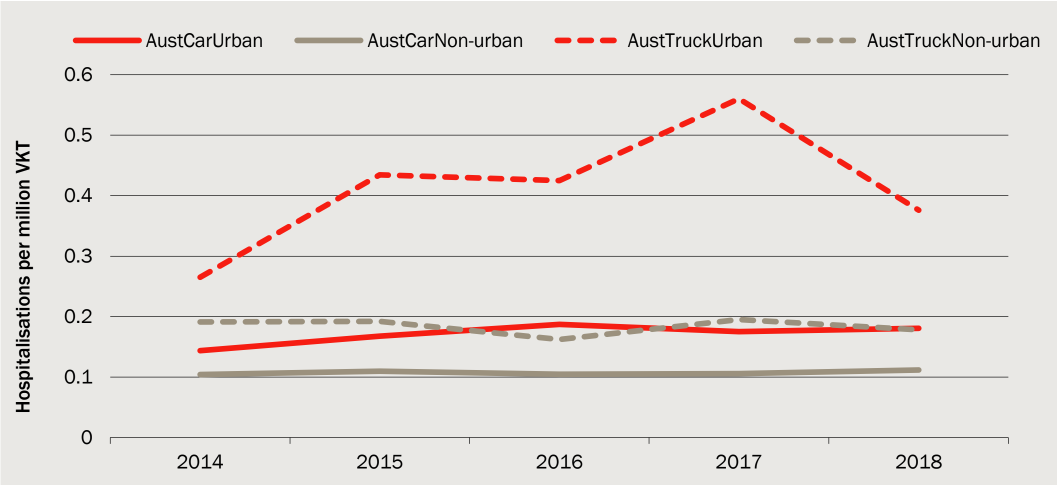
For our analysis, hospitalisations as a result of motor vehicle crashes were identified through the BITRE database of hospitalised injuries produced by the National Injury Surveillance Unit at Flinders University, under an agreement with the Australian Institute of Health and Welfare[27]. Hospitalisations as a result of a motor crash are classified when an injured person is admitted to hospital and subsequently discharged alive. This data is recorded annually and details in which remoteness area[28] the crash occurred. To estimate the number of incidences per vehicle type, we applied a weighted average using the rate of fatal crashes per region.

Urban areas have higher rates of hospitalisations from crashes than non-urban areas (chart 5.3), which contrasts with the rates of fatal crashes. This is likely due to lower driving speeds in urban areas reducing the severity but increasing the frequency of crashes. Trucks have higher rates of hospitalisations than cars. Apart from trucks in urban areas, the rate of hospitalisation has remained relatively stable.

27 https://www.bitre.gov.au/publications/ongoing/hospitalised-injury, accessed 7 September 2021

28 Remoteness areas: Major cities, Inner regional, Outer regional, Remote, Very remote

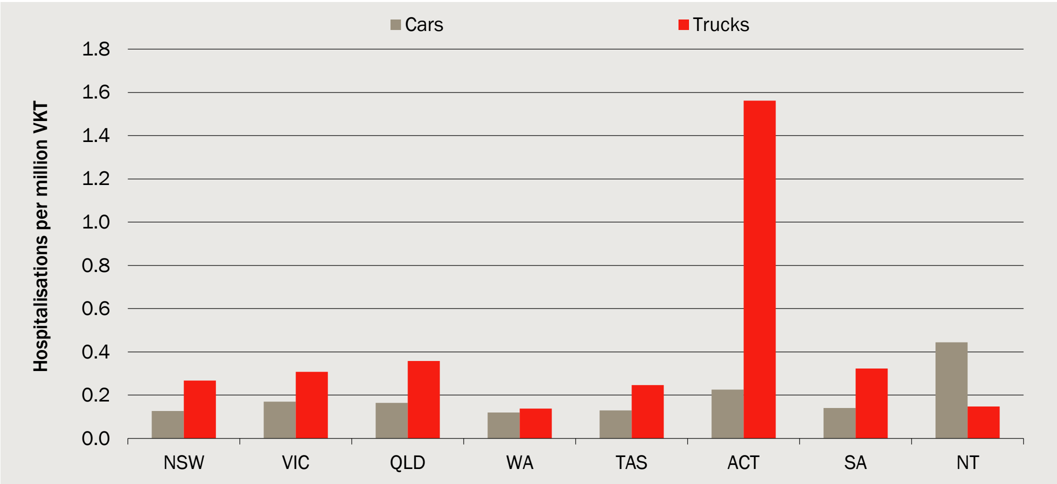
5.3 Hospitalisations per one million VKT for cars and trucks by region



Note: Any crash involving a truck is allocated as a truck crash, even if this also might involve a car.
Data source: The CIE, AIHW, ABS.

Chart 5.4 shows the hospitalisations rate for each State and Territory for cars and trucks. The ACT stands out among the regions, mainly due to low truck VKT but there being at least one crash. Apart from the NT, trucks have a higher estimated rate of hospitalisation per million VKT.

5.4 Average hospitalisations per million VKT in 2018-2019 by state

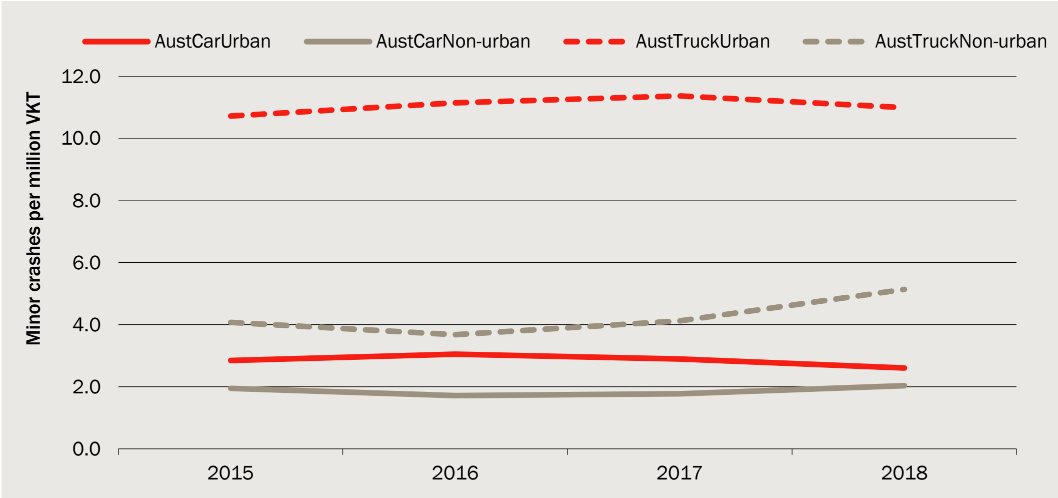


Note: Any crash involving a truck is allocated as a truck crash, even if this also might involve a car.
Data source: The CIE, AIHW, ABS.

Minor injury and property damage crashes

Minor injury crashes are incidents where the impacts of a crash are either an injury which does not result in hospital admission or death, or no injuries but damage to property. We estimate these two rates separately and combine for a total minor injury crash incident rate per million VKT. Chart 5.5 shows the estimated rate of minor crashes for cars and trucks in urban and non-urban regions. The rates have remained relatively stable, with urban having larger rates than non-urban.

5.5 Minor crashes per million VKT for cars and trucks by region



Data source: The CIE, Transport for NSW, ABS, BITRE.

Non-hospitalised injuries

Estimating the number of non-hospitalised injuries is challenging as there is limited data available for Australia. Two factors drive this:

- there is limited record-keeping pertaining to instances when an injured person presents at the Emergency Department and is not admitted to hospital, and
- there are no records of when an injured person presents to a general practitioner.

To account for this shortfall, we use the estimates from BITRE (2009)[29] that are based on data about the number of crashes, same-day hospital discharges and the ratio of hospitalised to non-hospitalised casualties in Queensland. Consistent with the approach used by Economic Connections (2017),[30] we then project this using the average growth rate (0.5 per cent) of no-fault compensation claims in Victoria and Queensland from 2006 to 2016. This results in an estimate of non-hospitalised injuries of 231 003 in 2018.

Property damage

To estimate the number of crashes resulting in only property damage we apply the same methodology as non-hospitalised crashes. This uses a ratio of property damage crashes to fatal crashes (302 to 1) as estimated in the BITRE study. We apply a growth rate of 0.4 per cent per year which is consistent with the estimates in the Economic Connections study. We apply a weighted average to allocate the crashes between regions and mode of transport.

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29 Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2009, *Cost of road crashes in Australia 2006*, https://bitre.gov.au/publications/2010/report_118.aspx

30 Economic Connections, 2017, Cost of road trauma in Australia 2015 - prepared for the Australian Automobile Association, https://www.aaa.asn.au/wp-content/uploads/2018/03/AAA-ECON_Cost-of-road-trauma-full-report_Sep-2017.pdf

In order to classify the injuries by vehicle type and region, we refer to data recorded by Transport NSW.[31] This provides detailed data regarding crashes where injuries do not result in a fatality or hospitalisation, which are classified as moderate and minor injuries. This database does not provide a breakdown by vehicle type, however this is reported separately in the annual statistical statements for road traffic crashes in New South Wales.[32] We combined the datasets using a weighted average, which results in the proportion of urban and non-urban crashes being consistent across all vehicle types.

Valuing improved safety

Australian Transport Assessment and Planning (ATAP) provides guidance on the cost of crashes based on the severity of injury. Fatal crashes are the most severe and the cost impact is reflective of the value of a statistical life. Non-fatal crashes which result in disability use the value of a statistical life[33] apportioned to the effective days of life lost as a result of an injury. ATAP present two methodologies to calculate the value of a statistical life, the hybrid human capital (HC) approach and the willingness to pay (WTP) approach. The hybrid HC approach centres on valuing loss of life, health and wellbeing on the basis of the cost of labour forgone in the economy and in the household. The WTP approach values society's willingness to pay for avoiding death, injury, and damage outcomes from road crashes. Typically the HC approach yields a lower value that WTP, as it does not factor in intangible life factors that people value, such as leisure and well-being. Estimates of the value of a statistical life significantly differ between approaches and studies, as shown in table 5.6. Both the ATAP HC and WTP estimates focus on the road transport sector, whereas the Office of Best Practice Regulation (OBPR) WTP estimate is for all sectors and takes account of comparable European estimates[34]. For these reasons, the OBPR estimate is the most reasonable assumption for our central case analysis.

5.6 Value of statistical life estimates

Approach	Value of life	Source
	$m	
ATAP Hybrid human capital	2.80	Transport and Infrastructure Council
ATAP Willingness to pay	8.39-8.50	Transport and Infrastructure Council
OBPR Willingness to pay	**4.70**	**Office of Best Practice Regulation**

Note: In 2020 dollars, OBPR WTP estimates used in the central case.

Source: The CIE.

31 https://roadsafety.transport.nsw.gov.au/statistics/interactivecrashstats/nsw.html?tabnsw=3, accessed 7 September 2021

32 https://roadsafety.transport.nsw.gov.au/statistics/reports.html, accessed 7 September 2021

33 The value of a *statistical* life is the value of reducing the average number of deaths by one.

34 Abelson (2008), Establishing a Monetary Value for Lives Saved: Issues and Controversies for the Office of Best Practice Regulation, https://www.researchgate.net/publication/255548143_Establishing_a_Monetary_Value_for_Lives_Saved_Issues_and_Controversies

We can estimate the cost of crashes to Australia by applying the value of a statistical life to the various severities of crash types. We categorise crash types as fatal, resulting in a hospitalised injury, or resulting in a minor injury. As crashes generally occur between two or more vehicles and there may be more than one occupant per car, the number of fatalities/injuries per crash is greater than one (table 5.7).

5.7 Casualty rates by road crash type

Crash type	Fatalities per crash	Hospitalised injuries per crash	Minor injuries per crash
Fatal	1.09	0.45	0.27
Hospitalised injury	n.a	1.20	0.19
Minor injury	n.a	n.a	1.20

Source: AAA 2017.

Total crash costs combine the value of the statistical life, whether lost completely in a fatal crash or partially lost in a crash resulting in major or minor injury, with the expected number of persons involved plus property damage. Table 5.8 provides an overview of the crash cost assumptions used in this analysis. The central case estimates are based on the **OBPR willingness to pay estimates**, which combines the OBPR value of life with ATAP estimates of other crash costs.

5.8 Crash cost assumptions

Approach	Fatal	Hospitalised injury	Minor injury and property
	$/crash	$/crash	$/crash
ATAP Hybrid human capital	3 023 121	104 965	15 098
ATAP Willingness to pay	9 512 902	153 895	18 492
OBPR Willingness to pay	**5 841 526**	**153 895** [a]	**18 492** [a]
AAA Hybrid	5 036 541	304 377	12 918

[a] There is no OBPR estimate for hospitalised injury and minor injury and property, so the ATAP figure is used for our analysis in this scenario.

Note: In 2020 dollars.
Source: The CIE.

The fatal crash cost combines the value of the life lost with damage to property and general costs, such as vehicle towing, emergency services and administrative. Hospitalised injury crash costs combine permanent disability costs with temporary serious injury costs. In 2015, 12 per cent of hospitalised cases resulted in the person becoming lastingly disabled.[35] Each of the studies provide estimates for serious and non-serious hospitalised injuries, of which we apply the 'serious' estimate to the expected 12 per cent of incidences resulting in disability and the 'non-serious' estimate to the remainder. The minor injury and property estimates combine the cost of injuries which do not result in hospitalisation as well as costs of property damage.

35 Economic Connections (2017), Cost of road trauma in Australia 2015 - prepared for the Australian Automobile Association, https://www.aaa.asn.au/wp-content/uploads/2018/03/AAA-ECON_Cost-of-road-trauma-full-report_Sep-2017.pdf

Overall cost of crashes in Australia

We apply these cost estimates per crash to the Australian crash data to estimate the cost of road crashes per year. Table 5.9 shows the total safety costs per year for Australia. Minor injury and property is the largest cost category, contributing to approximately 50 per cent of total annual crash costs.

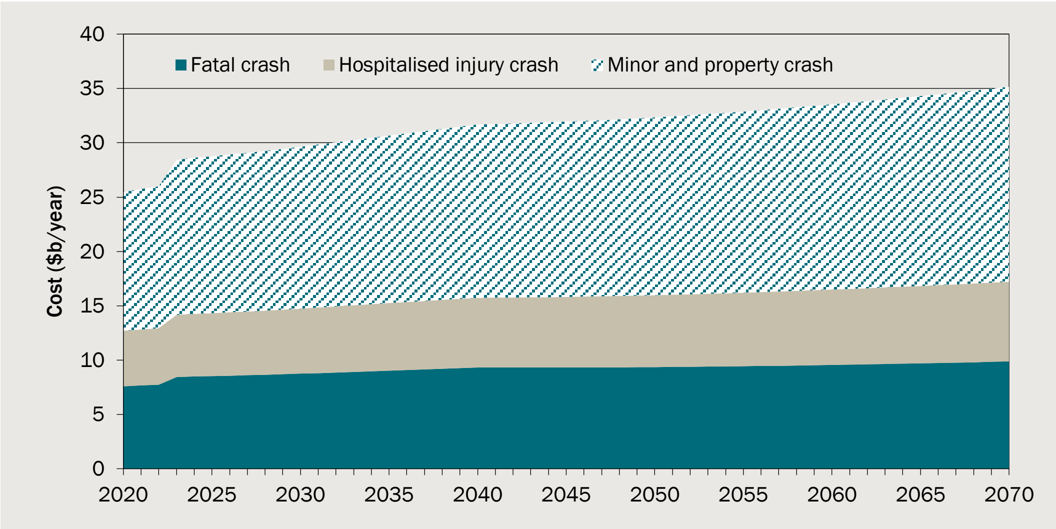
5.9 Total road crash costs for Australia in 2020

Crash category	Cost
	$m
Fatal crash	7 588
Hospitalised crash	5 102
Minor and property injury crash	12 767
Total crash costs	**25 457**

Note: Based on using OBPR value of life and ATAP estimates for other crash-related costs. In 2020 dollars
Source: The CIE.

Crash costs are anticipated to increase over time due to the increasing transport task. Chart 5.10 shows the trajectory of crash costs between 2020 and 2070. Crash costs increase rapidly between 2022 and 2023 to account for VKT returning to the trend before COVID-19. The fatal crash rate remains relatively stable due to the trend of decreasing fatal crashes each year balanced by increasing VKT. Both hospitalised injury crashes and minor injury and property crashes increase in the forward projections.

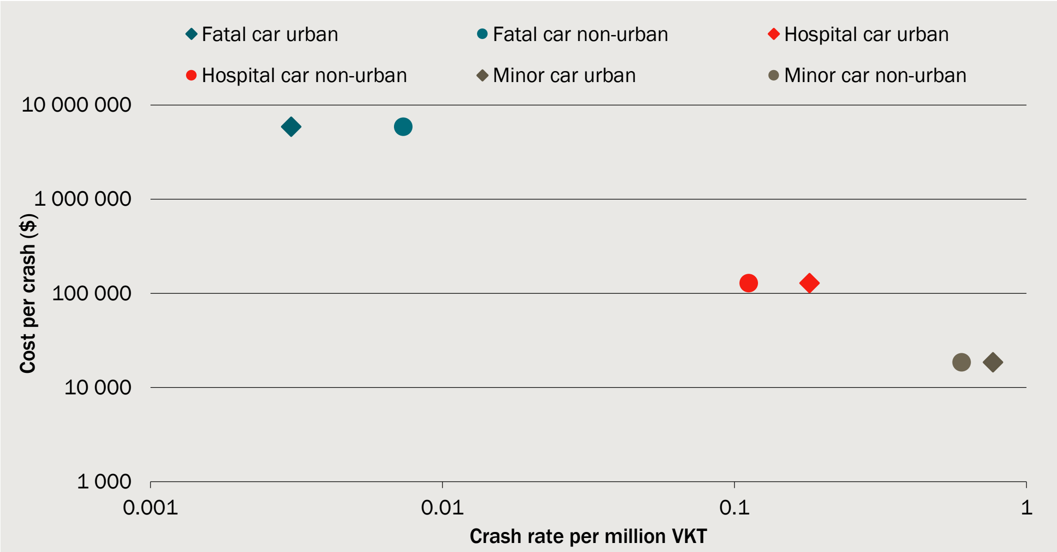
5.10 Road crash costs without CAVs



Note: Based on using OBPR value of life and ATAP estimates for other crash-related costs.
Data source: The CIE.

Chart 5.11 shows the cost per crash and expected crash rate for cars by region. Hospitalised and minor injury crashes are more frequent in urban areas whereas for fatal crashes non-urban is more frequent. Fatal crashes are significantly more costly than hospitalised and minor injury crashes.

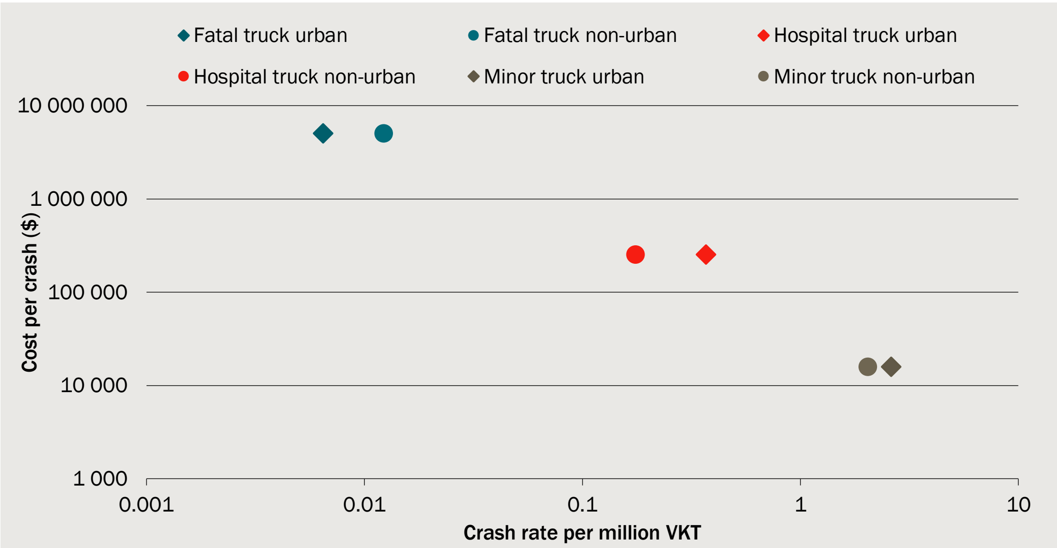
5.11 Crash costs and crash rate per million VKT for cars



Data source: The CIE.

Chart 5.12 shows the crash costs and expected crash rate for trucks by region. It follows the same trends of urban and non-urban visible for cars.

5.12 Crash costs and crash rate per million VKT for trucks



Data source: The CIE.

Comparison of crash costs under alternative assumptions

Chart 5.13 shows the range of estimates from various published studies for the annual total cost of road crashes in Australia based on different methodologies and input assumptions. The lower range of estimates represent the HC methodology whereas the central and upper range estimates represent the WTP approach. Within WTP estimates, the lower range are based on the OBPR value of a statistical life estimate whereas the upper range is based on the ATAP value of life estimate.

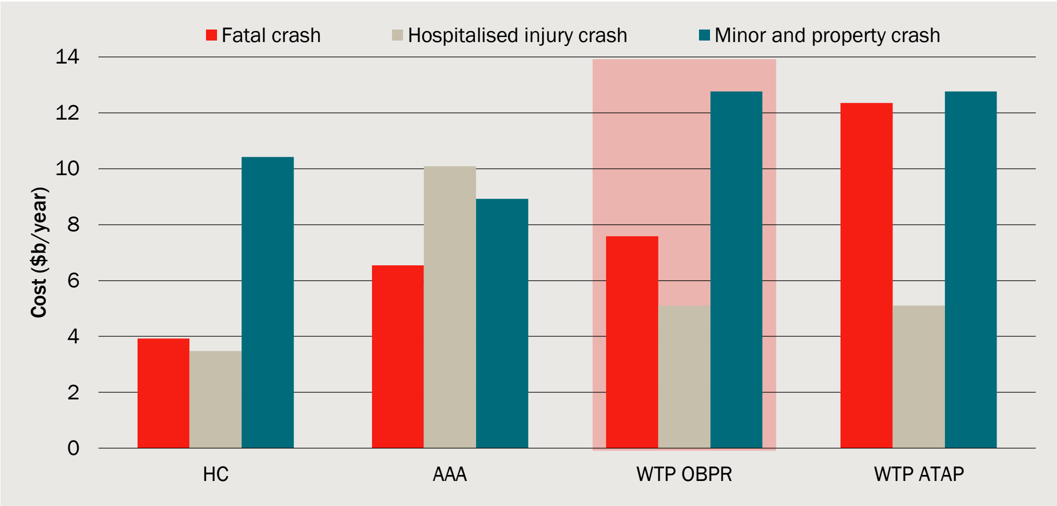
5.13 Comparison of cost of road crashes with previous studies

Study	Method	Cost of road crashes
		$m
BITRE 2009	Hybrid human capital	25 807
BITRE 2009	WTP roads	39 963
AAA 2017	ECON Hybrid human capital	21 837
AAA 2017	ECON WTP OBPR	24 042
AAA 2017	ECON WTP ATAP	32 085
CIE 2021	**WTP OBPR**	**25 457**

Note: In 2020 dollars.
Source: The CIE, AAA.

Chart 5.14 shows the annual total crash costs by crash type for each of the estimation methodologies in the CIE model. The HC approach delivers the lowest value for fatal and hospitalised crashes, whereas the WTP approach results in the highest estimates for fatal and minor injury and property crashes.

5.14 Total annual crash costs by crash type and methodology



Note: In 2020 dollars.
Data source: The CIE.

Safety cost reductions expected from CAVs

CAV technology at each level of automation introduces safety to benefits to the vehicle occupants and other road users. CAV technology has the ability to mitigate the negative effects of driver errors, which are considered a leading factor solely or in combination with other factors in more than 93 per cent of public roadway crashes.[36]

36 Singh, 2015, *Critical Reasons for Crashes Investigated in the National motor Vehicle Crash Causation Survey*, National Highway Traffic Safety Administration.

Studies have attempted to demonstrate the effectiveness of various existing level 1/2 technologies. However, these studies are often limited to testing scenarios and not in combination with the full CAV system. Estimating the safety impacts of level 3/4/5 is more speculative as the technology is still in development and testing is generally limited to simulation modelling. As a result, benefits are mostly attributed to the removal of human error and assuming that the technology will develop to this standard over time.

Safety cost impacts of low levels of automation

Previous studies have provided effectiveness estimations of low-level CAV technology based on field tests or simulation experiments. For example, the Insurance Institute for Highway Safety has published several reports about the testing results of Forward Collision Warning, Autonomous Emergency Braking, Autobrake, Blind Spot Warning, Lane Departure Warning and Rearview Cameras[37]. Efforts have been made to summarise and aggregate these benefits, such as by Jermakian (2011),[38] which estimates the maximum potential crash reduction of CAV technologies in the US passenger cars. Kockelman and Li (2016)[39] provides a combined benefit estimate for 15 CAV technologies for light vehicles. Chang (2016)[40] summarises the CAV related research about heavy vehicles, which was conducted by National Highway Traffic Safety Administration (NHTSA).

However, there are three major limitations existing in this literature:

1 not all CAV technologies that have been tested have been included,

2 estimates of CAV effectiveness were only based on one or two studies, in which limited experiment conditions or evaluation methodologies were considered, and

3 few studies have evaluated the performance of CAV technologies under specific conditions, e.g. extreme weather.

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37 For example see Cicchino (2017), Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates and Cicchino (2017), Effects of Blind Spot Monitoring Systems on Police-Reported Lane-Change Crashes. These studies are based on US data.

38 Jermakian, 2011, Crash avoidance potential of four passenger vehicle technologies. https://www.researchgate.net/publication/50288058_Crash_avoidance_potential_of_four_passenger_vehicle_technologies

39 Study based on US data, Kockelman et al, 2016, Valuing the safety benefits of connected and automated vehicle technologies. Proceedings of the Transportation Research Board 95th Annual Meeting.

40 Study based on US data, Chang, 2016, Summary of NHTSA Heavy-Vehicle Vehicle-To-Vehicle Safety Communications Research. National Highway Traffic Safety Administration, Washington, D.C.

Estimation of benefits for low level automation systems study

A recent study (Yue, 2018)[41] summarised and compared the various studies to estimate the effectiveness of combined low-level CAV technology. The study compared 12 separate CAV technologies and 9 integrated systems which could deal with 6 types of crash events and 23 pre-crash scenarios. Ten of these technologies meet the standards of automation level 1, with the remainder at level 0.

The scenarios tested in Yue (2018) considered a subset of 86 per cent of light vehicle crashes and 78 per cent of heavy truck crashes. For the 14 per cent for light vehicles and 22 per cent for heavy trucks which are not considered, these include vehicle-animal-related crashes, vehicle-cyclist-related crashes, parking and opposite direction-related crashes, some subcategories of run-off-road crashes like vehicle failure crashes, and some other non-specified crashes.

For light vehicles, the study estimates that the crash reduction rate is at least 33 per cent of the total subset of crashes for the conservative scenario and 45 per cent of crashes for the aggressive scenario. For heavy vehicles, the CAV technology could reduce at least 41 per cent of the total subset of heavy vehicle crashes in the conservative scenario and 54 per cent of crashes for the aggressive scenario. When compared to total crashes, this results in a reduction of 28 per cent (conservative scenario) and 39 per cent (aggressive scenario) for light vehicles and 32 per cent and 42 per cent respectively for heavy vehicles. These estimates are based on the assumption that there is a 100 per cent market penetration for all these CAV technologies.

Safety cost impacts of high levels of automation

High level automation technology is still in the development stage and therefore it has not been thoroughly tested in the real-world environment. This means that to estimate the safety impact of these technologies, researchers must rely on simulation models of historical data coupled with assumptions on adverse driver behaviour being removed by technology. As a result, there is a broad range of estimates in the literature for the safety impact of high-level automation.

Conservative estimates consider that some crashes are inevitable due to technological error or human behavioural factors.

More optimistic estimates take the number of crashes where human error was the cause, estimated at 93 per cent, and assume these crashes would all be avoided at 100 per cent CAV uptake. The 93 per cent figure was drawn from the NHTSA National Motor Vehicle Causation Survey and is widely cited in the literature.[42] The reliance on this

41 Yue et al (2018), Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low level automation systems, https://www.sciencedirect.com/science/article/abs/pii/S0001457518301404

42 Fagnant and Kockelman (2013), Preparing a Nation for Autonomous Vehicles, https://www.sciencedirect.com/science/article/abs/pii/S0965856415000804

estimate by the public (including the US House and Senate[43]) prompted a review by the Casualty Actuarial Society (hereafter the CAS study), which sought to provide a more considered estimate of benefits.

CAS review of high-level automation safety impact estimations

The CAS study is based on the premise that a future of CAVs will look much different and involve different risks. As drivers rely more on the vehicle technology and less on themselves, the crash causation variables will change. The study revaluated the crash statistics of the National Motor Vehicle Crash Causation Survey[44] to determine whether CAV technology would prevent the crash, asking two key questions: would the technology have been operable (technological issues), and would the technology have been operated safely (behavioural issues).

Technological issues are where the technology may be inoperable due to environmental issues such as weather, vehicle technology failure or infrastructure technology failure.

Firstly, crashes can occur in inoperable weather. The study defines this as snow, sleet, rain, blowing snow and dust storms. Accounting for these factors in crashes, this results in the number of preventable crashes reduced by over 12 percentage points. It is important to note that in practice this is location specific. For example, San Diego has on average less than 65 days of precipitation per year, while Seattle averages 150 days.

Secondly, crashes can occur due to vehicle error, such as the braking system malfunctioning. As the technology advances drivers will be less engaged, and therefore less able to intervene in instances where they need to overcome a system error such as a blown tire. Adjusting for these situations in the crash data decreases the likelihood of preventing crashes by 12.6 percentage points.

Finally, for a small number of crashes, the traffic control device operating the intersection was not working properly. CAV technology communicates with the traffic control devices to determine actions, and if not operating correctly it can lead to crashes. Accounting for this represents a 0.4 percentage point decrease in the likelihood of preventing crashes. While this number is small now, as technology advances, automated vehicles will become more reliant on these systems.

Behavioural issues focus on how other drivers on the road respond to and impact the CAV. For example, CAVs that do not speed may not only encourage their drivers to disengage the system but may also be a risk to other drivers on the road, for example on Chicago's highways, where the speed limit is 55 miles per hour but the average uncongested speed is typically closer to between 70 – 80 miles per hour.

In the US approximately 41 million people receive speeding tickets each year, which shows drivers regularly prioritise speed over safety. While a fleet of automated vehicles

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43 Casualty Actuarial Society (2014), Restating the National Highway Transportation Safety Administration's National Motor Vehicle Crash Causation Survey for Automated Vehicles, https://www.casact.org/sites/default/files/database/forum_14fforum_completefall2014.pdf

44 NHTSA (2008), National Motor Vehicle Crash Causation Survey, report to congress, https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811059

may create a more efficient transportation system, a law-abiding automated vehicle's restrictions may encourage the driver to take over in situations in which speed is the main concern. The study estimates that 2.8 per cent of crashes are due to drivers who 'always drive aggressive', are racing, are fleeing or are in a hurry. These drivers would be unlikely to engage the autonomous system on a vehicle.

Partially automated vehicles (level 3) would require in some instances the driver to intervene. Inhibition as a result of alcohol and other drugs is present in a significant number of crashes. This can increase the risk in two main ways. First, it may increase the pass-off risk of a partially automated vehicle. An inebriated driver may not be as capable of taking over the driving task as a sober person. Second, it may increase the incidence of alcohol in the driver's seat. An individual may be less likely to have a designated driver or call a cab if they believe they will not have to drive the automated vehicle. While this may decrease the crash frequency of each drinking and driving occurrence, it may expand the subset of inebriated drivers on the road.

Allowing human drivers to be partially involved in driving creates risks. Part of the potential value from CAVs comes from their predictability. Vehicles are able to travel very closely together at high speeds, enabling them to increase highway capacity and fuel efficiency. However, the more involved the driver is, the less predictable the driving becomes. In our current environment, over 30 per cent of crashes involve a behavioural characteristic that may cause the automated vehicle to be used incorrectly.

Of the 93 per cent of crashes related to driver error, only 51.7 per cent remain avoided due to the combined impacts of technological and behavioural risks. This results in a net reduction of crashes of 48 per cent.

Safety impact assumptions

Table 5.15 shows the safety impact assumptions used in the model for the low, medium and high scenarios for cars and trucks at the levels 1/2 and 4/5 automation.

- The low and high scenario assumptions for cars and trucks at 1/2 automation refer to the lower and upper bounds of Yue (2018).
- The low scenario for the 4/5 automation refers to the CAS study, while the high scenario refers to the 93 per cent estimate based on driver error.
- The medium scenario for both tiers of automation is based on an average of the low and high scenarios.

For the central case impacts of CAVs presented, the medium impacts are used.

5.15 Reduction in crash costs across all crashes from CAVs

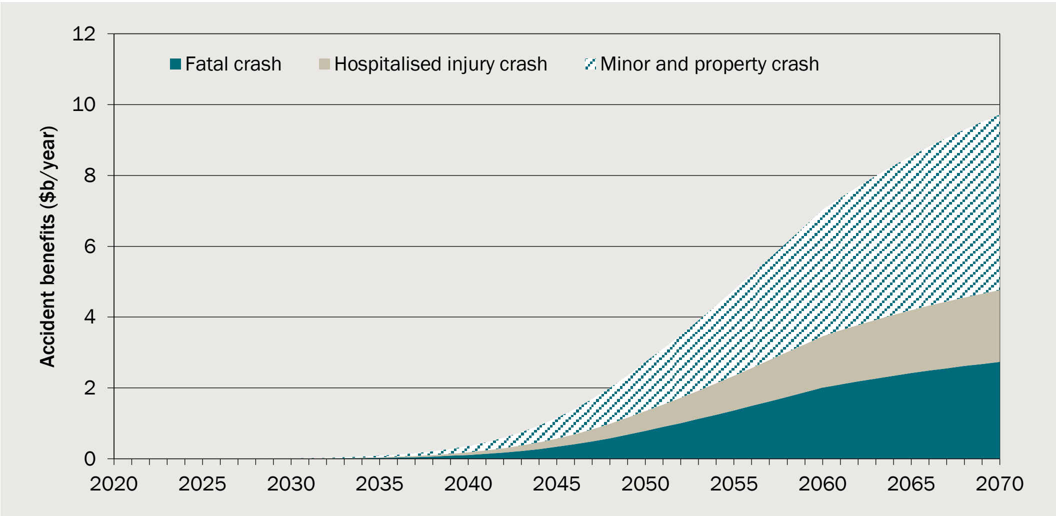
Region	Low		Medium (used in central case estimates)		High	
	Level 1/2 automation	Level 4/5 automation	Level 1/2 automation	Level 4/5 automation	Level 1/2 automation	Level 4/5 automation
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
Cars						
Capital city	-28	-48	-34	-71	-39	-93
Regional	-28	-48	-34	-71	-39	-93
Long distance	-28	-48	-34	-71	-39	-93
Trucks						
Capital city	-32	-48	-37	-71	-42	-93
Regional	-32	-48	-37	-71	-42	-93
Long distance	-32	-48	-37	-71	-42	-93

Source: The CIE.

Estimates of the benefits of CAVs for baseline traffic

Over the period from 2020 to 2070 the safety benefit from CAVs in the central case is $152 billion (chart 5.16). This includes saving over 8000 lives that would otherwise be lost in road crashes. The safety benefits increase significantly once CAV penetration reaches a critical point, which is projected from around 2050 onwards. The reduction in minor and property crashes is the largest component of totals, delivering over 50 per cent of the benefits by 2070.

5.16 Road crash benefits from CAVs



Note: Based on using OBPR value of life and ATAP estimates for other crash-related costs.

Data source: The CIE.

6 The impact of CAVs on transport cost

CAVs can reduce the costs for transport, such as the costs related to use of driver time and fuel. From 2020 to 2070, transport cost savings are almost $1.6 trillion under the base case CAV uptake scenario and central case assumptions about the impacts of CAVs. This figure includes:

- reduced transport time costs for private car users as they no longer need to perform the driving task, valued at $583 billion,[45]
- reduced business time costs of almost $250 billion, along with reduced commercial vehicle (including light commercial) and bus time costs of more than $700 billion. Together, business and freight time cost savings are valued at $962 billion, and
- reduced fuel use of $54 billion due to smoother driving and light and heavy vehicle platooning for regional and long distance travel.

Components of road transport cost

CAVs are expected to impact some costs road users face for their travel. The main costs directly borne by road users are as follows:

- the cost of driver and passenger time, which travellers could otherwise use for other purposes such as work, leisure or rest,
- vehicle operating costs (VOC), including fuel, oil, tyres, repairs and maintenance,
- new vehicle costs (i.e. CAVs are expected to cost more to buy and maintain), and
- freight cost of time, which refers to the cost of time that freighted goods spend in-transit.

Parameter values used to estimate these costs are obtained from the Australian Transport Assessment and Planning (ATAP) PV2 publication,[46] with estimates escalated to 2021 dollars using inflators from the Australian Bureau of Statistics. To illustrate by way of example, the cost of a 20km trip by car in 2021 would consist of:[47]

45 This is based on the number and distance of trips being the same as without CAVs. Benefits from new usage are considered separately.

46 ATAP, 2016, *Australian Transport Assessment and Planning Guidelines — PV2 Road Parameter Values*, available at: https://www.atap.gov.au/parameter-values/road-transport/index

47 All costs are in 2020 dollars. This example assumes the trip has an average speed of 60km/hour in stop-start traffic, and that the vehicle is a medium car driving in an urban area. The assumed value of time for a private light vehicle is $18.33 per hour per occupant, which is based on the value of $14.99 per hour from ATAP (in 2013 dollars) escalated to 2021 using ABS (2021) *Average Weekly Earnings, Australia*. Fuel and other vehicle operating cost

- 20 minutes of travel time at a cost of $6.11 per person,
- $2.40 of fuel costs, and
- $5.20 of other vehicle operating costs including depreciation of the vehicle.

Freight vehicles incur additional costs for the freight cost of time, which for a B-Double truck taking a 20 minute trip would be $23.50.[48] B-Double trucks can carry approximately 40.5 tonnes of freight.

Expected direct impacts of CAVs on transport cost

The components of direct road transport costs affected by CAVs are:

- the cost of travel time
- vehicle operating costs, due to changed fuel consumption, and
- costs of new vehicles.

Costs of new vehicles are considered in chapter 9. The other costs are considered below.

Travel time cost

CAVs are expected to have reduced travel time costs compared to non-CAVs. The main impact would be for Level 4 and 5 automation,[49] where the driver is freed from the task of driving. According to the definitions from SAE, for Level 4 the driver must remain attentive and be required to re-engage with the driving task or the vehicle will move to a safe position (e.g. parking the vehicle in a safe manner).

There is a 100 per cent reduction for commercial passenger and freight vehicles, which would no longer require a driver for Level 4 and 5 automation. As a result, there is no longer a driver in the car incurring a cost for their travel time. For example, Waymo have been operating Level 4 CAVs providing a driverless ridesharing service in Arizona.[50]

For private vehicles and commercial vehicles that still require someone to be in the car, the cost of travel time is likely to reduce partially. High levels of autonomy can allow occupants that are freed from the task of driving to instead use time for leisure, work, rest or other purposes. The value of being freed from the driving task is uncertain and likely to be influenced by the following factors:

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assumptions are obtained from ATAP, and are indexed based on the automotive fuel price index and All Groups CPI, respectively: ABS, 2021, *Consumer Price Index, Australia*, June 2021.

48 This is based on the value of freight time from ATAP PV2 for B-double trucks, which is $64.91 per hour, which is then escalated using the 'Road Freight Transport' series from the *Producer Price Indexes, Australia* publication by ABS.

49 Level 1 and 2 automation may result in improved ride quality because of features like cruise control making acceleration/deceleration more gradual. These impacts are expected to be negligible, and are not quantified given the degree of uncertainty associated with existing estimates of the value of time between modes, which differ far more in 'quality' than Level 1 or 2 compared to manual cars.

50 See https://waymo.com/waymo-one/

- the sort of activities people can engage in during trips will affect the value they place on their time – a survey of 1500 people conducted by Fraunhofer Institute and Horvath & Partners (2016) found that 75 per cent of respondents were willing to pay for a range of secondary services that could be provided during autonomous driving and were willing to pay for 'free time' during travel.[51]
- people who use CAVs may be those who expect to receive the highest value from being free from the task of driving.
- for those people who enjoy the task of driving, this may actually increase the cost of travel time since they are no longer engaging in the task they enjoy.

For business car trips and light commercial vehicles, CAVs will free up the driver to either engage in the kind of leisure/relaxation that private vehicle drivers would. However, it would also likely free up that time to be used for business purposes. In the case of a tradesperson travelling between jobs, there might be paperwork to complete, calls to make to clients or suppliers, or other tasks that can be done in the time now freed from the driving task. However, for delivery vehicles, there may be fewer productive tasks for the driver to engage in if their role is mostly related to loading and unloading goods.

There may be some impact of CAVs on freight times because CAVs do not need to stop for rest breaks or sleep like human drivers. However, these impacts are expected to be smaller than the impacts on the cost of driver time.

Vehicle operating costs including fuel

Vehicle operating costs including fuel consumption depend on driving behaviour. For example, vehicle operating costs per kilometre are higher in stop-start traffic and at lower speeds.

The main functions of CAVs that will affect vehicle operating costs include:[52]

- saved fuel due to convoy driving (i.e. platooning), which reduces wind resistance, and
- saved fuel due to smoother driving (i.e. speed regulation).

Platooning is most relevant for freight vehicles, while speed regulation is more relevant for urban environments. Basic speed regulation is likely to already occur with Level 1 and 2 automation for long-distance travel.

Speed regulation is achieved through a range of CAV technologies, such as:

- Adaptive Cruise Control (ACC), whereby speed control adapts to changing traffic conditions using Radar or LiDAR,

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51 Fraunhofer IAO and Horvath & Partners, 2016, *"The Value of Time" — Potential for user-centred services offered by autonomous driving*, available at: http://www.iao.fraunhofer.de/lang-en/images/iao-news/studie-value_of_time_EN.pdf

52 Based on: Andersson, P. and Ivehammar, P., 2019, 'Benefits and Costs of Autonomous Trucks and Cars', *Journal of Transportation Technologies*, 9(2), pp.121-145, available at: https://www.researchgate.net/publication/331664154_Benefits_and_Costs_of_Autonomous_Trucks_and_Cars

- Cooperative Adaptive Cruise Control (CACC), whereby ACC is extended using vehicle-to-vehicle communications to achieve longitudinal automated vehicle control, noting this capability assumes C-ITS has been delivered in Australia, and
- controllers that advise on/set the optimal path of vehicles through intersections, as an add-on to CACC.

Both platooning and speed regulation technologies have significant network effects, in that they are able to achieve better driving outcomes such as more consistent speed at higher penetration rates. This is the case for both technologies regardless of whether they use vehicle-to-vehicle connectivity, since even unconnected automated vehicles drive more predictably, thus facilitating smoother driving.

Analysis of the impacts of CAVs on vehicle operating costs has been focussed on fuel costs, rather than other types of operating costs such as maintenance. This is partially because the evidence available is focussed on fuel costs rather than other vehicle operating costs. In principle, however, there would be some savings associated with other vehicle operating costs to the extent they are reduced by smoother driving.

Valuing reduced road transport cost

Travel time cost

As mentioned above, travel incurs a cost of driver and passenger time, which travellers could otherwise use for other purposes such as work, leisure or rest. Because Level 4 and 5 CAVs free the driver from the driving task, this results in smaller costs of travel time. Therefore, it is a benefit of CAVs that they free up drivers to engage in work, leisure or rest while travelling.

The reduction in the cost of travel time is easy to quantify for taxis, buses and freight vehicles. For these trips, if the vehicle was a non-CAV, there would be a driver, who is no longer required to be in the vehicle if it is a CAV. Accordingly, there is a full saving of the value of one person's travel time for each taxi, bus and freight trip.[53] This assumes that for level 4 and 5 automated vehicles there is no one required to be in the vehicle. There are a few possible exceptions to this, namely:

- some buses may have a non-driving staff member present with potential to support the service to aid passengers with mobility impairment in the same fashion as guards on driverless trains,[54]

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53 The job impacts of CAVs are discussed in chapter 13. For the purpose of estimating travel time cost savings, we implicitly assume that the value of driver time from ATAP reflects the opportunity cost of that time, which is the value drivers freed from the driving task would derive from an alternative use of their time. This is likely to be employment in another occupation.

54 Note that trials of driverless shuttle buses in NSW have not had such a staff member, and have only had passengers as occupants on trips. See https://www.transport.nsw.gov.au/data-and-research/research-hub/research-hub/research-projects/driverless-shuttle-bus-trial

- wheelchair taxis which might require someone to still be in the vehicle to assist passengers boarding the taxi and with luggage, and
- freight journeys where an occupant is required to be in the vehicle to load/unload the payload, to ensure the security of the payload or to otherwise coordinate the journey.

For the remainder of trips, the reduction in the value of travel time is less certain. This includes private car, business car (excluding taxis), and light commercial vehicles. For these trips, while the driver no longer has to perform the driving task they still remain in the vehicle. Therefore, they incur some cost of travel time, albeit a reduced cost because they are free from the driving task.

The extent of the reduction in cost of travel time from CAVs freeing drivers from the driving task is unknown, and estimates rely on speculation about preferences of drivers (box 6.2). We draw the following conclusions based on this evidence:

- Stated preference evidence available to-date suggests a wide range of potential benefits between 0-55 per cent. The more recent studies among this literature typically have higher estimates than earlier studies.
- Comparison between car drivers and passengers and between modes suggests that a significant component of driver value of time (~25-40 per cent) is associated with the driving task itself, which would be saved if the vehicle were a CAV. The differences between public transport and car will be an underestimate of the benefit of CAVs, since public transport avoids the driving task but this is offset by it not being a personal vehicle.
- This is supported by views of experts obtained through workshops that with a high penetration of CAVs there would be significant savings of ~30 per cent (Milakis et al, 2017).

6.1 Literature review for value of time savings from CAVs

There are three broad sources of evidence for the difference between the value of time for CAV passengers compared to non-CAV drivers. Most of the literature examining this issue relates to the value of time saving for private car travellers.

Stated preference

Surveys can be used to elicit the value of travel time or willingness to pay for being in a CAV compared to a non-CAV.

A recent stated preference study is Kolarova et al (2018)[55], which found that the value of time for a private autonomous vehicle was 55 per cent lower than private non-autonomous vehicles for low and middle-income earners, and 42 per cent lower for high income earners.

55 Kolarova, V., Steck, F., Cyganski, R, and Trommer, S, 2018, 'Estimation of the value of time for automated driving using revealed and stated preference methods', *Transportation Research Procedia*, Volume 31, 2018, pp.35-46, available at: https://www.sciencedirect.com/science/article/pii/S2352146518301182

Similarly, Haotian et al (2020)[56] find that riding in private autonomous vehicles reduces the value of travel time by 32, 24 and 18 per cent for suburban, urban and rural drivers respectively. These reductions are approximately halved for shared autonomous vehicles.

Yap, Correia and van Arem (2016)[57] find that the value of travel time inside an autonomous vehicle is not perceived to be lower than other modes for regress for train trips, including non-autonomous private cars. This is based on a survey where respondents were asked about hypothetical autonomous vehicle travel. The authors highlight the role of uncertainty and a lack of trust in autonomous vehicles in influencing the results, and potentially the lower benefits from egress trips compared to other trips due to their short distance.

Cyganski et al (2015) report that only a small proportion of survey respondents declared it would be an advantage of a CAV (level 3 or higher) to be able to work on the move.

Fraunhofer and Horvath & Partners (2016) is also a stated preference study relating to CAVs, but does not provide estimates of the difference between value of time for autonomous and non-autonomous vehicles. Rather it estimates the value of add-on services for autonomous vehicles.

The key issue with the earlier stated preference studies is that they reflect current perceptions of CAVs and their comfort, safety, and reliability levels. These perceptions are likely to shift as penetration of CAVs rises and passengers have more experience travelling in these vehicles. More recent studies (such as Haotian et al [2020] and Kolarova et al [2018]) yield significantly higher estimates than older studies (such as Yap Correia and van Arem [2016]), which may be associated with respondents to survey instruments becoming more comfortable with CAVs as they receive greater exposure in the media and elsewhere.

Conjecture based on value of time differences between existing travel options

While existing evidence about value of time differences between car drivers and passengers or even between modes is sparse, this is typically a key source of evidence referred to in literature reviews such as Andersson & Ivehammar (2019)[58] and Milakis et al (2017).[59]

56 Zhong, H., Li, W., Burris, M.W., Talebpour, A., and Sinha, K.C., 2020, 'Will autonomous vehicles change auto commuters' value of travel time?', *Transportation Research Part D: Transport and Environment*, available at: https://trid.trb.org/view/1697927

57 Yap, M., Correia, G. and van Arem, B., 2016, 'Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips', *Transport Research Part A: Policy and Practice*, Volume 94, December 2016, pp.1-16, available at: https://www.sciencedirect.com/science/article/abs/pii/S0965856416307765

58 Ibid.

59 Milakis, van Arem, B, and van Wee, B., 2017, 'Policy and society related implications of automated driving: A review of literature and directions for future research', *Journal of*

Ian Wallis and Associates (2014) estimates that the value of time for car passengers is 40 per cent below the value of time for car drivers. This 40 per cent difference was used as an estimate of the difference in the value of time for autonomous vehicles compared to non-autonomous vehicles in Wadud (2017).[60]

The value of time prescribed by ATAP for road drivers and passengers is 40 per cent of Average Weekly Earnings (AWE), while the value of time for public transport is around 33 per cent of AWE[61] based on the most recent Public Transport parameter Guidelines in 2006.[62] However, these values are estimated using different methodologies, are not explicitly compared by ATAP, and the public transport guidelines are now 15 years old. On a similar note, Transport for NSW does not recommend estimating a vehicle quality benefit for users switching from car to public transport, which refers to a benefit to users of either mode based on that mode having a superior quality to the other in terms of comfort, convenience or related factors.[63]

While previous versions of the UK Transport Analysis Guidance (TAG) prescribed a value of time that was 25 per cent lower for car passengers than drivers (see Wadud, 2017[64]), the most recent version of the TAG prescribes the same value of time for car drivers and passengers. Nash (2010) argues that it has become the norm to adopt a single value of time for reasons of equity.[65]

Douglas and Jones (2018)[66] conducts a stated preference experiment to estimate the value of private travel time. They find that the values of time for car and public transport are 39 and 30 per cent of AWE, respectively. This implies that time is valued around 25 per cent less for public transport travel compared to car travel. This is despite car users having higher income on average, which is typically associated with higher values of time. This may be a reasonable indicator of the value travellers place

Intelligent Transportation Systems, Volume 21, 2017, pp.324-348, available at: https://www.tandfonline.com/doi/full/10.1080/15472450.2017.1291351

60 Wadud, Z., 2017, 'Fully automated vehicles: A cost of ownership analysis to inform early adoption', *Transportation Research Part A: Policy and Practice*, 101, pp.163-176, available at: https://eprints.whiterose.ac.uk/115936/1/TCO-accept%20manuscript-TRA.pdf

61 This is based on full-time adult ordinary time AWE of $1165.20 in 2006, a working week of 38 hours, and a value of time of $10 for public transport (in $2006).

62 Australian Transport Council, 2006, *National Guidelines for Transport System Management in Australia — Urban Transport*, available at: https://www.atap.gov.au/sites/default/files/National_Guidelines_Volume_4.pdf

63 Transport for NSW, 2020, *Economic Parameter Values*, p.53, available at: https://www.transport.nsw.gov.au/news-and-events/reports-and-publications/tfnsw-economic-parameter-values

64 Ibid, p.8.

65 Nash, C., 2010, *Current debates on the cost-benefit analysis of transport projects in Great Britain*, Seminario Sobre Evaluacion Economica de Proyectos de Transporte. Madrid, Spain

66 Douglas, N. and Jones, M., 2018, 'Estimating the Value of Private Travel Time for NSW Australia', *Australasian Transport Research Forum 2018*, table 14, available at: https://www.researchgate.net/publication/328737273_Estimating_the_Value_of_Private_Travel_Time_for_NSW_Australia

on avoiding the driving task, but there are also a range of other quality differences between car and public transport travel. The authors find only a difference of around 10 per cent between the value of time of a car driver alone compared to a driver with a passenger, suggesting that either the value of time for a passenger is much lower than for a driver, or that drivers do not place much value on the cost of time for their passengers.

Expert opinion

This category refers to judgements by subject-matter experts not based on either of the sources of evidence above.

The key example of this type of evidence is from Milakis et al (2017)[67], where 20 experts provided estimates of the relative value of time for autonomous vehicles (level 3 or higher) compared to non-autonomous vehicles across multiple scenarios for technological development and government policy. Under the scenario with the most optimistic take-up (61 per cent of vehicles autonomous by 2050), the value of time saving was on average 31 per cent across the expert estimates. Under the most pessimistic scenario, (10 per cent of the fleet being autonomous by 2050), the saving in the value of time was on average 2 per cent. It is not clear what drives this difference, but we expect it is due to a smaller proportion of the road network allowing autonomous travel, which means that drivers only occasionally can drive autonomously. Accordingly, we expect that the higher estimate (31 per cent) is a more appropriate estimate of the reduction in the value of time for CAVs when driving autonomously.

Assumed reductions in the value of time for CAVs compared to non-CAVs are shown in table (table 4.3). These numbers are based on the following:

- As discussed above, we assume that the value of time reduces by 35 per cent for private cars which is equivalent to a reduction of $6.41 in 2021 dollars. This is the midpoint of the estimates from Ian Wallis and Associates (2014) and the high-uptake estimate from Milakis et al (2017). This assumption reflects a greater emphasis on recent stated preference evidence such as Kolarova et al (2018) compared to older stated preference evidence with lower estimates. For high and low cases to be tested in sensitivity analysis, we use 40 per cent (consistent with Ian Wallis and Associates, 2014) and 20 per cent (placing some weight on the findings of Yap, Correia and van Arem (2016).
- We assume that business cars (excluding taxis) and light commercial vehicles have the same reduction in dollars ($6.41) as private vehicles. This is based on $6.41 being an appropriate estimate of the benefit of freeing the driver from the driving task, but there being no further saving in terms of productive use of business time. This is a

67 Milakis, D., Snelder, M., van Arem, B., van Wee, B. and Correia, G., 2017, 'Development and transport implications of automated vehicles in the Netherlands: Scenarios for 2030 and 2050', *European Journal of Transport and Infrastructure Research*, January 2017, available at: https://www.researchgate.net/publication/307174317_Development_and_transport_implications_of_automated_vehicles_in_the_Netherlands_Scenarios_for_2030_and_2050

conservative assumption, given that business travel time could be used productively if drivers are freed from the driving task. However, there is no literature examining the issue of non-freight business travel from which to draw any conclusions about the magnitude of this benefit.

  – The value of time for business cars is a weighted average reduction for taxis and other business cars. Taxis represent 17 per cent of business car travel, and are assumed to be driverless and hence receive a 100 per cent saving in all cases.

- Freight vehicles receive a 95-100 per cent saving in the central and high cases, with a low case of a 63 per cent reduction based on McKinsey (2018), which estimates the saving of freight wage costs if drivers are still required for pick-up/drop-off only.[68]

The central case estimates of the impacts of CAVs presented in this report use the central estimates of the reduction in the value of driver time. Sensitivity analysis uses the low and high estimates.

6.2 Reduction in value of driver time for CAVs compared to non-CAVs

Type of vehicle	Low	Central case	High
	Per cent	Per cent	Per cent
Private vehicles	20	35	40
Business cars	22	26	46
Light commercial vehicles	12	21	24
Freight vehicles	63	95	100

Source: The CIE.

As discussed above, estimates of this reduction in the value of time for taxis and freight vehicles are more certain compared to estimates for private and other business vehicles that will still have passengers.

A key factor that would tend to increase the estimates is that the people likely to use CAVs would be those with higher values of time due to disliking travel, a high opportunity cost, or business travellers. As a result, using an average value of time across the entire passenger/driver population is likely to understate the benefit of CAVs in reducing travel time costs.

Fuel costs

Level 4 and 5 CAVs reduce fuel costs significantly beyond Level 1 and 2, due to a combination of speed regulation technologies and platooning (table 6.4).

For Level 1 and 2 we assume there is a 5 per cent improvement in fuel consumption compared to non-CAVs. This is based on literature around the impacts of eco-driving for

68 McKinsey Center for Future Mobility, 2018, *Route 2030 — The fast track to the future of the commercial vehicle industry*, p.19.

low level CAVs, including Anderson et al (2014)[69] reporting a 4-10 per cent reduction for Level 1, 2, and 3 CAVs, and Wadud (2017) concluding that a 5 per cent reduction from CAV functions would be possible at a low level of take-up of CAVs.[70]

The evidence underpinning the larger reductions for Level 3, 4 and 5 is explained below for speed regulation and platooning separately. Platooning benefits are applied to long-distance travel, and speed regulation benefits are applied to capital city travel, while the average of platooning and speed regulation benefits are applied to regional areas.

6.3 Reduction in fuel consumption for CAVs compared to non-CAVs

Level of CAV	Low	Central	High
	Per cent	Per cent	Per cent
Level 1 and 2			
Capital cities	0	-5	-10
Regional	0	-5	-10
Long distance	0	-5	-10
3, 4 and 5			
Capital cities	-10	-25	-35
Regional	-7.5	-17.5	-27.5
Long distance	-5	-10	-20

Source: The CIE.

Speed regulation technologies

A number of studies have measured changes in fuel consumption from Level 4 and 5 automation on urban roads, typically using simulations or real-world driving data. However, these studies cover a range of different technologies, and also different algorithms for the same technology. For example, fuel cost savings from controllers following Pulse-and-Gliding (PnG) algorithms are associated with larger fuel savings than linear quadratic algorithms (Li, Peng, Li and Wang, 2012).

We assume that there is a fuel cost saving of 25 per cent from CAVs on urban roads. This is approximately the average fuel cost saving of the studies listed in table 6.4, which all relate to speed regulation technologies in the vicinity of intersections. Key uncertainties associated with these estimates relate to the following:

- Some of the results in table 6.4 are based on simulations that do not replicate realistic driving environments. For example, Asadi & Vahidi (2011)[71] estimates a 47 per cent

69 Anderson, J.M., Kalra, N., Stanley, K.D., Sorensen, P., Samaras, C. and Oluwatola, O.A., 2014, Autonomous Vehicle Technology. A Guide for Policymakers. RAND, Santa Monica, CA.

70 Ibid.,

71 Asadi, B. and Vahidi, A., 2011, 'Predictive Cruise Control: Utilizing Upcoming Traffic Signal Information for Improving Fuel Economy and Reducing Trip Time', *IEEE Transactions on*

reduction in fuel usage for their algorithm relative to Adaptive Cruise Control (ACC) for a sequence of 10 intersections spaced 1 kilometre apart. However, when running a similar simulation based on actual traffic signal phasing and timing data from a road in the USA, the fuel saving reduces to 24 per cent.

  – Fuel savings in simulated environments may not always be higher than in real environments, and the impact of this issue on estimated fuel savings is uncertain.
  – However, to the extent that each study is providing an indication of the saving for a subset of the road network (e.g. signalised intersections, roundabouts), the combination of multiple technologies across the road network might yield a similar result in aggregate. That is, if there is a 25 per cent fuel saving for intersections, other urban roads, and regional roads, then the aggregate fuel saving would still be 25 per cent.

- The technologies that are more effective at minimising fuel usage may become those that are implemented in CAVs sold to consumers. That is, among the range of algorithms tested in the literature, the algorithms producing the largest fuel savings (such as that tested by Bichou & Rakha, 2019) may be more likely to be adopted than those producing small savings (such as the algorithm tested by Khondaker & Kattan, 2015). This would tend to suggest that estimates at the high end of the range from the literature are more likely to be achieved. The more conservative expectation (which we've adopted) is that the fuel savings likely to be achieved are the average of the studies in the literature.
- Relatively few studies focus on fuel savings in the vicinity of intersections, which may have greater scope for fuel savings than areas of road away from intersections.
- Many of the studies report simulation results assuming 100 per cent penetration of cars with their algorithm. This will overstate the benefits relative to a road environment with non-CAVs and with other CAVs that adopt different algorithms.

6.4 Fuel cost savings from Level 4 and 5 CAVs on urban roads

Study	Impact on fuel consumption	Ways in which fuel consumption is reduced
Wu, Zhao, and Ou (2011)	31% saving in urban conditions	Optimal acceleration/deceleration
Khondaker and Kattan (2015)	16% with 100% CAVs, lower with less	Variable speed limit control algorithm
Li, Peng, Li, and Wang (2012)	20% saving compared to a linear quadratic (LQ)-based controller in automated car-following scenarios	Pulse-and-Gliding (PnG) controller
Zohdy and Rakha (2016)	33%, 45% and 11% saving for a traffic signal, all-way-stop and roundabout, respectively	Controller providers advice about optimum course of vehicles equipped with Co-operative Adaptive Cruise Control (CACC)
Ala, Yang, and Rakha (2016)	19% saving at a penetration rate of 100%, higher fuel consumption below 30% penetration	CACC using vehicle-to-infrastructure communication and vehicle queue predictions in vicinity of intersections

Control Systems Technology, available at: https://cecas.clemson.edu/~avahidi/wp-content/uploads/2016/10/behrang.pdf

Study	Impact on fuel consumption	Ways in which fuel consumption is reduced
Kamalanathsharma, Rakha and Yang (2015)	26% at a penetration rate of 100%	CACC using vehicle-to-infrastructure communication in vicinity of intersections
Asadi and Vahidi (2011)	24% at a penetration rate of 100%	CACC using vehicle-to-infrastructure communication to optimise intersection flow
Bichou & Rakha (2019)	43% at a penetration rate of 100%	An algorithm to optimise flow through intersections.
Anderson et al/RAND (2014)	15-33%	Sensors and inter-vehicle communication

Source: Kamalanathsharma, Rakha and Yang, 2015, 'Networkwide Impacts of Vehicle Ecospeed control in the vicinity of traffic signalised intersections, *Transport Research Record Journal of the Transportation Research Board*, 2503(20503): 91-99.

Platooning

Zhang et al (2020)[72] is a comprehensive literature review of fuel economy impacts from truck platooning. We have extracted the estimated fuel reduction from each study that they identified, and **the average reduction in fuel consumption from platooning is 10 per cent**. Importantly, trucks likely cannot platoon at all times, with platoons sometimes not being available. It is unclear whether trucks may wait until a platoon is available, but this will depend on the value of freight arriving more quickly compared to the fuel economy saving. By applying a 10 per cent reduction in fuel consumption from platooning, we implicitly assume that autonomous trucks are platooning at all times that they are driven autonomously, which may tend to produce an overestimate of realized fuel savings. The magnitude of this impact from this issue is uncertain.

There is no evidence about the fuel economy benefits from platooning of cars or other light vehicles. In the absence of that information, we assume they receive the same proportional benefit as trucks do from platooning.

6.5 Studies estimating fuel consumption reductions from platooning

Lead author	Year	Method	Fuel reduction result	Midpoint of reduction range
				Per cent
Bonnet	2000	Track test + simulation	21% for following trucks	21
Browand	2004	Track test + wind tunnel test	8-11% depending on spacing	10
Alam	2010	Simulation + road test	3.8-7.7% depending on relative weights	6
Lu	2011	Road test	4-5% for lead truck and 10-14% for following	8
Tsugawa	2011	Road test	14%	14
Davila	2013	CFD + track test	8% for lead and 16% for follower	12
Lammert	2014	Track test	2.9-9.7% for lead and 2.7-5.3 for following	5

72 Zhang, L., Chen, F., Ma, X. and Pan, X., 2020, 'Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research, *Journal of Advanced Transportation*, 2020, available at: https://www.hindawi.com/journals/jat/2020/2604012/#abstract

Lead author	Year	Method	Fuel reduction result	Midpoint of reduction range
				Per cent
Smith	2014	Road test + CFD	Not publicly available	N/A
Tsugawa	2014	Road test	8-15% depending on gap	12
Alam	2015	Road test	3.9-6.5% for small grade, 4% increase for uphill	5
Humphreys	2016	CFD + track test	13%	13
Humphreys	2016	CFD + track test	4% for combined	4
McAuliffe	2017	Track test	5.2-7.8%	7
McAuliffe	2018	Track test	13%	13
Average				**10**

[a] This assumes no platooning uphill.
Source: Zhang et al (2020), The CIE.

For regional travel, it is unclear to what extent fuel cost savings will reflect speed regulation compared to platooning benefits. For simplicity, we assume that the net fuel saving for regional travel is the average of the speed regulation and platooning fuel savings. This means the overall central case assumptions about the reduction in fuel use from Level 4 and 5 CAVs is:

- 25 per cent for urban travel
- 10 per cent for long distance travel, and
- 17.5 per cent for regional travel.

Note that these fuel reductions are measured relative to non-CAVs. We also assume that Level 1 and 2 CAVs reduce fuel use by 5 per cent. The reported overall impacts of CAVs are the difference between the 5 per cent reduction from Level 1 and 2 and the impacts for Level 4 and 5 set out above.

Central case estimates of the transport cost savings of CAVs (baseline traffic)

From 2020 to 2070, transport cost savings are measured at almost $1.6 trillion under the base case CAV uptake scenario and central case assumptions about the impacts of CAVs. This figure includes:

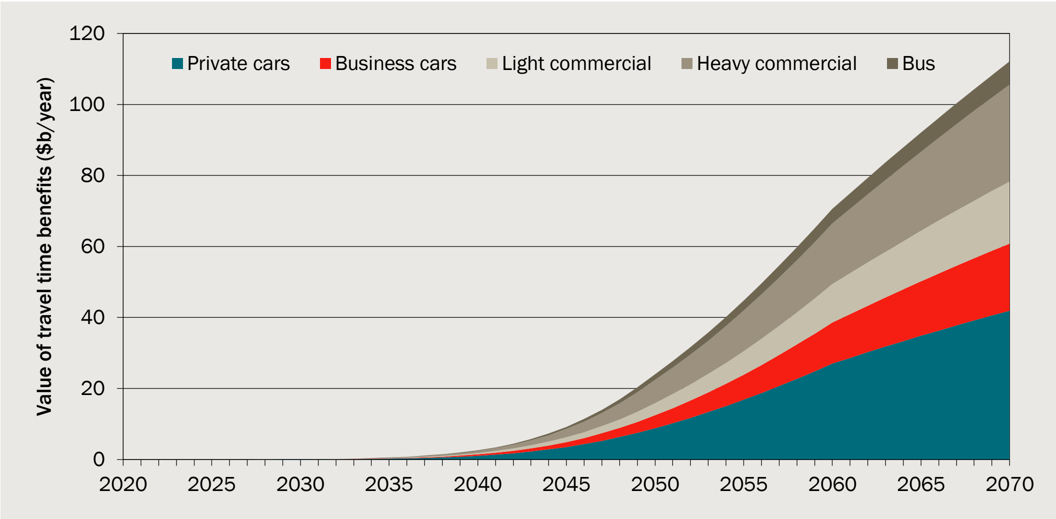
- reduced transport time costs for private car users as they no longer need to perform the driving task are valued at $583 billion[73]
- reduced business time costs are almost $250 billion, along with reduced commercial vehicle (including light commercial) and bus time costs of more than $700 billion. Together, business and freight time cost savings are valued at $962 billion, and
- reduced fuel use amounts to $54 billion due to smoother driving and light and heavy vehicle platooning for regional and long distance travel.

73 This is based on the number and distance of trips being the same as without CAVs. Benefits from new usage are considered separately.

The benefit of reduced costs of travel time are largest for private cars due to them having the largest share of travel time (chart 6.6). Heavy commercial vehicle benefits are high relative to their share of travel time because they have a 95-100 per cent saving in the cost of travel time, since Level 4 and 5 CAVs are assumed not to have drivers.

Benefits rise smoothly with the profile of CAV adoption. One risk to achieving benefits, particularly in intermediate years, is if travellers maintain a lack of trust in CAVs that results in them valuing their travel time in a similar way to time spent driving a non-CAV. This risk is mitigated because early CAV adopters are likely to be those who feel a greater sense of trust in CAVs or have a higher value of time than average.

6.6 Value of travel time benefits



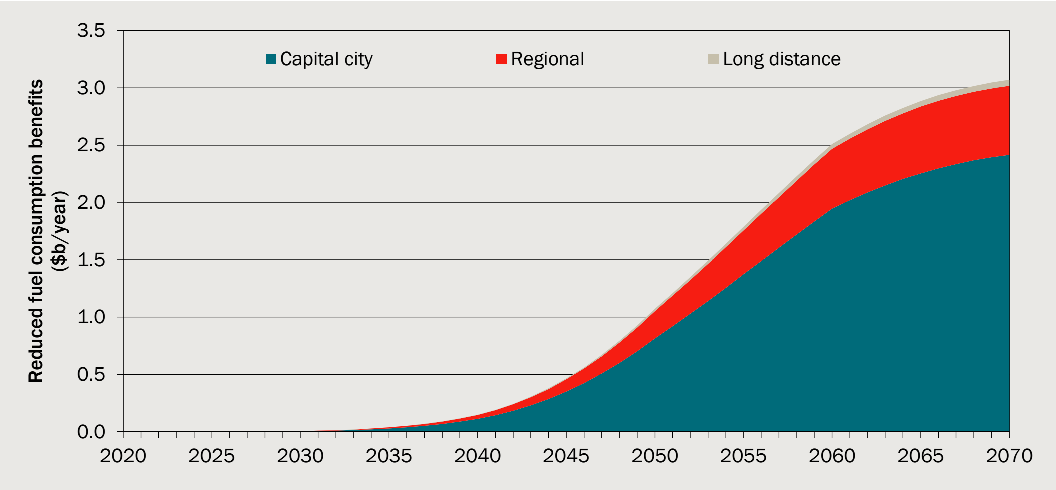
Data source: The CIE.

Fuel consumption benefits are largest in capital cities (chart 6.7). This is both because capital cities represent the highest share of fuel costs in the base case and because there is a larger proportional reduction from speed regulation technologies applied in urban settings compared to the reduction in fuel use from platooning.

Fuel consumption benefits are low in early years, rise rapidly with the greater adoption of CAVs, but then taper off and would reduce in terms of the benefit per vehicle kilometre. This is because of the projected decline in fuel consumption under the base case as the penetration rate for electric vehicles increases. Electric vehicle take-up has been forecast by CSIRO (2021)[74], and we extrapolate these projections to 2070, as discussed further in chapter 8. Benefits from fuel consumption are only 4 per cent of the size of benefits from reduced travel time.

74 CSIRO, 2021, *Electric vehicle projections 2021*, available at: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/csiro-ev-forecast-report.pdf

6.7 Reduced fuel consumption benefits



Data source: The CIE.

7 Road capacity impacts of CAVs

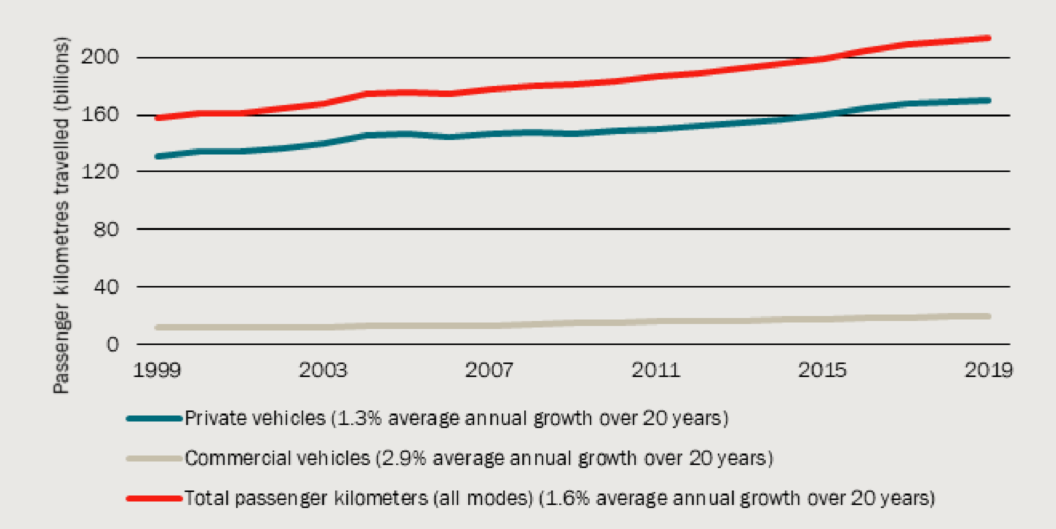
A key potential benefit from the introduction of CAVs is an increase in road network capacity. CAVs are expected to have the capability of travelling with smaller headways and operating with faster response times than existing non-automated, human controlled vehicles. Increased road capacity translates into less congestion, and hence less costs related to congestion, such as travel delays, travel time variability, additional fuel use and additional air pollution.

There are two schools of thought about the impacts of CAVs. The first is that they will negatively impact on road capacity at low levels of penetration and capability, and then increase capacity thereafter. The second is that they will have positive impacts immediately. We find that under the first scenario, the benefit of CAVs from 2020 to 2070 is $321 billion but is heavily back-ended with negative impacts to 2050 of $55 billion. Under the second scenario, the capacity benefits are $531 billion from 2020 to 2070. However, there is no interim period of negative capacity impacts.

Trends in road network congestion

Australia's population is highly urbanised, with a significant proportion of the population living in its capital cities. The road network is critical for the movement of people and goods; this movement includes travel via private vehicles and commercial vehicles. Private and commercial vehicle passenger kilometres travelled in Australia capital cities has grown steadily in the last 20 years between 1999 and 2019 (shown in chart 7.1). As set out in chapter 3, the road transport task is expected to continue growing.

7.1 Private vehicle passenger kilometres travelled in capital cities since 1999-2000



Data source: Bureau of Infrastructure, Transport and Regional Economics 2020, p.92.

Growth in traffic and demand for trips in localised areas contributes to the congestion observed in capital cities. The Australian Automobile Association (2018) measured several performance metrics across each of the capital cities in Australia to determine the change in congestion between 2013 to 2018.[75] Results for each city are shown in table 7.2. Three key metrics are shown:

- Average speeds — measured across capital city arterial road networks
- Congestion — measured as average speed as a percentage of free flow (POFF) speeds
- Variability — measured as the coefficient of variation of average speeds.

7.2 Measures of congestion between 1 January 2013 to 30 June 2018

City	Measures of congestion (% change since 1 January 2013)		
	Average Speed	Congestion (POFF)	Variability
Adelaide	54.3 km/h (– 2.5%)	93.9% (+ 0.2%)	24.5% (– 0.9%)
Brisbane	71.5 km/h (– 3.7%)	96.3% (– 0.5%)	21.7% (+ 1.2%)
Canberra	65.5 km/h (+ 1.0%)	95.5% (– 0.1%)	23.9% (– 0.9%)
Darwin	72.2 km/h (+ 5.1%)	97.7% (+ 3.6%)	20.8% (– 1.9%)
Hobart	65.0 km/h (– 0.1%)	94.3% (+ 0.1%)	22.6% (– 1.9%)
Perth	61.6 km/h (– 1.1%)	94.8% (+ 2.0%)	24.3% (– 1.0%)
Melbourne	59.9 km/h (– 8.1%)	93.6% (+ 0.5%)	27.9% (+ 0.6%)
Sydney	58.2 km/h (– 3.5%)	92.5% (– 0.2%)	26.0% (+ 0.4%)
Capital Cities weighted average*	**61.1 km/h (– 4.3%)**	**93.9% (+ 0.3%)**	**25.5% (+ 0.2%)**

Source: Australian Automobile Association, 2018, Road Congestion In Australia. Canberra. Retrieved from https://www.aaa.asn.au/wp-content/uploads/2018/10/AAA-Congestion-Report-2018-FINAL.pdf

75 Australian Automobile Association. (2018). Road Congestion In Australia. Canberra. Retrieved from https://www.aaa.asn.au/wp-content/uploads/2018/10/AAA-Congestion-Report-2018-FINAL.pdf

The above table indicates that congestion is generally getting worse with a decline in average speeds and travel time reliability. This decline is even more significant in populous capital cities such as Sydney and Melbourne. Considering the growth in private vehicle passenger kilometres travelled is likely to continue, this suggests that congestion will only get worse in the future.

In 2015, BITRE developed estimates of the costs of congestion and how these could change from 2015 to 2030. They expected that total costs of congestion across capital cities would be $30 billion in 2020, rising to $49 billion in 2030. This represents annual growth of almost 5 per cent. This is the total costs relative to free flow speeds. They also presented a measure of 'avoidable' costs of congestion, which is the costs of congestion above the level that would exist if there were an efficient use of roads. This was somewhat lower, as not all congestion would be avoided with efficient use of roads, but also expected to increase rapidly at 5 per cent per year from 2020 to 2030.

7.3 BITRE projections of the costs of congestion across capital cities

	Total congestion costs			Avoidable congestion costs		
	2020	2030	Annual growth	2020	2030	Annual growth
	$B $2010	$B $2010	Per cent	$B $2010	$B $2010	Per cent
Sydney	10.10	15.32	4.3	8.18	12.60	4.4
Melbourne	8.36	13.15	4.6	6.38	10.19	4.8
Brisbane	4.60	8.00	5.7	3.35	5.94	5.9
Adelaide	2.21	3.28	4.0	1.50	2.25	4.2
Perth	4.12	7.76	6.5	2.98	5.69	6.7
Hobart	0.18	0.25	3.2	0.11	0.16	3.4
Darwin	0.07	0.11	5.0	0.04	0.07	5.2
Canberra	0.43	0.66	4.5	0.27	0.42	4.7
Total metro	**30.08**	**48.54**	**4.9**	**22.82**	**37.32**	**5.0**

Note: For the Upper Baseline scenario.

Source: BITRE 2015, *Traffic and congestion cost trends for Australian capital cities*, November, https://www.bitre.gov.au/publications/2015/is_074.

Effective road network capacity change expected from CAVs

A key benefit from the introduction of CAVs is the potential increase in road network capacity. CAVs are expected to have the capability of travelling with smaller headways and operating with faster response times than existing non-automated, human controlled vehicles. The expected impact on road network capacity has been researched across numerous studies; results from these studies vary widely, in part due to the underlying assumptions made. Such assumptions include:

- Market penetration of CAVs and composition of the level of automated vehicle types
- Level of automation
- Vehicle behaviours (e.g. aggressive/cautious fleets)

- Available CAV functions and capabilities (e.g. availability of platooning and cooperative driving and availability of infrastructure to support data exchange and communications)
- Road environment and constraints

There are also gaps in knowledge and conflicting evidence, which further increases the range of estimates presented.

Research indicates that road network capacities are likely to increase when market penetration of CAVs exceeds approximately 40 per cent (Sonnleitner et al. (2020); Task Force B.2 World Road Association (2021)). These increases in capacity are often tied to a more mature level of advanced CAV capability.

Some studies found road capacity to **improve immediately** upon CAV introduction – Heaslip et al. (2020) found increases at 20 per cent penetration on freeways, and Lu et al. (2020) found marginal benefits to capacity on urban road networks at 10 per cent penetration.[76] Conversely, other studies found that road capacity was likely to **decrease initially** at low levels of CAV penetration (Sonnleitner et al. (2020); Task Force B.2 World Road Association (2021)).[77]

Studies often assume and estimate road capacity impacts with increasing levels of automation alongside increasing market penetration. Capacity impacts are also expected to differ depending on the type of road environment. Atkins (2016) modelled varying levels of CAV penetration on motorways and urban roads junctions.[78] Assuming cautious fleet behaviours resulted in **decreases** in road capacity in all road environments, while behaviours better reflective of that seen in human-controlled vehicles saw **immediate increases** in road capacity. Across all road environments modelled with default legacy fleet behaviours, Atkins found capacity increases ranging from 5 to 24 per cent at 100 per cent penetration of CAVs. With assertive behaviours, this range increased to 25 to 67 per cent at 100 per cent penetration.

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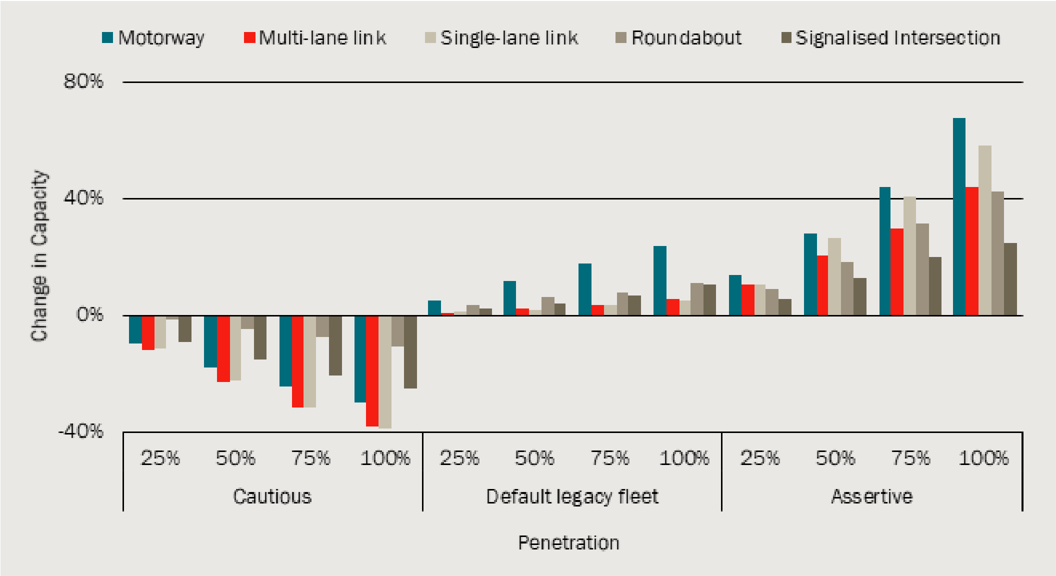
76 Heaslip, K., Goodall, N., Kim, B., & Aad, M. A. (2020). Assessment of Capacity Changes Due to Automated Vehicles on Interstate Corridors. Virginia: Virginia Transportation Research Council . Retrieved from http://www.virginiadot.org/vtrc/main/online_reports/pdf/21-r1.pdf; Lu, Q., Tettamanti, T., Hörcher, D., & Varga, I. (2020). The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation. *Transportation Letters, 12*(8), 540-549. doi:10.1080/19427867.2019.1662561.

77 Sonnleitner, J., Friedrich, M., & Richter, E. (2020). Guide for the simulation of AVs with macroscopic modelling tool. *CoEXist Deliverable D2.8*. Retrieved from https://www.h2020-coexist.eu/resources/; Task Force B.2 World Road Association (PIARC). (2021). Automated vehicles: challenges and opportunities for road operators and road authorities. World Road Association.

78 Atkins. (2016). Research on the Impacts of Connected and Automated Vehicles (CAVs) on Traffic Flow. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/530091/impacts-of-connected-and-autonomous-vehicles-on-traffic-flow-summary-report.pdf.

7.4 Estimated change in road capacity from zero penetration by behaviour



Data source: Atkins. (2016). Research on the Impacts of Connected and Automated Vehicles (CAVs) on Traffic Flow. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/530091/impacts-of-connected-and-autonomous-vehicles-on-traffic-flow-summary-report.pdf.

While Atkins (2016) modelled both varying levels of penetration along with CAV behaviours, other studies have assumed CAV behaviours and capabilities increase with market penetration.

A Passenger Car Unit (PCU) is a metric used to measure road capacity. Sonnleitner et al. (2020)[79] derived effective capacity levels (measured by PCU factors) across three stages of CAV uptake (shown in table 7.5). Their study assumed Basic AV to include 20 to 40 per cent fleet penetration with cautious, risk minimising behaviours, Intermediate AV to include less cautious behaviours in less complex road environments with a 40 to 60 per cent fleet penetration, and Advanced AV to include vehicles with Level 4 capabilities in most road environments at 80 to 100 per cent penetration. The results of this study identify that at low levels of CAVs, the capacity on the road network is **initially expected to decrease** but will increase on motorways and arterial roads for Intermediate AV penetration and capabilities. At high levels of CAV penetration, the road capacity increase is expected to range between 18 to 37% across all road environments modelled.

7.5 PCU factors (Capacity change%) for AV-classes on different roadway types

	Basic AV	Intermediate AV	Advanced AV
Motorway	1.20 (–17%)	0.77 (+30%)	0.73 (+37%)
Arterial	1.26 (–21%)	0.81 (+23%)	0.76 (+32%)
Urban Street	N/A[a]	1.32 (-24%)	0.85 (+18%)

[a] For basic AV, no automation is available on urban streets since it is assumed that driving task is too demanding for AVs of this class.

Source: Sonnleitner, J., Friedrich, M., & Richter, E. (2020). Guide for the simulation of AVs with macroscopic modelling tool. *CoEXist Deliverable D2.8*. Retrieved from https://www.h2020-coexist.eu/resources/

79 Sonnleitner, J., Friedrich, M., & Richter, E. (2020). Guide for the simulation of AVs with macroscopic modelling tool. *CoEXist Deliverable D2.8*. Retrieved from https://www.h2020-coexist.eu/resources/.

Lu et al. (2020) investigated the impact of AVs on urban road network capacity.[80] The authors found capacity to **improve immediately** with the introduction of AVs in an urban context. The impact of introduction of connectivity capabilities for AVs was not considered in this study; introducing this factor could contribute to a further increase the road capacity benefits estimated. Lu et al. noted that the benefits estimated in this study may differ from estimates provided in other research due to modelling of a network in urban contexts rather than across individual intersections. Their study found road capacities to moderately increase initially, and observed more significant benefits after 50 per cent market penetration, identifying a 24 per cent increase in road capacity at 100 per cent penetration (shown in table 7.6).

7.6 Change in capacity and PCU factors for urban road network

Market Penetration	PCU (average of CAVs and non-CAVs)	Capacity change
0%	1.00	+0%
10%	0.98	+2%
20%	0.96	+4%
30%	0.94	+6%
40%	0.92	+8%
50%	0.90	+11%
60%	0.89	+13%
70%	0.87	+15%
80%	0.85	+18%
90%	0.83	+21%
100%	0.81	+24%

Source: Lu, Q., Tettamanti, T., Hörcher, D., & Varga, I. (2020). The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation. *Transportation Letters, 12*(8), 540-549. doi:10.1080/19427867.2019.1662561.

The range of capacity changes identified across various studies highlights the impact of CAV behaviour assumptions and road environment on expected benefits. However, capacity impacts are expected to be maximised when observing higher levels of penetration, and less risk averse vehicle behaviours.

A summary of capacity increase estimates at 100 per cent market penetration of CAVs from the literature is presented in table 7.7.

80 Lu, Q., Tettamanti, T., Hörcher, D., & Varga, I. (2020). The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation. *Transportation Letters, 12*(8), 540-549. doi:10.1080/19427867.2019.1662561.

7.7 Summary of change in road network capacity at 100% market penetration

Study	Methodology	Road Network	Level of Automation	Impact on capacity
Lu et al. (2020)	Microscopic Traffic Simulation, SUMO	Urban network	Level 5 – 'Full Automation' **without** CV technology	+ 24%
Sonnleitner et al. (2020) for CoEXist	PTV VISSIM microsimulation	Motorway	Advanced AVs	+ 37%
		Arterial		+ 32%
		Urban Street		+ 18%
Atkins (2016)	PTV VISSIM 8 microsimulation	Motorways	CAVs with default legacy fleet behaviour/ assertive behaviour	+ 24 to 67%
		Signalised junctions (urban)		+ 10 to 25%
Heaslip et al. (2020) for Virginia Transport	VISSIM Microsimulation	Freeway (Interstate highways)	Mix of AVs/CAVs	+ 29% to 86%
Task Force B.2 World Road Association (2021)	Microsimulation	Uninterrupted flow on German Autobahns (Freeway)	Level 4/5 Automation	+ 30%

Source: Lu, Q., Tettamanti, T., Hörcher, D., & Varga, I. (2020). The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation. *Transportation Letters, 12*(8), 540-549. doi:10.1080/19427867.2019.1662561.; Sonnleitner, J., Friedrich, M., & Richter, E. (2020). Guide for the simulation of AVs with macroscopic modelling tool. *CoEXist Deliverable D2.8*. Retrieved from https://www.h2020-coexist.eu/resources/; Atkins. (2016). Research on the Impacts of Connected and Automated Vehicles (CAVs) on Traffic Flow. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/530091/impacts-of-connected-and-autonomous-vehicles-on-traffic-flow-summary-report.pdf; Heaslip, K., Goodall, N., Kim, B., & Aad, M. A. (2020). Assessment of Capacity Changes Due to Automated Vehicles on Interstate Corridors. Virginia: Virginia Transportation Research Council . Retrieved from http://www.virginiadot.org/vtrc/main/online_reports/pdf/21-r1.pdf; Task Force B.2 World Road Association (PIARC). (2021). Automated vehicles: challenges and opportunities for road operators and road authorities. World Road Association.

It is clear that the impacts of CAVs on road network capacities can vary widely depending on the scenario considered. While capacity benefits are expected to be positive at 100 per cent market penetration and can range anywhere between 10 to 30 per cent[81] for urban network (potentially higher for motorways) in the literature reviewed, the initial benefits at lower levels of penetration varies. Capacity impacts could well be negative in the early days, due to both the limited automation provided and negative impact of low levels of CAVs in mixed traffic (e.g. safety risk perceived by other drivers). It is possible that once uptake of CAVs reaches approximately 40 per cent, capacity impacts become positive. An alternative outcome from estimated capacity impacts of CAVs suggests that capacity impacts are always positive, and in similar manner, experience more significant positive benefits at market penetrations of 40 per cent or greater.

To estimate the road capacity impacts of CAVs we adopt the first view, i.e. that CAVs will take up more road capacity than a standard vehicle at low levels of penetration. We

81 The Automated and Zero Emission Vehicle Infrastructure Advice by Infrastructure Victoria (2018) quoted an increase in flow capacity between 1.5 and 2.0 (i.e. 50% to 100% increase) based on literature reviews by the Technical University of Berlin. The report did not provide detail on the exact sources or methodologies used to derive these factors (e.g. theory-based inspiration, simulation of real road network operation) and the modelling seemed to assume the increase in capacity will occur immediately (i.e. no ramp-up). The report did include a sensitivity test using a reduced capacity increase factor of 1.25 (i.e. 25% increase) acknowledging the associated uncertainty. Our literature review has largely focussed on the studies involving simulation of real road network, which is likely to provide a more realistic estimate of road capacity benefits by CAVs.

also test the alternative scenario that CAVs always use less road capacity than a standard vehicle.

Valuing increased road network capacity

Additional road network capacity allows for road traffic to move more freely during periods when there is currently congestion. The benefits that derive from this are the same as those that come from major road investments, such as road widenings, intersection improvements and tunnels. These are:

- reductions in travel time delays for road users — reduced travel time is valued using the value of travel time, similar to chapter 6. This value is highest for business and freight and lower for private cars
- reductions in the variability of travel time — unpredictable travel time has an additional cost, because people have to allow for more time to undertake their trip
- reductions in vehicle costs — less congestion reduces fuel use and reduces wear and tear on vehicles, and
- reductions in air pollution and GHG emissions, arising from less fuel use.

Increased road capacity has the largest benefits where and when demand for roads is exceeding capacity. Primarily this is in major cities during AM and PM peak periods, although congestion is extending through longer periods if the day and into weekends in capital cities.

To measure the congestion costs associated with the impacts of CAVS, we have calculated **marginal costs of congestion** by using the BITRE projections of the costs of congestion.[82] These costs represent the impact on other road users of 1 less car equivalent or 1 more car equivalent. For example, if a CAV uses only 80 per cent of the road capacity of a standard car, then it avoids 0.2 standard cars for each kilometre driven. We then apply a benefit based on 0.2 multiplied by the kilometres driven multiplied by the marginal cost of congestion.

The marginal cost of congestion captures time delay costs, changes to vehicle operating costs, changes to travel time reliability and changes to air pollution. To estimate this we have used the following formula:

$$MCC_t = \left(\frac{TCC_t^H - TCC_t^L}{VKT_t^H - VKT_t^L}\right) - \frac{TCC_t^L}{VKT_t^L}$$

Where:

MCC_t is the marginal congestion cost in time t

TCC_t^H is the total congestion cost at time t in the high vehicle demand scenario and TCC_t^L is the total congestion cost at time t in the low vehicle demand scenario

82 BITRE 2015, *Traffic and congestion cost trends for Australian capital cities*, November, https://www.bitre.gov.au/publications/2015/is_074.

VKT is the total vehicle kms expressed in passenger car units at time t in the high vehicle demand scenario and VKT_t^L is the same figure in the low vehicle demand scenario

This formula first calculates the impact on total congestion costs of additional vehicle traffic, and then subtracts the amount that is experienced by the new traffic rather than imposed on others.

We have then inflated the BITRE estimated from 2010 dollars to 2020 dollars using the wage price index.

The resulting estimates are shown in table 7.8. Each additional passenger car equivalent kilometre of travel, costs other car users from 9 cents (Darwin) to 51 cents (Brisbane) in 2020. The impacts are larger in 2030.

7.8 Marginal congestion costs

Capital city	2020	2030
	$/PCU km	$/PCU km
Sydney	0.44	0.61
Melbourne	0.41	0.55
Brisbane	0.51	0.73
Adelaide	0.37	0.50
Perth	0.45	0.70
Hobart	0.13	0.16
Darwin	0.09	0.12
Canberra	0.16	0.22

Source: The CIE, based on BITRE 2015, *Traffic and congestion cost trends for Australian capital cities*, November, https://www.bitre.gov.au/publications/2015/is_074.

Trends in marginal congestion costs beyond 2030 will depend on expenditure on road capacity. This will also depend on the uptake of CAVs — a driverless vehicle has a lower cost related to congestion than one with a driver. We have projected forward marginal congestion costs through applying the BITRE CAV uptake projections for the base case, the CAV impacts on transport costs set out in the previous chapter and continued growth in the costs of congestion based on the trend from the BITRE estimates of the costs of congestion above from 2020 to 2030. We assume that this trend flattens somewhat, to grow at half the rate from 2030 onwards, consistent with our assumptions about the decline in speeds from chapter 3.

We have allocated the marginal congestion costs to different types of benefits and traffic based on the shares of these in total congestion costs, and traffic shares. This is shown in table 7.9.

7.9 Share of marginal congestion costs attributed to different benefits

Type of benefit	Share of marginal congestion cost
	Per cent
Reduced private vehicle time cost	38.4
Reduced private vehicle operating cost	5.9
Reduced business (non-freight) cost	40.3
Reduced business (freight) cost	12.4
Reduced air pollution	3.0
Total	**100.0**

Source: The CIE, based on based on BITRE 2015, *Traffic and congestion cost trends for Australian capital cities*, November, https://www.bitre.gov.au/publications/2015/is_074.

Comparison to other estimates of the cost of congestion

The marginal congestion costs used above are broadly consistent with a range of other estimates, set out in table 7.10.

7.10 Benchmarks of road decongestion costs

City	Source	Description	Estimate of cents per avoided VKT	Year (year of prices)
Sydney	IPART	Avoided costs from reduced road use (time, VOCs, reliability and environmental externalities)	55	2016 (2016 prices)
Sydney	TfNSW	Costs of extra road use for other users (time, VOCs, reliability and environmental externalities)	36	2016 (2016 prices)
Melbourne	CIE and Jacobs for Infrastructure Victoria	Avoided costs from reduced road use (time, VOCs, reliability and environmental externalities)	200-250 for AM and PM peaks Up to 25 cents for inter-peak and evenings	2020 (2018 prices)
Melbourne	ATAP/Victorian Department of Infrastructure	Costs of extra road use for other users (time, VOCs and reliability)	22 (off-peak) 22 (light peak) 84 (moderate peak) 118 (heavy peak)	2005 (2014 prices)
Melbourne	CIE calculated based on Melbourne Metro business case	Costs of extra road use for other users (time, VOCs and reliability)	120	2031 (2015 prices)
Christchurch	New Zealand Transport agency	Costs of avoided vehicles because of diversion to public transport (time, VOCs, crash costs, environmental externalities)	NZ 34 cents	2008 (unclear)

City	Source	Description	Estimate of cents per avoided VKT	Year (year of prices)
Wellington	New Zealand Transport agency	Costs of avoided vehicles because of diversion to public transport (time, VOCs, crash costs, environmental externalities)	NZ 100 cents	2008 (unclear)
Auckland	New Zealand Transport agency	Costs of avoided vehicles because of diversion to public transport (time, VOCs, crash costs, environmental externalities)	NZ 156 cents	2008 (unclear)

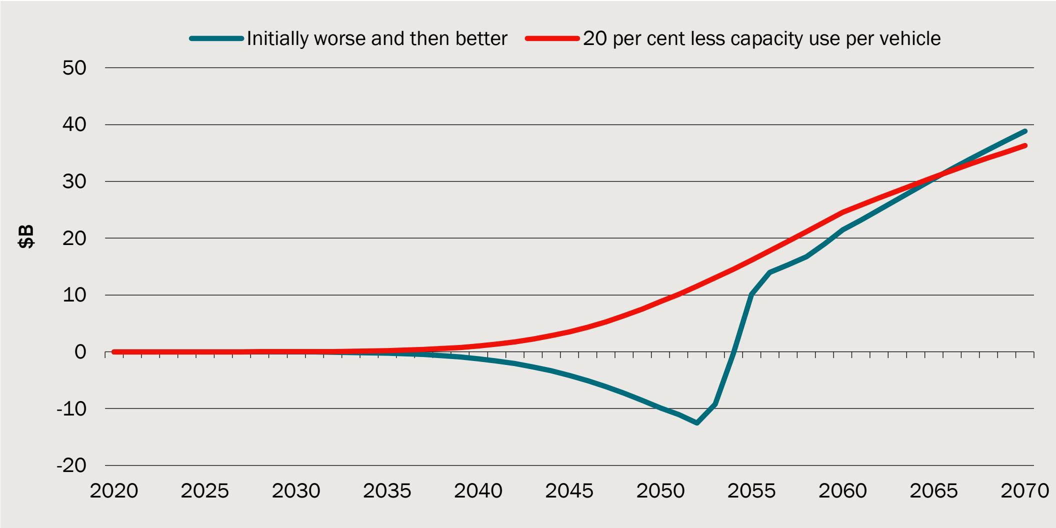
Sources: IPART 2016, *External benefits and costs*, Final report — Information paper 7: https://www.ipart.nsw.gov.au/files/sharedassets/website/shared-files/pricing-reviews-transport-services-publications-review-of-public-transport-fares-in-sydney-from-july-2016/external_benefits_and_costs_-_public_transport_fares_final_report_ip_7.pdf; TfNSW 2016, *Principles and Guidelines for Economic Appraisal of Transport Investment and Initiatives*, Table 21, http://www.transport.nsw.gov.au/sites/default/files/media/documents/2017/principles-and-guidelines-for-economic-appraisal-of-transport-investment.pdf; ATAP 2018, *Australian Transport and Planning Assessment Guidelines*: M1 — Public Transport, https://atap.gov.au/mode-specific-guidance/public-transport/files/M1_Public_transport.pdf, Table 11; Public Transport Victoria 2016, *Melbourne Metro business case: Appendix 5,* https://metrotunnel.vic.gov.au/__data/assets/pdf_file/0020/40484/MM-Business-Case-Feb-2016-APPENDIX-05.PDF and CIE calculations; New Zealand Transport agency 2018, *Economic evaluation manual*, p 3-49, https://www.nzta.govt.nz/assets/resources/economic-evaluation-manual/economic-evaluation-manual/docs/eem-manual.pdf; The CIE and Jacobs 2020, Estimating the social marginal cost of public transport in Victoria, prepared for Infrastructure Victoria, https://www.infrastructurevictoria.com.au/document/estimating-the-social-marginal-cost-of-public-transport-in-victoria-cie-24-june-2020/.

Estimates of the benefits of CAVs for baseline traffic

Before considering the changes in road traffic induced by CAVs, the estimated overall capacity benefits from CAVs are very large but occur primarily after 2050. When applying the BITRE base case CAV uptake:

- under the one view in the literature that CAVs will take up more road capacity than a standard vehicle at low levels of penetration, there would be capacity costs until just after 2050, and then larger capacity benefits thereafter (teal line, chart 7.11)
- under the alternative view of CAVs always using less road capacity than a standard vehicle, there would be small benefits that gradually build as CAV uptake increases (red line, chart 7.11).

7.11 Capacity benefits without additional traffic



Data source: The CIE.

We find that under the first scenario, the benefit of CAVs from 2020 to 2070 is $321 billion, but is heavily back-ended with negative impacts to 2050 of $55 billion. Under the second scenario, the capacity benefits are $531 billion from 2020 to 2070. However, there is no interim period of negative capacity impacts.

These impacts would dwarf the impacts of infrastructure investment aimed at increasing road capacity. For example, WestConnex, one of the largest capacity expansion projects to a road network in an Australian city, was estimated to reduce road congestion costs in Sydney by $24 billion over a 30-year period.[83] At high levels of uptake CAVs would have this level of impact in a single year, albeit impacting across all Australian cities rather than only Sydney.

This does not account for any inducement of traffic as a result of CAVs, which is discussed in chapter 10.

83 WestConnex Update Strategic Business Case, 2015, https://www.westconnex.com.au/media/yejnwxmw/westconnex-updated_strategic_business_case.pdf.

8 Direct environmental impacts of CAVs

CAVs will directly reduce environmental impacts from car use, through reducing fuel consumption. We find that the reduction in Greenhouse Gas (GHG) emissions associated with CAVs is worth $10 billion over the period from 2020 to 2070.

Indirectly, CAVs may lead to negative environmental impacts, because they induce additional car traffic. This is measured in chapter 10.

Emissions from fuel usage

Fuel consumption in 2020

The resource cost of fuel consumption for each vehicle and travel type is based on a fuel efficiency of that vehicle and the resource cost of fuel per litre of 79 cents (table 8.1).[84] Greenhouse gas emissions are as per ATAP guidelines[85], and we assume the cost of carbon is $60 per tonne of CO2-equivalent. The cost of carbon is aligned to an escalated cost used in Austroads guides, as set out in ATAP 2020.[86] This cost of carbon is also similar to a 12-month rolling average of the traded prices of EU Emissions Allowances. However, these have changed markedly over this period and the most recent data (November 2021) are over A$100 per tonne of CO2-equivalent.[87]

8.1 Fuel consumption and GHG emission assumptions

Type of travel	Type of distance	Speed of included states	Fuel	Fuel	Fuel	GHG	GHG	GHG
			Resource cost $ per litre	L/100 vkm	Resource cost $/vkm	Kgs/L	Kgs/vkm	$/vkm
Capital city	Private cars	45.4	0.79	12.8	0.10	2.28	0.29	0.02
Regional	Private cars	80.0	0.79	8.6	0.07	2.28	0.20	0.01

84 This is based on the current price of fuel as at July 2021 (133.4 cents per litre) and excluding GST and fuel excise, see: https://www.accc.gov.au/media-release/petrol-prices-rise-on-the-back-of-higher-international-crude-oil-prices

85 See https://www.atap.gov.au/parameter-values/road-transport/appendix-b-emission-conversion-factors

86 See ATAP 2020, PV5: Environmental Parameter Values, Draft for public consultation, July, https://www.atap.gov.au/sites/default/files/documents/pv5-environmental-parameter-values-public-consultation-draft.pdf.

87 See https://tradingeconomics.com/commodity/carbon.

Type of travel	Type of distance	Speed of included states	Fuel	Fuel	Fuel	GHG	GHG	GHG
			Resource cost $ per litre	L/100 vkm	Resource cost $/vkm	Kgs/L	Kgs/vkm	$/vkm
Long distance	Private cars	80.0	0.79	8.6	0.07	2.28	0.20	0.01
Capital city	Business cars	45.4	0.79	16.1	0.13	2.28	0.37	0.02
Regional	Business cars	80.0	0.79	10.8	0.09	2.28	0.25	0.01
Long distance	Business cars	80.0	0.79	10.8	0.09	2.28	0.25	0.01
Capital city	Light commercial	45.4	0.79	13.1	0.10	2.28	0.30	0.02
Regional	Light commercial	80.0	0.79	8.9	0.07	2.28	0.20	0.01
Long distance	Light commercial	80.0	0.79	8.9	0.07	2.28	0.20	0.01
Capital city	Heavy commercial	50.0	0.79	56.2	0.44	2.67	1.50	0.09
Regional	Heavy commercial	80.0	0.79	34.0	0.27	2.67	0.91	0.05
Long distance	Heavy commercial	90.0	0.79	69.2	0.55	2.67	1.85	0.11
Capital city	Bus	30.0	0.79	60.4	0.48	2.67	1.61	0.10
Regional	Bus	30.0	0.79	25.3	0.20	2.67	0.68	0.04
Long distance	Bus	80.0	0.79	28.7	0.23	2.67	0.77	0.05

Note: For the basis of speed assumptions see chapter 3.
Source: The CIE.

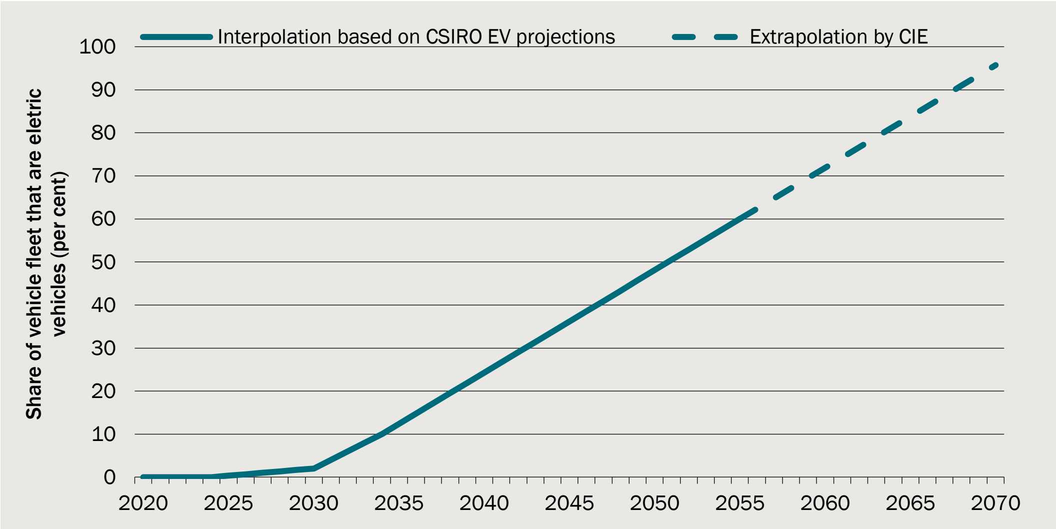
Projected emissions intensity of vehicle fleet

Consistent with the calculations in chapter 6, we assume that fuel consumption for non-electric vehicles is unchanged over time, but that fuel consumption for electric vehicles is lower than vehicles with Internal Combustion Engines (ICEs).

However, the emissions intensity of fuel use is projected to significantly decline as electric vehicle take-up increases. Electric vehicle take-up has been forecast by CSIRO (2021)[88], and we extrapolate these projections to 2070 based on the 'current trajectory' scenario. This scenario is projected to reach 60 per cent of the vehicle fleet being electric by 2055, and our extrapolation based on a 2.4 percentage point increase per year suggests almost 100 per cent penetration of EVs by 2070 (table 8.2).

88 CSIRO, 2021, *Electric vehicle projections 2021*, available at: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/csiro-ev-forecast-report.pdf

8.2 Share of vehicle fleet that is an electric vehicle



Data source: CSRIO (2021), The CIE.

Future emissions intensity is the product of:

- an index of EV uptake, taking a value of 1 at 100 per cent EV uptake, and
- an index of relative emissions intensity between EVs and ICEs in each year.

Emissions intensity of both EVs and ICEs are projected to decrease, but at a faster rate for EVs (table 8.3).

We extrapolate these estimates of emissions intensity using a constant Compound Annual Growth Rate (CAGR) of -1.2 per cent for ICE and -3.9 per cent for EVs. By 2070, electric vehicles have 11 per cent of the emissions intensity of ICE vehicles. Note that we only have these projections for battery electric vehicles excluding plug-in hybrids.

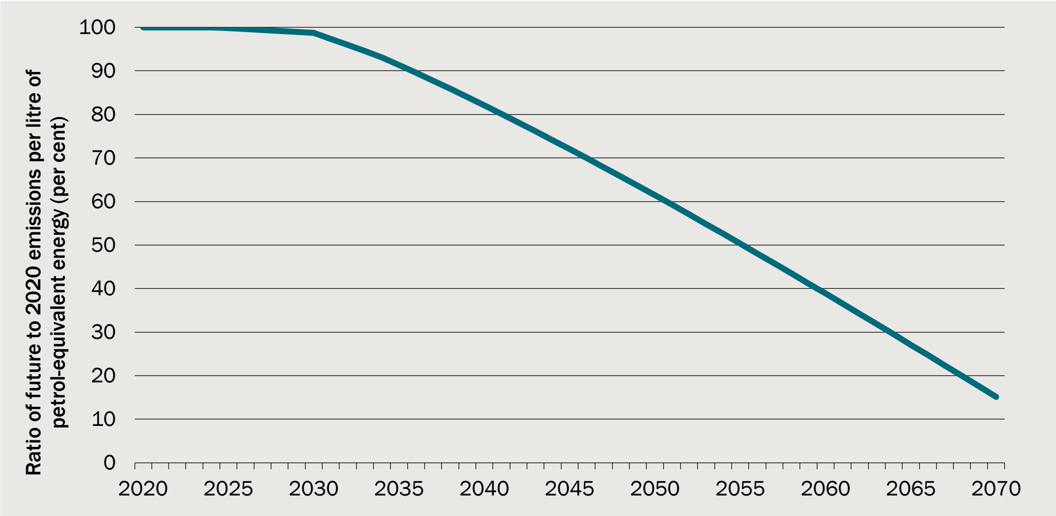
8.3 Relative emissions intensity of electric vehicles

Year	Internal Combustion Engines	Battery electric, excluding plug-in hybrids	Ratio of EV to ICE emissions per kilometre
	g CO2-equivalent per km	g CO2-equivalent per km	Per cent
2020	222	111	50
2025	208	83	40
2030	196	68	35

Source: https://www.industry.gov.au/sites/default/files/2020-12/australias-emissions-projections-2020.pdf

Combining the relative emissions intensity of electric vehicles and the share of fleet that is electric, this implies that vehicle emissions will fall dramatically to be around 15 per cent of their current level by 2070.

8.4 Projected emissions intensity for entire vehicle fleet

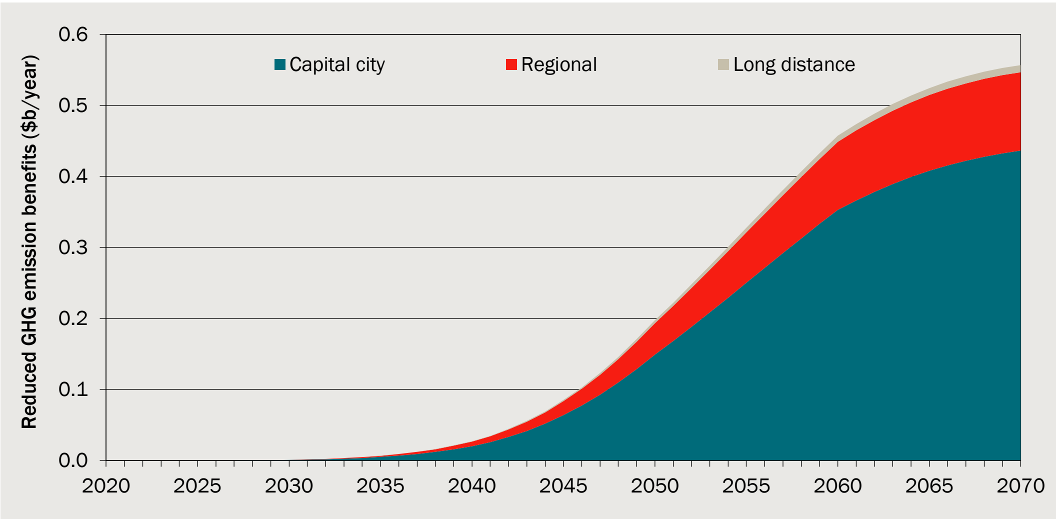


Data source: The CIE.

Estimates of the impact of CAVs on emissions

CAVs directly impact on the greenhouse gas emissions of the vehicle fleet through influencing fuel consumption. We apply the proportional reductions in fuel consumption explained in chapter 7 (see table 8.1) as proportional reductions in greenhouse gas emissions from CAVs. Accordingly, these follow the same time profile as the fuel reduction benefits, but are approximately 18 per cent of the magnitude of the fuel cost benefits.

8.5 Reduction in cost of GHG emissions associated with CAVs



Data source: The CIE.

The total value of GHG reductions associated with CAVs over this period is $9.8 billion.

Other environmental impacts

The only environmental impacts of CAVs that we quantify are impacts on GHG emissions. Kopelias et al (2020) reviewed the literature about environmental impacts of CAVs and this predominantly focusses on emissions impacts. While it notes that there are also environmental noise impacts there is little evidence available in the literature relating to these impacts.[89]

89 Koplias, P., Demirid, E. and Skabardonis, A., 2020, 'Connected & Autonomous Vehicles — Environmental Impacts — A review', *Science of the Total Environment*, Volume 712, April 2020, available at: https://www.sciencedirect.com/science/article/abs/pii/S0048969719352295

9 Costs associated with enabling CAVs

Enabling CAVs will have costs related to infrastructure and costs related to the vehicles themselves. There is substantial uncertainty about costs, given the early stage of development, and how competitive factors could play out in pricing.

Overall, we expect that costs related to vehicles would be in the order of $473 billion from 2020 to 2070 under the central case.

Costs related to infrastructure are also substantial, largely related to communications infrastructure. The cost of achieving 100 per cent cellular coverage for paved roads across all of Australia is estimated to be in the order of around $10 to 20 billion dollars (order of magnitude estimate of costs). This is the cost for coverage that would not already be provided by communications companies on a commercial basis. If some areas remain uncovered then the costs would be lower.

Costs for road infrastructure, such as improved signs and lines, are more difficult to attribute to CAVs, as these would likely be required in any case. However, based on attribution by share of vehicles, these costs are estimated at $2.4 billion from 2020 to 2070.

Infrastructure costs to support Level 4 & 5 CAVs

There are four basic requirements needed to support AV operation:

1. a range of sensors to support the vehicles understanding of the local environment to allow localisation, navigation and safe operation of the vehicle. These elements are not described in further detail here and are considered as part of the cost and operation of the vehicle
2. satellite positioning systems
3. road related infrastructure, and
4. cellular (and potentially other) forms of communication.

Positioning

Satellite positioning systems have been noted to be deficient for accurate real time positioning (particularly for moving vehicles) in Australia. This impacts a wide range of industries (including mining and agriculture) and work is underway to improve the accuracy and robustness of these services in the coming years through the SouthPAN

SBAS program with an investment of $224.9 million over three years (2020 – 2023).[90] For this report, we assume this accurate positioning will be available in the near future and we have not considered positioning further, other than to note that additional positioning accuracy can be provided with cellular coverage, allowing improvement from +/- 10cm down to +/-1 or 2cm.

Road-related infrastructure

Categories of road-related infrastructure needed to support Level 4/5 CAVs

The *Assessment of Key Road Operator Actions to Support Automated Vehicles* by Austroads[91] outlined a range of potential future infrastructure needs for AVs. Some long-term considerations for physical infrastructure needed to support AV operation from this report are summarised in table 9.1. None of these requirements are as yet known to be of significant additional cost and have not been considered further in this report. Many of these improvements can be considered on a case-by-case basis or considered and absorbed in improved design standards over time. For example, there may be investment in pavement strengthening when seeking increases in gross vehicle weight which may also be advantageous to the consideration of AV platooning, but the strengthening isn't specifically required because of AV platooning.

9.1 Initial considerations for changes to facilitate the introduction of AV

Design element	Key issues	Modification AC may require
Alignment	▪ Stopping sight distance ▪ Horizontal alignment ▪ Superelevation etc.	▪ Improved ability to read the road with improved headlight technology (e.g. LED, laser light and infrared) and automatic braking systems will change stopping sight distances and vertical curve lengths. ▪ Guidance systems could affect horizontal curve design.
Cross section	▪ Roadway width and shoulder width, median intersection design, tuning lanes.	▪ Long term changes to vehicle design will change these key requirements e.g. reduced lane widths if vehicles are narrower.
Intersection	▪ Intersection sight distance models are based on driver behaviour rather than vehicle and roadway capacity.	▪ In the short to medium term seeking to simplify intersection arrangements and interactions between vehicles. In the longer term if there is the greater potential for coordination between vehicles intersections could be made more compact.
Structures	▪ Dynamic loading due to platooning vehicles	▪ May require a revision of design standards including loading assumptions. Note this may lead to greater numbers of heavy vehicles being attracted to a corridor or provide another reason to use a particular lane as well as decreased spacing between vehicles.

90 https://www.ga.gov.au/scientific-topics/positioning-navigation/positioning-australia/about-the-program

91 Austroads, 2017, *Assessment of key road operator actions to support automated vehicles*, available at: https://austroads.com.au/publications/road-design/ap-r543-17

Design element	Key issues	Modification AC may require
Pavements	▪ Loading due to platooning vehicles	▪ May require a revision of design standards including loading assumptions.
Freeways/ motorways	▪ Design of certain aspects of urban freeways/motorways focusses on acceleration lanes, high-occupancy vehicle lanes, and entrance and exit ramps.	▪ In the long term homogeneous fleets of AV will, improve throughout due to certainty of interactions and could require changes to ramp lengths depending on potential light and heavy vehicle platooning requirements. In the short term differences in the level of conservation of AV operation will impact negatively on road operation, requiring at least current level of infrastructure provision.

Source: Austroads (2017) Table 9.1.

It is important to note, however, that Level 1 and 2 AVs rely heavily on road signs and road line marking. Level 4 and 5 AVs will also be required to consider longitudinal and lateral line marking and road signs to ensure they comply with road rules even if not required for the vehicle's internal localisation needs. Improved sign maintenance and improved line marking standards and maintenance are needed to improve the operation of AVs in the medium term (at least 20 years), to support these vehicles operating on our roads today and we can assume in the longer term (for Level 4 and 5 AVs) as well. The investment in signs and lines needs to be considered to ensure that the benefits of these vehicles are realised.

Road sign maintenance represents a small fraction (~1 per cent) of total road maintenance costs, because these activities are generally allied to another task such as sign knockdown.[92] These costs have not been considered further.

There will be some ongoing maintenance costs for pavement markings to support Level 4 and 5 CAVs and these are considered below.

Maintenance costs of pavement markings

Our estimate of the annual costs of maintaining pavement markings to support Level 4 and 5 CAVs is based on multiplying the length of markings replaced each year by a unit cost for markings. The assumptions underlying this calculation are explained below.

Austroads (2020)[93] considered maintenance costs of pavement markings to support Level 1 and 2 AV machine vision systems. The focus for pavement markings to support any level of driving automation is the same — to ensure that the markings can be read by any user including machine vision systems. There are a range of reasons why road pavements may not require line marking or why they cannot be marked, and so the assumptions do not allow for additional markings on local roads which have not previously been marked. CAVs will be required to solve more complex problems in these environments than the absence of line markings, such as identifying parked and moving cars, identifying pedestrians and navigating narrow roads. CAVS will be required to operate on these roads through using other methods, such as sensors and communications networks, but

92 Based on WSP partnerships in road maintenance contracts.

93 Austroads, 2020, *Implications of Pavement Markings for Machine Vision*, available at: https://austroads.com.au/publications/connected-and-automated-vehicles/ap-r633-20

would not operate at the same speeds as would occur on roads that have lines and wider widths.

Indicative costs for continuous pavement markings of 150mm width (all costs, both sides of the road) are detailed in table 9.2. Source 1 rates were based on an awarded program of works between $1 million and $1.5 million and is thought to be reliable. An increase of 10-20 per cent for shorter sections due to set up costs could be expected. Source 2 rates were based on an internal government program budget-estimation tool.

9.2 Cost of continuous pavement markings

Life	Type	Width	Cost – source 1	Cost – source 2
		mm	$/km	$/km
Shorter life	Paint	150	2300	1 160 – 1 240
Longer life	Cold applied plastic	150	3600	4 200 – 8 000
	Thermoplastic	150	3600	2 500 – 13 500
	Tape	150	18000	25 000

Source: Austroads (2020) Table A.1.

The road network can be broken down by state or territory, and by road type category. The road lengths used by this report are based on data from BITRE[94].

9.3 Length of the road network

State	Urban				Non-urban			
	Highway	Arterial	Local	Total	Highway	Arterial	Local	Total
NSW	1 501	4 069	34 688	**40 258**	10 341	69 845	88 127	**168 313**
VIC	1 676	5 097	30 930	**37 703**	6 593	30 477	74 249	**111 318**
QLD	1 100	2 379	27 825	**31 304**	10 916	19 062	165 315	**195 293**
SA	290	1 931	10 280	**12 501**	3 485	14 480	62 812	**80 777**
WA	1 489	1 683	16 393	**19 565**	9 944	15 174	112 236	**137 355**
TAS	349	567	3 066	**3 982**	1 529	3 289	11 096	**15 913**
NT	24	313	963	**1 299**	2 650	13 692	1 797	**18 139**
ACT	60	3354	2 760	**3 155**	39	66	359	**464**
Total	**6 488**	**16 372**	**126 906**	**149 767**	**45 496**	**166 103**	**516 152**	**727 751**

Source: BITRE (2018) *Australian Infrastructure Statistics Yearbook 2018*.

Austroads (2020) estimated costs based on data provided in table 9.2 and 9.3 above, but this only covered highways and arterial roads. To estimate maintenance requirements for local roads, we have conservatively applied an assumption that 50 per cent of local roads require pavement marking maintenance.

Table 9.4 extends Austroads (2020) by including costs for local roads. The initial capital spend for full replacement of all line markings is estimated to be approximately $2.1 billion, which is the midpoint of the lower and upper bound estimates from table 9.4.

94 BITRE (2018) *Australian Infrastructure Statistics Yearbook 2018*

Note that in Victoria there is a defined set of standards that apply to road classes of all types, this means non-urban arterial roads have a minimum of three line markings per Austroads (2020). As our analysis is of all Australian states, we recognise that line marking requirements are inconsistent for arterial roads. As such, we have amended calculations to show that the minimum line markings on a non-urban arterial road is one.

9.4 Capital cost for full replacement of line markings

Road	Road length	Number of lines		Length of line		Rate	Cost	
		Lower	Upper	Lower	Upper		Lower	Upper
	km	Number	Number	km	km	$/km	$m	$m
Urban								
Highway	6 488	5	8	32 440	51 904	1 800	58	93
Arterial	16 372	3	8	49 116	130 976	1 800	88	236
Local	63 453	1	1	63 453	63 453	1 800	114	114
Non-urban								
Highway	45 496	3	6	136 488	272 976	1 800	246	491
Arterial	166 103	1	5	166 103	830 515	1 800	299	1495
Local	258 076	1	1	258 076	258 076	18 000	464	464
All regions								
Total	**555 988**			**705 676**	**1 607 900**		**1 269**	**2 894**

Source: WSP.

Austroads (2020) outlined discussions with road operators noting the following broad maintenance routines:

- Highway lane markings need to be maintained every three years — i.e., 33 per cent needs to be replaced each year
- Arterial road lane markings need to be maintained every five years — i.e., 20 per cent needs to be replaced each year.
- The maintenance requirement on local roads was not considered as part of the Austroads investigation. A conservative maintenance cycle of 20 per cent replacement each year has been assumed, which aligns to requirements for arterial roads.

These rates of replacement imply annual maintenance costs for replacing line marking are approximately $474 million, based on the midpoint of the lower and upper estimates in Table 9.5.

9.5 Annual maintenance costs by road type

Road	Road length replaced each year		Annual maintenance cost	
	Lower	Upper	Lower	Upper
	km	km	$m	$m
Urban				

Road	Road length replaced each year		Annual maintenance cost	
	Lower	Upper	Lower	Upper
	km	km	$m	$m
Highway	10 705	17 128	19	31
Arterial	9 823	26 195	18	47
Local	12 691	12 691	23	23
Non-urban				
Highway	45 041	90 082	81	162
Arterial	33 221	166 103	60	299
Local	51 615	51 615	93	93
All regions				
Total	**163 096**	**363 814**	**293**	**655**

Source: WSP.

Attribution of pavement marking maintenance costs to Level 4 and 5 CAVs

Austroads (2020) noted that road operators currently only receive 65 per cent of the funding requirement for the line marking assumptions outline above. The additional effort to bring the line marking up to a fully serviceable level (able to be consistently read by machine reading) to achieve benefits for all AVs (levels 1 through 5) is 35 per cent of the total year maintenance value above or $166 million.

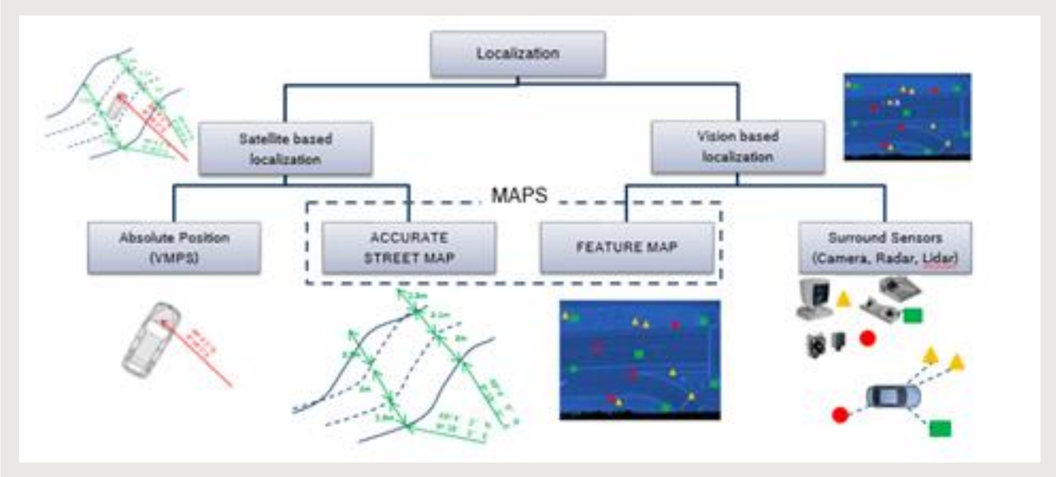
This yearly maintenance value of $166 million for all AVs can then be considered for attribution against Level 1 and 2 (in the near term) and Level 4 and 5 in the long term. We allocate the $166 million in costs between Level 1/2 and Level 4/5 based on the share of vehicles that are level 4/5 CAVs in each year. For example, by 2070, with 81 per cent of vehicles being CAVs in the base case uptake scenario, this means there is a cost of $134 million in pavement marking maintenance attributable to Level 4 and 5 CAVs. The total pavement marking maintenance costs attributed to Level 4 and 5 CAVs for the period 2020 to 2070 is $2.4 billion.

Cellular Communication

Cellular communication is an important CAV enabler. Cellular communication is critical to AV operation. It is important to note that **continuous** cellular connectivity is not necessarily a safety critical requirement for CAV operation. Safe (albeit significantly degraded) operation may be possible without it.

Chart 9.6 outlines one approach to sensor fusion used by CAVs. The street map element is dynamic — real-time information can be provided to vehicles via cellular connection.

9.6 Sensor fusion and localisation



Data source: Bosch 2015.

CAVs can operate in a degraded form (e.g., potentially at a lower speed), with imperfect and out-of-date information regarding lane availability and information like road works alerts. It is noted that a lower level of positioning accuracy may result without the availability of cellular communications.[95] Vehicles without cellular connectivity are less likely to have access to systems which allow for better optimisation of traffic signals and movement through traffic networks. Vehicles without cellular connective also potentially require lower operating speeds (given uncertainties the automated vehicle systems have with their environment and the position of the vehicle).

It is important to note that some information could potentially be made available through vehicle-to-vehicle interactions or another short-range connection with infrastructure. However, these connections would be uncommon in rural and regional areas. If there were unusual and unmapped changes to the road network at a time when the vehicle did not have cellular access it may cause significant degradation of AV function such that a level 4 vehicle may fall back to requiring human control (e.g. Level 2). However, this would be more problematic for the operation (or rescue) of a Level 5 vehicle (without the ability to drive the vehicle manually), potentially stranding a vehicle, so in practice may limit access by Level 5 vehicles to areas with cellular coverage.

To develop cost estimates for cellular tower coverage we have utilised work undertaken for Infrastructure Victoria ('IV', 2018) – *ICT Infrastructure Advice for Automated and Zero Emission Vehicles*.[96]

Given the cost of cellular communication infrastructure it is considered unfeasible to cover 100% of the whole road network. The approach taken in IV (2018), which is also taken in this report was to only consider complete coverage on paved roads. **The cost of**

95 https://www.ga.gov.au/scientific-topics/positioning-navigation/positioning-australia/about-the-program

96 https://www.infrastructurevictoria.com.au/wp-content/uploads/2019/04/ICT_Infrastructure_Advice_for_Automated_and_Zero_Emission_Vehicles.pdf

100 per cent cellular coverage for paved roads across all of Australia is estimated to be around $10 to 20 billion dollars. This is an 'order-of-magnitude' estimate of costs.

The IV (2018) analysis involved a comprehensive review of the Victorian cellular network mapped using GIS and engagement with telecoms companies. For the purposes of obtaining an order-of-magnitude cost estimate, we use the same approach as taken by IV (2018). Key assumptions made to support this cost estimate include that:

- towers have a 5km coverage radius,
- all regional and rural towns will have cell coverage,
- all urban roads are paved,
- non-urban highway and arterial roads are paved, and
- the Cellular blackspot program may result in some additional infill of towers.

By using the shares of the road network that are of paved and unpaved we can obtain an order-of-magnitude estimate of costs across all states.

The detailed methodology taken to develop costs for cellular tower coverage is as follows:

1 Gather road length statistics by highway, arterial and local (paved) roads and split by state[97]

2 Identify split of paved and unpaved roads (table 9.7) (note that only lengths for 2015 are provided in the *Yearbook 2020*).[98] Apply split to non-urban local roads to identify paved length

3 Consolidate IV number of towers needed to cover rest of the Victorian network (see table 9.8)

4 Calculate the number of cell towers needed per km (total towers divided by kilometres covered

5 Understand the percentage of the Victorian network to be covered by new cell towers

Recognising that Victoria has high population and urban density in comparison to other states, we have adjusted the assumption to the percentage of road requiring network coverage based on our understanding of the road network and population density in each state. These assumptions are detailed in table 9.10.

Costs:

1 Research for the IV (2018) report found that the average site costs between $570 000 and $815 000, based on new cell tower installations in Victoria and New South Wales over the preceding three years (prior to 2018). This considered the cost of design, civil work, tower supply and erection, communications hut, security, power, communications and mobile network operator-supplied equipment, and contingency. The same cost assumption has been applied to this estimate (given this is only an order of magnitude estimate).

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97 BITRE, 2018. Australian Infrastructure Statistics Yearbook.

98 BITRE, 2020, Australian Infrastructure Statistics Yearbook https://www.bitre.gov.au/sites/default/files/documents/bitre_aus_infrastructure_yearbook_2020.pdf

Costs considering the number of towers required and these assumptions are provided in table 9.9.

9.7 Share of road network that is paved, by state and territory

State	Paved
	Per cent
Victoria	57
New South Wales	49
Queensland	38
South Australia	33
Western Australia	35
Tasmania	58
Northern Territory	46
Australian Capital Territory	97

Source: WSP.

9.8 Victorian base data

Victoria	Highway & arterial (m, a, b, c)	Local (s)
Total length of sealed roads to be covered by projected new cell towers (kms)	7 843	7 679
Number of new towers (No.)	1 036	1 062
Non-urban road length (kms)	37 070	74 249
Paved non-urban (kms)	Assumed paved	42 085
Share of paved non-urban network covered by new cell towers (per cent)	21%	18%

Source: WSP.

9.9 New towers required

State	Assumed share requiring covering		Kms covered by new towers			Number of new towers needed		Towers per km	
	Highway & Arterial	Local	Paved non-urban local	Highway & Arterial	Local	Highway & Arterial	Local	Highway & Arterial	Local
	Per cent	Per cent	Kms	Kms	Kms	No.	No.	No.	No.
VIC	21	18	42 085	7 843	7 679	1 036	1 062	0.13	0.14

Source: WSP.

9.10 Adjusted assumed coverage for each state

State	Highway & arterial	Local
	Per cent	Per cent
VIC (IV)	21	18
NSW	25	35
QLD	30	45

State	Highway & arterial	Local
	Per cent	Per cent
SA	25	45
WA	40	50
TAS	25	45
NT	40	60
ACT	21	35

Note: Assumes different density of road network. I.e. nearly all states have a lower density of townships / cellular coverage than Victoria.

Source: WSP; Victorian coverage in 2018 determined for IV.

9.11 Km coverage calculations

State	Assumed percentage requiring covering			Kms covered by new towers		Number of towers needed	
	Highway & arterial	Local	Paved non-urban local	Highway & arterial	Local	Highway & arterial	Local
	Per cent	Per cent	Kms	Kms	Kms	No.	No.
VIC	21%	18%	42 085	7 843	7 575	1 036	1 062
NSW	25%	35%	43 555	20 047	15 244	2 648	2 137
QLD	30%	45%	62 763	8 993	28 243	1 188	3 960
SA	25%	45%	20 436	4 491	9 196	593	1 289
WA	40%	50%	39 795	10 047	19 897	1 327	2 789
TAS	25%	45%	6 410	1 204	2 884	159	404
NT	40%	60%	824	6 531	495	863	69
ACT	21%	35%	349	22	122	3	17

Source: WSP.

9.12 Adjusted estimate of towers (using additional coverage estimates)

State	Number of towers needed		Highway + arterial (all roads) cost estimate		Local paved cost estimate	
	Highway & Arterial	Local	Low	High	Low	High
	No.	No.	$m	$m	$m	$m
VIC	1 036	1 062	591	844	605	866
NSW	2 648	2 137	1 509	2 158	2 257	3 227
QLD	1 188	3 960	677	968	735	1 051
SA	593	1 289	338	484	1 590	2 273
WA	1 327	2 789	756	1 082	230	330
TAS	159	404	91	130	40	57
NT	863	69	492	704	10	14
ACT	3	17	2	2	9	14

Source: WSP.

Communications costs have been allocated over time by assuming that all communications costs must be spent by the year that 25 per cent of vehicle kilometres are driven by CAVs. Under the central case, this is reached in 2048. Costs between 2020 and 2048 are allocated to each year based on the number of CAV vehicle kilometres in each year divided by the total CAV vehicle kilometres over this period (that is, spending tracks the uplift in penetration rates). This results in almost all costs being incurred between 2030 and 2050. The total cost estimate for additional communications infrastructure to support CAVs in the central case estimates is $13.5 billion, which is an average of the low and high estimates.

9.13 Summary of communications network costs

State	Number of towers needed		All paved roads cellular coverage cost	
	Highway & arterial	Local	Low	High
			$m	$m
VIC	1 036	1 062	1 196	1 710
NSW	2 648	2 137	2 728	3 900
QLD	1 188	3 960	2 934	4 195
SA	593	1 289	1 073	1 534
WA	1 327	2 789	2 346	3 355
TAS	159	404	321	459
NT	863	69	532	760
ACT	3	17	11	16
Total			**11 141**	**15 930**

Source: WSP.

Level 4&5 CAV Vehicle Costs

The cost of CAVs to consumers is an important consideration when seeking to project their impact as it has a direct relationship with their uptake. Higher costs would likely result in — assuming the economy trends as it does today — slower mass uptake and lower overall fleet penetration.

There are two key considerations to regarding costs of AVs:

- Capital Costs (CAPEX)
- Operating Cost (OPEX)

CAPEX

Given the lack of highly automated vehicles currently available on the market, costs have been based on existing literature, considering the advertised costs for Tesla's 'full self-driving' features.[99]

99 https://www.tesla.com/en_AU/support/full-self-driving-computer

There is little available literature on the expected cost of highly automated vehicles to consumers, and much of this focuses on the cost of expensive associated hardware, such as LiDAR. While there have been significant cost reductions in such hardware in recent years, Original Equipment Manufacturers (OEMs) will need to recoup research and development costs and this should be considered when projecting the cost to consumers. Boston Consulting Group (BCG) estimated that 'fully automated features will cost approximately US $10 000, an interesting comparison against Tesla's cost for level 2 automation (see later).[100]

A Market Forecast for CAVs (2015) by the British Government's innovation agency, Catapult, undertook further analysis of the BCG forecast referenced above. This forecast applied:

- +50% on cost of autonomy package for OEM costs
- +30% for additional vehicle costs

It is important to note that the BCG forecast is based on assumptions regarding the relationship between cumulative uptake and cost reduction rates for autonomy packages, based on the observed economies of scale for partially automated features. This relationship was found by the UK analysis to be equivalent to a learning curve with a learning rate of 90-95 per cent.

The forecast projected costs for the UK central scenario for automated features by vehicle category: light duty vehicle (LDVs), heavy goods vehicles (HGVs) and buses.

9.14 UK projections of "average" incremental prices for CAV features

	2020	2025	2030	2035
LDVs				
Baseline, L0	19 000	18 800	18 800	18 900
L3	22 700	22 600	21 800	21 600
L4/5	-	25 300	25 200	24 100
HGVs				
Baseline, L0	93 600	96 700	99 700	101 600
L3	97 400	100 400	102 700	104 300
L4/5	-	103 100	106 100	106 800
Buses				
Baseline, L0	147 000	149 700	152 500	154 300
L3	150 700	153 500	155 500	157 000
L4/5	-	156 200	158 900	159 400

Source: Prices in 2015 GBP Market Forecast for CAVs (UK, 2015) - Table 3.5.

100 https://www.bcg.com/en-au/publications/2015/automotive-consumer-insight-revolution-drivers-seat-road-autonomous-vehicles

The scenarios described in this forecast are shown in the table 9.15. Note these forecasts are for level 4 and 5 vehicles. The year associated with the percentage of new sales is also shown for reference.

9.15 Uptake scenarios for UK cost conclusions

UK Scenario	Per cent of new sales			This forecast
	2025	2030	2035	
Progressive	0.4%	8.0%	30.0%	High
Central	0.3%	3.0%	10.0%	Medium
Obstructed	0.0%	0.2%	3.0%	Low

Source: UK 2015.

The additional cost on top of the standard vehicle cost when first introduced (2025) from this work was GBP 6 500 (AUD $12 250).

Ongoing Operational Costs (OPEX)

There is strong recognition globally of the need for (and cost of) for ongoing maintenance of advanced driver systems by the NTC. The NTC has been developing policy leading to regulation of Automated Driving System Entities (ADSE's) [101] — ADSEs may be original equipment manufacturers (OEMs) but could also be separate entities. ADSE's will be responsible for maintaining the functions of automated driving systems in service.

Consideration of Vehicles available on the market

Tesla's 'full self-driving' feature is one of the most advanced commercially available automated driving systems available. However, it is important to note that the system is considered to align largely to SAE Level 2 automated driving. Automated driving company Waymo noted the distinction themselves, regarding Tesla's system to be less likely to achieve higher levels of automated automation due to the absence of LiDAR sensors[102]. The focus of this report is on more advanced SAE Level 4 and 5 systems. Therefore, while consumers may consider costs for Tesla's system to be higher due to its 'unique selling point' in the market at present, costs for more advanced systems can also be assumed to be higher in the future as well. All of this needs to be countered by consideration of decreasing costs in components over time which has often been stated by industry players but not yet evidenced. One example of this is an Aptiv estimate from 2017 predicting a 90% reduction of CAV system costs by 2025.[103]

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101 https://www.ntc.gov.au/sites/default/files/assets/files/2021-06-22%20NTC%20Policy%20Paper%20-%20A%20national%20in-service%20safety%20law%20for%20automated%20vehicles.pdf

102 https://www.forbes.com/sites/johanmoreno/2021/01/22/waymo-ceo-says-tesla-is-not-a-competitor-gives-estimated-cost-of-autonomous-vehicles/?sh=171817b2541b

103 https://www.reuters.com/article/us-autos-delphi-idUSKBN1DY2AC

There are two options for Tesla's 'full self-driving' features:

- Up-front (available in Australia): AUD $10 100
- Subscription (US only): AUD $269 / month

It should be noted that depending on the year and configuration of the vehicle a hardware upgrade may be required, costing US $1500 (AUD $2065)[104]. This may be indicative of rollout across the industry, as OEMs seek to be first past the post by issuing earlier, but less advanced releases that don't support later upgrades to more highly automated features.

For comparison, Waymo have been quoted as comparing the current costs of retrofitting their automated vehicle hardware on a typical vehicle to be approximately the same as a 'moderately priced S-Class' which traded at US $180 000 (AUD $247 000). It is important to note that this is the cost of hardware, associated systems and installation. This does not consider the costs OEMs could potentially seek to recover in relation to the significant investment made in CAV development and software. In 2020, the average amount spent by Australian's on a new car was approximately $40 000.[105]

Cruise Origin has been estimated to cost $50 000 USD when in full production. There is no indication of what date this may be achieved. It is important to note that this Level 5 vehicle would likely only be able to operate at lower speeds or city speeds[106] so would not be suitable for all trips. The price tag should be considered relative to the cost of a standard EV base (e.g. Chevy Bolt) at approx. $40 000 USD.

Importance of future ownership models

The cost of a vehicle bought by an individual for private use or a company for corporate travel will continue to be governed heavily by affordability of vehicles, given the key benefits are recognised to be value of time for an individual. If we shift from considering the operation and value from an individual to fleet operation, the scale of the benefits captured by the vehicle become larger. As a result, there may be willingness to consider much higher than normal capital and operational costs, so long as there is a reasonable return on investment. This consideration applies to robo-taxis and automated freight operations. It is more compelling when considered alongside the potential life of 1 million miles for a vehicle e.g. as claimed for the Cruise Origin.

Summary

Some of the views promoted in the media on the costs of CAVs are expected to be optimistic.[107] Given the information noted above and uncertainty in any cost projections

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104 https://www.cnet.com/news/tesla-full-self-driving-explained-its-capabilities-cost-and-puzzling-over-promise/

105 https://www.canstarblue.com.au/vehicles/average-car-price/

106 https://www.theverge.com/2020/1/21/21075977/cruise-driverless-car-gm-no-steering-wheel-pedals-ev-exclusive-first-look

107 For example, https://www.forbes.com/sites/uhenergy/2019/05/21/self-driving-automobiles-how-soon-and-how-much/?sh=1df115ae38bd.

we have sought to provide a broad range of costs with two, competing scenarios based on ownership, fleet penetration and technology costs (table 9.16).

9.16 Cost scenarios for CAVs over and above standard vehicles

Scenario	Overall vehicle penetration (aligned with BITRE penetration curves)	Level of private ownership	Level of fleet ownership	Cost estimate range (beginning 2025)
				$/vehicle
High cost	Low	Low	Medium	50 000-70 000
Low cost	High	Medium	High	15 000-25 000

Source: WSP.

For the high-cost scenario, costs of $50 000 to $70 000 are assumed over and above the costs of a standard vehicle with relatively low overall vehicle penetration. For the low-cost scenario a range of $15 000 to $25 000 over and above the cost of a standard vehicle are assumed. This assumption relies on high levels of fleet ownership and medium levels of private ownership. For the purposes of point estimates, the analysis uses $15 000 per vehicle as the low estimate, $20 000 per vehicle as the medium estimate and $50 000 per vehicle as the high estimate.

Additional operational costs for automated systems have not been separated and are assumed to be covered in the costs outlined above.

For heavy commercial vehicles, there is less information on expected costs. These are anticipated to be only somewhat higher than for light vehicles. For the analysis, a 20 per cent premium for heavy commercial vehicles has been used.

Summary of costs related to CAV uptake

Under the base case uptake scenario, and the medium costs of $20 000 per vehicle, vehicle-related costs would amount to $473 billion from 2020 to 2070. If vehicle costs are higher, at the upper end such as $50 000, then uptake would be lower, and more akin to the BITRE barriers to broad adoption scenario. In this case vehicle costs would be lower in total at $443 billion, even though the cost per vehicle would be higher.

Annual costs of pavement marking maintenance are allocated between Level 1/2 and Level 4/5 CAVs, and the share allocated to Level 4/5 CAVs reaches $134 million per year by 2070. In total between 2020 to 2070, the cost attributable to Level 4/5 is modest ($2.4 billion).

Communications costs are a comparatively modest $10–20 billion compared to the vehicle costs.

10 People and business responses to CAVs

CAVs will eventually represent a major change in the level and structure of costs for transportation. Inevitably, people and businesses will respond to the opportunities that it leads to. In many cases, this will occur in ways which will further increase the benefits of CAVs. However, there may also be responses that reduce the benefits of CAVs.

The key responses to changes in the level and structure of transport costs include:

- **Lower transport costs and congestion leading to induced traffic**. If road transport is less costly to people, we would expect that they will do more of it. This could be because they switch from other modes such as public transport or active transport, take additional trips they wouldn't have taken, choose to take longer trips or choose to live and work in places that require more travel.
  - induced travel has both costs and benefits
  - people able to make additional trips do this because it is beneficial for them. These benefits could be large where people currently have high levels of transport disadvantage, such as the elderly and people with disability
  - however, additional trips lead to negative impacts on others through reducing some of the congestion-reduction benefits set out in chapter 7
- **reduced active transport**, because of reduced walking and cycling trips and reduced active transport components of public transport trips
- **increased use of shared vehicles**. CAV vehicles may be substantially more expensive than a standard vehicle. If this eventuates, the ability to share vehicle costs across more people and the lower cost for driverless on-demand transport could change the composition of car demand towards more shared vehicles
- **higher utilisation of freight vehicles** — the estimates in previous chapters assume similar vehicle numbers as with no CAVs. However, for freight, where no driver is needed then vehicle utilisation could be substantially increased. This would reduce the number of vehicles required, further reducing freight costs
- **changes to private car parking provision**, such as less car spaces close to destinations (such as office buildings and along streets) and more car spaces further away where land is less expensive.

These impacts can be measured and valued, except for changes to car parking provision, for which the evidence is more limited about what might occur.

Induced road traffic

New traffic generation as a result of improvements in road conditions is a very important phenomenon in transport modelling and economics. This is called 'induced' traffic. At its most extreme, people argue that a new motorway or other traffic improvement generates so much new traffic that it does not impact on congestion at all. While this view is not plausible, it is likely that a major change such as CAVs would lead to induced traffic, and that this would have significant impacts.

Infrastructure Australia notes the main forms of induced traffic are:

- changing mode — for example, public transport passengers switch to car because CAVs make car travel more attractive than bus or rail
- making additional journeys — for example, people are willing to make additional car journeys because of the improvement in accessibility
- changing destination — for example, drivers decide to travel to more distant destinations because the improvement makes the journey time acceptable
- changing time of travel — for example, drivers decide to travel in the peak period because the improvement reduces journey times to an acceptable level
- land use changes — for example, over time, CAVs may lead people to disperse further than they typically would, or encourage businesses to locate further from their labour markets.[108]

Infrastructure Australia has noted that induced demand can reduce the benefits for major road projects by as much as 25 per cent.

For CAVs, induced demand impacts are just as relevant as for road capacity improvements. CAVs will make road transport substantially more attractive. It may even have impacts above and beyond the impacts of typical road improvements, because people may send their CAVs home, rather than parking them at their destination.

Inducement from CAVs may be additional CAV travel or may also be additional non-CAV travel. For example, if CAVs improve road capacity, then this would encourage additional CAV and non-CAV travel.

Approach to measuring inducement

To value the impacts related to inducement, we use the approach set out in the Infrastructure Australia Assessment Framework.[109] This is shown in chart 10.1.

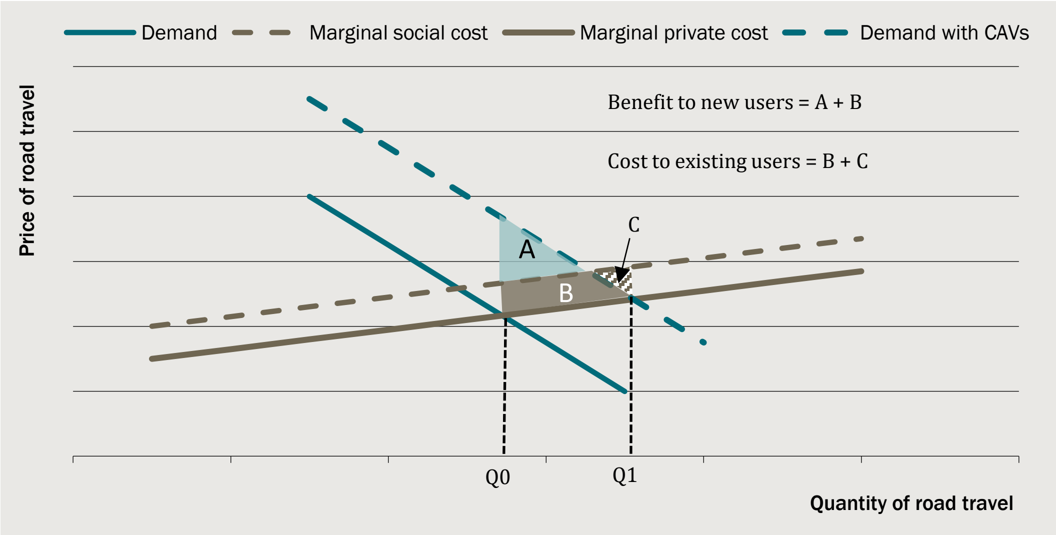
- There is a benefit to new users of the roads — this is typically approximated by the rule of half. This is that the benefit to a new user is approximated by half the benefit to a user who would drive in the base case. In chart 10.1 this is Area A plus Area B.
- Because roads are not priced efficiently, additional use leads to costs for others, through congestion and additional environmental externalities. These are set out in chapter 7. In chart 10.1 this is Area B plus Area C.

108 Infrastructure Australia 2021, Assessment Framework, *Guide to economic appraisal,* Box 6, https://www.infrastructureaustralia.gov.au/sites/default/files/2021-07/Assessment%20Framework%202021%20Guide%20to%20economic%20appraisal.pdf

109 Infrastructure Australia 2021, Assessment Framework, *Guide to economic appraisal,* https://www.infrastructureaustralia.gov.au/sites/default/files/2021-07/Assessment%20Framework%202021%20Guide%20to%20economic%20appraisal.pdf

In some cases, inducement of traffic will lead to higher benefits and in some cases to lower benefits. This depends on how large the change is in demand for roads, and how large the impacts are on others.

10.1 Measuring the impacts of induced traffic



Data source: The CIE.

The level of induced response to CAVs has been estimated through using the 'elasticity of demand'. This measures how much the quantity of travel demanded changes for a given change in the transport cost (measured in chapter 7). The transport cost is the total transport cost. Various estimates of the elasticity of demand are available, which have been summarised in published and confidential papers, and used as part of business case processes.

- Wardman (2012) estimates a long run car time elasticity of -0.26 based on a meta-analysis of 69 UK studies[110]
- BITRE has a transport elasticities database. This indicates long run elasticities for car traffic of -0.22 to -0.31, as well as other less applicable values related to specific aspects of cost[111].

Based on this, we allow for an elasticity with respect to generalised cost of -0.3.[112] That is, if the generalised cost of transport falls by 10 per cent, there is a 3 per cent increase in the amount of road travel for private cars, business cars and light commercial vehicles.

For freight, the literature appears to be more mixed. Some of the BITRE road freight elasticities are quite high.[113] These tend to be for inter-state freight, where rail is a viable

110 Mark Wardman (2012). Review and meta-analysis of U.K. time elasticities of travel demand. , 39(3), 465–490. doi:10.1007/s11116-011-9369-2.

111 https://www.bitre.gov.au/databases/tedb

112 This value approximates these two sources and is consistent with other confidential sources that are used in business cases for road projects.

113 https://www.bitre.gov.au/databases/tedb

alternative. In comparison, for business cases for major projects, it has typically been assumed that the road freight elasticity is zero. We have applied an elasticity of -0.1.

Valuing the benefits and costs of induced demand

To measure the benefits of induced demand, we have taken the average cost saving for CAVs (from chapter 7) in a particular segment (e.g. private cars in capital cities) and used the rule of half to estimate the value of the new trips. That is, if the benefit was 50 cents per vehicle km for a CAV, then the benefit for new users is 25 cents per additional vehicle kilometre.

This approach is somewhat conservative, as for some induced demand, a car was not the alternative mode. For example, if a person currently used community transport, public transport or on-demand transport because they could not drive, then a CAV would offer a very large improvement compared to the options currently available to them.

To measure the costs of induced demand, the same approach is followed as for chapter 7, with the additional vehicle kilometres generating congestion costs for other road users.

Summary of impacts of induced demand

The benefits for new traffic are estimated at $75 billion from 2020 to 2070. This covers people who have changed mode, are taking trips they would not otherwise have taken or are travelling further. This does not account for a range of smaller impacts that may occur such as health externalities related to active transport or public transport.[114]

On the negative side, induced traffic is expected to raise congestion costs on the road network. This leads to substantial costs of $248 billion, as more traffic reduces speeds and generates increased fuel use and air pollution.

Impacts of reduced active transport

Induced demand for CAVs reflects substitution away from other modes of transport. For shorter trips, this likely would include some substitution away from walking and cycling. A range of studies have examined whether active transport users are likely to substitute to CAVs.

- Booth et al (2019) surveyed Australians of driving age and found that substantial minorities of respondents indicated they would be likely to use CAVs instead of walking, cycling and/or public transport.[115]

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114 Technically these are known as resource cost corrections.

115 Booth, L., Norman, R., and Pettigrew, S., 2019, 'The potential implications of autonomous vehicles for active transport', *Journal of Transport & Health*, 15:100623, available at: https://www.sciencedirect.com/science/article/abs/pii/S2214140519302178

- Pettigrew (2021) also interviewed Australian and some European/US stakeholders including government and CAV manufacturing company staff.[116] This study found that the most likely scenario was that CAVs would result in more urban sprawl and less walking, while a less likely but more beneficial scenario was that people relinquish private vehicle ownership for a combination of walking, public transport and on-demand transport.
- Although it was focussed on Level 3 CAVs, Lehtonen et al (2021)[117] collected survey data from current car users about their expected use of public transport and active travel once L3 automation is available. Most didn't foresee changes in their active transport behaviour (67 per cent) or public transport use (62 per cent). However, a higher intention to use CAVs was associated with an expected decrease in public transport, and to a lesser extent, active transport.

Estimating the fall in active transport

We estimate the fall in active transport (walking and cycling) as a result of induced demand due to CAVs. This is based on the product of three variables:

- the number of induced vehicle kilometres[118] as a result of CAVs, discussed earlier in this chapter,
- the share of induced trips that reflect substitution from other modes, as opposed to additional kilometres travelled (whether longer trips or additional trips), and
- the share of substitution from other modes that is from walking and cycling respectively (as opposed to, say, train or bus).

The result of this multiplication is the reduction in active transport kilometres from walking and cycling.

Note that we assume there is no active transport for long distance travel, and only estimate changes in active transport for capital city and regional travel.

The share of induced trips that reflect substitution from other modes is unknown, and making an assumption for this share is highly speculative. We have sought to calibrate the share for capital cities and regional areas separately to arrive at plausible estimates of the reduction in walking kilometres. The calibrated share of kilometres that reflect

116 Pettigrew, S., 2021, 'The potential effects of autonomous vehicles on walking', *Global Health Promotion*, Jun 23, available at: https://pubmed.ncbi.nlm.nih.gov/34159871/

117 Lehtonen, E., Innamaa, S., Nordhoff, S., and Malin, F., 2021, 'Are multimodal travellers going to abandon sustainable travel for L3 automated vehicles?', *Transportation Research Interdisciplinary Perspectives*, 10 (August), available at: https://www.researchgate.net/publication/351428327_Are_multimodal_travellers_going_to_abandon_sustainable_travel_for_L3_automated_vehicles

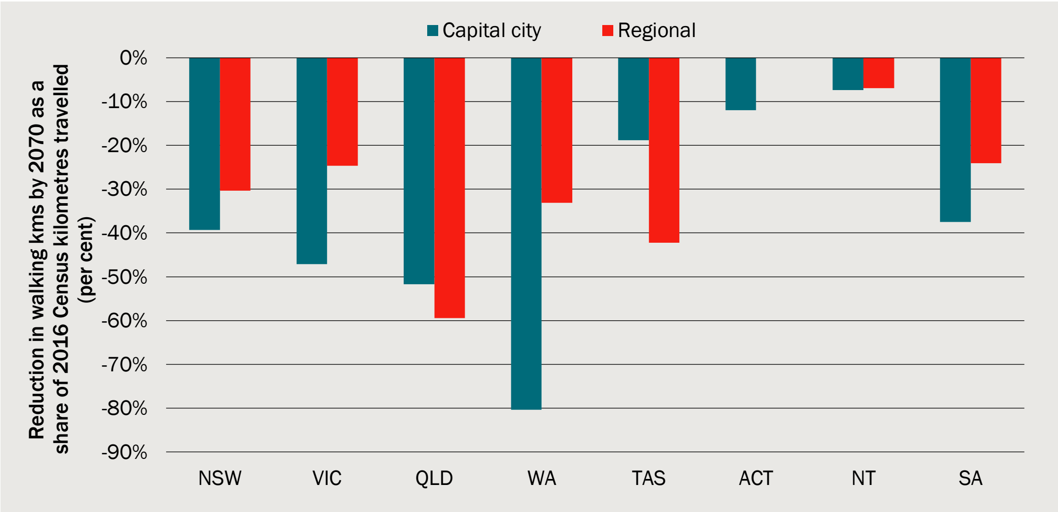
118 Note that because this calculation uses vehicle kilometres rather than passenger kilometres, we assume that each induced vehicle kilometre that was substitution from walking/cycling resulted in one lost trip kilometre from those modes. That is, one kilometre less of walking/cycling results in one more vehicle kilometre of driving. This would be consistent with substitution from active transport to CAVs being from solo trips, such as commuting.

substitution rather than additional travel is 10 per cent for both capital cities and regional travel. The rationale for this level is discussed below.

The share of substitution that is from walking and cycling is estimated based on the share of walking and cycling trips as a proportion of non-car trips in the ABS Census Journey to Work data.[119] This share is estimated separately for capital cities and other travel, but not estimated separately for each state and territory due to a lack of reliability at this level of disaggregation.[120]

Applying the 10 per cent share of kilometres that are substitution from other modes yields significant reductions in walking kilometres. By 2070, walking kilometres would reduce by as much as 80 per cent in Perth relative to the 2016 level[121] (chart 10.2). This shows that using a higher share (such as 20 per cent) would result in a reduction in walking kilometres by more than the current level of walking, which is not plausible.

10.2 Reduction in walking by 2070 as a share of 2016 walking kilometres



Data source: ABS Census Journey to Work data, the CIE.

119 This data is published by the ABS and has been accessed through the Census Tablebuilder platform. A discussion of this dataset is available here: https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/2071.0.55.001~2016~Main%20Features~Feature%20Article:%20Journey%20to%20Work%20in%20Australia~40

120 Estimated values for individual states and territories are volatile, partially reflecting some non-zero active transport mode share for very long commutes (e.g. greater than 250 kilometres), which is not plausible. This may reflect where Census respondents indicate they walked to work on Census day, but they are temporarily living at/near the worksite rather than their usual residence which is far away. For example, a Fly-In-Fly-Out worker staying at the Super Pit mine near Kalgoorlie, but who usually resides in Perth, may have walked to work on Census day, but the calculated kilometres for their commute may be based on their place of usual residence (Perth).

121 While walking kilometres would likely have increased by this point, we expect that this is a reasonable cross-check given the level of precision required for this calibration.

Valuing the cost of reduced active transport

The private costs and benefits of active transport relative to CAVs would be captured through the approach above, applying the rule of half. This will include private benefits from active transport such as reduced mortality and morbidity associated with active transport.

However, the external benefits and costs from active transport will not be captured through the rule of half approach. ATAP identifies three externalities from active transport (table 10.3). The only one that is relevant to CAV substitution and not accounted for above is health system costs, therefore, the focus is on this externality.

10.3 Externalities associated with substitution away from active transport

Externality from active transport	Relevant to substitution from active transport to CAVs?
"Reduced health system costs because active individuals are less prone to illness and place less demand on health system resources"	Yes, CAV use instead of active transport is likely to increase health system costs
"Sometimes reduced crash costs if cyclists and pedestrians are diverted from the road environment"	No, relevant to projects that shift active transport to safer (non-road) environments rather than increases or decreases in active transport
"Reduced congestion costs if an active travel initiative causes a modal shift away from motor vehicles towards walking and cycling. Social benefits associated with new active travel are not subject to the rule of the half."	Yes, but re-congestion costs of induced demand already measured separately, as noted above.

Source: Extracted from ATAP Mode Specific Guidance – M4 Active Travel, 5. Estimation of Benefits, available at: https://www.atap.gov.au/mode-specific-guidance/active-travel/5-estimation-of-benefits, the CIE.

Based on escalation of ATAP parameter values to 2020,[122] the health system benefits of active travel are:

- $1.09 per kilometre for walking, and
- $0.54 per kilometre for cycling.

It is worth noting that ATAP calculates these parameter values by estimating the share of current health costs by the number of currently inactive people. However, health costs today would be caused by inactivity today and in the past, hence this level may be higher or lower than the true long term cost of inactivity. Of more importance is that the timing of health costs may be much later than the timing of inactivity. For the purposes of this study, costs are aligned to the timing of when reduced activity occurs for simplicity.

The estimated additional costs to the health system as a result of less active transport are $6.8 billion over 2020 to 2070 under the central case estimates.

122 ATAP Mode Specific Guidance – M4 Active Travel, 5. Estimation of Benefits, available at: https://www.atap.gov.au/mode-specific-guidance/active-travel/5-estimation-of-benefits. We have escalated to 2020 dollars based on the Total Health Price Index published by AIHW.

New business models

There have been significant and ongoing shift in the way passenger and freight road transport is offered to end users and businesses over time. Two key trends are driving new business models over the last few years which have the potential to drive the uptake of CAVs:

1 Rideshare: as part of a wider Mobility as a Service offering. The long term vision is driverless rideshare or "robo-taxis", removing the need for a driver.

2 Automated freight: besides the obvious advantage of CAVs for long haul, traditional freight brokers have shifted to web based brokering, fuelling freight consolidation. This consolidation is favourable for driverless small package deliveries in relatively limited ODDs. This is driving the development of smaller driverless delivery vehicles.

Other business models will evolve over time as the potential for automation increases and in particular the potential to decrease costs.

Potential vehicle cost savings from subscription models for cars and light commercial vehicles

There is insufficient evidence about the expected uptake of subscription models for CAVs to estimate the benefits and costs of such business models. Further, subscription models will have a range of benefits and costs, such as changes to convenience, changes to parking requirements at homes, waiting time for shared vehicles to arrive, and more. Hence, we have not sought to comprehensively model the impacts of sharing of vehicles.

However, to illustrate the potential vehicle cost savings that would arise, if annual CAV purchases could be reduced by 20 per cent due to subscription models (achieving the same number of CAV vehicle kilometres), this would provide a significant saving of $282 billion over 2020 to 2070.[123] This shows there are significant potential savings, but their magnitude will completely depend on the reduction in annual vehicle purchases that can be achieved by subscription models, which is unknown.

Expected improvements in freight utilisation

There is scope for increased utilisation of freight vehicles. In Australia, the standard hours for solo drivers are a maximum of 144 hours of work time over 14 days (less than 11 hours per day).[124] If this were increased, then a smaller vehicle fleet may be required to meet the same freight task. McKinsey analysed the impact of CAVs on utilisation of freight vehicles and state that by increasing driving hours from 11 hours per day to 20, freight could be moved faster and more flexibly. They find that even with an increase in vehicle kilometres as a result of CAVs inducing demand, the truck fleet may shrink by 20

123 This assumes the cost of new vehicles is $40 128 for private and business cars, and $50 523 for light commercial vehicles (based on the Australian average new car and utility vehicle costs from https://www.canstarblue.com.au/vehicles/average-car-price/, accessed on 4 November 2021), plus a cost of $20 000 for level 4/5 CAV capabilities.

124 https://www.nhvr.gov.au/safety-accreditation-compliance/fatigue-management/work-and-rest-requirements/standard-hours

per cent.[125] However, they expect that annual sales are likely to remain steady as more highly utilised vehicles are replaced more frequently. This essentially reflects a view that a vehicle has a limited number of kilometres it can do, and a CAV will reach its estimated kms in a shorter number of years because it is driving more intensively.

Other evidence is less supportive of the view that a vehicle has a limited number of kilometres. Transport for NSW (TfNSW) suggests that both the age and the use of a vehicle are important. To give an idea of relative importance, TfNSW considers that 15-30 per cent of depreciation is use-based, 70-85 per cent being time-based.[126] Use-based depreciation aligns to a view that a vehicle can do a limited number of kilometres, while time-based depreciation aligns to a view that a vehicle can be in service for a particular number of years. If CAVs can do more kilometres in total, because they are operating more intensely over a shorter period, then a 20 per cent reduction in fleet size would result in a 14-17 per cent fall in vehicle purchases based on the TfNSW figures.[127]

We have assumed that there would be no reduction in annual vehicle purchases as a result of changes to freight utilisation, consistent with McKinsey's findings for the central case estimates.

However, if annual vehicle purchases could be reduced by 17 per cent for each heavy vehicle which is a CAV, this would imply a saving in vehicle costs of $21.3 billion between 2020 to 2070.[128]

125 https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/distraction-or-disruption-autonomous-trucks-gain-ground-in-us-logistics

126 Transport for NSW, 2020, *Technical note on the calculation of vehicle operating costs*, p.8, available at: https://www.transport.nsw.gov.au/system/files/media/documents/2020/09062020%20-%20TfNSW%20Technical%20Note%20-%20VOC%20v1.0.pdf

127 14 per cent is 20 per cent multiplied by 70 per cent being time based. 17 per cent is 20 per cent multiplied by 85 per cent being time based.

128 This assumes the cost of a heavy vehicle is $162 432 (the weighted average heavy vehicle cost from the National Transport Commission cost model, available here: https://www.ntc.gov.au/sites/default/files/assets/files/Updated%20NTC%20operator%20cost%20model%20-%202020.xlsx), plus the cost of making it a Level 4/5 CAV ($24 000 as assumed elsewhere in this analysis).

11 Summary of expected benefits and costs

The eventual impacts from CAVs are estimated to be very large, with a net positive impact of $1.4 trillion from now until 2070 under central case assumptions (table 11.1). From 2020 to 2070:

- reduced crash costs are expected to be worth $152 billion, with more than 8000 lives saved
- reduced transport time costs for private car users as they no longer need to perform the driving task are valued at $583 billion
- reduced business time costs are more than $250 billion
- reduced commercial vehicle (including light commercial) and bus time costs are more than $700 billion
- reduced fuel use amounts to $54 billion, and a further $10 billion from the value of avoided GHG emissions.

Transport capacity impacts are also very large. Increased road capacity because CAVs can travel closer together has a benefit of $321 billion over the 50-year period. However, additional transport demand offsets a large part of this, with a cost of $248 billion. There are also some small negative impacts from reduced active transport use as some people switch to using cars.

There are also benefits because of new usage of the road network. These are conservatively valued at $75 billion. This could be substantially higher, particularly for groups with high levels of transport disadvantage.

The large benefits also require substantial costs, primarily for the CAVs themselves. Costs under the base case uptake scenario are $473 billion. A further $10-$20 billion is expected in communications infrastructure costs and $2.4 billion in pavement marking maintenance.

The benefits are expected to occur towards the back-end of the 50 year period considered. By 2050, the net impacts are $13 billion. From 2051 to 2070, the net impacts are $1.4 trillion.

11.1 Summary of impacts of CAVs

Item	2020 to 2070	To 2030	2031 to 2050	2051 to 2070
	$b	$b	$b	$b
Avoided crash costs				
reduced fatal crash costs	43.2	0.0	4.5	38.7
reduced other crash costs	108.6	0.0	10.9	97.7

Item	2020 to 2070	To 2030	2031 to 2050	2051 to 2070
	$b	$b	$b	$b
Transport benefits, CAV users				
reduced private vehicle time cost	583.2	0.0	47.5	535.7
reduced business time cost	251.7	0.0	19.0	232.7
reduced commercial vehicle and bus time cost	710.1	0.1	59.5	650.5
reduced fuel use	54.0	0.0	6.3	47.7
Transport system capacity benefits, current demand				
reduced congestion costs	320.5	-0.1	-55.0	375.6
Other benefits and costs				
changes in GHG emissions	9.8	0.0	1.1	8.6
Vehicle cost savings from sharing/freight utilisation	0.0	0.0	0.0	0.0
Impacts of additional road demand				
benefits to new users	74.8	0.0	1.7	73.1
additional congestion costs	-248.4	0.0	-5.2	-243.2
lost active transport benefits	-6.8	0.0	-0.4	-6.4
Costs of enabling CAVs				
additional vehicle costs	-473.0	-0.2	-62.8	-409.9
additional transport infrastructure costs	-2.4	0.0	-0.3	-2.0
additional communications costs	-13.5	-0.1	-13.5	0.0
Combined benefits and costs of CAVs	**1412.0**	**-0.2**	**13.4**	**1398.8**

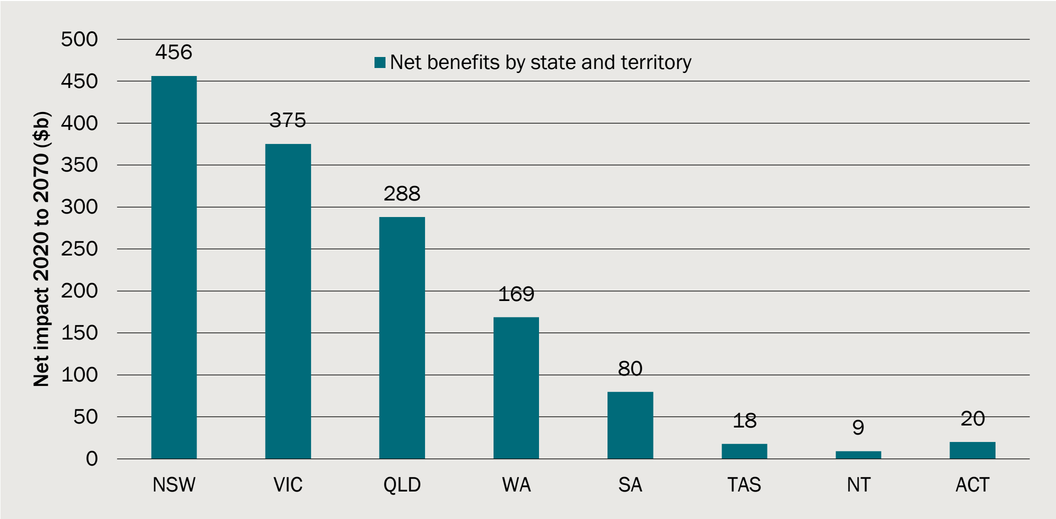
Note: In 2020 dollars.

Source: The CIE and WSP.

Benefits across states and territories

The largest net benefit accrues to the largest states. This is because these states have more vehicle kilometres impacted, and because avoided congestion benefits are relatively higher in more populous states (chart 11.2).

11.2 Benefits and costs by state and territory

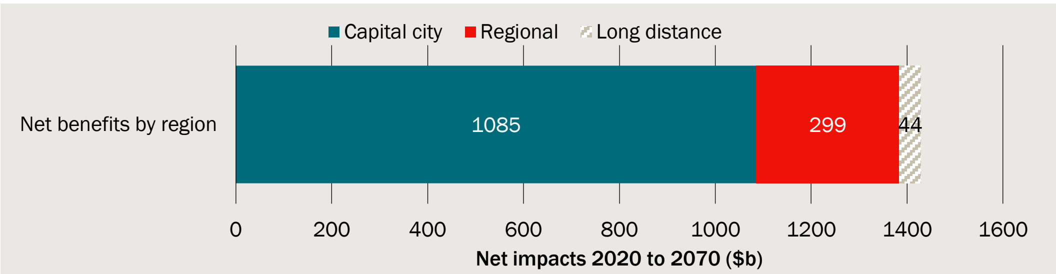


Note: Measured from 2020 to 2070. The road infrastructure costs are not allocated to state and territories, so the sum of the state and territories does not equal the Australia impact.
Data source: The CIE and WSP.

Benefits across metropolitan and regional

The net benefits accrue most strongly to capital city travel, with $1085 billion of net benefit, followed by $299 billion for regional and $44 billion for long distance inter-state freight. This assumes that there is the same take up across areas. If inter-state freight can achieve earlier take up on key freight routes, then this would increase the share of benefits related to long distance travel.

11.3 Net benefits by region

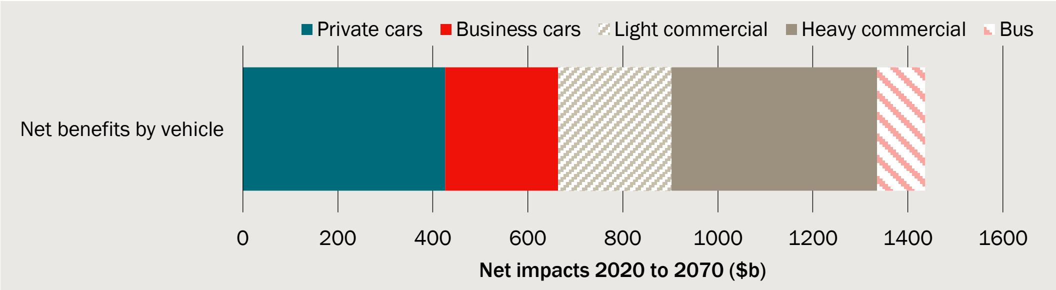


Note: Measured from 2020 to 2070. Individual totals do not include communications costs of road infrastructure costs.
Data source: The CIE and WSP.

Benefits across different vehicle types

The benefits accrue particularly strongly for private cars and heavy commercial. The first has large benefits because it is the dominant share of road traffic. The second has benefits well in excess of its share of road traffic because heavy commercial is able to achieve travel with no driver (similarly with bus).

11.4 Net benefits by vehicle type

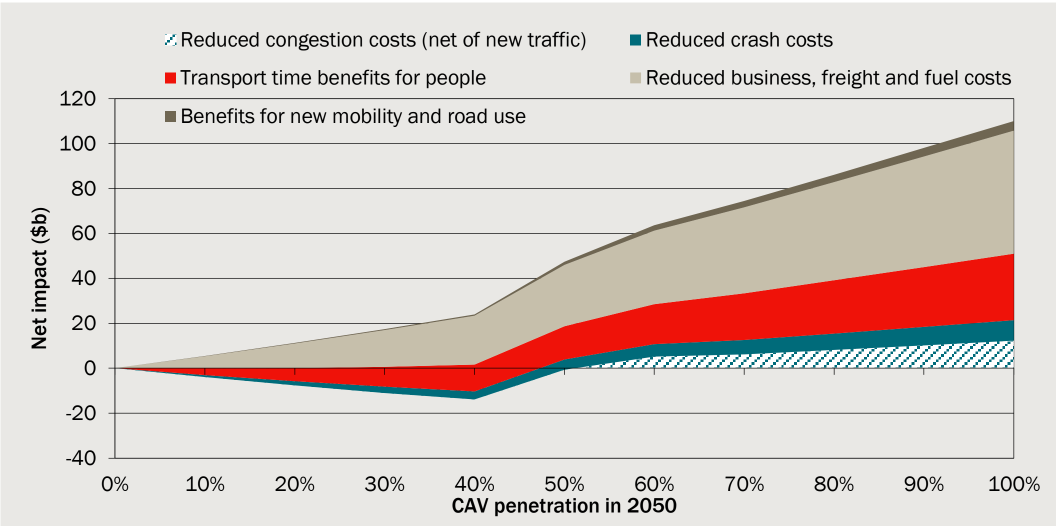


Note: Measured from 2020 to 2070. Individual totals do not include communications or road infrastructure costs.
Data source: The CIE and WSP.

Benefits and costs at different levels of CAV penetration

To highlight the impacts of different levels of CAV penetration, in chart 11.5 we show benefits in a single year (2050) with different levels of CAV penetration. This does not include costs, such as the costs of buying vehicles and putting in communications networks. This is because the costs in one year, such as the cost of buying a CAV, are related to benefits across multiple years — i.e. all the years the CAV is then operated. Initially, there are negative congestion cost impacts. However, these are more than outweighed by other benefits. By the time penetration gets above 50 per cent, benefits are ~$40 billion per year, and capacity impacts begin to be positive as well. At 100 per cent penetration, benefits are over $100 billion per year.

11.5 Benefits with different levels of penetration 2050



Note: Measured at 2050.
Data source: The CIE and WSP.

12 *Sensitivity analysis for impacts of CAVs*

There are very large uncertainties about the impacts of CAVs. To highlight some of the key uncertainties, we have constructed two scenarios:

- a scenario linked to the BITRE's scenario where society embraces CAVs, which has more rapid uptake, lower costs and higher benefits
- a scenario linked to the BITRE's scenario where there are barriers to broad adoption, costs are high per vehicle ($50 000) and benefits are at the low end of expectations.

A summary of impacts is shown in table 12.1.

Under the low scenario, the uptake levels remain at a level where capacity effects are never positive. While there are some reductions in transport costs and improvements in safety, these are also much more modest. Vehicle costs are almost the same as the central case, even with lower uptake, because of much higher per vehicle costs. At costs of $50 000 per vehicle for light vehicles, only a small share of people would take up. And overall, the costs outweigh the benefits. Note that this partly reflects that benefits are valued using averages, such as an average value of time and average vehicle kilometres driven — in practice for this scenario, it will be people with a very high value of time who would take up CAVs, or people who have a high amount of driving or people who uptake through models such as shared use.

Under the high scenario, take up occurs much more rapidly, driving higher benefits. Overall, CAVs are about three times as impactful in terms of their net positive impacts than under the central case.

12.1 Impacts of CAVs under alternative scenarios, 2020 to 2070

Item	Central case	Low case	High case
	$b	$b	$b
Avoided crash costs			
reduced fatal crash costs	43.2	9.0	104.3
reduced other crash costs	108.6	22.6	261.4
Transport benefits, CAV users			
reduced private vehicle time cost	583.2	125.2	1109.2
reduced business time cost	251.7	80.1	736.3
reduced commercial vehicle and bus time cost	710.1	167.4	1278.9
reduced fuel use	54.0	10.8	123.3
Transport system capacity benefits, current demand			
reduced congestion costs	320.5	-266.5	737.4

Item	Central case	Low case	High case
Other benefits and costs			
changes in GHG emissions	9.8	2.0	22.4
vehicle cost savings from sharing/freight utilisation	0.0	0.0	37.4
Impacts of additional road demand			
benefits to new users	74.8	3.3	192.9
additional congestion costs	-248.4	2.1	-502.8
lost active transport benefits	-6.8	-0.7	-14.5
Costs of enabling CAVs			
additional vehicle costs	-473.0	-443.3	-642.1
additional transport infrastructure costs	-2.4	-0.9	-4.3
additional communications costs	-13.5	-15.9	-11.1
Combined benefits and costs of CAVs	**1412.0**	**-304.8**	**3428.5**

Note: In 2020 dollars.

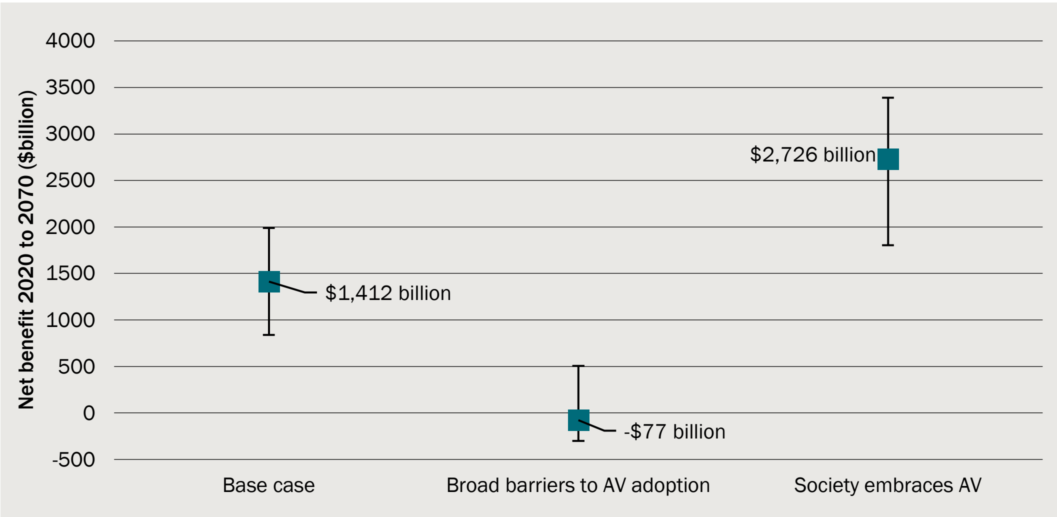
Source: The CIE and WSP.

The uptake scenarios and the vehicle costs are a critical component of overall impacts. In chart 12.2 we show the range of results from varying benefits within each scenario. The base case scenario is linked to medium vehicle costs, Broad barriers to AV option scenario is linked to high vehicle costs and Society embraces AV to low vehicle costs.

- For scenarios with low to medium vehicle costs and reasonable uptake, net benefits are always very large
- If vehicle costs are high and uptake low, net benefits could be high if the optimistic end of assumptions about CAV impacts occurs or could be negative otherwise (i.e. result in a net cost).

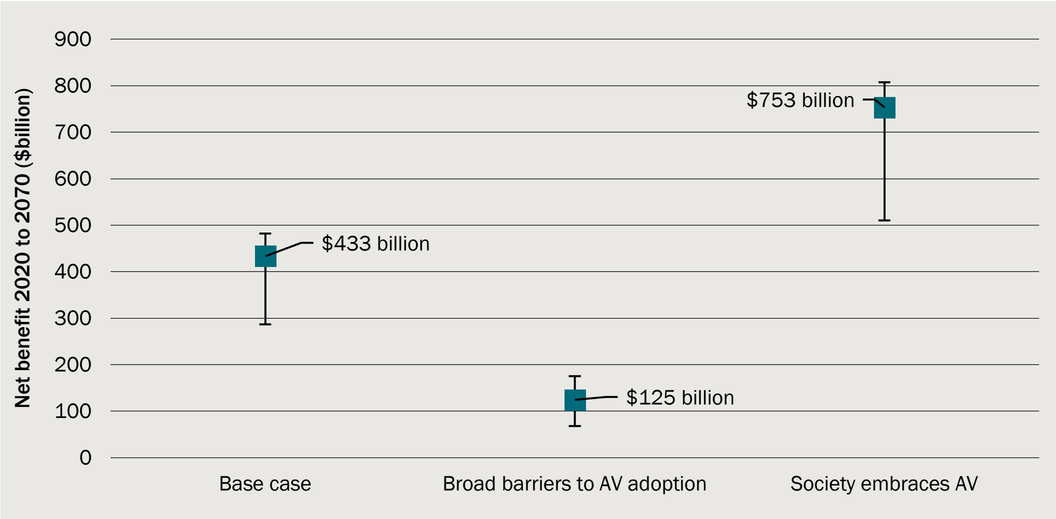
If heavy commercial vehicles are considered separately (chart 12.3), the pattern across scenarios is similar, but with no set of assumptions yielding a net cost. This suggests that the positive returns from CAV features for heavy vehicles are more certain.

12.2 Net benefit under different uptake and benefit assumptions



Data source: The CIE and WSP.

12.3 Net benefit for heavy commercial vehicles under different assumptions



Data source: The CIE and WSP.

13 How impacts will flow through the economy and society

The impacts from CAVs will have broader impacts on the economy and society. Some of these are positive and some are negative. We have not undertaken a full economic modelling exercise to map out the CAV scenarios to their overall economic impacts, but below show the types of changes that are likely to occur, and the implications of this.

Job impacts from CAVs

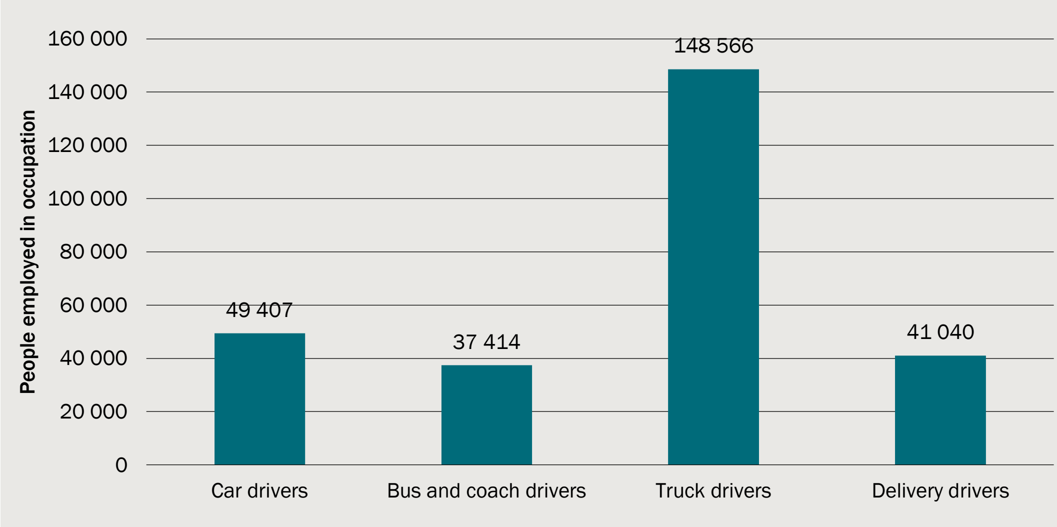
Productivity improvements — achieving the same output with fewer inputs — can directly reduce the need for jobs in a particular sector. In the case of CAVs, there will undoubtedly be less need for truck drivers, bus drivers, taxi drivers and other on-demand transport drivers if vehicles are connected and automated. Past productivity improvements have reduced the need for many jobs, and these jobs no longer exist. However, the overall level of unemployment has not changed.

While the evidence suggests that productivity growth does not impact on long term unemployment[129], where transition is rapid then there can be short term impacts on structural unemployment due to a misalignment of skills and demand.

The level of employment in 'driving' is very high. Based on the ABS census in 2016, there were almost 150 000 people employed as truck drivers, almost 50 000 as car drivers, 37 000 as bus drivers and 41 000 as delivery drivers (chart 13.1). This has almost certainly increased significantly since 2016 with the introduction and expansion of on-demand transport (outside of taxis) and increased use of delivery services.

129 See for example Productivity Commission 2020, Productivity Insights: Australia's long term productivity experience, No. 3/2020, https://www.pc.gov.au/research/ongoing/productivity-insights/long-term/productivity-insights-2020-long-term.pdf, Figure 2.

13.1 People employed as vehicle drivers



Note: Car drivers includes road and rail drivers not further defined.
Data source: ABS Census Table Builder.

In 2018 the ABS released an experimental account for the transport sector as a whole for the 2015/16 financial year, of which road transport is one part. This suggested more than one million jobs in transport, and that road transport accounted for about half the output of the total transport sector.[130] Not all these jobs relate to driving. However, this suggests there could be more jobs impacted than based on the ABS Census estimates.

A rapid transition to driverless freight or driverless taxis would lead to these people needing to retrain and find new jobs. The highest qualification level of drivers, particularly truck drivers, tends to be completed school to year 10 or year 12, and certificate III and IV. Car drivers tend to have higher level qualifications — most likely because driving has offered an easy entry into the labour market for many migrants.

The central case scenario for uptake has a very slow adjustment towards CAVs. Under this sort of scenario, transition to new jobs would likely happen relatively slowly, minimising transitional issues. Even under more rapid uptake assumptions in the BITRE 'Society embraces CAVs' scenario, uptake is still relatively gradual.

There are also positive job dimensions related to CAVs, particularly in terms of how CAVs improve accessibility to the labour market. There is substantial academic and policy literature looking at the impacts of accessibility on labour market outcomes that suggests improved accessibility is associated with improved outcomes.

Matas, Raymond and Roig (2010) examined the impact of accessibility to employment on female workforce participation in Barcelona and Madrid. In their model, variables controlled for factors such as education level, personal characteristics and residential segregation. Matas et al (2010) conducted a simulation where women had greater

130 ABS 2018, 5720.0 Australian Transport Economic Account: An Experimental Transport Satellite Account, Table 11 and Table 2.

accessibility and found that the female employment rate would increase for all women, and increase most for less educated women (11-19 per cent).[131]

Similarly, a study by the Productivity Commission in 2010 found that family location in relation to transport options may limit work opportunities for women by constraining access to alternative caring arrangements for children.[132] The study found that policies on transport can influence the opportunity cost of working through their effect on commuting time and/or the ability to telecommute to work.

Matas et al (2010) also found that when commuting costs are too high, especially in relation to the offered wage, workers tend to refuse job opportunities. Moreover, the efficiency in looking for jobs declines as distance to the employment opportunities increases. This was particularly prominent for disadvantaged groups with a greater concentration of unskilled workers. These workers tend to rely more on informal methods of search and are also averse to incurring increasing transport costs and distance increases. Therefore, according to Matas et al (2010), search efficiency declines with distance but at different rates according to worker qualification.[133]

Many of the studies of accessibility have difficulty in addressing causality. A recent US study used redundancies as a random event to consider how rapidly redundant workers found new jobs, and new jobs at a similar wage rate.[134] Because the events were random, this addresses the issue of causality. This study found that improved job accessibility led to less time required before finding a new job and less time for finding a new job without large reductions in income.

The uptake of CAVs would increase accessibility of people to jobs, because the costs of road transport would be lower. As such, it could be expected to have some long term positive impacts on labour force participation and unemployment. However, the major factor driving labour force participation and unemployment would be expected to be people's education and skill levels.

Economy-wide impacts of improved freight productivity

When CAVs reach significant levels of penetration then they will materially reduce the costs of road freight. Sectors that use road freight, which is most sectors of the economy, would then have a reduced cost of one of their inputs into production. This in turn would at least to some extent be passed through in reduced prices charged for their outputs.

131 Matas A, Raymond J-L, Roig J-L 2010, *Job Accessibility and Female Employment Probability: The Cases of Barcelona and Madrid,* Urban Studies, vol. 47, no. 4, pp. 769-787, April 2010

132 Gilfillan G and Andrews L 2010, *Labour Force Participation of Women Over 45,* Productivity Commission Staff Working Paper, Canberra

133 Matas et al (2010), *Job Accessibility and Female Employment Probability: The Cases of Barcelona and Madrid,* Urban Studies, vol. 47, no. 4, pp. 769-787, April 2010

134 Andersson, Fredrik, John Haltiwanger, Mark Kutzbach, Henry Pollakowski, and Daniel Weinberg. 2011. "Job Displacement and the Duration of Joblessness: The Role of Spatial Mismatch." Working paper.

We have used the CIE Regions Computable General Equilibrium model to consider the pattern of impacts of road freight cost changes across Australia and across states and territories (see Appendix A) that could result from CAVs. This has been done for a 30 per cent increase in road freight productivity, which is based on the current labour share of road freight costs being 30 per cent, and this being able to be removed through CAVs. That is, without needing drivers for all road freight, costs could be reduced by 30 per cent. This is equivalent to the expected impacts if all freight moves to being driverless, although there would also be some other cost reductions (fuel) and cost increases (vehicles). The analysis is based on current industry structure (rather than projecting changes to this into the future).

Consumer prices would initially fall if reduced freight costs are passed on to consumers

One potential implication of reduced freight costs is reduced consumer prices, at least in the short term. Under the model, for a 30 per cent reduction in road freight costs, consumer prices fall by 1.5 per cent. In the more dispersed states, such as the Northern Territory and WA, the reduction in consumer prices is expected to be somewhat larger.

13.2 Impact of a 30 per cent reduction in road freight costs on consumer prices

Area	All sectors
	Per cent
National	-1.5
NSW	-1.3
VIC	-1.3
Qld	-1.6
SA	-1.6
WA	-2.0
TAS	-1.8
NT	-2.5
ACT	-1.6

Source: The CIE.

In the longer term, productivity gains in the road freight sector could feed into higher real wages (under the model, 1.7 per cent for a 30 per cent freight cost reduction), which would then offset some of the direct price reduction impacts. That is, real labour costs would increase, while real freight costs would decrease.

For producers, reductions in road freight costs also have benefits. A producer selling into an international market would likely be able to obtain a higher factory, farm or mine gate price, if road freight costs are lower. For example, suppose the global price of a commodity is $100 per tonne delivered. The price that the exporter receives will be $100 less all the shipping and other freight costs. Suppose shipping and transactional costs were $20 per tonne and road freight was $30 per tonne, then the exporter would expect to receive $50 per tonne. If the road freight costs fall to $25 per tonne, then the exporters price increases to $55 per tonne. This could lead to an expansion of exports, employment and higher profits for exporters.

Again, in the long term, these impacts would be expected to generate real wage growth, and employment levels would move to a long term natural level.

Across the Australian economy, the impacts of a 10 per cent freight productivity improvement is estimated as a 1.0 per cent increase in Gross Domestic Product (GDP) and 1.7 per cent increase in real wages.

Spatial changes to cities and regions

The mass take-up of automobile travel was the catalyst for spreading cities globally. Prior to this, cities were shaped around walking and public transport, leading to much more compact urban forms.

The introduction of CAVs as outlined in this report would provide a reduction in the overall cost (including the cost of time) of car transport. The effects are not of the same magnitude as the introduction of the car. However, CAVs may further encourage dispersion by reducing transport costs.

Kulish et al (2011) used the Alonso-Muth-Mills model to consider interactions between transport costs, urban structure and housing prices.[135] The Alonso-Muth-Mills model is a well-established conceptual model for considering such interactions. It is based on a monocentric city that has a single CBD that people go to for work, and assumes a fixed population and a given income level. People then trade-off living closer to the CBD versus the price and density of housing — if transport costs are lower, then this makes living further away from the CBD more preferable than would otherwise be the case.

For a scenario where the transport costs were halved, then Kulish et al (2011) showed that the overall city radius would be 50 per cent larger than would otherwise be the case. The overall cost changes from CAVs are not of that order of magnitude — and we don't know exactly how big the changes are because we have not measured costs for non-road transport or costs that are not impacted such as vehicle operating costs. Approximately, with uptake at 2070 levels, costs would be in the order of 20 per cent lower for private car transport. Roughly applying the approach in Kulish (2011), this could lead to an expansion of city size of ~10-20 per cent.

The consequences of this are that some of the transport benefits are translated into location and housing benefits. The model used by Kulish et al (2011) predicts that lower transport costs would lead to:

- lower land prices and lower housing costs
- larger dwellings, and
- less dense cities.

135 Kulish, M., A. Richards and C. Gillitzer 2011, "Urban structure and housing prices: some evidence from Australian cities", *Reserve Bank of Australia Research Discussion Paper,*https://www.rba.gov.au/publications/rdp/2011/2011-03/alonso-muth-mills-model.html .

These changes would occur because people privately obtain benefits from making these choices. Whether this is beneficial overall would depend on the extent to which there are public costs related to different urban structures. Most Australian work has found that the public costs, such as those related to infrastructure, are higher for greenfield low density housing development. For example:

- Infrastructure Victoria found that infrastructure costs are generally higher in greenfield areas than for small dispersed developments in established areas or high density developments. However, there was a wide variation in costs depending on the capacity of existing infrastructure, and even wide variation across greenfield areas[136]
- The CIE has found infrastructure costs are quite dependent on the specific area, but are generally higher for greenfield areas for Sydney. In Western Sydney development areas, infrastructure costs could be several hundred thousand dollars per person and job accommodated.[137] In comparison, developing existing areas of Western Sydney more densely had costs of ~$50 000 per person and job.[138]

This suggests that in the absence of other changes in policies, there may be pressure for additional infrastructure costs to support people's decisions to choose to live further from their place of work or from existing developed areas.

Mobility constrained groups will have large increases in accessibility

Elderly people and those with travel-restrictive medical conditions are expected to greatly benefit from increased access to travel. CAVs give the prospect of greater flexibility and improved quality of life for these groups, and recent evidence suggests there is a strong appetite for CAVs among older adults.[139] There may be a more gradual adoption process for older adults to CAVs, but early positive interactions with CAVs can support positive perceptions and acceptance.[140]

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136 Infrastructure Victoria 2019, Infrastructure provision in different development settings, https://www.infrastructurevictoria.com.au/wp-content/uploads/2019/04/Infrastructure-Provision-in-Different-Development-Settings-Metropolitan-Melbourne-Volume-1-Technical-Paper-April-2019.pdf.

137 The CIE 2020, *Western Sydney Place Based Infrastructure Compact: Economic evaluation PIC 1,* https://gsc-public-1.s3-ap-southeast-2.amazonaws.com/s3fs-public/appendix_6_-_economic_evaluation_pic1.pdf?VXsvtuGPqSpnGsqX1eb6F.depWtRp3n6.

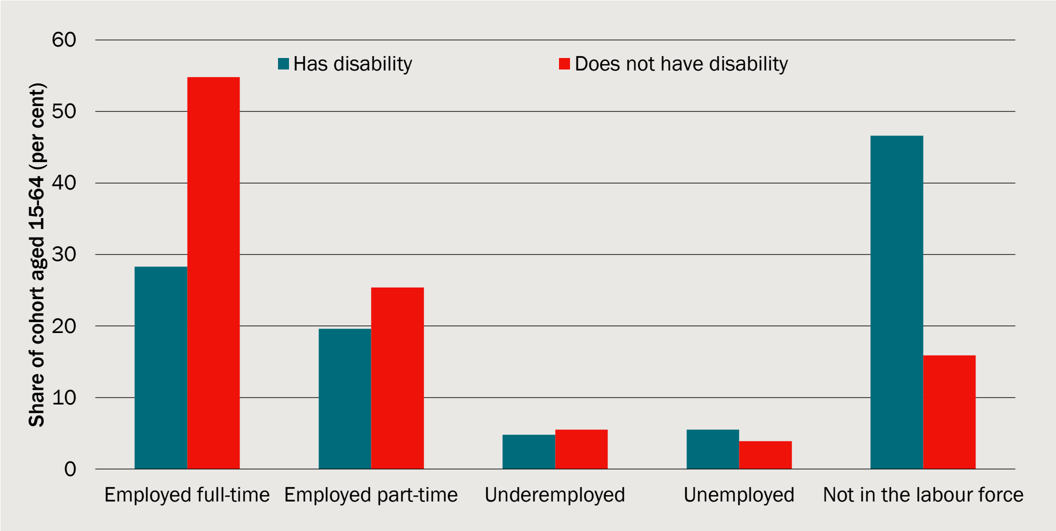
138 The CIE 2020, *Western Sydney Place Based Infrastructure Compact: Economic evaluation PIC 2,* https://gsc-public-1.s3-ap-southeast-2.amazonaws.com/s3fs-public/appendix_6_-_economic_evaluation_pic_2.pdf?YI2OKoda1ZmXFIXYZH3cXVDJurKoxcM.

139 Faber, K., van Lierop, D., 2020, 'How will older adults use automated vehicles? Assessing the role of AVs in overcoming perceived mobility barriers', *Transportation Research Part A: Policy and Practice*, Volume 133, March 2020, pp.353-363, available at: https://www.sciencedirect.com/science/article/pii/S0965856419312091

140 Classen, S., Mason, J., Wesal, J., Sisiopiku, V., and Rogers, J., 2020, 'Oldder Drivers' Exerpience with Autonomated Vehicle Technology: Interim Analysis of a Demonstration Study, *Frontiers in Sustainable Cities*, available at: https://www.frontiersin.org/articles/10.3389/frsc.2020.00027/full

There are both economic and social returns to this impact. These returns are factored in to some extent by the general measure we have for the benefits from induced road use. However, this is likely to be a very conservative estimate for specific groups that have limited ability to drive themselves now. By facilitating travel by people with disability and older adults, it may be possible to increase the size of the labour force (as discussed earlier in this chapter), since difficulty with commuting may be a barrier to working. People with a disability are almost three times as likely to not be in the labour force (chart 13.3). Increases in the participation rate (i.e. the size of the labour force as a share of the working age population) are difficult to achieve, but transportation remains a key barrier to employment for people with disabilities.

13.3 Workforce participation by disability status



Data source: CIE.

From a social perspective, CAVs can promote engagement with friends, family and in community activities.

While the magnitude of the increase in travel is uncertain, Harper et al (2016) estimates that enhanced accessibility for these groups from CAVs could increase total travel by up to 14 per cent.[141] This is somewhat higher than the expected inducement in road demand in general, which for full CAV uptake would reach ~10 per cent.

CAVs may also reduce costs for government programs to provide mobility, such as on-demand subsidies and community transport provision. For some travellers with disability to be able to use CAVs, they must be wheelchair accessible, which may necessitate government funding and somewhat mitigate other cost savings to government.

141 Harper, C.D., Hendrickson, C.T, Magones, S., Samaras, C., 2016, 'Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly and people with travel-restrictive medical conditions', *Transportation Research Part C: Emerging Technologies*, Volume 72, available at: https://www.sciencedirect.com/science/article/abs/pii/S0968090X16301590

Appendix A CIE Regions model

Reductions in freight costs act as a positive productivity shock for the road freight sector. Within this sector, the impacts of this would be:

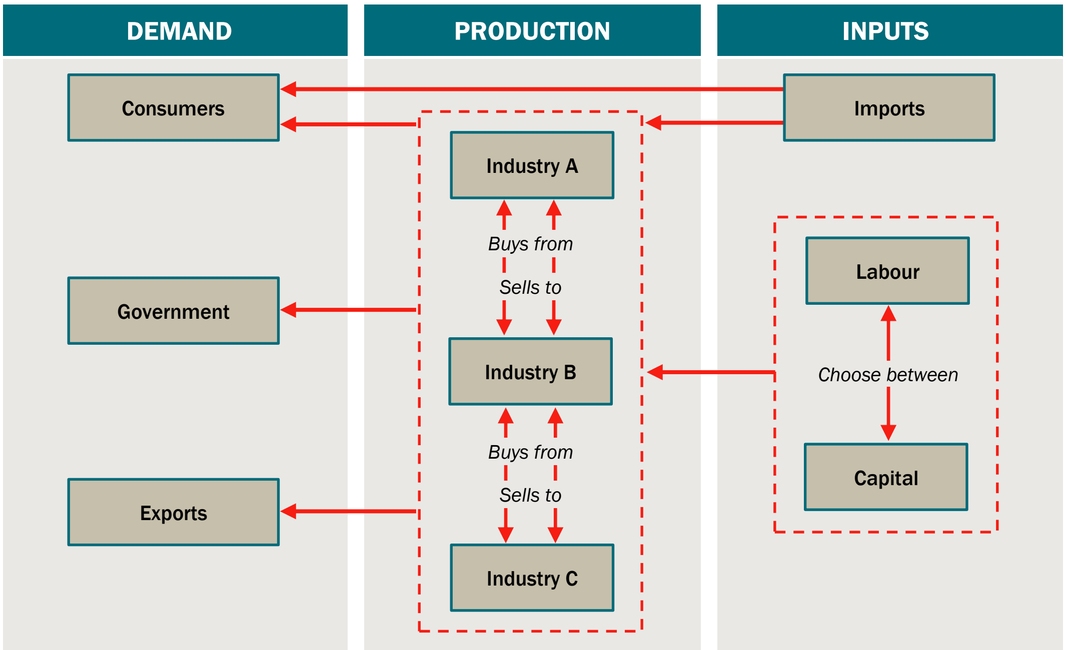
- reduced prices for road freight
- increased quantity of outputs for road freight.

The economy-wide impacts of these changes within the road freight sector will reflect the interlinkages of this sector with the rest of the Australian economy. The best way to model these interlinkages is with a computable general equilibrium (CGE) model. A CGE model provides a complete view of the overall economy, covering:

- demand from consumers, government and exports
- production and linkages between producing sectors (e.g. construction uses quarry outputs), and
- inputs (labour and capital).

A schematic of a CGE model is shown in chart 13.4.

13.4 Interactions in an economy-wide model



Data source: The CIE.

CIE-REGIONS model is a general equilibrium model of the Australian economy. It was developed by the Centre for International Economics based on the publicly available

MMRF-NRA model developed by the Centre of Policy Studies for the Productivity Commission.[142]

Some of the key aspects of this model are that it:

- uses the latest input-output table
- provides a detailed account of industry activity, investment, imports, exports, changes in prices, employment, household spending and savings and many other factors;
  - this version of the CIE-REGION model identifies 59 industries and commodities (table 13.5)
- accounts for Australia's six states and two territories as distinct regions
  - accounts for differing economic fundamentals in the states and territories
  - state and territory results can be further disaggregated down to statistical division (SD) level
- includes specific details about the budgetary revenues and expenditures of each of the eight state and territory governments and the Australian Government (the government finances in CIE-REGIONS align as closely as practicable to the ABS government finance data)
  - specifically accounts for major taxes including land taxes, payroll taxes, stamp duties and others at the state level, as well as income taxes, tariffs, excise, the GST and other taxes at the federal level
  - traces out the impact of transfers between governments
- can be run in a static or dynamic mode. The dynamic version allows analysis to trace impacts over time as the economy adjusts, being particularly useful over the medium to longer terms. For this project, the model is being used in its static mode.

13.5 CIE-REGIONS industries/commodities and margin services

Industries/commodities			
1	Livestock	31	Electricity generation – other
2	Crops	32	Electricity supply
3	Forestry	33	Gas supply
4	Fishing	34	Water supply
5	Coal	35	Construction
6	Oil	36	Wholesale trade
7	Gas	37	Retail trade
8	Iron ore	38	Mechanical repairs
9	Other metal ores	39	Accommodation and food services
10	Other mining	40	Road passenger transport

142 Productivity Commission 2006, *Potential Benefits of the National Reform Agenda*, Report to the Council of Australian Governments, available at http://www.pc.gov.au/research/commissionresearch/nationalreformagenda

Industries/commodities			
11	Food, drink and tobacco	41	Road freight transport
12	Textiles, clothing and footwear	42	Rail passenger transport
13	Wood products	43	Rail freight transport
14	Paper products	44	Pipelines
15	Printing and publishing	45	Ports
16	Petroleum products	46	Transport services
17	Chemicals	47	Water freight transport
18	Rubber and plastic products	48	Ship charter
19	Other non-metal construction materials	49	Air passenger transport
20	Cement	50	Air freight transport
21	Iron and steel	51	Communication services
22	Other metals	52	Finance
23	Metal products	53	Business services
24	Transport equipment	54	Dwellings
25	Other equipment	55	Government administration and defence
26	Other manufacturing	56	Education
27	Electricity generation – coal	57	Health
28	Electricity generation – gas	58	Other services
29	Electricity generation – oil	59	Waste management
30	Electricity generation – hydro		

Source: CIE-REGIONS database.

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