

Environmental Impacts of Connected and Automated Vehicles (CAVs) – Stage Two report: Assessment of Policy Scenarios

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Executive summary

Connected and Automated Vehicles (CAVs) will have significant environmental impacts, both positive and negative. This report, which is the second stage of the iMOVE project investigating the impacts of CAVs, looks at opportunities to encourage the positive impacts while minimising the negative impacts. It builds on the first stage of this project, an extensive literature review, which revealed the known and hypothesised impacts of CAVs. The impacts are assessed across three levels:

- **Vehicle level**, which relates to CAVs themselves;
- **Transport system level**, which relates to the overall environmental impact on transport systems; and
- **Urban system level**, which relates to the impact on the city more broadly.

The scale of environmental impact has been included, where it is known and quantified.

This report includes an assessment of the policy implications of various impacts and attempts to qualify the findings through an expert survey group consultation. The policy analysis draws on 16 factors identified from the stage one report which relate to CAVs. These factors cover the three levels discussed above, and have both positive and negative environmental impacts. Each of these factors have been linked to possible regulatory and policy tools that may encourage or mitigate some impacts depending on the policy outcomes sought.

Six scenarios were then developed to explore possible CAV use case scenarios by 2050. The scenarios include combinations of different levels of CAV uptake, regulation and shared use, ranging from entirely unregulated in production, use, and in competition with public transport, to tightly regulated through design and production, and limited to only shared use which complements public transport. Scenarios also consider the uptake of CAVs in the fleet. The outcomes of this analysis was then informed by an expert survey group's responses.

Key findings

The key findings of the report are:

- *Many environmental impacts will not be seen while CAVs are at a low penetration level.*
- *With uptake below 50%, there are not thought to be significant environmental impacts, as the fleet is not large enough to maximise benefits or externalities. This reveals the need for Government policies to be forward thinking about what type of transport and urban future is desired, and implement policy settings to support the realisation of that future.*
 - Most of the expert survey group respondents believe there will be low penetration of CAVs in the Australian motor vehicle fleet by the year 2050, up to 40%, noting connected vehicles are expected to arrive earlier than the full CAV vehicles. This means the impacts from CAVs are unlikely to be seen until after 2050 (full discussion of the results of the expert group survey is in chapter 4).
 - Proactive regulation and policy, which support a future vision, will be critical in guiding the adoption of CAVs, in a manner which ensures environmental benefits are maximised.

- *Policy and regulatory tools present the best opportunity to maximise the positive benefits of CAVs and minimise negative effects. Policymakers should consider environmental impacts when developing CAV policies.*
 - Allowing highly deregulated production and use of CAVs has the potential, if met with high uptake, to increase the energy use of motor vehicle transport, the number of trips and vehicle kilometres travelled, and undermine public and active transport.
- *At the vehicle level, the greatest positive environmental impacts can be seen in scenarios which permit eco-driving, limit speed and place design regulations or policies on vehicle manufacturers.*
- *At both the transport and urban system levels, the greatest positive environmental impacts can be seen in scenarios which ensure that CAVs operate in a way which complements, rather than competes with, public transport, while limiting private use.*
- *At the urban system level, the greatest potential for negative impacts is associated with ubiquitous and unregulated use of CAVs.*
- *The impact of some CAV factors remain unclear based on the expert survey group.*
 - This uncertainty can moderate the environmental outcome of policy scenarios. The expert survey group's rating on the CAV factors can support a further review of the identified policies and reveal more targeted solutions to maximise the benefits and avoid the negative impacts of the CAV transition in Australia.
- *Insufficient research has been undertaken to date to disaggregate the environmental impacts of CAVs from the emissions reductions offered through the increased uptake of electric vehicles.*
 - Therefore, there is uncertainty about the additionality of the environmental impact of CAVs compared with EVs.
- *Similarly, there has been insufficient research to date to disaggregate the environmental impacts of automated vehicles from vehicles with a high level of connectivity.*
 - Anecdotally, it is believed that a combination of automation and connectivity will provided the greatest environmental benefits.

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Glossary of terms

Automated Vehicle (AV) – a vehicle that is able to drive without human input or attention, at least some of the time.

Connected and Automated Vehicle (CAV) – a vehicle that is able to drive without human input or attention, at least some of the time, while also communicating with other Connected and Automated Vehicles.

Eco-driving – technologies which ensure vehicles drive in more ecologically friendly ways, consuming less energy.

Electric Vehicle – a vehicle which is powered by electricity, stored on board via a battery.

GHG – Greenhouse gases – Emissions which contribute to global warming and climate change.

Platooning – the operation of CAVs grouped closely together, through communications and coordinated movements.

Public transport (PT) – collective transport, which generally operates along a fixed route and set times, which any member of the public may use for a fare.

Shared vehicles – vehicles which may be shared by multiple members of the community, for example taxis/ride sourcing, or operated as pooled collective transport.

Urban sprawl – unplanned and often rapid expansion of urban areas into the surrounding rural land.

Vehicle kilometres travelled (VKT) – a measure of the total distance travelled by all vehicles within a specific geographic area over a certain period.

1 Introduction

The first stage of the environmental Impacts of CAVs project involved an extensive literature review, revealing the known and hypothesised impacts of CAVs. A summary of stage one is provided in chapter 2. The second stage of this project, covered by the current report, includes a number of main components.

Firstly, it undertakes a policy scenario analysis which aligns environmental impacts with potential regulatory and policy tools, and then seeks to understand how different policy combinations and CAV uptake levels may affect environmental impacts. Policy analysis is presented in chapter 3 of this report. It draws on the stage one report which identified 16 factors which relate to environmental impacts of CAVs. Each of these 16 factors are aligned with potential regulatory and policy tools. These tools are available to governments should they wish to influence the production and use of CAVs. Four policies are related to the production of vehicles and five policies are related to the ways CAVs are used. Development of these policies has been informed by the stage one report and expert survey group responses.

Six policy scenarios were then developed and analysed, each one having a set of different potential regulatory and policy settings, aligning to how the vehicles are produced and used, and the level of uptake. Alignment of policies and regulations, production and use of CAVs and levels of CAVs uptake is important as it reveals the combinations of policies which may have the greatest positive environmental impact from CAVs, and identifies key policies which may have negative environmental impacts.

Due to insufficient data, the policy analysis does not consider at the additional environmental impacts of CAVs in addition to electric vehicles, or the distinct environmental impacts between connected and automated components.

Secondly, the report presents the outcomes of an expert group survey (chapter 4) and aligns them to CAV transition and policy scenarios.

Lastly, policy implications are presented in chapter 5. They are drawn from the policy analysis and expert survey group responses. The policy implications provide guidance for what good regulatory and policy tools might look like and recommended policy objectives.

2 Stage one summary

Stage one of this project reviews existing literature to investigate how transitioning from conventional vehicles to CAVs will impact transport systems and the environment. The stage one report explores the positive and negative environmental impacts of CAVs, synthesising findings from the scholarly literature and technical reports. It includes a discussion and analysis of the environmental impacts of CAVs at vehicle level, transport system level, and urban system level, across the major CAV implementation models. The main findings of the literature review are:

Potential positive environmental impacts:

- CAVs technologies can foster more streamlined driving behaviours and enable vehicles to operate more efficiently, cooperate with other vehicles, and travel on faster guided routes. These advantages will improve vehicle fuel efficiency and reduce greenhouse gas (GHG) emissions per kilometre travelled.
- Improved vehicle connectivity technologies enable “platooning” of heavy automated vehicles, and the coordinated flow of CAVs can increase traffic efficiency, road capacity, and overall transport network performance, potentially lowering GHG emissions and energy consumption.
- CAVs will enable more on-demand trips with their advanced route planning and automation systems. Expanded car-sharing programs may reduce the need to own a car and allow multiple users to share a single vehicle, thus reducing the number of vehicles on the road and promoting more efficient use of resources.
- The reduced parking demands of CAVs may free more land resources in urban areas, which can then be repurposed for residential and commercial development. Such infill development would allow denser urban cores and increase energy-efficient occupancy.
- Studies show different trends in decreasing GHG emissions for different CAV penetration levels. While various scenarios promise reductions in emissions with increasing CAV penetration, the rate and extent of reductions vary.

Potential negative environmental impacts:

- CAVs will bring new forms of mobility that can generate additional vehicle travel on roads, such as more empty trips. These additional travel demands may offset and diminish the potential emission reductions per vehicle facilitated by new technologies.
- Efficient CAVs operation can reduce the perceived value of travel time. The reduced driving burden of CAVs and the time saved by mobility gains might then be used for additional distance and time spent on travel. Increased road capacity enabled by CAVs may also attract more vehicle travel, thus increasing transport pollution, noise, and other environmental burdens.
- Increased convenience and mobility gains could potentially shift residential choices and increase sprawl in urban areas. Increased accessibility in urban areas could also disperse land use, activity patterns, and transport patterns, generating second-order environmental impacts over the long term.

- CAVs could reduce public transport (PT) use by providing more convenient and cost-effective transport options. If more PT passengers switch to car use, total vehicle travel will increase, generating higher environmental burdens.
- CAV transportation will likely deploy, operate, and maintain substantial sensors, data processing, storage, and communication devices in transport systems, which will consume more electricity, generate higher emissions, and hinder environmental outcomes.
- Other computational demands of CAV systems, including cybersecurity technology for CAVs, could generate additional energy and environmental costs.

As seen above, Stage one found that CAVs have both positive and negative environmental effects. However, many of these environmental effects are related to broader use and policy contexts. By promoting the use of electric and low-emission car models, better traffic flow, and more intelligent routing, these technologies have the potential to lower GHG emissions and air pollution. By limiting needless accelerations and decelerations, CAVs can improve fuel efficiency and reduce carbon footprints and energy consumption. In addition, shared automated mobility services may result in fewer cars on the road, easing traffic and lowering overall emissions. On the other hand, the production and use of CAVs will demand more energy and could cause an accumulation of electronic waste which harms the environment.

Even though CAVs present new possibilities for environmentally friendly transportation, cautious planning, regulation and policy, and innovation are required to minimise potential environmental harm and optimise their benefits. Moreover, vehicle adoption patterns, such as vehicle ownership models, are anticipated to significantly impact whether CAVs will decrease or augment overall vehicle kilometres travelled (VKT) and ensuing GHG emissions. Some studies suggest that the favourable emission outcomes might not materialise at lower CAVs penetration rates, with the most significant emission reductions probably occurring within the 60–80% range of CAVs penetration. Further research is required in fields where research gaps exist, to inform policy aimed at increasing the positive impacts while reducing the expected negative impacts.

3 CAV policy context and scenarios

3.1 CAV factors and environmental impacts

Stage one of this project undertook an extensive review of the literature which revealed the known and hypothesised environmental impacts of CAVs. Chapter 3 builds on that stage to deliver a policy analysis.

A summary of key findings from stage one is shown in Table 1. These factors are grouped into three levels, which were revealed in the stage one report:

- **Vehicle level**, which relates to CAVs themselves;
- **Transport system level**, which relates to the overall environmental impact on the transport systems; and
- **Urban system level**, which relates to the city more broadly. The scale of environmental impact has been included, where it is known and quantified.

Factors which have a positive environmental impact are shaded green in Table 1, while factors with a negative environmental impact are shaded red. Where possible, an indication of the scale of environmental impact is given. All factors and impacts are drawn from the stage one report.

Vehicle level factors, shaded in grey in Table 1 relate to the CAVs themselves. These represent factors of the vehicle, such as eco-driving or maximum speeds, which mainly decrease or increase energy usage, and therefore impact the environment. The vehicle materials also have environmental impacts in several ways. Firstly, there is increased energy use, both onboard through CAV computing, but also in the broader environment as CAVs need connected networks, which use energy. There are also potentially increased particulate emissions from the extra weight of CAVs, due to batteries and computing technology. Lastly, there are input resources via manufacturing, particularly relevant for the batteries and end-of-life (e.g. recycling of the vehicles).

Transport system level factors, shaded in yellow in Table 1 relate to the broader transport system. This includes the ways in which vehicles interact with each other via CAV operation, such as route selection optimisation, and platooning and traffic harmonisation, but also the ways in which they are used. This highlights the potential for easier travel, empty running, broadening of the potential pool of motorists to include those who do not or cannot drive (due to age, ability, desire, etc), which all have negative environmental impacts. Transport system level factors also relate to how CAVs are used, with there being potentially positive impacts by operating in a more shared way and augmenting public transport, or potentially negative impacts by operating in a private way which could undermine public transport.

Urban system factors which are beyond the vehicles and the transport system, are shaded in blue in Table 1. These represent the broader impacts which may emerge across cities, due to changed urban forms and transport habits. This considers how CAVs could support more compact cities, leading to more infill development, fewer cars, and declined need for parking. Conversely, CAVs could exacerbate urban sprawl, leading to larger cities and several negative environmental impacts. Similarly, changes in urban form and changes in transport choices may have much broader impacts on travel patterns. These urban changes are linked to the ways in which CAVs are used and therefore shaped by policy. Lastly, the communications infrastructure and road maintenance themselves have a wide variety of potential impacts, again dependent on policy settings.

Table 1 CAV Factors and Environmental Impacts – summary from stage one

Factor	Environmental impact	Note
Vehicle Level		
Eco-driving	Up to 15% decrease in energy use	Contingent on uptake above 50%
Faster maximum driving speeds	Up to 40% increase in energy use	Contingent on uptake above 50%
Vehicle material	Increased energy use (computation and communication), particulate emission (brake and tyre) and increased resources (including battery disposal)	
Transport System		
Route selection optimisation	Up to 12% decrease in energy use; Likely to increase trip length and VKT	Contingent on uptake above 50%
Platooning and traffic harmonisation	Up to 15% decrease in energy use	Contingent on uptake above 50%
Easier and more attractive travel	Up to 10% increase in energy use; More road construction.	Contingent on uptake above 50%
Shared vehicles	90% decrease in energy use	
Empty VKT	Up to 10% increase in energy use	
Increased use of vehicles by those who cannot drive	Up to 5% increase in travel and energy use	
Shift from active and public transport to CAV	Up to 10% increase in energy use	
CAVs used to support public transport for last mile	Large mode shift towards CAV+PT mix	
Urban System		
Communications infrastructure, road maintenance	Large variation	Dependant on policy settings
Declining parking requirements	Facilitates infill and compact cities	Dependant on shared CAV (with no at home parking required)
Increased parking requirements	Spill over parking effects into other areas which require more parking	More likely to be linked to individual CAV (with destination parking required)
Increased urban sprawl	Increased air pollution, noise pollution, GHG emissions; greater requirement for land, infrastructure and resources.	More likely to be linked to individual CAV and low regulation of use
Travel pattern changes	More trips (including empty trips); longer trips; increased fleet size	More likely to be linked to individual CAV and low regulation of use

Note: Green shading indicates positive environmental impacts and red shading indicates negative environmental impacts.

Source: All factors shown in this table are from the Stage One Report.

Some of the factors are also contingent on the level of uptake of CAVs and how they are used. It should be noted that the literature from the stage one report is not always clear if the environmental impact is measured compared with internal combustion engine vehicles, or (non-connected and automated) EVs; this means there is some uncertainty about the additionality of the environmental impact of CAVs compared with EVs. The level of impact is also affected by factors such as vehicle uptake, policies on use, and broader urban changes.

These CAV transitions and environmental issues have also been considered by the expert survey group to gain broader opinions in the Australian context. In general, the expert survey group agrees with these transition factors identified above but retain slightly different views on specific issues and impacts. The detailed expert survey group's ratings of the CAV factors and their environmental impacts is summarised in chapter 4.

3.2 Relationship between environmental impacts and CAV uptake

Some of the environmental factors shown in Table 1 are linked to CAV uptake. Five factors, discussed below are highly sensitive to CAV uptake, with no benefits at uptakes below 25%, and full benefits for uptakes above 50%. Two factors are at the vehicle level, related to how vehicles themselves are used (eco-driving and maximum driving speed) and three are related to the transport system (route selection, platooning, and easier travel). Some of these factors have positive environmental impacts (marked in green), while others have negative environmental impacts (marked in red). Importantly, these impacts do not scale in a linear way with uptake, but rather have exponential impacts, based on uptake. With uptake below 25%, there are not thought to be any benefits, as the fleet is not large enough to be maximising benefits of connectivity. With a medium uptake of 25% to 50% these benefits begin to be seen, but in a limited way. It is only with a high uptake of over 50% that the full benefits of connectivity can be seen, such as connected eco-driving, route selection based on fleet wide information, and platooning and traffic harmonisation. However, this high level of CAV uptake also provides full effect of faster driving speeds, and easier and more attractive travel, which have negative environmental consequences. The expert survey group participants agreed on the relationships between environmental impacts and CAV uptake.

3.3 Regulation and policies, and CAV factors

The ultimate effects of CAVs will be determined by regulation and policy. Different regulatory and policy configurations will allow, or forbid, certain elements of CAV design or operation, and therefore play a role in the environmental impacts. To support the policy analysis, a set of potential regulatory and policy tools have been developed, which cover the vehicles themselves (related to technology and design) and the use of the vehicles (related to shared or individual use, and operating parameters), shown in Table 2. Each of these potential regulatory and policy tools could either allow or forbid certain factors (shown in Table 1) and therefore change the environmental impact.

At a vehicle production level, there are permissible technologies, including eco-driving and platooning, which could be permitted or forbidden by policy. There are also vehicle design and operations regulations which could be required or not. Product stewardship would require manufacturers to ensure their vehicles have low resource impacts, and are easily recycled, which would minimise vehicle material impacts. Similarly, potential regulatory and policy tools of communications infrastructure, which the vehicles rely on to operate, could place requirements for efficiency standards and renewable energy targets. This would reduce communications infrastructure impacts.

At the vehicle operation level there are potential regulatory and policy tools on vehicle use and the road system. The use of vehicles can be regulated in several ways, including if private use is permitted or forbidden, if shared use is permitted or forbidden, and if CAVs are required to operate complementary to public transport or not. Similarly, there are potential regulatory and policy tools covering if a CAV can operate without any occupants (and even the conditions under which they may, for example CAVs could be permitted to operate without an occupant only while operating in a shared use context which compliments public transport). Lastly, there are potential road system regulatory and policy tools around speed limits. The combinations of these regulatory settings have potential to drastically shift environmental outcomes.

Table 2 Mapping of potential regulatory and policy tools with CAV factors

Potential regulatory and policy tools	Permitted/required	Forbidden/not required
Vehicle production		
Permissible technology – Eco-driving	Allows Eco-driving Increases Route selection optimisation	Forbids Eco-driving Decreases Route selection optimisation
Permissible technology – Platooning permitted	Increases Platooning and traffic harmonisation ; Easier and more attractive travel	Decreases Platooning and traffic harmonisation ; Easier and more attractive travel
Design/op regulation – Product stewardship	Decreases Vehicle material	Increases Vehicle material
Design/op regulation – Communications infrastructure	Decreases Communications infrastructure	Increases Communications infrastructure
Vehicle / Road systems		
Private use of CAV	Increases Easier and more attractive travel ; Increased use of vehicles by those who cannot drive ; Shift from active and public transport to CAV ; Declining parking requirements ; Increased urban sprawl ; Travel pattern changes	Decreases Easier and more attractive travel ; Increased use of vehicles by those who cannot drive ; Shift from active and public transport to CAV ; Declining parking requirements ; Increased urban sprawl ; Travel pattern changes
Shared use of CAV	Increases Shared vehicles ; Empty VKT ; Shift from active and public transport to CAV ; Declining parking requirements (Compact) ; Increased parking requirements (Spillover) ; Increased urban sprawl ; Travel pattern changes	Decreases Shared vehicles ; Empty VKT ; Shift from active and public transport to CAV ; Increased parking requirements (Compact) ; Declining parking requirements (Spillover) ; Increased urban sprawl ; Travel pattern changes
CAV complements PT (no competition with PT)	Increases Shared vehicles ; CAVs used to support public transport for last mile Decreases Shift from active and public transport to CAV	
Operation without occupant (empty running)	Increases Empty VKT ; Declining parking requirements (Compact) Decreases Increased parking requirements (Spillover)	Increases Declining parking requirements (Compact) Decreases Empty VKT ; Increased parking requirements (Spillover)

Raised speed limits	Increased Faster maximum driving speeds	Decreased Faster maximum driving speeds
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Note: Green shading indicates positive environmental impacts, and red shading indicates negative environmental impacts.

The impact of factors (shown in Table 1) is linked to each potential regulatory and policy tool's permissiveness, or requirement. For example, either encouraging or discouraging approaches such as eco-driving and route selection optimisation would either increase or decrease the benefits from these approaches. Similarly, a design requirement around product stewardship would reduce the impacts of vehicle material, while not having product stewardship would leave vehicle material unregulated, leading to an increased negative environmental impact.

This section has analysed how policies could manage CAV factors and the potential environmental outcomes. These CAV factors and impacts have been further evaluated in consulting the expert survey group. The expert survey group's responses provide additional insights to the likelihood or the level of importance of each CAV factor in assessing the policy impacts (see Table 5). In general, the expert survey group provide high ratings on the impacts of eco-driving, change in travel cost, route selection optimisation, change in mobility and travel patterns, and impacts on active and public transport modes. The expert survey group's ratings on the impacts of production material/design, infrastructure, and Shared CAV are moderate.

3.4 Policy scenario development

Six policy scenarios have been developed for this analysis. These scenarios can be mapped onto a conceptual framework, shown in Figure 1. This framework considers CAV uptake (from low to high) and potential CAV use (from highly individualised to highly collectivised). These scenarios range from being highly deregulated, where the vehicle production and vehicle use is not strongly affected by regulatory or policy tools, to highly regulated, where production of vehicles has minimum standards which seek positive environmental benefits, and the use is regulated through policies which shape the ways in which CAVs can be used. This provides a spectrum of different potential outcomes, based on level of regulation and policy intervention. Policy scenarios also consider the overall CAV uptake, which explores the ways in which the environmental impacts of different production and use settings may change with uptake.

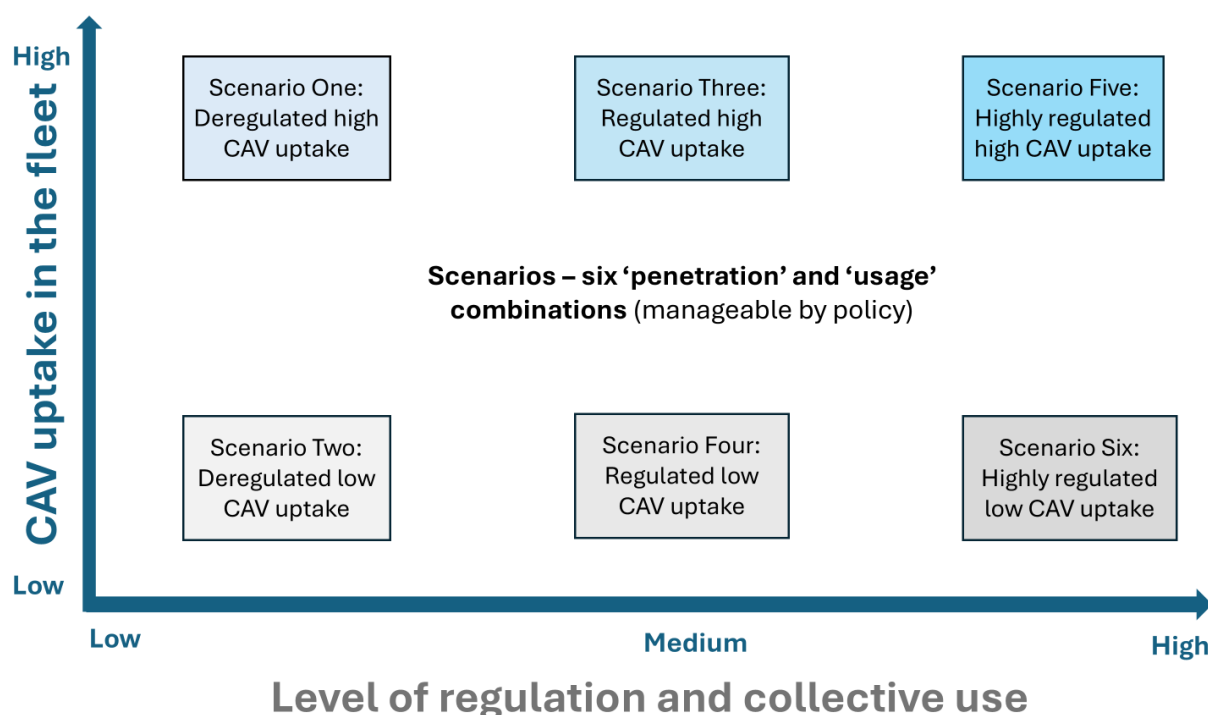


Figure 1 Scenarios within the uptake and use framework

Each of these scenarios has a different configuration of potential regulatory and policy tools (from Table 2), which align with the use context. Further, each are moderated by uptake (as discussed in section 3.2). The various policy and regulatory settings are shown in Table 3.

These scenarios provide a spectrum of outcomes, from highly unregulated and individually used CAVs to tightly regulated and collectively used CAVs. Similarly, in each potential regulatory and policy tool context, there are low and high uptake scenarios, revealing how impacts may change as uptake increases over time. This conceptual mapping has informed the policy settings in each scenario, developing six scenarios, discussed in Appendix One, and summarised below.

Table 3 Potential regulatory and policy tools per scenario

Potential regulatory and policy tools	Scenario One: Deregulated high CAV uptake	Scenario Two: Deregulated low CAV uptake	Scenario Three: Regulated high CAV uptake	Scenario Four: Regulated low CAV uptake	Scenario Five: Highly regulated high CAV uptake	Scenario Six: Highly regulated low CAV uptake
CAV Uptake	Full adoption	Low adoption	Full adoption	Low adoption	Full adoption	Low adoption
Vehicle production						
Permissible technology – Eco-driving	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed
Permissible technology – Platooning permitted	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed
Design/op regulation –	Deregulated	Deregulated	Required	Required	Required	Required

Product stewardship						
Design/op regulation – Communications infrastructure	Deregulated	Deregulated	Required	Required	Required	Required
Vehicle / Road systems						
Private use of CAV	Allowed	Allowed	Allowed	Allowed	Controlled	Controlled
Shared use of CAV	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed
CAV complements PT (no competition with PT)	CAV in competition with PT	CAV in competition with PT	Shared CAV complements PT	Shared CAV complements PT	All CAV complements PT	All CAV complements PT
Operation without occupant (empty running)	Allowed	Allowed	Allowed (limited)	Allowed (limited)	Allowed (limited)	Allowed (limited)
Raised speed limits	Allowed	Allowed	Allowed (limited)	Allowed (limited)	Allowed (limited)	Allowed (limited)

3.5 Policy scenario discussion

A comprehensive analysis of each of the six scenarios is provided in Appendix One. The section below compares the different environmental impacts at each of the vehicle, transport system, and urban system levels. For each level, a comparison of different environmental outcomes, resulting from the scenario analysis, is provided. The policy scenario analysis is also informed by the expert survey group responses, with commentary added through the discussion. This approach merges the literature and theoretical perspectives with the perspectives of Australian CAV and transport experts, providing a rounded and robust appraisal.

3.5.1 Vehicle Level

There are two components to vehicle level environmental impacts: permissible technology and design requirements. All six scenarios allow the permissible technologies of eco-driving, meaning that the beneficial environmental impacts of eco-driving are stable across all scenarios, but modified by uptake (only being realised in scenarios one, three and five). The benefit of eco-driving was fully agreed upon by everyone in the expert survey group.

Each scenario treats speed limits differently, with scenarios one and two raising speed limits in many contexts, while three and four have some restrictions, and five and six have more restrictions. This means that the negative environmental impacts of increased speed limits are most acute in scenario one, and least acute in scenarios three and five. Again, this is moderated by uptake, with the negative effects only being realised in scenarios one, three and five. The expert survey group also considered the impact of speed limits, and some participants agreed that it would have a positive environmental effect.

Regulating the production of vehicles, through product stewardship and communications infrastructure, scenarios three, four, five and six all have lower impacts on vehicle materials, with reduced energy use, particulate emissions and resource demands than scenario one. These impacts are not linked to uptake, but rather scale in relation to CAV uptake. The expert survey group

participants partly agreed with the outcome of these production requirements. They rated them as moderately important in policy direction.

At the vehicle level, the greatest positive environmental impacts can be seen in scenarios which permit eco-driving, restrict speed limit increases, and place design regulations on vehicle manufacturers.

3.5.2 Transport System Level

At a transport system level, CAVs in all scenarios would communicate with each other, leading to network efficiencies, through route selection optimisation, freeway travel harmonisation, and potentially decreasing congestion. These benefits are stable across scenarios, but only are only realised at the higher uptake levels of in scenarios one, three and five. The expert survey group participants acknowledged these technology transitions (e.g. platooning) but only partly agreed on their aggregate impacts at the transport system level (e.g., on network efficiency or congestion).

The ways in which CAVs can be used varies between scenarios. In scenarios one and two, CAVs may be used privately and shared, but shared CAVs are permitted to compete with public transport. This has the potential to make travel easier and more attractive, which could increase use by those who do not currently drive and cause a shift from public transport to CAVs. In combination, this could significantly increase energy requirements and increase congestion on the road network.

In contrast, scenarios five and six only permit CAVs to be used in a shared context, but also regulate this shared use so that shared CAVs could not be used for trips which mimic quality public transport routes (e.g., running between two railway stations on the same line, or along a tram line). As such, CAVs would be used as feeders to public transport, expanding the reach and potentially causing a large mode shift from private motor vehicle to CAVs and public transport. This has the potential to see full benefits from shared vehicles and a large mode shift towards public transport.

Scenarios three and four sit in the middle of this spectrum, allowing both private and shared use of CAVs, but regulating CAVs in shared use to complement public transport. The above issues were also considered by the expert survey group. The participants fully agree with the negative impacts of private CAV usage on the total travel demand, active and public transport, and the environment. They support the strategy of fostering high collective use of CAVs, such as CAV-PT integration and shared CAVs.

At the transport system level, the greatest positive environmental impacts can be seen in scenarios which ensure that CAVs operate in a way which complements, rather than competes with, public transport, while limiting private use.

3.5.3 Urban System Level

At the urban system level, there are a wide variety of different possible outcomes. Having ubiquitous, unregulated private and shared use of CAVs, such as is seen in scenario one and two, has the potential to exacerbate urban sprawl, making cities spatially larger while increasing direct and indirect emissions. Exacerbated urban sprawl will also place peri-urban areas under increased pressure, which increases demand for land resources and competition for land. This could have the flow on effect of generating more vehicle trips, and increasing distance of trips, contributing to congestion and entrenching car dependency. Scenarios one and two could have a mixed effect on parking, with empty running potentially decreasing demand in some areas, but at the cost of increased vehicle kilometres travelled and congestion.

Conversely, scenarios five and six have the potential for significant environmental benefits at the urban level. Uptake of shared CAVs, with restrictions on use in competition with public transport has the significant potential to reduce car parking demand and requirements in some areas, which could facilitate infill development and compact city design. This could reduce pressures on urban fringes, helping to contain urban sprawl. While there is still the distinct possibility that urban travel patterns may change, as the value of time alters, and people are willing to spend more time travelling, this may be moderated by regulations which restrict the use of CAVs.

Again, Scenarios three and four sit in the middle of the spectrum. Having private use of CAVs has the potential to have similar urban effects as scenarios one and two, but to a less extent, due to regulations on use particularly in shared contexts. In all cases, the scenario effects would be modified by uptake.

The expert survey group also shared their views on the impacts of CAV transition at the urban system level. They agree with the factor that CAVs will shift urban travel patterns but only partly agree on the impacts on urban structure change. They support the strategy to maximise the collective use of CAVs complemented by urban planning approaches to prevent the negative urban impacts that might occur in the future.

At the urban system level, the greatest positive environmental impacts can be seen in scenarios which ensure that CAVs operate in a way which complements public transport, while limiting private use. The greatest potential for negative impacts is associated with ubiquitous and unregulated use of CAVs.

3.5.4 Summary

The policy scenario analysis above illustrates the great potential for CAVs to have very positive, or very negative environmental impacts, depending on the uptake and regulations imposed. The potential impacts of each potential regulatory and policy tool in each scenario are shown in Table 4. Allowing highly deregulated production and use of CAVs has the potential, if met with high uptake, to increase the energy use of motor vehicle transport, the number of trips and vehicle kilometres travelled, and undermine public and active transport. There is also the potential that the ubiquitous use of CAVs in a deregulated way could accelerate urban sprawl, potentially undermining urban consolidation and compact city planning.

A CAVs adoption pathway which has tighter regulation of the production of vehicles and in their use has great potential for environmental benefit. CAVs could complement public transport, increasing use of public transport. This has the potential to reduce the need for vehicle ownership and vehicle use. This is particularly important when considering urban areas which already have access to quality public transport (for example, the inner cores of the major cities in Australia), where CAVs which are only used in a complementary fashion would not play a large role. CAV use which complements public transport could support low-car infill development and compact city development while providing residents with a non-private method of travel to urban areas lacking public transport.

Notably, many effects may not be seen at low uptake levels, this reveals the need for Government policies to be forward thinking, about what type of transport and urban future is desired, and implement policy settings to support the realisation of that future.

Table 4 also provides the expert survey group's ratings (H, M) on each CAV policy scenario, taking their relevant responses from the survey. These ratings are used as an additional reference to inform the environmental impacts and policy assessment. At the production level, the expert survey group agree that regulation of CAV production allowing permissible technology and design requirements would generate a positive environmental outcome, although some of them are not quite certain

about the level of impacts of vehicle platooning, data communication, and infrastructure change.

At the operation level, the expert survey group fully agree on the negative environmental impacts of private use of CAVs, caused by increased travel demand, travel distance, and reduced active and public transport. They agree on the approaches enabling high collective use of CAVs (e.g., CAVs and PT integration, shared CAVs), to manage the negative impacts on the environment.

Table 4 Estimated environmental impact from potential regulatory and policy tools by scenario

Potential regulatory and policy tools	Scenario One: Deregulated high CAV uptake	Scenario Two: Deregulated low CAV uptake	Scenario Three: Regulated high CAV uptake	Scenario Four: Regulated low CAV uptake	Scenario Five: Highly regulated high CAV uptake	Scenario Six: Highly regulated low CAV uptake
CAV Uptake	Amplifies overall environmental impact	Limits overall environmental impact	Amplifies overall environmental impact	Limits overall environmental impact	Amplifies overall environmental impact	Limits overall environmental impact
Vehicle production						
Permissible technology – Eco-driving	Positive environmental impact (H)	Positive environmental impact (H)	Positive environmental impact (H)	Positive environmental impact (H)	Positive environmental impact (H)	Positive environmental impact (H)
Permissible technology – Platooning permitted	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)
Design/op regulation – Product stewardship	Negative environmental impact (M)	Negative environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)
Design/op regulation – Communications infrastructure	Negative environmental impact (M)	Negative environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)	Positive environmental impact (M)
Vehicle / Road systems						
Private use of CAV	Negative environmental impact (H)	Negative environmental impact (H)	Negative environmental impact (H)	Negative environmental impact (H)	Positive environmental impact (H)	Positive environmental impact (H)
Shared use of CAV	Mixed environmental impact (H)	Mixed environmental impact (H)	Positive environmental impact (M)	Positive environmental impact (M)	Very positive environmental impact (M)	Positive environmental impact (M)
CAV complements PT (no competition with PT)	Negative environmental impact (H)	Negative environmental impact (H)	Positive environmental impact (H)	Positive environmental impact (H)	Very positive environmental impact (H)	Very positive environmental impact (H)
Operation without occupant (empty running)	Negative environmental impact (H)	Negative environmental impact (H)	Mixed environmental impact (H)	Mixed environmental impact (H)	Mixed environmental impact (H)	Mixed environmental impact (H)
Raised speed limits	Negative environmental impact (M)	Negative environmental impact (M)	Mixed environmental impact (H)	Mixed environmental impact (H)	Mixed environmental impact (H)	Mixed environmental impact (H)

Note: Green shading indicates a positive environmental impact; grey shading indicates a mixed environmental impact; and red shading indicates a negative environmental impact.

Note: the ranking (H, M) reflects the expert survey group viewpoints on the environmental impacts of different CAV uptake

and policy scenarios. H denotes that the expert survey group agree with the environmental impact of a policy; M denotes that the expert survey group partly agree with the environmental impact of a policy.

4 Expert Survey Group

The expert survey group consultation survey was conducted by the RMIT University team to investigate how the future adoption of CAVs will impact Australia's transport systems, focusing on CAV environmental impacts. The survey explores both positive and negative CAV environmental impacts that might occur in Australia, aiming to identify valuable insights that will support strategy and policy development. Particularly, the survey seeks respondents' opinions on CAV factors and transitions and suggestions to maximise the positive effects of CAVs and mitigate the negative impacts, drawing on their knowledge of Australia's transport systems. The findings of the expert survey group add real world expert views on critical issues considered in stage two, such as up take of CAV and the ways in which they may be used. This strengthens the policy analysis, and reveals some potential pathways for CAVs adoption. However, this is moderated by two factors: firstly, the small pool of CAV experts in Australia, and secondly a small sample of only 17.

The survey was conducted following approval from the RMIT Human Research Ethics Committee. The survey was distributed to 38 key experts, including industry, policymakers from State and Commonwealth Governments, and international experts to gain broader opinions. Seventeen of the approached participants completed the survey (45% response rate), including two government policymakers, eight industry professionals, and seven international transport experts.

4.1 Summary of the expert survey group findings

The information gained from the survey has been synthesised and analysed to inform the policy assessment. The detailed results of the survey questions are provided in the Appendix. The main survey findings are grouped below by whether respondents agreed, partially agreed or did not agree with the impact of the factors.

Respondents agreed:

- **Regulatory and infrastructure readiness:** Respondents suggested that relevant regulations (e.g., data privacy) and existing transport infrastructure, including public transport systems, will require specific consideration before widespread CAV adoption.
- **Platooning and efficiency gains:** Respondents consider that increased driving efficiency and platooning of CAVs will generate additional environmental benefits compared to vehicle electrification alone. Their views on the benefits of increased vehicle sharing are diverse.
- **Impact on ownership and travel behaviour:** Respondents believe that CAVs will alter vehicle ownership patterns and travel behaviour, generating substantial environmental impacts. Improved traffic efficiency and vehicle interaction would have a positive outcome.
- **Changes in mobility and public transport use:** Respondents agree that CAVs will generate new forms of mobility (e.g., empty travel), increase vehicle travel demand, and decrease public transport usage. Changes with increased commercial vehicle and public transport automation are also considered.

Respondents partially agreed:

- **Low CAV penetration by 2050:** Most respondents believe there will be a lower penetration of CAVs in the Australian motor vehicle fleet by the year 2050, up to 40%. However, connected vehicles may arrive earlier than the full CAV vehicles.

- **Key adoption drivers:** Most respondents believe that technological advancement, government incentives, and market forces would strongly influence the future uptake of CAVs in Australia.
- **Safety, congestion, and data costs:** Most respondents agree that vehicle connectivity technologies can reduce road hazards and congestion. The negative environmental impacts of data computation and communication are also considered.
- **Pricing mechanisms and shared CAV adoption:** Most respondents suggest implementing pricing mechanisms and supporting shared CAV usage could be an effective policy solution in Australia. Other strategies to integrate CAV and PT systems are also supported.
- **Environmental benefits in logistics and vulnerable groups:** Many respondents believe that CAVs will generate a positive environmental outcome for the logistics and freight industries. This transition can also benefit vulnerable groups and urban commuters.

Respondents did not agree:

- **Limited urban structure impact:** Respondents do not firmly believe that CAVs will significantly impact the urban structure. Only some recommended early-stage environmental assessments and urban planning strategies.

4.2 Linking the expert survey group's responses to the policy assessment

The expert survey group's responses to CAV factors and impacts have been discussed in the earlier sections assessing CAV policies and scenarios. The original consultation survey covers ten questions seeking the expert survey group's viewpoints on transitions, impacts, and regulations linked to the CAV factors in the policy assessment framework. In each question, the participants were asked to choose the grade of agreement on the stated CAV factors and impacts. We rate each CAV factor based on a subjective assessment of the expert survey group's responses. For example, if the expert survey group's views on a CAV factor or transition skew toward agreeing, we deem that factor important or likely to happen and rank it as 'high' in that context. On the contrary, if the expert survey group's responses skew toward disagreeing on a CAV factor, we deem that factor less important or less likely to happen, and a 'low' ranking is assigned to that factor. If the expert survey group's views are nearly balanced between agreeing or disagreeing, a 'medium' rating is given. Some CAV factors (e.g., platooning, vehicle sharing) were investigated in more than one question; their rating was then assessed separately for different contexts (see Table 5).

The expert survey group's ratings on the CAV factors are presented in Table 5. H denotes a high level of participant agreement with the stated transition, environmental impacts, or policy regulation associated with a factor. M denotes that the participants' viewpoints on a factor are diverse and do not skew toward agree or disagree. L denotes that the participants generally disagree with the stated transition, environmental impacts, or policy regulation associated with a factor. Table 5 shows that the participants rated H for many factors at the vehicle and transport system levels, such as eco-driving, easier travel, and transport mode change. The participants also rated M for some CAV factors under investigation, such as vehicle sharing and communication costs. This means that although the environmental impacts of CAV are identified, some of them will be very limited from the participants' perspective. The participants' views on the long-term changes at the urban system level are relatively conservative, meaning they are less likely to be seen in the future.

Survey participants' views on to potential regulatory and policy tools and their environmental impacts are as follows:

Eco-driving – respondents agreed that CAVs would lead to eco-driving (allowed by policy scenarios) and that they would generate positive environmental impacts.

Faster maximum driving speeds – respondents partly agree that faster maximum driving speeds (allowed or limited by policy scenarios) will generate negative environmental impacts.

Vehicle material/design – respondents partly agree that CAVs will require vehicle material change and increase communication costs and road maintenance (regulated or deregulated by policy scenarios). They partly agree that these changes will generate negative environmental impacts. They agree on the environmental impact assessment of CAV technologies before deployment.

Route selection optimisation – respondents agree that CAVs will lead to route selection optimisation and generate positive environmental impacts.

Platooning and traffic harmonisation – respondents agree that CAVs will increase vehicle platooning and road traffic harmonisation (allowed by policy scenarios). They partly agree that these changes will generate positive environmental impacts.

Easier and low-cost travel – respondents agree that CAV will reduce individual travel costs, which will increase total travel demand (allowed or controlled by policy scenarios). They agree that these changes will generate negative environmental impacts and agree on implementing policies (e.g., a pricing mechanism) to manage vehicle travel demand.

Shared vehicles – respondents partly agree that CAVs will increase shared-vehicle travels (allowed by policy scenarios) and the environmental impact of this change. They suggest implementing a strong policy to support the shared CAV travels.

Empty VKT – respondents agree that CAVs will generate more empty travels (allowed or limited by policy scenarios), negatively impacting the environment.

Increased use of vehicles by those who cannot drive – respondents agree that CAVs will increase travel demand for people who cannot drive (allowed by policy scenarios).

Shift from active and public transport to CAV – respondents agree that travellers will shift from public transport or active transport to CAVs (managed by policy scenarios). They agree that this shift will generate negative environmental impacts.

CAVs used to support public transport for last mile – respondents agree that integrating CAVs with public transport networks (managed by policy scenarios) is an effective strategy to mitigate the environmental impacts.

Communications infrastructure – respondents partly agree that communication infrastructure (regulated or deregulated by policy scenarios) is a key concern to broad CAV transition. They partly agree that change in communication infrastructure will add environmental costs.

Declining parking requirements – Compact cities – respondents partly agree that CAVs will reduce parking demand. This change can lead to a more compact built environment and generate positive environmental outcomes.

Increased parking requirements – Parking spillover – respondents partly agree with implementing land use policy to manage the potential increase in parking demand in suburban areas.

Increased urban sprawl – respondents generally disagree that urban sprawl will increase due to the CAV transition. They partly agree with implementing urban policy to manage and monitor urban structure changes.

Travel pattern changes – respondents agree that CAV will lead to travel pattern changes (allowed or controlled by policy scenarios). They agree that these changes in travel patterns will generate negative environmental impacts.

Table 5 Expert survey group rating on CAVs factors

CAV factors	Expert survey group rating		
	Effect of uptake	Effect of environmental impacts	Effect of policy
Eco-driving	H	H	
Faster maximum driving speeds		M	
Vehicle material/design	M	M	H
Route selection optimisation	H	H	
Platooning and traffic harmonisation	H	M	
Easier and low-cost travel	H	H	H
Shared vehicles	M	M	H
Empty VKT	H	H	
Increased use of vehicles by those who cannot drive	H		
Shift from active and public transport to CAV	H	H	
CAVs used to support public transport for last-mile			H
Communications infrastructure	M	M	
Declining parking requirements – Compact cities		M	
Increased parking requirements – Parking spillover			M
Increased urban sprawl		L	M
Travel pattern changes	H	H	

Note: H denotes that the participants generally agree with the CAV factor; L denotes that the participants generally disagree with the CAV factor; M denotes that the participants' viewpoints do not skew towards agree and disagree (or partly agree). Empty cells mean that the expert survey group did not investigate such an issue.

Responses from the expert survey group informed the policy analysis in two ways. Firstly, the responses were used to frame the analysis, identifying views and perspectives related to possible outcomes and the need for policy intervention. Secondly, the expert survey group's ratings on

changing factors are used as an additional reference to inform the environmental impacts of policy scenarios. The survey provides external ratings on the likelihood and the environmental importance of CAV factors under each scenario¹. This policy assessment model, informed by the expert survey group's responses, extends the earlier work in which the CAV impacts were predefined and solely informed by the literature or international experiences. The survey work also filled the policy gap in the previous investigations by addressing more targeted issues in Australia. Adding the expert survey group consultation to the assessment framework will better understand the impacts of identified strategies and reveal possible approaches to mitigation in the Australian context. This policy assessment framework, informed by the expert survey group consultation, enables policymakers to further review CAV policy and mitigation strategies proposed or being trailed in Australia to avoid the negative impacts of the CAV transition.

¹ This consultation survey enhances the assessment of the policy scenarios and the environmental outcomes. We acknowledge that this survey is still based on a small group consultation. Further investigation is needed to gain broader experts' advice and feedback.

5 Policy implications

The policy analysis and expert survey group responses reveal several key policy implications. These relate to both the ways in which CAVs could be best regulated, and the likelihood of certain environmental impacts – both positive and negative – being realised. It is important to recognise that many of these impacts are only likely to be seen when CAV uptake exceeds 50%, which is not likely in the near future. However, the need for long-term planning and policy development is highlighted in both the policy analysis and expert survey group. The key policy implications from this report are:

- At the vehicle level, the greatest positive environmental impacts can be seen in scenarios which permit eco-driving, restrict speed limit increases, and place design regulations on vehicle manufacturers.
 - The role of regulation or policy in design, production, and disposal of CAVs is crucial to maximising vehicle level environmental benefits, while minimising negative environmental consequences of CAVs.
- At the transport system level, the greatest positive environmental impacts can be seen in scenarios which ensure that CAVs operate in a way which complements, rather than competes with, public transport, while limiting private use.
 - The role of regulation in use of CAVs is crucial to maximising transport system environmental benefits, while minimising negative environmental consequences of CAVs.
- At the urban system level, the greatest positive environmental impacts can be seen in scenarios which ensure that CAVs operate in a way which complements public transport, while limiting private use. The greatest potential for negative impacts is associated with ubiquitous and unregulated use of CAVs.
 - The role of regulation or policy in use of CAVs and supporting communication infrastructure is crucial to maximising urban system environmental benefits, while minimising negative environmental consequences of CAVs.
- Many effects – both positive and negative - may not be seen at low uptake levels. With uptake below 25%, there are not thought to be any benefits, as the fleet is not large enough to be maximising benefits of connectivity. This reveals the need for Government policies to be forward thinking, about what type of transport and urban future is desired, and implement policy settings to support the realisation of that future.
 - Proactive regulation, which supports a future vision, will be critical in guiding the adoption of CAVs, in a manner which ensures environmental benefits are maximised.
- Some CAV factors and impacts are still not certain based on the expert survey group. This uncertainty can moderate the environmental outcome of policy scenarios. The expert survey group's rating on the CAV factors can assist in a further review of the identified policies and reveal more targeted solutions to avoid the negative impacts of the CAV transition in Australia.
- Most respondents believe there will be a lower penetration of CAVs in the Australian motor vehicle fleet by the year 2050, up to 40%. However, the connected vehicles may arrive earlier than the full CAV vehicles. This means the impacts, both positive and negative,

from CAVs are unlikely to be seen until after 2050, and many impacts of CAV are only realised with a fleet uptake of over 50%.

6 Conclusion

Most environmental impacts of CAVs will only manifest themselves at uptake levels of 50% and above. As a result, and in order to achieve positive environmental benefits from the deployment of CAVs, policy makers and regulators need to develop clear forward-looking policies, policy settings and regulations, to support their vision of the type of transport and urban environment they envisage for the future. Noting the dependency of environmental impacts on CAV uptake, policy makers will benefit from proactive approaches to policy and regulation. This will enable them to influence the environmental impacts and ensure positive environmental benefits are maximised.

Further detailed research may be useful in two areas: firstly to disaggregate the environmental impacts of CAVs from the emissions reductions offered through the increased uptake of electric vehicles; secondly to disaggregate the environmental impacts due to vehicle automation from those that are a result of high levels of vehicle connectivity. Further research in these two areas would be useful to ensure policymakers could tailor solutions that maximise the positive environmental impacts of CAVs while reducing potential negative effects.

Appendix One: Detailed scenario analysis

Scenario One: Deregulated with high CAV uptake

This scenario envisages a future with high, almost ubiquitous, CAV uptake, with a highly deregulated and individualised use context. Vehicle manufacturers are permitted to add technology to vehicles including eco-driving and platooning, while they are not regulated for the materials used in the production of the vehicle, or for materials and energy used in communications infrastructure to support CAV. Users are allowed to use CAVs in a private capacity (ownership and use), while shared use is permitted in all cases, including in direct competition with public transport. This scenario allows for CAVs to operate without an occupant (empty running). Additionally, it is envisaged that speed limits are increased, in recognition of increased operational safety.

Vehicle level environmental impacts

CAVs would be allowed to have technology which can decrease energy use, and the high CAV uptake could see the full benefits of these being realised. This means that, in total, energy use could decrease. However, increased speed limits will allow for faster driving speeds, which could see energy use increase. As such, CAVs in Scenario One could consume slightly more energy.

A lack of vehicle regulations means that vehicles could become heavier, and require more resources. This could increase particulate emissions from brakes and tyres in the areas of operation. There are also likely to be increased resource requirements, which have upstream impacts from material extraction and production, and downstream effects from disposal (particularly batteries). Notably, these environmental impacts are also likely to be seen, at least to some extent, in EVs (which are not CAVs). This means these impacts may be marginal at the per vehicle level. However, increased vehicle ownership is possible by expanding the potential pool of those who may own a vehicle (i.e., those who cannot drive, due to age, physical ability, or attainment of a driver's licence), resulting in an overall negative environmental impact.

Transport system level environmental impacts

At a transport system level, CAVs would communicate with each other, leading to network efficiencies, through route selection optimisation, freeway travel harmonisation, and potentially decreasing congestion. The high CAV uptake could see the full benefits of these being realised. This has the potential to decrease energy use. However, the ubiquitous use of CAVs has the potential to increase travel, by making it easier, which could also lead to a shift away from public and active transport to CAVs. This would be amplified by the policy settings which allow shared CAVs to operate in competition with public transport. Further, empty running would allow CAV users to be dropped at their destination, with the vehicle driving away to find a parking space, causing empty vehicle kilometres travelled. This could lead to increased energy use per vehicle, along with an increase in travel (from both new travel and travel diverted from public and active transport). It is also possible that this increased travel would exacerbate congestion and traffic volumes. These environmental impacts could essentially act to nullify the transport system benefits.

Urban system level environmental impacts

The ubiquitous uptake and use of CAVs are likely to have several negative environmental impacts. While there may be declined parking requirements in some areas, which facilitates infill development and compact city design, this would be minimised by higher levels of private ownership and use of CAVs. There is also the potential for increased car parking demand and pressure, from CAVs running

empty to locate a parking space. Urban travel patterns may also change, as the value of time alters, and people are willing to spend more time travelling. As such, there is a high potential for increased travel, from new trips, trips diverted from public transport, longer trips, and empty running. These impacts have the potential to increase demand for road construction. Similarly, potential travel pattern changes could increase urban sprawl. Lastly, a lack of regulation of communications infrastructure may lead to increased resource consumption (including energy).

Scenario Two: Deregulated with low CAV uptake

Like scenario one, this scenario envisages a future with a highly deregulated and individualised CAV use context, but a low uptake.

Vehicle level environmental impacts

CAVs would be allowed to have technology which can decrease energy use, however, the low CAV uptake would not see these benefits being realised. This means that many of the environmental advantages and disadvantages of CAVs at the vehicle level are unlikely to be seen.

A lack of vehicle regulations means that vehicles could become heavier, and require more resources. This could increase particulate emissions from brakes and tyres in the areas of operation. There are also likely to be increased resource requirements, which have upstream impacts from material extraction and production, and downstream effects from disposal (particularly batteries). Notably, these environmental impacts are also likely to be seen, at least to some extent, in EVs (which are not CAVs). This means these impacts may be marginal at the per vehicle level. However, increased vehicle ownership is possible by expanding the potential pool of those who may own a vehicle (i.e., those who cannot drive, due to age, physical ability, or attainment of a driver's licence), resulting in an overall negative environmental impact, but this would be lower than in scenario one, due to decreased uptake of CAVs.

Transport system level environmental impacts

At a transport system level, CAVs can communicate with each other, leading to network efficiencies, through route selection optimisation, freeway travel harmonisation, and potentially decreasing congestion, however, low CAV uptake means these benefits are unlikely to be realised. Modest uptake of CAVs also has a minimised potential to increase travel, by making it easier.

A modest uptake of CAV could mean an outsized effect on shared CAV, which has the potential to cause a shift away from public and active transport to CAV. This would be amplified by the policy settings which allow shared CAVs to operate in competition with public transport.

Further, empty running would allow CAV users to be dropped at their destination, with the vehicle driving away to find a parking space, causing empty vehicle kilometres travelled. This could lead to increased energy use per vehicle, alongside an increase in travel (from both new travel and travel diverted from public and active transport). It is also possible that this increased travel would exacerbate congestion and traffic volumes. These environmental impacts would be a net negative, but lower uptake is likely to minimise these disbenefits.

Urban system level environmental impacts

The lower uptake and use of CAVs is likely to have a decreased negative environmental impact, compared with scenario one. However, there is still the potential for negative environmental impacts from altered parking behaviours, and some urban travel patterns may also change, as the value of time alters, and people are willing to spend more time travelling. As such, there is a high potential for increased travel, from new trips, trips diverted from public transport, longer trips, and empty

running. As is the case in scenario one, these impacts have the potential to increase demand for road construction, and increase urban sprawl. Lastly, a lack of regulation of communications infrastructure may lead to increased resource consumption (including energy).

Scenario Three: Regulated with high CAV uptake

This scenario envisages a future with high, almost ubiquitous, CAV uptake. However, unlike scenario one, vehicles and their use are more regulated, permitting private ownership and use, but regulating shared operation to be complementary to public transport. Vehicle manufacturers are permitted to add technology to vehicles including eco-driving and platooning, and are regulated for the materials used in the production of the vehicle, and for materials and energy used in communications infrastructure to support CAV. This scenario only allows for CAVs to operate without an occupant (empty running) in a shared capacity. Additionally, it is envisaged that speed limits are increased in some cases, in recognition of increased operational safety.

Vehicle level environmental impacts

CAVs would be allowed to have technology which can decrease energy use, and the high CAV uptake could see the full benefits of these being realised. This means that in total, energy use could decrease. While increased speed limits will allow for faster driving speeds, which could see energy use increase, a more limited application could significantly reduce increased energy use. As such, CAVs could consume less energy.

Stricter vehicle regulations could limit the weight and resource inputs for vehicles. This could minimise particulate emissions from brakes and tyres in the areas of operation. However, there could still be increased resource requirements, which have upstream impacts from material extraction and production, and downstream effects from disposal (particularly batteries). Regulation requiring product stewardship could mitigate environmental impacts from production and reprocessing of materials. Notably, these environmental impacts are also likely to be seen, at least to some extent, in EVs (which are not CAVs). This means these impacts may be marginal at the per vehicle level. However, increased vehicle ownership is possible by expanding the potential pool of those who may own a vehicle (i.e., those who cannot drive, due to age, physical ability, or attainment of a driver's licence), resulting in a potentially negative environmental impact.

Transport system level environmental impacts

At a transport system level, CAVs would communicate with each other, leading to network efficiencies, through route selection optimisation, freeway travel harmonisation, and potentially decreasing congestion. The high CAV uptake could see the full benefits of these being realised. This has the potential to decrease energy use by 45% or more. Ubiquitous use of CAVs has the potential to increase travel, by making it easier, which could also lead to a shift away from public and active transport to CAVs. These effects could be decreased by the policy settings which require shared CAVs to operate in a complementary way with public transport. This would mean that shared CAVs could not be used for trips which mimic quality public transport routes (e.g., running between two railway stations on the same line, or along a tram line), but rather would be used as feeders to public transport, expanding the reach and potentially causing a large mode shift from private motor vehicle to the CAV and public transport.

Limitations on empty running would prevent private CAV users to be dropped at their destination, with the vehicle driving away to find a parking space, minimising empty vehicle kilometres travelled. However, ubiquitous CAV in private ownership and operation could lead to an increase in travel. It is also possible that this increased travel would exacerbate congestion and traffic volumes.

Urban system level environmental impacts

As is the case in scenario one, the ubiquitous uptake and use of CAVs (particularly privately owned and used) has the potential for several negative environmental impacts. While there may be declined parking requirements in some areas, which facilitates infill development and compact city design, this would be minimised by higher levels of private ownership and use of CAVs. Urban travel patterns may also change, as the value of time alters, and people are willing to spend more time travelling. As such, there is a high potential for increased travel, from new trips, and from longer trips. These impacts have the potential to increase demand for road construction. Similarly, potential travel pattern changes could increase urban sprawl. Lastly, even with regulation of communications infrastructure, there could lead to increased resource consumption (including energy), but less so than in scenario one.

Scenario Four: Regulated with low CAV uptake

This scenario envisages the same policy context as scenario three, but with low CAV uptake

Vehicle level environmental impacts

CAVs would be allowed to have technology which can decrease energy use, but the low CAV uptake means these benefits do not become fully realised. This means that many of the environmental advantages and disadvantages of CAVs at the vehicle level are unlikely to be seen.

Stricter vehicle regulations could limit the weight and resource inputs for vehicles. This could minimise particulate emissions from brakes and tyres in the areas of operation. However, there could still be increased resource requirements, which have upstream impacts from material extraction and production, and downstream effects from disposal (particularly batteries). Regulation requiring product stewardship could mitigate environmental impacts from production and reprocessing of materials. Notably, these environmental impacts are also likely to be seen, at least to some extent, in EVs (which are not CAVs). This means these impacts may be marginal at the per vehicle level. However, increased vehicle ownership is possible by expanding the potential pool of those who may own a vehicle (i.e., those who cannot drive, due to age, physical ability, or attainment of a driver's licence), resulting in a potentially increased environmental impact.

Transport system level environmental impacts

At a transport system level, CAVs can communicate with each other, leading to network efficiencies, through route selection optimisation, freeway travel harmonisation, and potentially decreasing congestion, however, low CAV uptake means these benefits are unlikely to be realised. Modest uptake of CAVs also has a minimised potential to increase travel, by making it easier.

A modest uptake of CAV could mean an outsized effect on shared CAV, which has the potential to cause a shift towards the CAV and public transport combination. This would be supported by the policy settings which require shared CAVs to operate in competition with public transport.

Limitations on empty running would prevent private CAV users to be dropped at their destination, with the vehicle driving away to find a parking space, minimising empty vehicle kilometres travelled. However, ubiquitous CAV in private ownership and operation could lead to an increase in travel. It is also possible that this increased travel would exacerbate congestion and traffic volumes.

Urban system level environmental impacts

Due to the lower uptake of CAVs, this scenario has a lower potential for negative environmental impacts. However, the same challenges and potential impacts exist. While there may be declined parking requirements in some areas, which facilitates infill development and compact city design,

this would be minimised by higher levels of private ownership and use of CAVs. Urban travel patterns may also change, as the value of time alters, and people are willing to spend more time travelling. As such, there is a high potential for increased travel, from new trips, and from longer trips. These impacts have the potential to increase demand for road construction. Similarly, potential travel pattern changes could increase urban sprawl. Lastly, even with the regulation of communications infrastructure, there could lead to increased resource consumption (including energy), but less so than in scenarios one or three.

Scenario Five: Highly regulated with high CAV uptake

This scenario envisages a future with high, almost ubiquitous, CAV uptake. However, unlike scenarios one through four, vehicles and their use are highly regulated, permitting only shared operation which is complementary to public transport. In effect, this scenario envisages a future where all personal travel in motor vehicles is replaced by shared CAVs which act to support the public transport system. Where no public transport exists, they would (in effect) form the public transport system. Vehicle manufacturers are permitted to add technology to vehicles including eco-driving and platooning, and are regulated for the materials used in the production of the vehicle, and for materials and energy used in communications infrastructure to support CAV. This scenario only allows for CAVs to operate without an occupant (empty running) in a shared capacity. Additionally, it is envisaged that speed limits are increased in some cases, in recognition of increased operational safety.

Vehicle level environmental impacts

CAVs would be allowed to have technology which can decrease energy use, and the high CAV uptake could see the full benefits of these being realised. This means that in total, energy use could decrease. While increased speed limits will allow for faster driving speeds, which could see energy use increase, a more limited application could significantly restrict increased energy use. As such, CAVs could consume less energy.

Stricter vehicle regulations could limit the weight and resource inputs for vehicles. This could minimise particulate emissions from brakes and tyres in the areas of operation. However, there could still be increased resource requirements, which have upstream impacts from material extraction and production, and downstream effects from disposal (particularly batteries). Regulation requiring product stewardship could mitigate environmental impacts from production and reprocessing of materials. Notably, these environmental impacts are also likely to be seen, at least to some extent, in EVs (which are not CAVs). This means these impacts may be marginal at the per vehicle level. However, there is the potential for drastically reduced numbers of vehicles used for personal transport. This would likely lead to a situation where there are fewer vehicles, which are used far more often. However, they would not be used in competition with public transport, potentially leading to significantly lower amounts of traffic and congestion (particularly in areas well served by public transport, like city cores). In totality, this could result in significantly reduced overall environmental impact.

Transport system level environmental impacts

At a transport system level, CAVs would communicate with each other, leading to network efficiencies, through route selection optimisation, freeway travel harmonisation, and potentially decreasing congestion. The high CAV uptake could see the full benefits of these being realised. This has the potential to significantly decrease energy use. Ubiquitous use of CAVs has the potential to increase travel, however, this would be significantly decreased by the policy settings which require shared CAVs to operate in a complementary way with public transport. This would mean that shared CAVs could not be used for trips which mimic quality public transport routes (e.g., running between

two railway stations on the same line, or along a tram line), but rather would be used as feeders to public transport, expanding the reach and potentially causing a large mode shift from private motor vehicle the CAV and public transport.

Limitations on CAVs operating in competition with public transport and some limitations on empty running would reduce shared CAV users to be dropped at their destination in busy areas, reducing congestion in areas well served by public transport. However, ubiquitous shared CAV operation could lead to an increase in travel in areas without restrictions. In this scenario, it is less likely that this increased travel would exacerbate congestion, but could increase traffic volumes in some parts of the city.

Urban system level environmental impacts

This scenario has the lowest potential for negative environmental impacts at the urban system level. Ubiquitous uptake of shared CAVs, with restrictions on use in competition with public transport has the significant potential to reduce car parking demand and requirements in some areas, which could facilitate infill development and compact city design. This could reduce pressures on urban fringes, helping to contain urban sprawl. While there is still the distinct possibility that urban travel patterns may change, as the value of time alters, and people are willing to spend more time travelling, this may be moderated by regulations which restrict the unfettered use of CAVs. There is the potential for decreased traffic levels and congestion, which could decrease demand for road construction. Lastly, even with the regulation of communications infrastructure, there could lead to increased resource consumption (including energy), but there would likely be a significant decrease in vehicles, which would lead to a net environmental benefit.

Scenario Six: Highly regulated with low CAV uptake

This scenario envisages the same policy context as scenario five, but with low CAV uptake.

Vehicle level environmental impacts

CAVs would be allowed to have technology which can decrease energy use, but the low CAV uptake means these benefits do not become fully realised. This means that many of the environmental advantages and disadvantages of CAVs at the vehicle level are unlikely to be seen.

Stricter vehicle regulations could limit the weight and resource inputs for vehicles. This could minimise particulate emissions from brakes and tyres in the areas of operation. However, there could still be increased resource requirements, which have upstream impacts from material extraction and production, and downstream effects from disposal (particularly batteries). Regulation requiring product stewardship could mitigate environmental impacts from production and reprocessing of materials. Notably, these environmental impacts are also likely to be seen, at least to some extent, in EVs (which are not CAVs). This means these impacts may be marginal at the per vehicle level. While overall vehicle numbers may not change drastically, all the CAVs would be used in a shared capacity, supporting public transport. This is likely to lead to CAVs being used more often, but potentially leading to significantly lower amounts of traffic and congestion (particularly in areas well served by public transport, like city cores). In totality, this could result in reduced overall environmental impact.

Transport system level environmental impacts

At a transport system level, CAVs can communicate with each other, leading to network efficiencies, through route selection optimisation, freeway travel harmonisation, and potentially decreasing congestion, however, low CAV uptake means these benefits are unlikely to be realised. Modest uptake of CAVs also has a minimised potential to increase travel, by making it easier.

While there would be a low uptake of CAV, the policy settings would mean they are all shared. Policy settings also require all shared CAVs to complement and feed public transport. This would mean that shared CAVs could not be used for trips which mimic quality public transport routes (e.g., running between two railway stations on the same line, or along a tram line), but rather would be used as feeders to public transport, expanding the reach and potentially causing a mode shift from private motor vehicle to the CAV and public transport.

Limitations on CAVs operating in competition with public transport and some limitations on empty running would reduce shared CAV users to be dropped at their destination in busy areas, reducing congestion in areas well served by public transport. However, ubiquitous shared CAV operation could lead to an increase in travel by in areas without restrictions. In this scenario, it is less likely that this increased travel would exacerbate congestion, but could increase traffic volumes in some parts of the city.

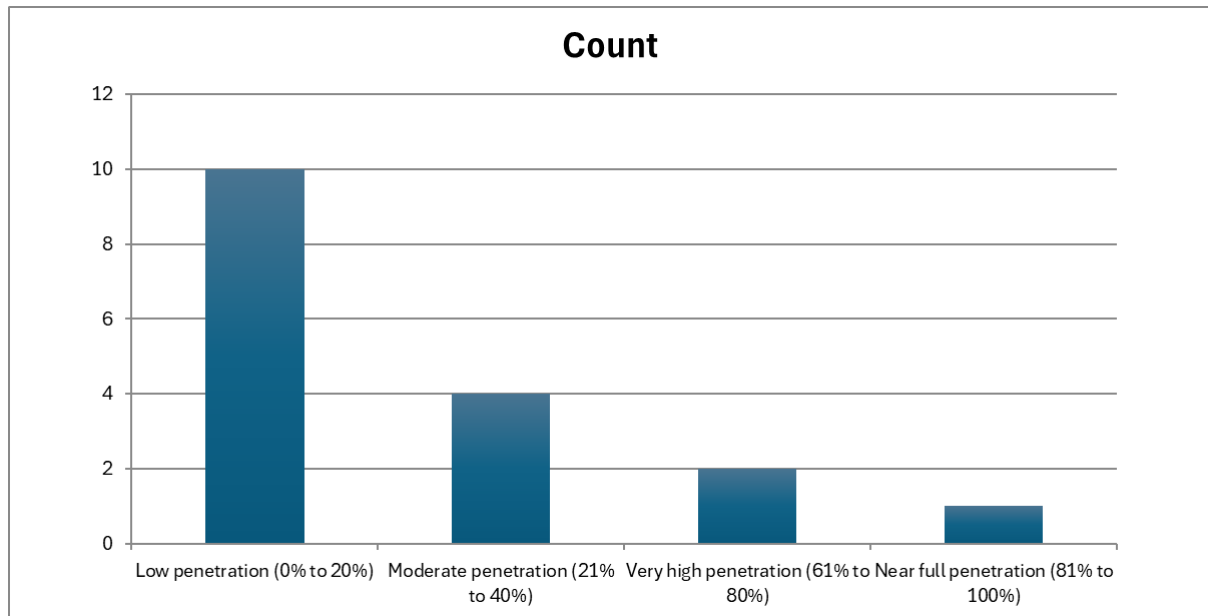
Urban system level environmental impacts

This scenario has a lower potential for negative environmental impacts at the urban system level than other scenarios. Modest uptake of shared CAVs, with restrictions on use in competition with public transport has the significant potential to reduce some car parking demand and requirements in areas (most likely those well served by public transport), which could facilitate infill development and compact city design. This could reduce some pressures on urban fringes, helping to contain urban sprawl. While there is still some possibility that urban travel patterns may change, as the value of time alters, and people are willing to spend more time travelling, this may be moderated by regulations which restrict the unfettered use of CAVs. There is the potential for decreased traffic levels and congestion, which could decrease demand for road construction. Lastly, even with the regulation of communications infrastructure, it could lead to increased resource consumption (including energy).

Appendix Two: Expert survey group's Responses to the survey questions

Q1: Penetration of CAVs in Australia's motor vehicle fleet by the year 2050

Participants' responses:



Participants' other comments:

"As a comment - this has been answered on the basis of a CAV having connected and/or automated features not driverless which I expect MUCH lower".

"It is unhelpful to bundle connected vehicles with automated vehicles in this quest. Connectivity will be introduced much earlier and faster than full automation".

"Connect does not equal automated so a bit hard to say. The question is very general".

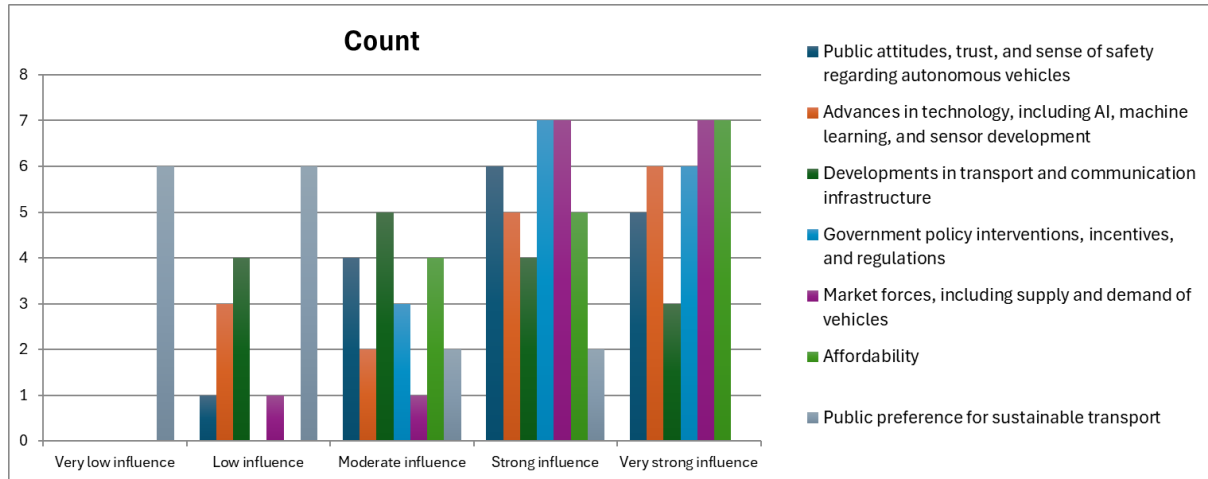
"20% by 2040".

"Full penetration by 2032".

"Connected Vehicles (through 4G/5G long-range communications) and Automated Vehicles (level 3 and above) are 2 very different things that have different levels of penetration over time. The concept of 'CAV' can be mentioned in the automotive industry but it does not have much practical meaning per se. I am responding to this survey from the point of view of Automated Vehicles. My responses to subsequent survey questions are based on the view that there will be a low level of AV penetration (under 20%) by 2035. Impacts are likely to be minimal/anecdotal".

Q2: In your view, to what degree will the following factors influence the adoption patterns of CAVs in Australia?

Participants' responses:



Participants' other comments:

"Adoption of AVs will have a different response to connected vehicles".

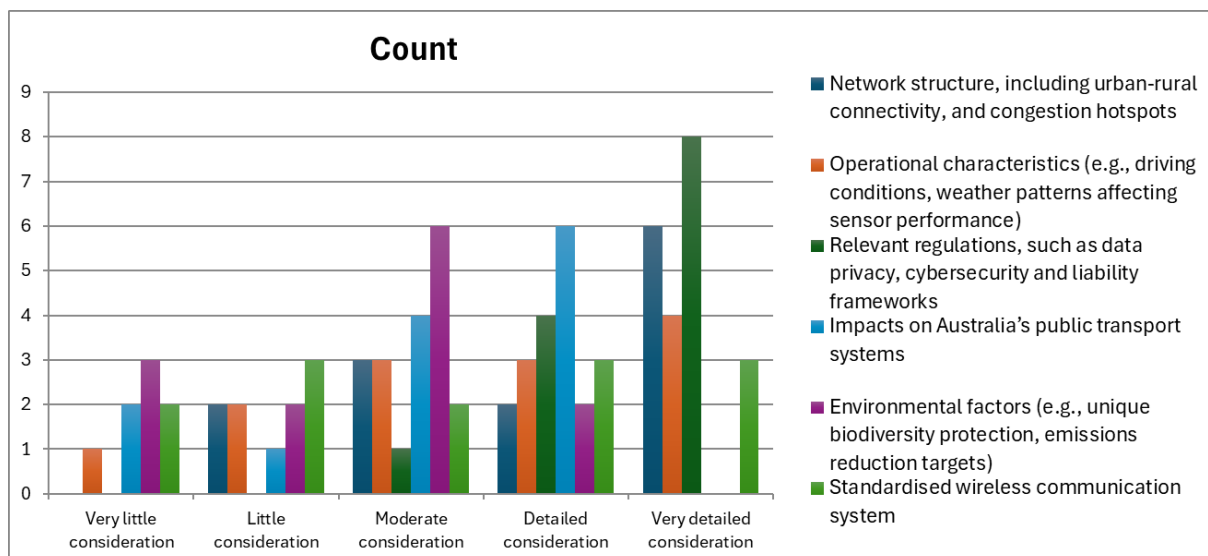
"Safety".

"Geopolitics / global market forces could have a strong influence, as well as the manufacturing origin of the vehicles used by Australians".

"Sensor development and other off-board energy cost reductions will have the biggest impact on penetration. AI and machine learning may assist but aren't an important factor next to the first two".

Q3: What key elements of Australia's transport systems and environment will require specific considerations ahead of the adoption of CAVs?

Participants' responses:



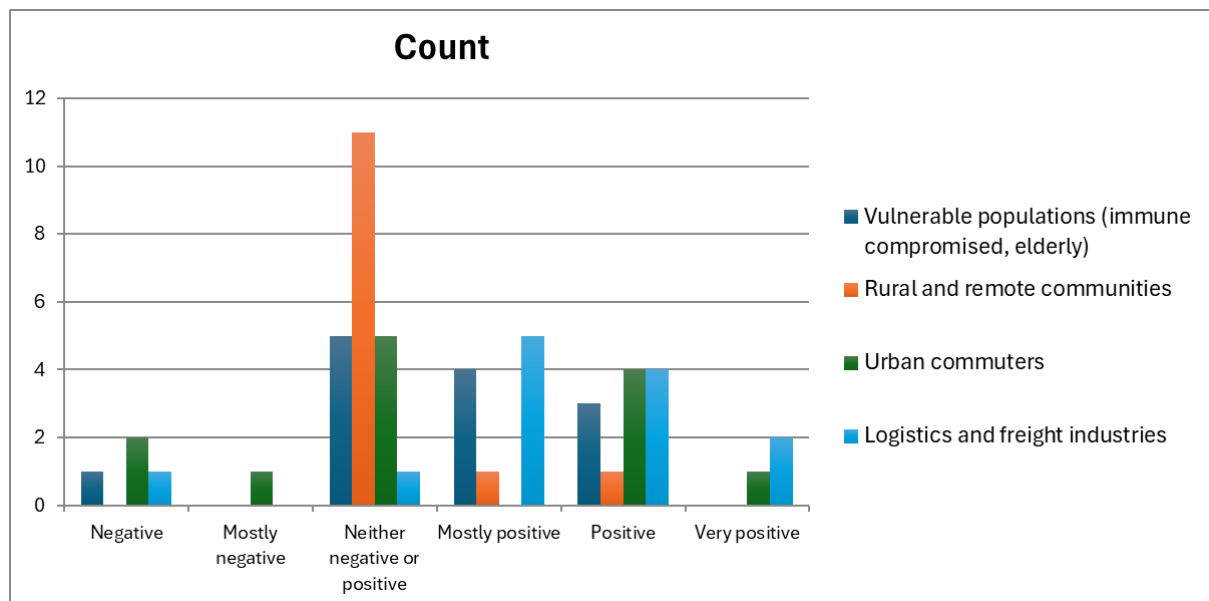
Participants' other comments:

"We don't think it is a useful expenditure of effort and money. This is a distraction from actual improvements in the transport system".

"We need a national approach to the provision of data, starting with governments adopting a harmonised system for sharing speed and road hazard data. This is the backbone to enabling real-time road safety info now and for future CAVs".

Q4: How will the potential environmental impacts of CAVs (emissions, energy reduction etc) affect the following groups?

Participants' responses:



Participants' other comments:

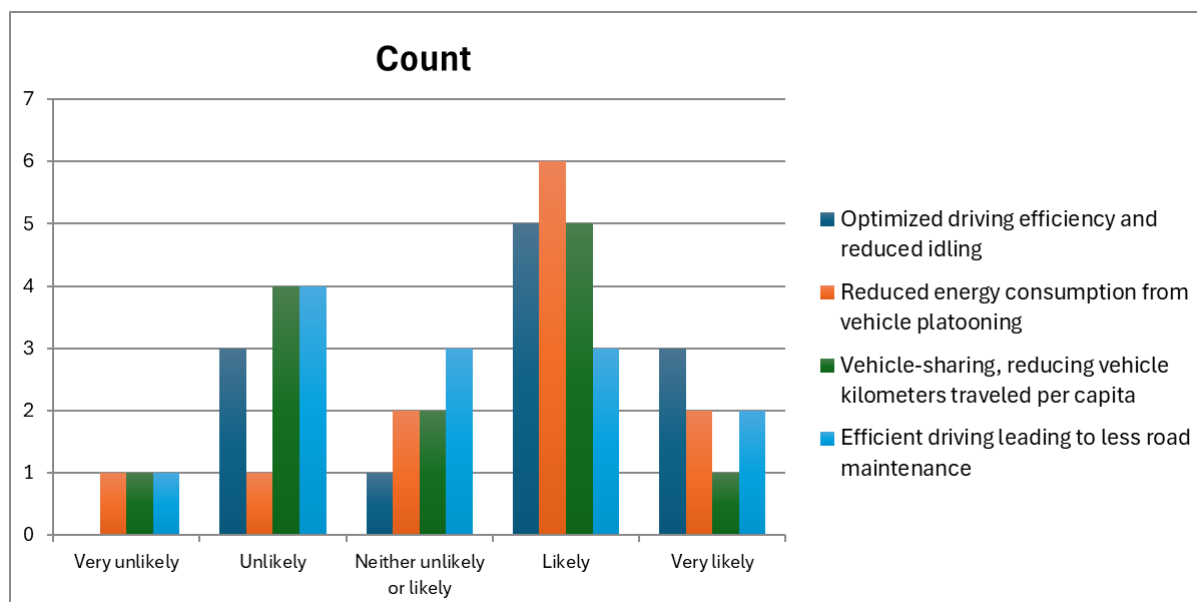
"This really depends on how it is implemented".

"Any environmental benefits should flow pretty much across the community. Downside impacts such as tyre particulates are likely to be concentrated in urban areas".

"This is all dependent on emission policies but we're going to see increased energy usage to deploy CAVS with the amount of datacentre reliance there will be initially. I can't see this changing in the initial 10 years of deployment".

Q5: In your view, what additional environmental benefits could automation offer beyond those achieved through vehicle electrification?

Participants' responses:



Participants' other comments:

"All of the above are entirely dependent on whether you adopt a road user pricing mechanism".

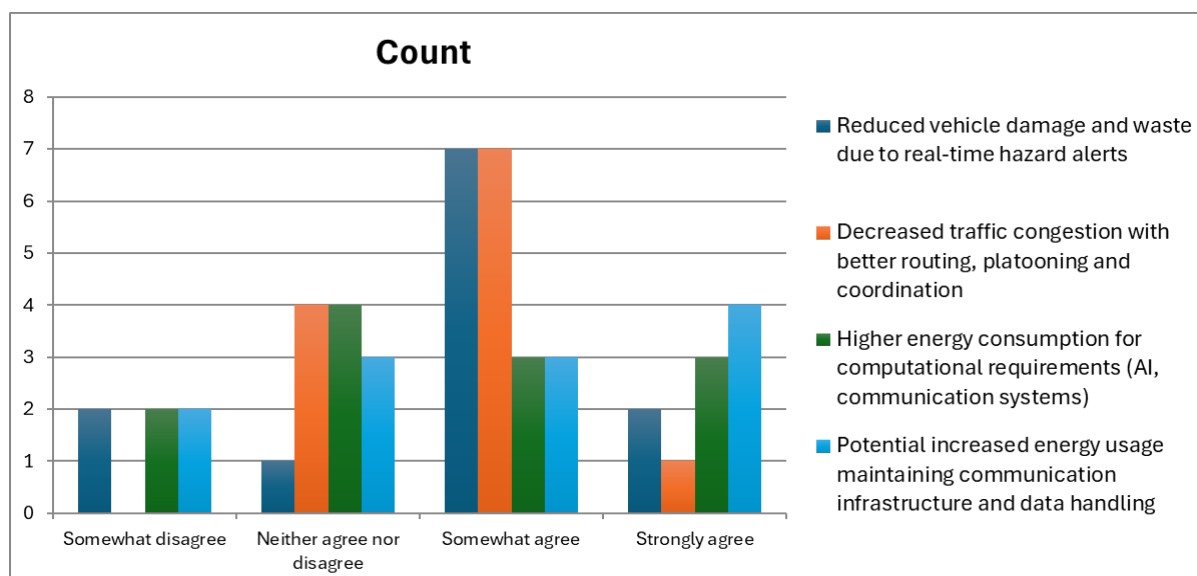
"Reduced need for parking; a range of driving optimisation opportunities including green waves and green light optimisation".

"Safety".

"The first option makes no sense. If you assume electrification is there and asking for benefits that CAVS brings on top, then idling isn't a thing. Platooning is a red herring for Australia, we have road trains".

Q6: In your view, what environmental outcomes are associated with increased vehicle connectivity (i.e., V2V, V2I and V2X) independent of the vehicle automation technologies?

Participants' responses:



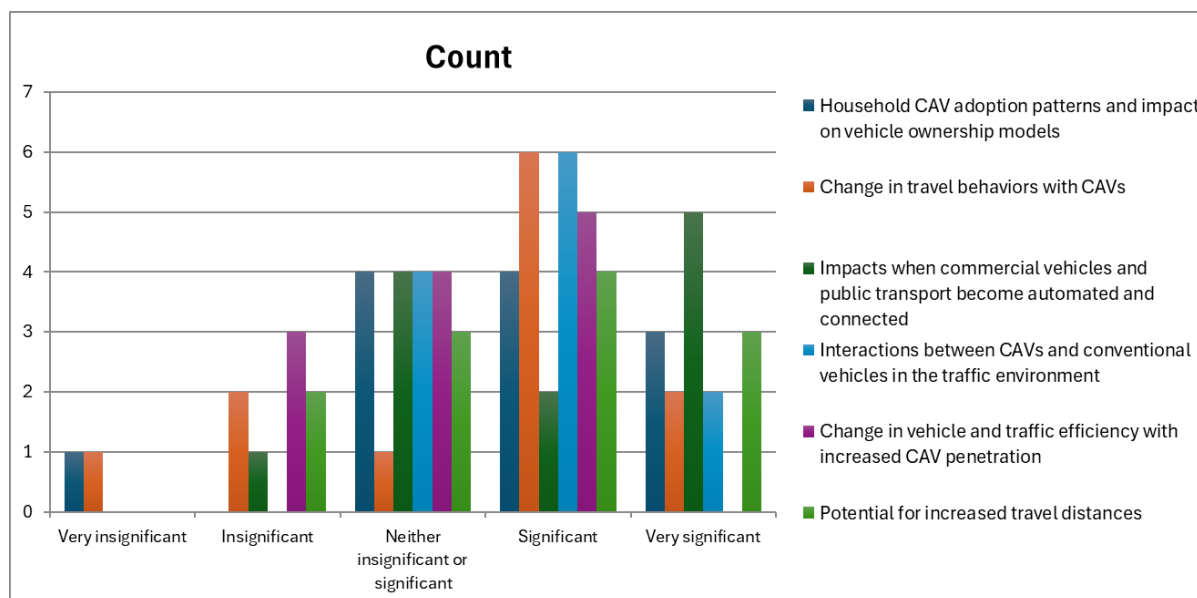
Participants' other comments:

"Freight priority at traffic lights - smooth traffic flow, reducing emission from heavy vehicles as they do not need to stop (include ICE heavy vehicles while we transition to electric; improved traffic flow for the remainder of the fleet reducing energy consumption and smothering traffic as they are not stuck behind trucks that stop and take time to accelerate; Emergency vehicle pre-emption at traffic lights - reduced adverse incidents and getting to the incident more quickly. Smoother driving and energy efficiency benefits public transport vehicles such as buses - green light priority, improving on-time performance; smoothing the ride and improving the ride and experience for passengers; and reducing energy consumption by public transport vehicles".

"These are all contingent on all the vehicles in the national fleet having these capabilities - and this is implausible".

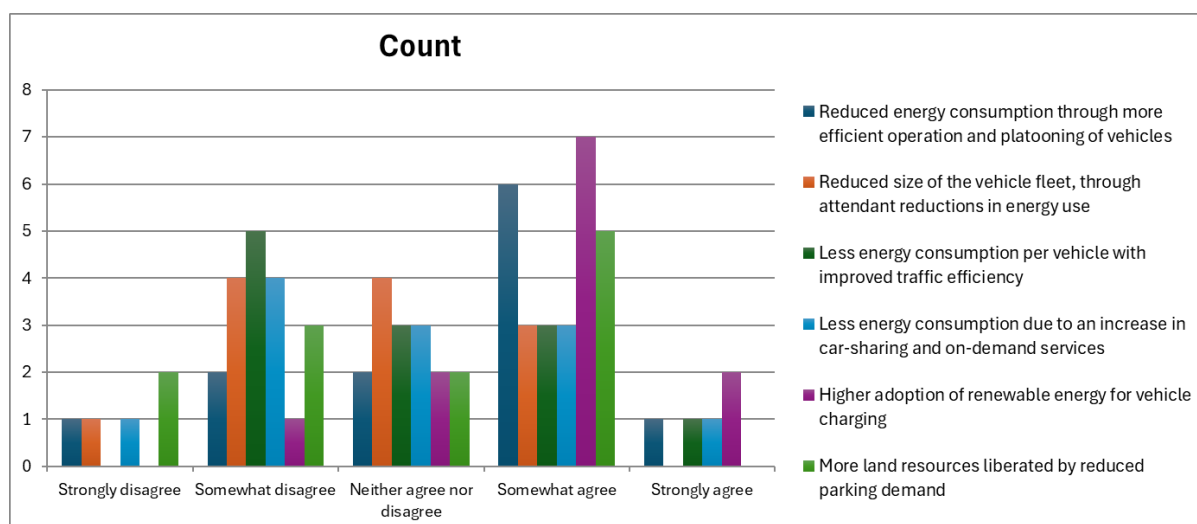
Q7: In your view, how significant are the following additional environmental implications of the CAV transition?

Participants' responses:



Q8: International investigations have suggested that the CAV transition could have positive effects on the environment. In your view, which effects will apply to Australia's environment?

Participants' responses:

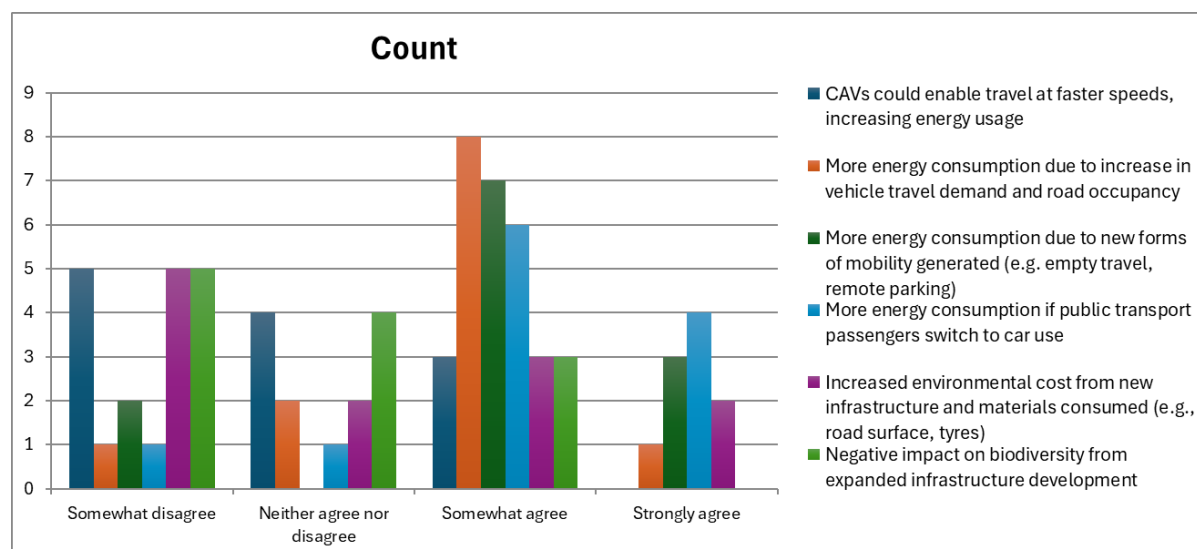


Participants' other comments:

"Most of these are contingent on reducing vehicle ownership and this is a very big assumption unless governments mandate a regular reduction in car parking levels - and there is no sign this is happening or going to happen".

Q9: International investigations have also considered the potential negative impacts of CAVs on the environment. In your view, which impacts will apply to Australia's environment?

Participants' responses:

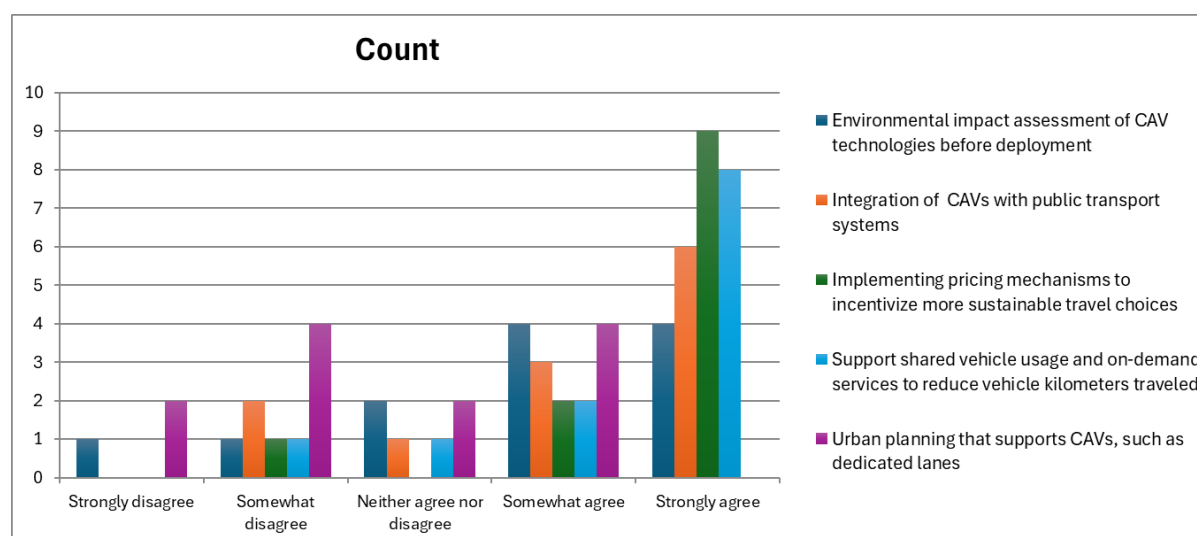


Participants' other comments:

"You've got no option for the increased energy usage due to data centres. Short term, CAVS will be highly dependent on these until AV-specific ICs reach maturity and open-distributed networking is prevalent for connected vehicles".

Q10: In your view, which of the following mitigation solutions, recommended in international studies, should Australian policy makers consider?

Participants' responses:



Participants' other comments:

"If we were going to do the last one, then we should expand it for buses way before CAVs. The hypocrisy of that suggestion is unreal".

Q11: If possible, please share any information about real-world projects (e.g., name and link of the project) on existing new vehicle trials or early deployment areas that can inform environmental impact assessments of connected and automated vehicles. [Note: Suggestions for potential examples could include details on test beds, regional trials, or public-private partnerships in connected and automated vehicle technology deployment.]”

Participants’ responses and suggestions:

“For more detail and scenario-modelled assessment of many of the impacts identified in this survey see Infrastructure Victoria’s Advice on Automated and Zero Emission Vehicle Infrastructure and supporting technical reports available at

<https://www.infrastructurevictoria.com.au/resources/advice-on-automated-and-zero-emissions-vehicles>”.

“Check Testing and Pilot Projects conducted at AIMES (Melbourne), FMTRC (NSW), MCity, KCity, CETRAN, CAVWAY, Millbrook Proving Ground”.