



Potential Impacts of Connected and Autonomous Vehicles

Thought Piece

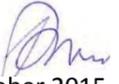
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Document Quality Statement

Principal	Auckland Transport	
Project title	Potential Impact of Autonomous and Connected Vehicles	
Project number	7519A1	
Version status	Final	
Project Manager	Greg Langton (Synergine Group Limited)	
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POTENTIAL IMPACTS OF CONNECTED AND AUTONOMOUS VEHICLES

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Executive Summary

Connected and autonomous vehicle (CAV) technology may provide new forms of urban transport and offer substantial benefits to improve the performance of the existing transport network. If the promised benefits of CAV technology are realised, there is potential to reduce the number of fatalities and injuries from vehicle accidents, reduce the environmental impacts of road transport, make efficient use of the space on road networks, and provide more accessible transport options to non-drivers. By anticipating the impacts of CAV technology, Auckland Transport can understand the implications of current investment decisions, and how the introduction of CAVs may be managed to optimise benefits and improve the performance of Auckland's transport network.

Development and uptake of new technologies is unpredictable, and depends on the complex evolution of a 'system of systems'. Interdependencies and the relative rates of change across systems play an important role, as transport preferences and behavior can change rapidly, while infrastructure networks adapt over longer timeframes. The precise nature and trajectory of CAV technology development and deployment is uncertain and likely to be non-linear, due to the wide range of vehicle forms and ownership models in which CAV technology may be applied.

Anticipating the rate of CAV transition is also uncertain. Current market intelligence suggests that the vehicle fleet transition to CAV technologies may take several decades, however the potential for unanticipated technological leaps, or barriers to progress, could significantly affect these estimates. From early stages of the fleet transition, safety, environmental and accessibility benefits can be generated, increasing in proportion to the share of fleet uptake. The capacity benefits of reconfiguring road space or platooning vehicles require at least 50% fleet uptake to generate substantial benefits. A 50% fleet transition to CAVs is predicted to arrive by 2055 (Litman, 2015), and could enable a 22% improvement in effective road capacity. By 2075 the entire fleet is predicted to have shifted to CAV technology, generating an estimated 80% road capacity increase (Shladover, Su, & Lu, 2012).

The predicted timeframes for fleet transition indicate that current investment plans to upgrade and expand transit and roading infrastructure will remain important to support Auckland's growth. The nonlinear nature of technological development creates uncertainty around the actual rate of uptake.

However, the role of transit services in leveraging the capacity of the existing network in the coming decades remains important. While platooning CAV technology offers moderate road capacity improvements relative to other transport modes, these may not be realised for at least 40 years. Given the unpredictable trajectory and rate of technology development, ongoing research and stakeholder engagement are important to guide investment decisions for the next 20-30 years.

The trajectory of CAV uptake and resulting mix of ownership models will be important to determine infrastructure impacts. Private provision of 'mobility as a service' using CAV technology could rapidly accelerate the rate of fleet transition. The likelihood of this model advancing is underpinned by the rate at which the cost of technology falls, the viability of the New Zealand market, and the adequacy of legal and insurance provisions.

Since CAV technologies could eliminate the parking, time, and vehicle ownership costs of travel, offering a flexible point-to-point service, this may affect the relative competitiveness of both rapid transit and private vehicle transport. In the absence of a managed approach by infrastructure providers, CAV technology could significantly increase the demands placed on transport infrastructure, and may limit the viability of some transit modes in the long term. However, high-capacity transit services will likely remain an important part of the transport network to ensure efficient movement of people during peak hours.

Under certain scenarios explored in this thought piece, significant uptake of single-occupant CAVs (without a reduction in vehicle size) could substantially increase trip generation and demand for roading infrastructure. In the absence of road pricing or prioritisation this may be detrimental to the transport network's overall level of service, in terms of enabling reliable and efficient movements across the city.

There remains uncertainty around the effects of CAV technology on travel behavior, and the resulting future of transport with these new technologies will likely be shaped by the strategic behavior of transport providers and vehicle manufacturers, as CAVs are transitioned into the market. Risks around the resilience of CAV fleets providing urban transport services (in place of private vehicles) and the inter-operability of technical systems, should be considered further to safeguard the transport network against disruption or mass failure.



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Introduction

The future of how we travel in cities could change dramatically with the introduction of CAV¹ technologies enabling more accessible and flexible transport services, and reducing the rate of death and injury from transport incidents.

This paper discusses the potential implications of CAVs for current transport investment plans, and addresses how the transformative impacts of CAVs may affect investment decision-making, and how the strategic aims of Auckland Transport can be achieved.

Vehicles may be ‘connected’ or ‘autonomous’, independent of one another. This paper has specifically focused on the convergence of these

technologies as the combined impact offers the most significant transformative benefits for transport services. This is a critical assumption underpinning the scenarios and impacts explored throughout the document.

The autonomous aspect of CAV technology is best understood as a spectrum of capabilities, outlined in Table 1.

Many current vehicle models already include a number of Level 1 or Level 2 semi-autonomous functions. These vehicles already operate on public roads, and technologies will likely progress along the spectrum toward Level 4, as costs decrease and the technological capabilities are refined.

TABLE 1: LEVELS OF VEHICLE AUTOMATION (RAND CORPORATION, 2014)

Automation	Capabilities
Level 0	No Automation <i>The human driver is in complete control of all functions of the car.</i>
Level 1	Function Specific Automation <i>One function is automated.</i>
Level 2	Combined Function Automation <i>More than one function is automated (e.g., steering and acceleration), driver must remain attentive.</i>
Level 3	Limited Self-Driving Automation <i>The driving functions are sufficiently automated that the driver can safely engage in other activities.</i>
Level 4	Full Self-Driving Automation <i>The driving functions are sufficiently automated that the vehicle can operate without a human driver¹.</i>

¹ Autonomous technologies are defined as those which enable vehicles to perform certain functions without a human driver, and are categorised from Level 0-4. Connected technologies are defined as those which enable vehicle-vehicle and vehicle-infrastructure communications, to support safe operation of vehicles and optimise traffic flows (KPMG, 2015). Connected and Autonomous Vehicles (CAV) refers to any combination of these technologies.

² Level 4 includes the core Level 5 automation capabilities published in alternative classification systems.

WIDER TRANSFORMATIONS FOR URBAN MOBILITY

Connected and autonomous vehicles are part of a wider transformation in the way we travel, communicate, and live in cities. As a complement to new power systems, engine design, safety systems and vehicle forms, CAVs could provide safer and more accessible transport services, support a shift to new energy sources, and substantially change how transport infrastructure is used. The nature, extent and time scale of this change is unpredictable.

The shift to CAV technology could take a variety of forms, which may be adopted over different time horizons. Current testing illustrates the diversity of options, with vehicles ranging in size from single-occupant ‘pods’, similar to the LUTZ Pathfinder or Hitachi Ropits (illustrated in Figure 1 and Figure 2), to full-size transit vehicles, such as the Yutong driverless bus (Figure 3).

The wider transformations and potential adoption scenarios of CAV technology are likely to affect transport infrastructure needs, urban planning, and the business models of private firms and transit providers. Testing of driverless cars by SMART (Singapore-MIT Alliance for Research and Technology), in a Singapore business park showcases the potential of new autonomous and connected vehicles to support a transformative change in mobility and how urban spaces are used (LTA, 2014).

New business models are being developed as a diverse range of companies are currently designing new autonomous vehicles and transport services to capture new sources of value which may disrupt current automotive and transport business models. Private firms including Google, Uber and Amazon are investing in autonomous technologies, looking to re-shape their business operations around new opportunities for autonomous transport. The broader transformation highlights that both the extend and nature of demand for transport infrastructure are shifting as a result of CAV technology, and infrastructure providers should anticipate potentially disruptive changes to urban transport.



FIGURE 1 – LUTZ PATHFINDER [PHOTO: TSCATAPPAULT.ORG.UK]

FIGURE 2 - HITACHI ROPITS [PHOTO: GUARDIAN.COM]



FIGURE 3 - YUTONG DRIVERLESS BUS [PHOTO: ZYNEWS.COM]

RATIONALE FOR SCENARIO DEVELOPMENT AND EVALUATION

The purpose of this thought piece is to outline and explain the potential impacts of CAV technologies on current and planned transport investment, specifically for rapid transit and major roading upgrades. The impacts are assessed in the context of Auckland Transport’s strategic goals and current investment plans, as outlined in the Integrated Transport Programme (ITP).

Historical development of disruptive technologies, including the internet, smartphones, and private automobiles illustrates how the implementation of new technologies is a non-linear, unpredictable and inherently complex process. Technological development is shaped by a ‘system of systems’ and the interdependencies between technical, behavioural, economic and political drivers are important to determine how a system is used and the trajectory of development.

Figure 4 illustrates the guiding framework for understanding the dependencies between multiple systems that are influenced by new technologies, and shows the critical linkages between parameters in different systems.

Rates of change vary widely across systems; preferences and travel behavior of firms and households can shift rapidly, while infrastructure networks and regulatory changes occur over significantly longer timeframes. Understanding the intermediate linkages between technological capabilities, travel behavior, aggregate travel demand and the corresponding infrastructural requirements is important to gauge the sensitivity of parameters across these systems.

Developing an understanding of the interdependent relationships between technological capability and travel behavior will be critical in determining the trajectory of technological development, as illustrated by the feedback effects in Figure 4.

The extent and nature of the benefits of CAV technologies, and the induced changes in travel behavior, may reinforce certain applications of the technology and likely scenarios that arise.

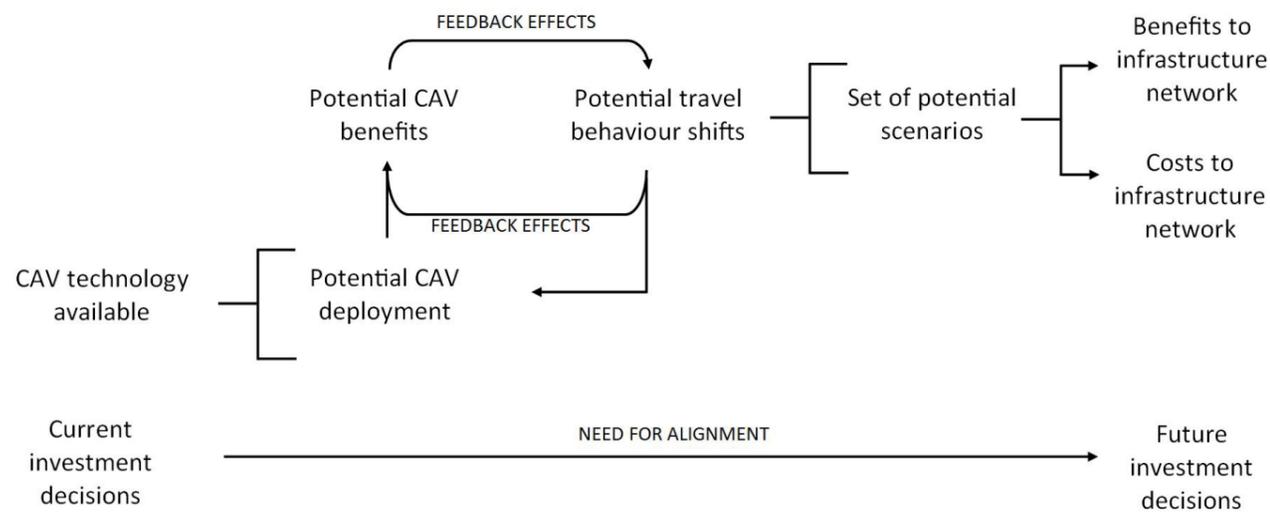
Alignment of current and future investment decisions, to ensure that current decisions allow for the future shifts driven by CAV technology, is key to capturing the potential benefits to the transport network.

Plausible and likely future scenarios are hypothesised, based on the current direction of technological development and testing and market observations.

The possible forms of implementation and transition pathways are outlined in each scenario, and linked to the potential benefits that may be achieved at different levels of fleet uptake.

Scenarios are used to understand the likely impacts on transport infrastructure, and evaluate how CAV technology may affect the viability of investment into rapid transit networks and major roading upgrades. Consideration is given to the critical parameters and assumptions within each scenario, and how sensitive the outcomes may be.

FIGURE 4 – GUIDING FRAMEWORK FOR EVALUATION



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Potential Benefits and Implementation Options

The potential benefits of CAV technology are outlined in Table 2. As shown, specific benefits are attributable to either autonomous or connected vehicle technology, and some require both types of technology working together. Connected vehicle technology encompasses vehicle-vehicle, vehicle-infrastructure, and vehicle-device communication systems that assist vehicle navigation and enable real-time data feedback for intelligent transport systems. A range of terminology has been used; ‘connected and autonomous vehicles’ provides an appropriately broad and representative definition for what these technologies could enable.

TABLE 2 - POTENTIAL BENEFITS OF CAV TECHNOLOGY

Technologies required	Nature of potential benefits	Key parameters influencing extent of benefits
Safety		
Autonomous Connected	Safer operation of motor vehicles using lane-keeping, adaptive cruise control, adaptive blind spot assist, “attention assist”, adaptive headlight technology.	Potential ‘risk compensation’ behaviour. Regulatory requirements for safety features.
Environmental benefits		
Autonomous	Improved fuel economy and reduced emissions as autonomous vehicles operate more efficiently.	Regulatory requirements for autonomous technology.
Efficient use of transport infrastructure		
Autonomous Connected	Eliminate the need for a driver, reducing a vehicle’s size and space requirements.	Size and physical forms of CAVs introduced.
Autonomous Connected	Reduced labour costs for public and private passenger transport services.	Public investment in CAV transit vehicles.
Autonomous Connected	Eliminate the need for vehicles to park at proximity to the occupants’ destination.	Mode shift from current private vehicle users to car-sharing or private CAVs.
Connected	Potential for vehicle platooning, reducing following distances between vehicles.	Inter-operability of vehicles and infrastructure systems to support platooning capabilities across the road network and vehicle fleet.

Technologies Required	Nature of potential benefits	Key parameters influencing extent of benefits
Efficient use of transport infrastructure		
Autonomous Connected	Reconfiguration of road space, dynamic lane reversal.	Uptake of CAV technology. Physical form of CAVs.
Autonomous Connected	Shift to car-sharing of CAVs in place of private ownership, reduce total fleet requirements.	Private sector investment Reliability and resilience. Special travel needs driving car-ownership decision.
Accessible and flexible transport services		
Autonomous	Transport services available to non-drivers (elderly, disabled, children).	Pricing of CAVs or CAV services will influence access to non-drivers.
Autonomous	Autonomous vehicles undertaking delivery and monitoring services.	Business models of private firms Pricing of CAVs.



POTENTIAL IMPLEMENTATION MODELS

A key possibility created by CAV technology is the development of new models for transport provision. Using CAVs to provide ‘mobility as a service’ in the form of vehicle-sharing, ride-sharing, or autonomous delivery and monitoring, creates new incentives for firms to manage their travel and freight needs. This may shift travel and consumption behavior as

individuals have more options to access goods and services, and reduced travel costs (time and monetary costs) in cities. There are also significant potential improvements to network efficiency, incentivising public providers to support the use of CAV technology in various forms.

OWNERSHIP MODEL: VEHICLE OR RIDE-SHARING SERVICE PROVIDER

Vehicle options	Large CAV	Small CAV	Single-occupant CAV	Delivery or monitoring vehicle
	Five occupants Vehicle-sharing	Two occupants Vehicle-sharing	Vehicle-sharing	No occupants

Infrastructure impacts:

Effective lane capacity	Net impact depends on mode shifts from transit and private vehicles. It is estimated that the same amount of travel could be achieved with 80-90% fewer vehicles (Claudel & Ratti, 2015), before accounting for induced demand. Increased lane capacity for smaller vehicle sizes, relative to traditional private cars.	Increased lane capacity; also potential to shift delivery trips to off-peak times to spread load.
Parking demand	Requirements for pickup and drop off points. Reduced demand for central city parking space.	
Travel behaviour	Increased demand; shift from current transit and private vehicle users as car-sharing enables car use without necessitating the cost of owning and maintaining a car. Provides an alternative to non-drivers who currently depend on transit services.	Potential impact on the business models for freight and corporate firms, shifting the timing and labour cost of trips.

OWNERSHIP MODEL: TRANSIT OPERATOR

Vehicle options	Automated, high-capacity bus	Large shuttle	Small shuttle
	40-60 occupants ride-sharing	8-15 occupants ride-sharing	4-7 occupants ride-sharing

Infrastructure impacts:

Effective lane capacity	Increased capacity for high-capacity arterial routes. Potential implementation as Bus Rapid Transit (BRT).	Large increase in capacity where service cost or convenience induces a shift from private vehicle to shuttle.	Moderate increase in capacity where users shift from private vehicle to shuttle.
Parking demand	Requirements for pickup and drop off points.		
Travel behaviour	Potential induced demand resulting from improved level of service, particularly during peak hours.		

OWNERSHIP MODEL: PRIVATE OWNERSHIP AND USE

Vehicle options	Large CAV	Small CAV	Single-occupant CAV	Delivery or monitoring vehicle
	Five occupants	Two occupants		No occupants

Infrastructure impacts:

Effective lane capacity	Overall impact depends on shift of users from transit to vehicle sharing, and private ownership to vehicle sharing. Backhaul trips likely to increase the amount of travel on roads. Very small single-occupant CAVs may enable reconfiguration of roadspace, potential implications for transport and land use planning where a full-sized lane may not be required.	Increased lane capacity; also increases potential to shift delivery trips to off-peak times (ie. overnight) to spread load.
Parking demand	Potential to shift parking capacity to lower-value locations, reducing demand for CBD parking.	Minimal parking requirements.
Travel behaviour	Potential substitute to rapid transit; provides an alternative to non-drivers or current transit users who perceive an improved level of service from using a private vehicle. May also be used for delivery trips that are currently not worthwhile for people to make; potential for increased travel demand.	May be used for trips that are currently not worthwhile for people to make; potential for increased travel demand.

Timeline for Available Technology

The estimated availability of CAV technology, and subsequent uptake by different vehicle forms, is summarised based on a review of market intelligence and existing literature.

Deployment of CAV technologies is likely to emerge in multiple forms, for which the time horizons for technological development will vary, and current estimates are highly uncertain. Figure 5 indicates the predicted emergence of CAV types, based on market surveys and estimates (Bertoncello & Wee, 2015; IEE, 2014; Litman, 2015).

The trajectory that CAV technology follows will be shaped by the relative rates of change for interdependent parameters; including the pace of technological development, fleet turnover, and timing of investments by public infrastructure agencies and private transport service providers.

Lower-capacity autonomous transport modes appear to be developing more quickly, which implies that fleet transition may see private CAVs or vehicle-sharing CAV services with higher share of uptake in the next two to three decades.

FIGURE 5 - PREDICTED TIMEFRAMES FOR WHEN TECHNOLOGY WILL BECOME AVAILABLE

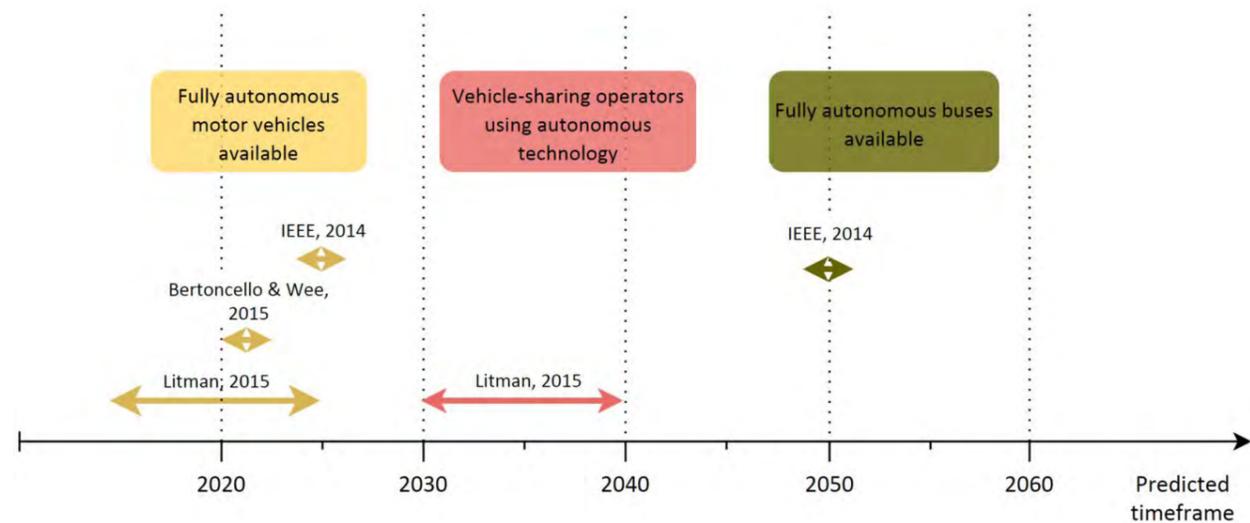
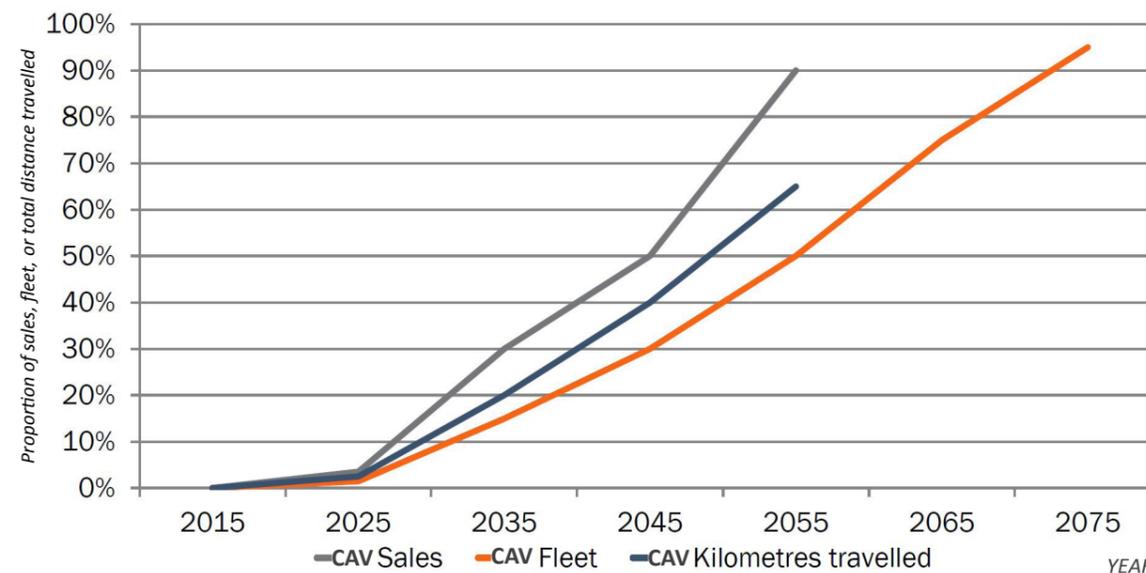


Figure 6 illustrates the predicted trajectory of new CAV sales, overall fleet share, and kilometres travelled by CAVs. The aggregate level of fleet uptake, determined by these factors, will likely lag behind the share of new vehicles sold with CAV technology. However the potential for CAVs to provide transport services for more than one 'owner' suggests that they may account for a

higher proportion of the total travel on roads, compared to traditional vehicles. Therefore, while the proportion of total fleet transition may lag behind the share of new sales with CAV technology, this may be counteracted by CAVs producing a higher share of total vehicle travel. Figure 6 shows the predicted trajectory of these parameters.

FIGURE 6 - PREDICTED TRANSITION OF NEW CAV SALES, OVERALL FLEET SHARE, AND TOTAL KILOMETRES TRAVELLED BY CAVS (ADAPTED FROM (LITMAN, 2015) (FEHR & PEERS, 2014))



ROLE OF STAKEHOLDER ENGAGEMENT

Engagement of relevant stakeholders from the early stages of transition is an important consideration for Auckland Transport. Investment and planning co-ordination across public sector agencies, private firms, and community engagement is critical to ensure the benefits of CAV technology are properly identified and can be captured in coming decades.

The following key stakeholders may be engaged at an early stage to guide and co-ordinate investments and planning.

POTENTIAL STAKEHOLDERS (adapted from ERNST & YOUNG, 2014)

- Vehicle manufacturers
- Suppliers
- Insurance providers
- Technology and telecommunications companies
- Government and regulatory bodies
- Dealers and retail networks
- Integrated mobility providers, including vehicle-sharing companies
- Emergency services

THE EXTENT OF BENEFITS ALONG THE TRANSITION

Given the length of timeframes estimated for transitions to CAV technology, the extent of benefits available at different levels of uptake is important. Based on existing literature and modelling, predicted benefits are outlined according to the type of benefit realised.

Where the rate of uptake is difficult to predict, adaptive planning processes that monitor and evolve according to the rate of progress may be useful to manage uncertainty around the timing of technology availability and uptake.

ROAD CAPACITY IMPROVEMENTS

Preliminary modeling for the capacity improvements offered by vehicle platooning, based on decreased following speeds and reductions in the space required for vehicles on the road network, suggests that following could be achieved (Shladover, Su, & Lu, 2012):

- 22% capacity improvements with CAV's at 50% of fleet
- 50% capacity improvements with CAV's at 80% of fleet
- 80% capacity improvements with CAV's at 100% of fleet

These figures do not account for the potential impact of induced demand, and the net improvement in travel time and reliability is uncertain. Relative to the capacity improvements of shifting transport mode share to other modes, these benefits are moderate and imply that the predominant advantage of autonomous

vehicles may be in providing flexible and on-demand services, rather than improving trip capacity at peak hour. Current lane capacity is approximately 2,000 people per hour for mixed traffic, 9,000 people per hour for buses, and 20,000-43,000 people per hour for bus rapid transit. The maximum estimated capacity improvement for CAVs would increase road capacity to 3,600 people per hour; substantially lower than that provided by bus.

Implementation of CAVs for car-sharing and ride-sharing services are hypothesised to reduce the total vehicle fleet required for a given number of trips, however the potential induced demand could counteract these effective capacity improvements.

ACCESSIBILITY OF TRANSPORT SERVICES

CAV technologies could enable greater service provision to non-drivers, by enabling flexible, on-demand, point-to-point trips. This holds particular value for elderly or disabled users who may have limited ability to use existing transit services.

The cost of CAV services is important in determining the benefits to accessibility; as long as it is a premium service, a large proportion of the population may be unable to benefit from the improvement in transport services. Where private providers are responsible for a large proportion of urban transport services, there may be a role for transit agencies to provide regulation or subsidies to ensure equitable access for lower-income groups.

Additionally, use of autonomous technology for transit can break the relationship between labour costs and the frequency of transit services (Cottrell, 2006), offering substantial opportunities to increase transit service frequency without a proportional increase in costs.

Targeted implementation of CAV technologies for these uses could generate significant benefits at any stage of transition; however the estimated timeframe for autonomous bus services is 35 years (IEEE, 2014).

Changes in the business models for freight and courier providers could also arise from CAV technology, enabling more cost-effective delivery services.

SAFETY BENEFITS

The benefits of safety improvements are likely to increase in proportion to the level of fleet uptake.

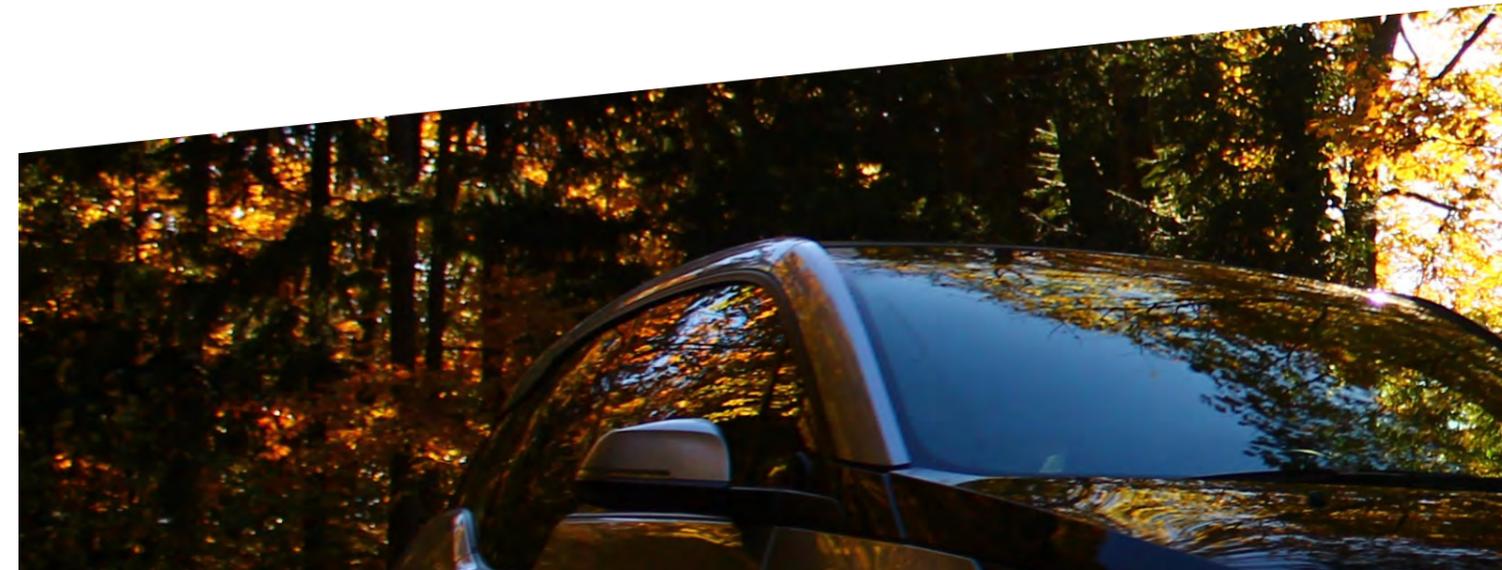
A potential barrier to the safety benefits of CAV technology is the effect of 'risk compensation', whereby safety improvements lower the perceived risk of operating a motor vehicle, inducing more risk-taking behavior by drivers than before the improvement (Aschenbrenner & Biehl, 1994).

This could pose a risk in the 'mixed fleet' stage of transition where traditional vehicles are sharing the roads with semi-autonomous and autonomous vehicles. Requirements for the comfort of vehicle occupants may limit the capacity benefits of CAV technology, where limited acceleration and deceleration rates reduce the potential throughput capacity, particularly at intersections (Le Vine, Zolfaghari, & Polak, 2015)

ENVIRONMENTAL BENEFITS

CAV technologies enable environmental benefits from improved fuel economy and reduced emissions, as autonomous or semi-autonomous vehicle operation is

more efficient than human operation. These benefits may be realised at all levels of fleet transition.



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Potential Future Scenarios

Four future scenarios are hypothesised, based on the variety of ownership models and vehicle forms that may be used to implement CAV technology.

Scenarios were developed using the various ownership and implementation models as a guide, since these models will be optimised according to the value proposition for private firms, public sector agencies and individual travellers. These value propositions may determine the timing of investments, relative risks taken by each party, and the rate at which costs of different services might fall.

The likely reality may be a combination of these scenarios, depending on the timing and risk-taking behavior of different entities as they implement CAV technology to capture market share and shift travel behaviours.

Note: Scenario A is a likely transition phase for all scenarios, while the cost of technology remains high or regulatory provisions are still under development. The possible length of this phase is uncertain, and may hinge on the interdependence between legal, economic, and technical systems to produce a CAV product or service that is safe, reliable, affordable, and with provision for accident risk.

For each scenario, the likely impacts on travel behavior are summarised, alongside the critical assumptions and parameters underpinning the scenario. The section following the scenarios will explain how the impacts of each scenario highlight the implications of CAVs for major investments in rapid transit and roading upgrades.

SCENARIO A

Uptake of CAV technology initially grows rapidly, however barriers to widespread implementation limit use to specialised functions. The level of CAV uptake plateaus after ten years, accounting for less than 5% of kilometres travelled.

Following rapid uptake of CAV technology over the next ten years as an indication of technology 'leadership', by corporates and wealthy road users, persistently high costs of CAV technology, lack of public acceptance, inability to obtain insurance coverage, or other barriers limit the uptake beyond a small share of total vehicle travel. The aggregate effect on the transport network is minimal as long as CAV technology remains as a specialized, premium product.

Impacts: Minimal impact overall. CAV technology remains an expensive and specialised product, used mostly by wealthy travellers or specialized commercial uses.

Critical assumptions: Barriers to uptake are significant, and uptake cannot progress beyond a low level despite strong investment and market-driven incentives to drive the new technology. Other scenarios will likely transition through this scenario, and progression of CAV uptake hinges on the price of CAVs reaching an affordable level, technological capabilities that enable the systems to operate and provide a level of reliability and resilience, alongside adequate legal and regulatory provisions to account for the risks of accidents involving CAVs.

Uncertain parameters: The length of time at which CAV technology may remain in this phase is uncertain, although significant investment and testing programmes by a number of vehicle manufacturers and transport providers suggests that competition in the market, and political will, are conducive to rapid development and uptake of CAV technology.

SCENARIO B

CAV technology implemented by car-sharing or ride-sharing operators has the predominant market share for urban travel. 'Mobility as a service' provided by CAVs accounts for approximately 80% of vehicle travel within thirty years.

Private operators of car-sharing or ride-sharing services, such as Uber or Zipcar, introduce fleets of autonomous vehicles to provide on-demand 'mobility as a service'. Leveraging their existing systems infrastructure and customer base, and economies of scale to transition the fleet rapidly, private car ownership falls rapidly and CAVs become the predominant vehicle technology, several decades before initial predictions. Fatal incidents on the road network are dramatically reduced. Large-scale fleet transition supports inter-operability, supporting the use of platooning technology to improve road network capacity.

Impacts: Potential shift from both transit and private vehicle users to car-sharing or ride-sharing services, increasing the number of trips on the road network, although a smaller fleet size may be required to provide the equivalent number of trips. The net impact of improved capacity and better fleet utilisation, with the likely induced demand, is uncertain. Demand for parking infrastructure falls rapidly, enabling re-purposing of road space to allow for other transport modes, or increase of capacity on motorways.

Critical assumptions: This scenario assumes that the relevant policy frameworks, regulation, and insurance provisions have been developed to support the viability of private firms using fleets of CAVs for urban transport services.

Uncertain parameters: The price level and pricing structure of car-sharing or ride-sharing services is uncertain, and may play a key role in determining the shift between transport modes. Road pricing may also factor into the total cost of CAV services. Access to transport services provided by CAVs may be limited for those without smartphone technology, or if the prices are sufficiently high to 'price out' lower income groups. Public transit services may continue to provide key services in this situation.

SCENARIO C

CAV technology in private vehicles has the predominant market share for urban travel, and fleet transition occurs over 50-60 years.

Vehicle manufacturers introduce CAV technologies, and in the absence of substantial investment by car-sharing providers of transit agencies to use CAVs as part of transport service provision, private ownership may take the larger market share for urban travel. Non-drivers, including elderly, disabled, and children, can now make trips that may not have been feasible using transit services, and the safety features of CAVs have dramatically reduced the number of fatal incidents on the road network. The slow fleet transition has created a long time period with a mixed fleet, and vehicles of varying levels of CAV technology.

Impacts:	Demand for parking in central locations may decrease, reducing the cost of trips. The slow transition period results in a mixed fleet of varying levels of CAV technology, creating barriers to inter-operability and hindering potential for vehicle platooning to generate capacity improvements. Trip generation increases substantially, as the cost of travel no longer includes the cost of parking a car at proximity to the occupant's destination. Privately-owned CAVs generate a larger number of backhaul trips, and are used to transport goods as well as people.
Critical assumptions:	This scenario assumes that investments made by private and public transport service providers have not been substantial enough to provide competitive options, relative to private vehicle transport. High levels of private ownership of CAVs requires the cost of new vehicles to fall to a level that is affordable for most individuals or households, and that transit or car-sharing services remain relatively expensive, or offer a lower level of service.
Uncertain parameters:	Pricing of private CAVs will be critical to determine the level of uptake. Where prices remain at a premium, consideration of transport service provision to lower income groups may be necessary.

SCENARIO D

CAV technology is implemented by transit providers, and expansion of the transit network enables it to support approximately 50% of urban travel, within 30 years.

In the form of driverless buses and shuttles, transit providers exploit the potential to increase the coverage of transit networks without a corresponding increase in labour costs. Transit vehicle fleets are upgraded to CAV technology, earlier than initial predictions, and large-scale investment supports inter-operability of systems. This results in a substantial increase in transit network coverage and frequency. Shuttles are introduced alongside bus or bus rapid transit as 'feeder services' to existing transit networks, in more sparsely populated areas.

Impacts:	Improved service coverage for transit services, including bus, BRT or rail modes, may induce a shift in mode share away from private vehicles to transit. CAV technology could enable increased frequency of transit services, improving the relative competitiveness of transit modes. In the case of technical or system faults, transit networks are more susceptible to failure, increasing the requirements for system resilience and redundancy.
Critical assumptions:	The uptake of CAV transit services may ultimately depend on the car ownership rate. Where transit services offer sufficient coverage to remove the necessity of owning a car, this will support the future viability of passenger transit. There is likely also to be a level of competition between CAV car-sharing options and transit.
Uncertain parameters:	Public and political resistance to eliminating transit jobs may be a potential barrier to the introduction of CAV transit vehicles. Recent experiences in a number of cities where resistance to the introduction of Uber is indicative of how organised labour movements and political figures may be unwilling to support the use of CAV technology in these forms.

IMPACTS ON CURRENT INVESTMENT PLANS FOR TRANSIT AND MAJOR ROADING UPGRADES

The implications of CAV technology for current investment plans are summarised below. Transport investments are grouped according to their primary purpose, relating to the performance of the transport network.

Goal of transport investment	Impact of CAV technology
<p>Improving road capacity and safety</p> <p>Additional Waitemata Harbour Crossing State Highway 1 widening Albany to Orewa Pūhoi to Wellsford Motorway SH1 widening Manurewa to Papakura East West Link SH20A, 20B widening Mill Road upgrade</p>	<p>Improvements in the effective road capacity may delay the need for capacity upgrades; unless CAV options induce sufficient travel demand that the effective capacity improvements are counteracted by a greater number of vehicles on the road. The likely net impact is uncertain, and depends on the use of road pricing and regulation. Safety improvements from semi-autonomous or fully autonomous vehicles may reduce the need for road safety improvements.</p>
<p>Improving road network connectivity</p> <p>Western Ring Route SH1/SH18 direct connection ramps East West Link Penlink</p>	<p>CAV technology is not likely to affect the benefits of improving connectivity of road networks, other than augmenting the impact of investments by increasing effective road capacity.</p>
<p>Improving transit travel times</p> <p>City Rail Link Northern Busway extension Southeastern Busway Westfield, Papakura rail expansion</p>	<p>CAV technology in transit vehicles may augment travel time improvements by allowing higher frequencies, however current predictions suggest that autonomous operation of transit vehicle on roads may take up to 35 years to become widely available (IEE, 2014). Where CAVs induce a shift away from transit, benefits of improved travel times may be limited; however the form of CAVs is critical to impacts on network capacity. Transit modes may also provide redundancy in the transport network, in case of technical failure of CAV systems.</p>
<p>Improving transit service coverage</p> <p>City Rail Link East West Link Avondale-Onehunga Rail Extension</p>	<p>Where CAVs induce a shift away from transit, the benefits of improved transit coverage may be limited.</p>
<p>Improved provision for active modes</p> <p>Harbour Bridge pathway Tāmaki Drive boardwalk Southern Motorway cycleway</p>	<p>The nature of active trips, particularly shorter trip length and separation from vehicle traffic, suggests that CAV technology may have little impact on investment into active modes.</p>

TRANSIT INVESTMENT AND CAV TECHNOLOGY

Upgrades to transit services, both for capacity and service coverage, have benefits in increasing the effective capacity across the whole network. Figure 7 illustrates the lane capacity of transport modes, including the potential improvements from CAV platooning at different shares of fleet uptake.

Given the capacity improvements offered by rapid transit modes remain higher than those of CAVs, optimisation of the road network may consider the optimal mix of transport modes, including traditional vehicles, CAVs, transit and active modes to offer the suitable degree of flexibility, peak hour capacity, and ease of travel.

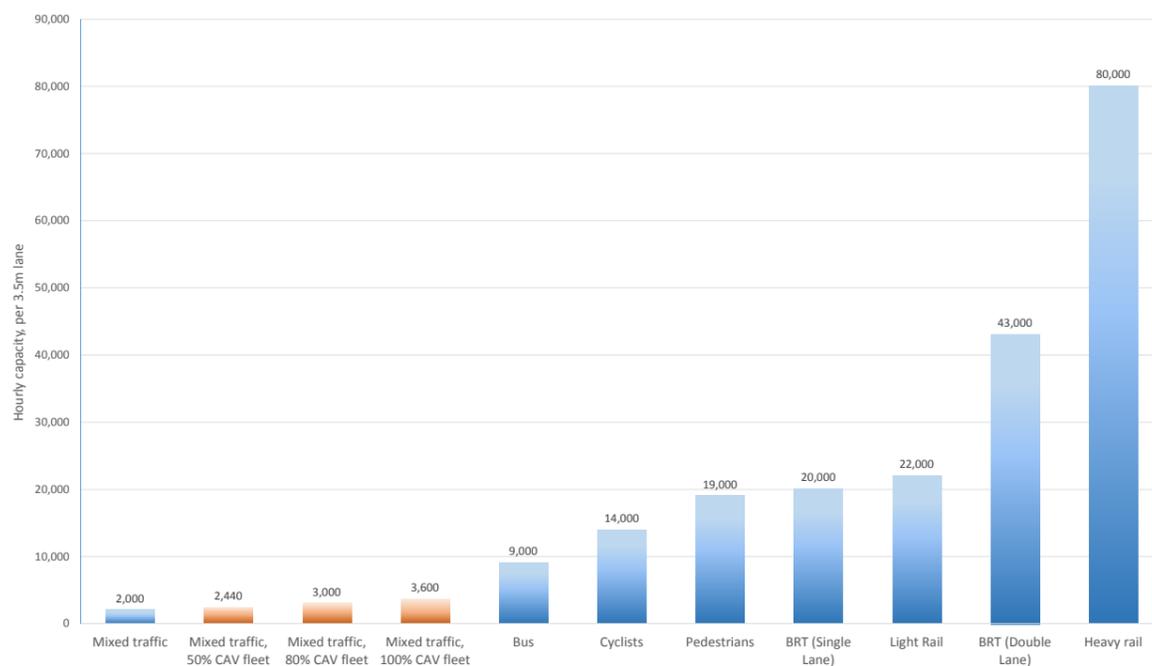
Preliminary modeling tested a range of scenarios, combining either car-sharing or ride-sharing CAVs with the availability of high-capacity public transit services (International Transport Forum, 2015). The results indicated that, for all combinations of ride-sharing or car-sharing services, with or without

rapid transit, travel volumes increased as a result of increased access to transport services created by CAVs. In the absence of high-capacity transit services, weekday travel volumes increased between 22-89% (with a 100% shared CAV fleet) and 60-90% (with a 50% shared CAV fleet).

This modeling work indicates the extent of induced demand that may arise from introduction of CAVs, in the absence of high-capacity transit services. Potential increases in trip generation illustrate why road pricing could play an important role to ensure the continued performance of the transport network, by managing traffic flows to optimise road capacity.

High-capacity transit services will likely remain an important part of the transport network to ensure efficient movement of people during peak hours.

FIGURE 7 - LANE CAPACITY OF TRANSPORT MODES (ASIAN DEVELOPMENT BANK, 2011) (SHLADOVER, SU, & LU, 2012)



KNOWLEDGE GAPS AND UNCERTAIN PARAMETERS

A number of critical parameters remain uncertain, and understanding these better will assist transport agencies to anticipate the effects and time horizons of CAV deployment and take the necessary steps to ensure the performance of the transport network.

- Pricing:** if the price of CAV services are at a premium level and exclude a large proportion of travellers, regulation or subsidies may be necessary to ensure that the safety, environmental benefits and improvements to transport accessibility are captured.
- Ethical issues:** While autonomous vehicles enable numerous safety features to become built-in to vehicle operation, the possibility of situations requiring the automation of decisions driven by ethical considerations is a potential issue. For example, a situation where an autonomous vehicle is faced with a potential collision and must prioritise between the safety of occupants over other road users, could have undesirable outcomes and public resistance, based on societal values around ethics and justice.
- Strategic behaviour:** there are likely to be first-mover and second-mover advantages for both transit agencies and private transport providers in capturing the market for transport services using CAV technology. Understanding Auckland's strategic potential for CAV technology, given our unique geography, market size and structure, and transport infrastructure will be pivotal in advising appropriate policy and regulatory actions to optimise the potential benefits of CAV technology.
- Impacts of demographic shifts on CAV uptake,** particularly as they affect the drivers of transport behaviour.
- Impacts on resilience and the potential impacts of minor or catastrophic failure of infrastructure networks supporting CAV vehicle fleets.**
- Value capture:** individual drivers may invest in CAVs or CAV services to reduce travel times, or for more convenient service, however the environmental or safety benefits (since they comprise both internal and external economic costs) may be less of an incentive for investment. Appropriate regulation and subsidisation may be considered by governing agencies to ensure these wider benefits are captured.
- Understanding the business models for CAV implementation:** drivers of investment decisions by transport agencies, private sector firms, and individual users, will be valuable to understand the relative risks faced by each party, and how infrastructure provision can be used to guide decisions and incentivise efficient use of the transport network.
- Understanding the relationship between vehicle form, levels and types of uptake,** and resulting impacts on travel behaviour is important to comprehend how CAV technology will affect demand for travel, and the potential to tailor the technology to different types and purposes of trips. This has significant potential to optimise use of the transport network.
- Stakeholder engagement:** the engagement process is an important consideration, and may require early action for Auckland Transport to work with other public sector organisations, private firms, and engage with communities to align investment to the needs of Auckland's transport network, and ensure future benefits of CAV technology can be assessed with some measure of certainty.

Conclusions

Scenarios A to D indicate that the future possibilities enabled by CAV technology vary widely. The strategic planning and investment decisions of car manufacturers, transit agencies, and urban transport service providers will be important to shape the future transport services offered by these new technologies. The wide range of future options opened up by CAV technology, and non-linear nature of technological development, also generate uncertainty around the rate and nature of technological transitions.

This uncertainty implies that the actual rate of transition may be substantially faster, or slower, than the estimates referenced in this paper. However, the rate of uptake does not significantly alter the role of rapid transit in leveraging transport network capacity, and current investments will remain important. Ongoing research, monitoring, and stakeholder engagement are important to manage uncertainty in this context.

The benefits of CAVs in improving safety, reducing environmental impacts, and providing more accessible transport services may be realised across the fleet transition to CAV technology, which is estimated to take several decades. However, certain benefits, particularly the potential to re-configure road space and increase the effective capacity of the road network using vehicle platooning, require at least 50% fleet transition for a 22% capacity increase, increasing to an 80% capacity increase for an entirely autonomous vehicle fleet (International Transport Forum, 2015).

In the absence of a managed approach by transport infrastructure providers, CAV technologies have

the potential to increase the demands placed on transport infrastructure, and reduce the viability of rapid transport modes. International Transport Forum modelling indicates that, in the absence of high-capacity transit investment, CAVs could increase trip generation by 22-90%, depending on the level of fleet uptake and models for CAV service provision (International Transport Forum, 2015). This could be to the detriment of the transport network's overall performance, and reduce the level of service available to urban residents and firms. The effective capacity improvements offered by CAV technology may delay the need for road capacity upgrades, although these capacity benefits may not be realised for several decades. Rapid transit modes could provide redundancy in the transport network, in case of technical failure in the systems supporting CAVs.

Since CAV technologies potentially eliminate parking costs, and time cost of travel, and potentially the costs of owning and maintaining a private vehicle, this may affect the relative competitiveness of both rapid transit and private vehicles. In light of this, regulation and road pricing mechanisms may be useful to manage traffic volumes that increase as a result of CAV uptake, since the road network currently allows free access on most routes.

The likely trajectory of CAV technology will be non-linear and shaped by interdependent relationships between the technical, political, and economic systems shaping the technology and its applications. Analysis of the interactions between systems, intermediate parameters, and relative shifts between travel behaviour and investment will be valuable to guide Auckland Transport's current and future plans.



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APPENDIX 1: INTEGRATED TRANSPORT PLAN

CURRENT AND PROPOSED TRANSPORT INVESTMENTS 2012-2041

Note: Projects are ranked from high to low cost in each project category.

Roading Projects

Major Projects

West Ring Route - Waterview to Westgate
 AMETI
 AWHC
 SH1 6-laning Albany to Orewa
 Puhoi to Wellsford Motorway
 SH1 widening Manurewa to Papakura
 SH1/SH18 direct connection ramps
 East West link
 SH20A widening
 Mill Road
 PENLINK
 SH20B four-laning
 Lake Road upgrade
 SH20 Mangere to Puhinui 6-laning
 SH16 4-laning Brigham Creek to Waimauku
 St Lukes Rd interchange
 Albany Highway upgrade
 Pukekohe Eastern Arterial
 SH1 Constellation to Greville
 SH18 eastbound widening
 South Bridges
 Tiverton-Wolverton
 Great South Road - Church to Portage
 Great South Road - Atkinson to Tamaki River bridge
 Great South Road - Te Irirangi to Redoubt
 Warkworth Western Collector
Auckland wide projects
 Other urban arterial road upgrades
 Greenfields arterial roads
 Greenfields state highway upgrades
 Rail grade separations

Bus and Ferry Public Transport Projects

Major Projects

City Centre bus Improvements
 Dominion Road upgrade
 Botany — Manukau Rapid Transit
 Manukau Bus Interchange
 Half Moon Bay Ferry Terminal upgrade
 Bayswater Ferry Terminal upgrade
 SH 20 Bus lanes and service improvements
Auckland wide projects
 Greenfields public transport infrastructure
 Integrated ticketing and fares
 Real time information upgrade

Rail and Busway PT Project

Major Projects

City Rail Link
 Avondale-Onehunga/Southdown Rail Extension
 Southeastern Busway
 Northern Busway Extension
 Airport Eastern Rail Link
 Third Rail Line: Westfield - Papakura
 Third Rail Line: Britomart - Westfield
 Papakura-Pukekohe Electrification and Stations
 Constellation-Westgate- Waterview Bus way
 Airport Northern Rail Link
 Botany — Manukau Rapid Transit*
 Manukau Bus/Rail Interchange
Auckland wide projects
 Electric Multiple Unit rolling stock and depot
 Rail park and rides
 Integrated ticketing and fares
 Real time information upgrade

Active Modes Projects

Major projects

Harbour Bridge Pathway
 Eastern Corridor Cycleway - Meadowbank to Glen Innes
 Tamaki Drive boardwalk
 Northern Motorway Cycleway
 Southern Motorway Cycleway
 South Bridges
 Western Rail Corridor Avondale to Swanson
 Kumeu to Huapai walking & cycling improvements
 Grafton Gully Cycleway
 Waterfront Cycleway — Westhaven to Britomart
 Wellsford to Te Hana
 Great South Road: Papakura - Drury
 Warkworth walking and cycling
 Old Mangere Bridge walking and cycling
 Pukekohe walking and cycling
 SH20B Puhinui Road
 Northwestern Cycleway ext — Lincoln Rd - Westgate
 Southwestern Cycleway ext — Maiero St - Waterview
 AMETI walk/cycleway Glen Innes - Pakuranga
Auckland wide projects
 Completing regional cycle network
 Cycleway development & construction
 Regional cycle development to Greenfields areas
 Regional Cycle parking

