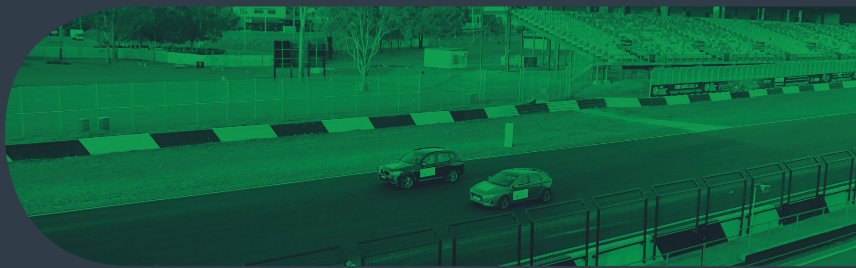
Transurban

NSW partially automated vehicle trials

Stage one—Sydney Orbital Network

December 2018



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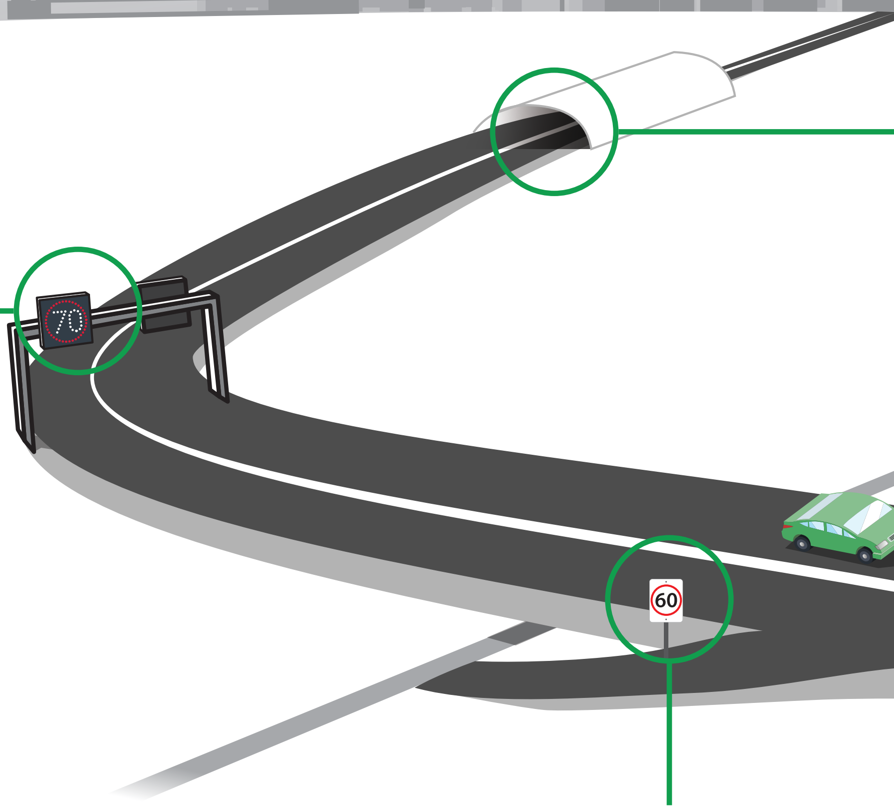
On-road findings



Electronic signs

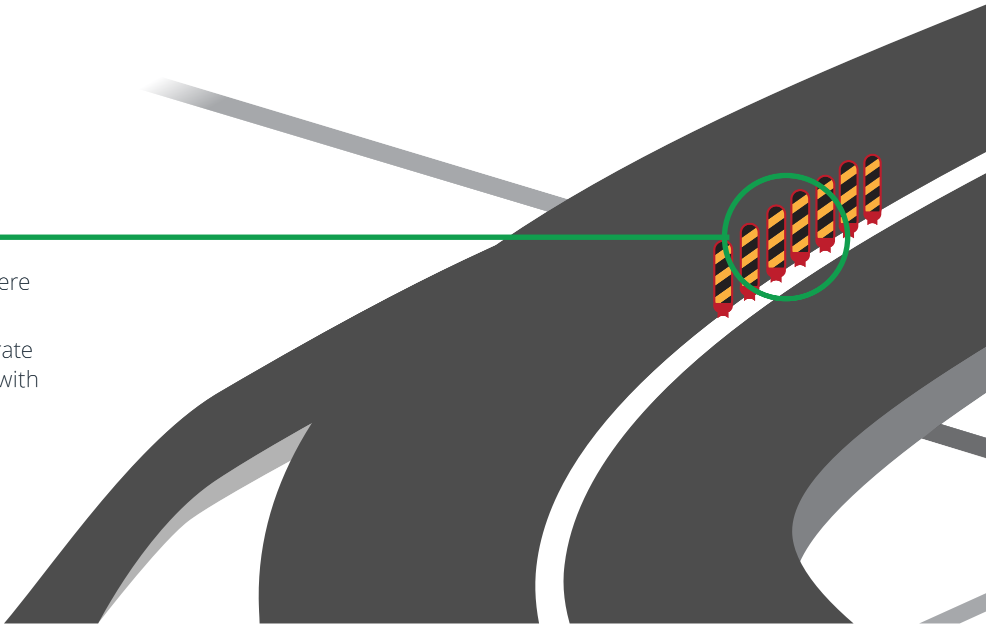
- Electronic speed signs were challenging for some vehicles
- Flashing signs were read more reliably than static signs
- Some sign types, locations and positioning were harder to read than others

Static signs

Static signs applying to specific conditions or locations were incorrectly interpreted as though they applied to the motorway

Digital maps

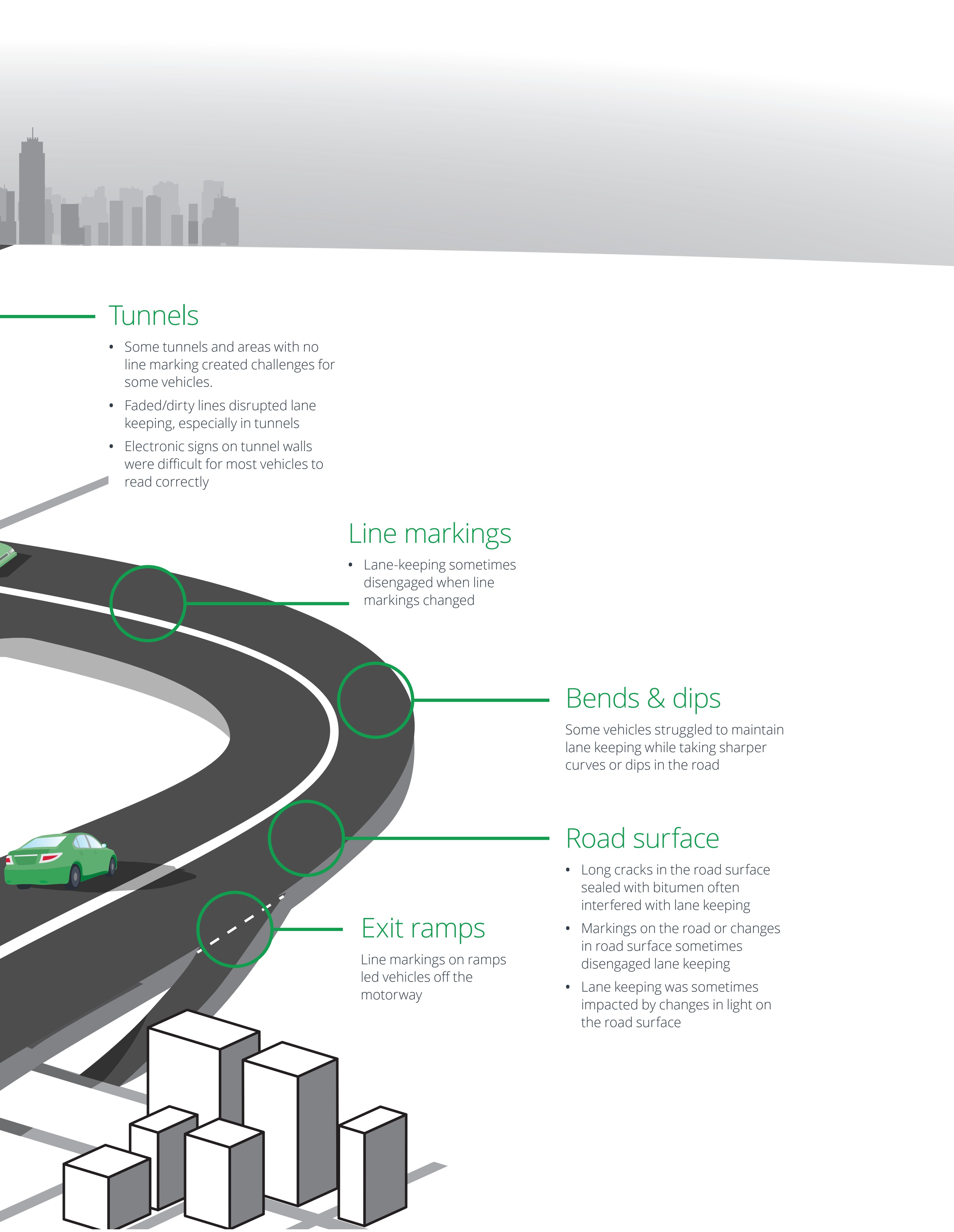
In some instances vehicles identified a change in speed limit where there was none, seemingly following speeds from a digital map



Other objects

- Stopped/merging vehicles were not always detected
- Permanent bollards to separate lanes sometimes interfered with lane keeping

Refer to the Findings and Recommendations section for detailed discussion on page six.



Tunnels

- Some tunnels and areas with no line marking created challenges for some vehicles.
- Faded/dirty lines disrupted lane keeping, especially in tunnels
- Electronic signs on tunnel walls were difficult for most vehicles to read correctly

Line markings

- Lane-keeping sometimes disengaged when line markings changed

Bends & dips

Some vehicles struggled to maintain lane keeping while taking sharper curves or dips in the road

Road surface

- Long cracks in the road surface sealed with bitumen often interfered with lane keeping
- Markings on the road or changes in road surface sometimes disengaged lane keeping
- Lane keeping was sometimes impacted by changes in light on the road surface

Exit ramps

Line markings on ramps led vehicles off the motorway

Contents

Executive summary	5
Findings and recommendations Snapshot	6
Introduction: collaboration key to CAV-ready roads	8
About the trials	9
What we trialled	**10**
How we ran the trials	**11**
Findings and recommendations	12
No road surface is flawless	**12**
Speed not limited to signs	**15**
Tunnel vision	**19**
Twists and turns in the road	**21**
Blinkered vision: CAVs can't see everything	**22**
Discussion	23
Glossary	24

Executive summary

Cars that can steer themselves, recognise speed limits and manage their speed are already driving on Australia's roads. Much of Australia's 50,000 kilometres of motorways were built decades ago. We need to assess them to understand if they are ready for highly automated vehicles.

With human error estimated to contribute to around 90 per cent of road accidents, technologies that assist the driver and eventually automate the driving task could provide significant improvements in road safety.

Transurban's trial of partially automated vehicles, the kinds already on our roads today, sets out to understand the infrastructure changes that we may need to make now and over the next few years to support the widespread use of these vehicles.

Launched in March 2018, the New South Wales (NSW) component of our trial program is a partnership with the NSW Government, Transport for NSW and Roads and Maritime Services. The first stage of the program involved a series of trials led by Transurban on the Sydney Orbital Network, with findings and recommendations detailed in this report. In the following stages, Transport for NSW is running the trials on the state's regional motorways.

Our trial programs have identified a number of challenges for vehicle manufacturers, infrastructure providers and regulators to consider and overcome in order to safely introduce connected and automated vehicles (**CAVs**) onto the roads.

Some of the Sydney trial findings are consistent with the results from our previous trials in Victoria in 2017. However, other findings are unique to the Sydney Orbital Network and warrant further investigation. These new findings include impacts of road surface conditions, line marking in tunnels, conditional speed limit signs, and fixed lane separations such as permanent bollards.

Some of the findings in this report will likely be addressed by new technology superseding the partial automation features we tested. However, we will adopt the recommendations where practical changes to design, operation and maintenance can have real impact now. Where the findings were inconclusive, we will work with vehicle manufacturers to investigate further.

Alongside our on-road vehicle trials, we are also researching community attitudes towards automated vehicles. The first part of this research looked at community attitudes towards partial automation and showed there are still a number of barriers to the community's acceptance and adoption of automated driving. Results from this research have already been published on our website **cavs.transurban.com**

With the technology moving so fast, it's important to monitor the types of vehicle technologies on the road as they are taken up by the community. As automated vehicles become more commonplace, industry and government will need to build community understanding of the safe use of driver-assistance features.

Key stats

- 4 trials
- 30 days spread over 6 months
- 40 on-road trial sessions
- 116 hours on the road
- 7,110 kms travelled
- 9 vehicle manufacturers
- 10 vehicles tested
- 4,125 observations recorded

Findings and recommendations

Snapshot

Findings from the NSW CAV Trials (Sydney Orbital Network) not seen in previous trials

		Finding	Recommendation
No road surface is flawless	**Sealed cracks**	Long cracks in the road surface sealed with bitumen often interfered with lane keeping	• Consider alternative methods of repairing cracks in road surfaces, or viability of colour-matching seals to road surface • Review maintenance intervention thresholds for resurfacing and line marking (and consider specific intervention threshold for crack seals). Measure regularly against thresholds • Revisit standards and guidelines for pavement repair
	Changes in road surface/ markings	Markings on the road (signs painted on the pavement), or changes in road surface (concrete/ asphalt) sometimes disengaged lane keeping	• Avoid excessive markings or changes in road surface • Investigate new materials/products designed for improved line marking contrast, wet weather visibility, etc. • Blend changes in road surfaces more gradually • Inform drivers of the capabilities of driver assistance features
	Environmental impacts	Lane keeping was sometimes impacted by changes in light on the road surface due to rain, shadows, glare and tunnel portals	• Share data with vehicle manufacturers to refine lane keeping technology • Inform drivers of the capabilities of driver assistance features
Speed not limited to signs	**Electronic signs**	Some sign types, locations and positions were more challenging to read than others	• Review sign type and positioning at problem locations • Investigate electronic sign standards, specifications and design guides (including for consistency), and consider readability criteria and guidelines
	Static signs	Static signs relating to specific conditions or locations were incorrectly interpreted as though they applied to the motorway. These included: • signs on buses • signs on parallel roads, in motorway bus lanes, at exit ramps (or advisory signs prior to exit ramps) • signs clarifying speed limit when electronic speed limit sign (ESLS) is off	• Investigate options to ensure signs remain visible where they apply (on ramps and parallel roads), but less visible from the main motorway • Share data with vehicle manufacturers to refine Traffic Sign Recognition algorithms • Revisit use of static signs explaining conditional speed limits • Explore longer-term options to alert vehicles when signs apply using available connected vehicle communications
	Digital maps	Sometimes vehicles identified a change in speed limit where there was none, seemingly following speeds from a digital map	• Highlight to vehicle manufacturers and map providers to help identify causes
Tunnel vision	**Shoulder and line markings**	• Some tunnels have very narrow/non-existent shoulders, with line marking right against the tunnel wall. Specific tunnels or locations with no line markings created challenges for some vehicles • Faded/dirty lines disrupted lane keeping, especially in tunnels	• Factor into future tunnel design wherever possible • Consider increasing frequency of cleaning dirty lines in tunnels • Paint clear edge line markings alongside all tunnel walls if necessary
	Electronic signs	• Electronic signs on tunnel walls were challenging for most vehicles	• Further investigate electronic signs in tunnels • Factor into future tunnel design as per current guidelines and specifications

Findings from the NSW CAV Trials (Sydney Orbital Network) not seen in previous trials (continued)

		Finding	Recommendation
Twists and turns on the road	**Sharp curves**	Some vehicles struggled to maintain lane keeping while taking sharper curves or dips in the road	• Inform drivers of the capabilities of driver assistance features • Investigate further at specific locations
Blinkered vision	**Bollards**	Permanent bollards separating lanes sometimes interfered with lane keeping	• Inform drivers of the capabilities of driver assistance features • Review approaches for attaching bollards to road surface • Avoid combining different objects and changes to road surface or markings in close proximity

Findings from the NSW CAV Trials (Sydney Orbital Network) that we also saw in our previous CAV Trials

	Motorway	Finding	Recommendation
Lines	**Line markings**	Changes in line markings (solid-dotted, expansion joints, dual lines, gap due to lane add) sometimes disengaged lane keeping	• Evaluate impact of painting line markings over expansion joints, drains and so on • Investigate options for line marking treatments where lines change (solid to dashed) or disappear (when a lane is added)
Exit ramps	**Line markings at exit ramps**	Vehicles favour solid lines, and would sometimes follow a solid line up an exit ramp, rather than continuing along main motorway	• Revisit standards/guidelines for line markings at exit ramps. Consider step-out treatments if suitable • Where available, suggest drivers choose middle lane(s) when using current automated driving features, if their vehicle is susceptible to these issues
Signs	**Electronic signs**	• Electronic speed signs were more challenging for some vehicles • Flashing signs were read correctly more reliably than continuous signs	• Share data with vehicle manufacturers to refine Traffic Sign Recognition algorithms • Review sign height and positioning at problem locations, and the design of new road furniture • Review and update electronic sign standards
Vehicles and objects	**Other vehicles on the road**	Vehicles travelling to the side of trial vehicles may not be detected. For example, trial vehicles did not create gaps to allow merging vehicles into traffic	• Where available, suggest drivers choose middle lane(s) when using current automated driving features, if their vehicle is susceptible to these issues
	Other objects on the road	Objects on roads may not be detected by CAVs, including debris, stopped vehicles, people getting out their vehicle (such as during an incident or breakdown), and roadworks equipment including traffic cones, plastic bollards, temporary and portable signs, and truck-mounted attenuators	• Inform drivers of the capabilities of driver assistance features

These findings and recommendations are discussed in detail in our **Victorian report**.

Introduction: Collaboration key to CAV-ready roads

In every state across Australia, trials of connected and automated vehicle (CAV) technology are planned or underway. From automated farming to urban shuttle trials, it seems our appetite to test promising new technologies is growing.

As the technology develops, so too does our understanding of its place in the world and its potential to impact existing industries.

Governments and legislators—aware of the need to balance creating an environment that fosters innovation with public safety—are busily preparing the policy roadmaps, regulatory frameworks and urban plans that will help CAV technology integrate into our roads safely.

Road operators are among the many industries engaged in CAV trials, using them both as a way to understand the opportunities the new technologies offer and to help shape their development and safe adoption.

With the technology developing so quickly, it is essential that across industry sectors we learn from each other and build on the diverse body of knowledge being compiled across Australia.

In partnership with the Victorian government and RACV, we first began trials of CAVs on CityLink and adjoining motorways in Melbourne in 2017. Our primary objective was to understand the types of changes that we may need to make to our roads to allow CAVs to be safely introduced.

What emerged was a set of findings from six major vehicle manufacturers showing how partially automated vehicles interacted with urban motorway infrastructure. These findings are the basis for our Sydney trials. In this report, we have noted where findings are consistent with observations in Melbourne and where new findings have emerged.

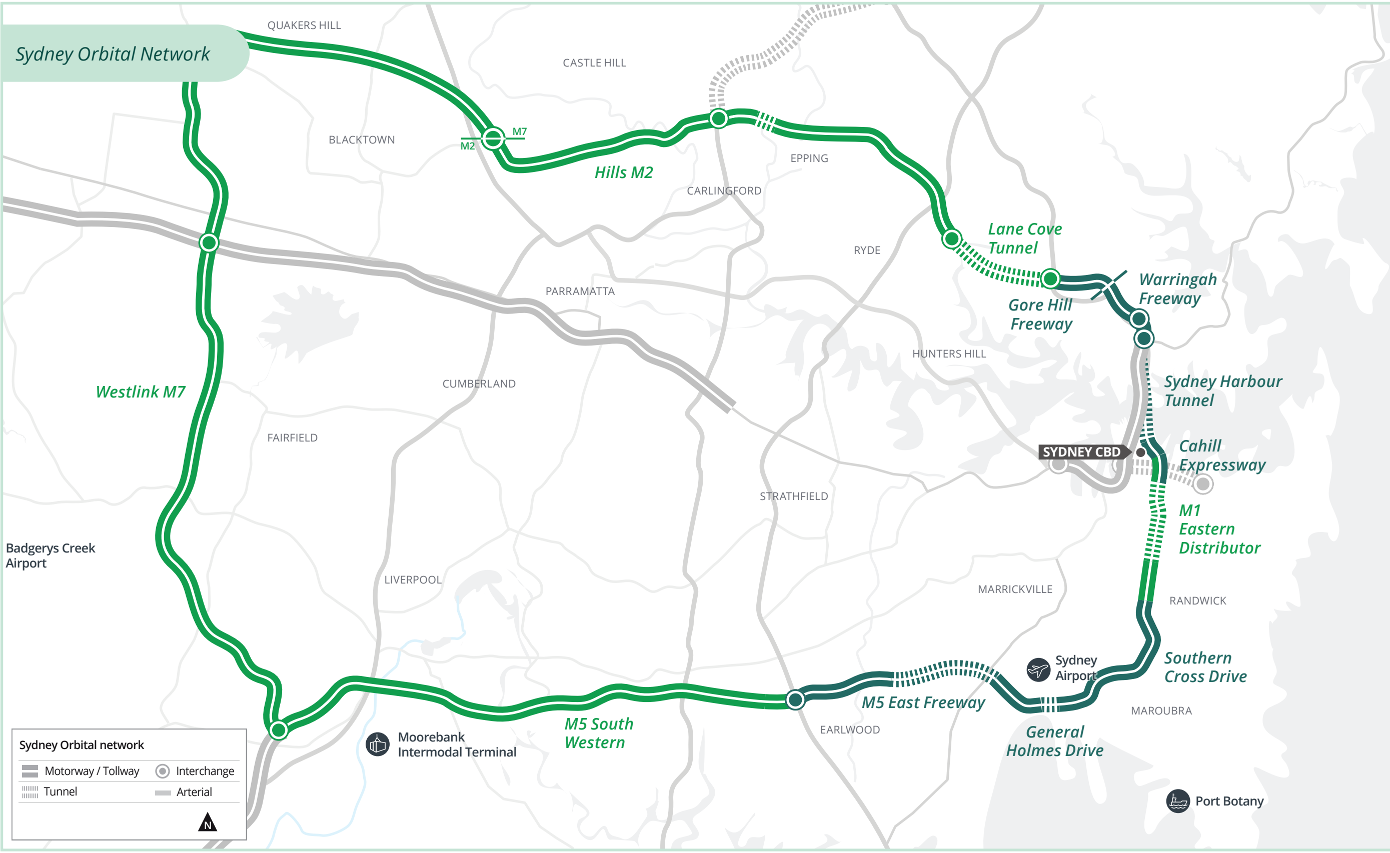
The NSW Government had an interest in understanding how to prepare for CAVs not only in Sydney, but also in regional areas where the majority of serious road crashes occur.

To capture the findings from both of these trial stages, we developed an Australian-first, purpose-built app to track, record and measure all interactions between CAVs and road infrastructure. The app improved the process of recording trial observations. It is now being used by Transport for NSW to collect data as it continues to trial vehicle technology across regional NSW.

The consolidated database of findings from multiple trials across different jurisdictions on urban and regional motorways enables more comprehensive analysis and sharing of findings with trial partners.

This kind of collaboration brings wider benefits such as the standardisation of data, which can then be built on and a forum for sharing information that will ultimately help all roads—toll roads and publicly operated roads—to be CAV ready.

About the trials



This report covers the first stage of the trials, which took place on Sydney's Orbital Network. Further stages, conducted on NSW's regional motorways, are not covered in this report.

The Orbital Network consists of 12 contiguous motorways forming a 113-kilometre loop around Sydney. It was developed in different stages using different road building methods, and is managed by a range of public and private sector owners/concessionaires. Driving around the Sydney Orbital Network, the variation across different sections is quite noticeable to a human driver.

The trials focused on identifying the:

- elements of the Sydney Orbital Network which were more challenging for vehicles using partial automation features and
- infrastructure changes that the asset owners could and should make now and over the medium term.

Our six month on-road trials involved ten current model vehicles with partial automation features, sourced from nine vehicle manufacturers.

The trials were not about comparing vehicle models or features. Manufacturers conduct their own tests before launching vehicles on the market, but their testing is commercially sensitive and generally not shared publicly. By working with a broad range of vehicles, our research identified common themes which in turn helps to inform our future road upgrades and operations. We believe this makes the findings useful to both road operators and governments.

Our findings are available via our website: **cavs.transurban.com**

What we trialled

We trialled latest model vehicles with partial automation features from Audi, BMW, Hyundai, Jaguar Land Rover, Mazda, Mercedes, Tesla, Toyota Lexus and Volvo.

What is partial automation?

Technology installed in partially automated vehicles generally helps vehicles:

- steer themselves and stay in their lane (known as latitudinal control)
- manage their speed relative to other vehicles on the road (known as longitudinal control) and
- recognise the speed limit.

Some of the vehicles and vehicle manufacturers in these trials were the same as those involved in our previous trials, which helped to highlight the pace and manner in which the technology is developing. For example, more vehicles now have Traffic Sign Recognition (TSR) activated in Australia, and those that already had this have improved in accuracy of reading signs. Some vehicles can now distinguish between signs applying to exit ramps versus those applying to the main carriageway. Also, some vehicles will now automatically reduce their speed if the speed limit changes, when driven with the relevant features activated. More vehicles have lane keeping technologies, and some now have features to help the vehicle change lanes automatically. With technology developing so quickly, it is important to keep abreast of these changes through ongoing trials.

Vehicle manufacturers highlight that current partial automation features are intended for driver-assistance only. They are not designed to automatically handle every scenario that may arise on the road. As long as they are used appropriately, these features can help to improve road safety.

Our trials looked at how vehicles with those features interacted with the motorway environment, including: speed signs, line markings, road surfaces, tunnels, bends in the road, entry and exit ramps, objects on the road, merging vehicles, different light and weather conditions, and congestion.

Partial automation features

Look out for these technologies as you make your way through the report.

Lane Keep Assist (LKA)
Reads lane lines and proactively intervenes with vehicle steering to ensure the vehicle stays in its lane.

Adaptive Cruise Control (ACC)
Building on standard cruise control functions, ACC sets a maximum speed, but may adjust speed based on distance to the vehicle in front.

Traffic Sign Recognition (TSR)
Camera technology detects and reads speed signs and displays them in the vehicle.

Implementations of these features vary across vehicles, for example in the range of speeds at which they function. Some of the trial vehicles allowed these features to be used in combination.

How we ran the trials

The Sydney Orbital Network trials were run between March and August 2018, building on the approach used for our previous CAV trials.

Professional drivers from Driving Solutions drove the trial vehicles and Transurban observers recorded CAV observations as they happened. Other passengers included trial partners (Transport for NSW and Roads and Maritime Services), vehicle manufacturers and representatives from various other motorways forming the Sydney Orbital Network.

Trial vehicles completed half circuits of the Sydney Orbital Network in both a clockwise and anticlockwise direction, while drivers and observers recorded how the vehicles' automated features responded to road infrastructure. Each trial iteration introduced further complexity with more vehicles, different light conditions, or different levels of congestion.

Observations were corroborated by video footage from four temporary cameras looking inside and outside the vehicle.

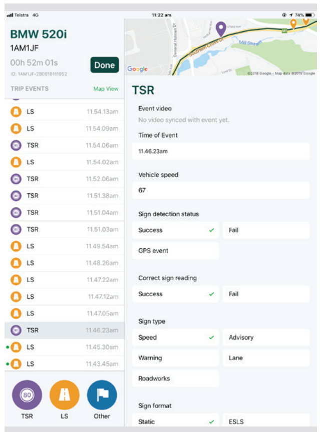
A bespoke iPad application was developed by Transurban allowing observers to log details and location of any interesting vehicle behaviours and link these with the supporting footage, for later post-processing analysis.

Following this structured approach, we collected 4125 observations. Analysis of these observations helped us identify themes and issues warranting further investigation. By providing data to participating vehicle manufacturers documenting the particular vehicle's responses, we gave vehicle manufacturers the opportunity to assess their vehicle's recognition and reaction performance.

However as an infrastructure owner and operator, our focus was on identifying any issues common to multiple vehicles—as common issues were more likely to warrant future changes to motorway infrastructure.

While we present quantitative information in this report, it is indicative only and not statistically significant.

Technology is constantly changing and, after these trials concluded, some vehicle models may have been modified and may now behave differently than in trials conducted previously.



Safety first

Each trial commenced with a session at Sydney Motor Sports Park (SMSP) for driver familiarisation with the auto manufacturers. This gave drivers the opportunity to become familiar with activating and deactivating the automated features of each vehicle prior to testing in live-traffic situations.

Each on-road session commenced with a briefing which included safety, vehicle technology and route guidance.

Trial drivers remained in control of the vehicle at all times.

Figure 1: Sydney Orbital Network trials timeline

Trial 1	Trial 2	Trial 3	Trial 4	Data analysis & validation	Implementation
March/April	May	June	August	May–November	December
2 vehicles	*2 vehicles*	*3 vehicles*	*3 vehicles*	*All vehicles*	
Off-road (SMSP) On-road in non-peak.	Off-road (SMSP) On-road in peak and off-peak including twilight and night.	Off-road (SMSP) On-road in peak and off-peak including dawn and early morning.	Off-road (SMSP) On-road in peak and off-peak including dawn, morning, evening and night testing.	Post processing of data from cameras, audio recordings and observations. Analysis of findings.	Release of findings and recommendations. Commence implementation of recommendations.

Findings and recommendations

Some of the trial findings were consistent with the results from our previous trials, but other findings were more specific or even unique to the Sydney Orbital Network.

No road surface is flawless

Lane Keep Assist

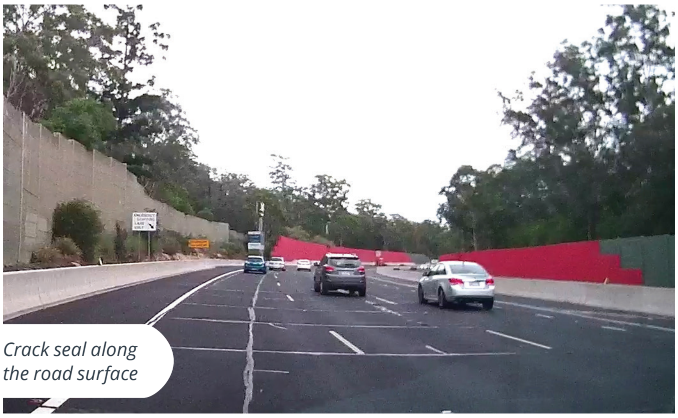
Results snapshot

Motorway	Finding	Recommendation
Crack sealing	Long cracks in the road surface sealed with bitumen often interfered with lane keeping	• Consider alternative methods of repairing cracks in road surfaces, or viability of colour-matching seals to road surface • Review maintenance intervention thresholds for resurfacing and line marking (and consider specific intervention threshold for crack seals). Measure regularly against thresholds • Revisit standards and guidelines for pavement repair
Changes in road surface/markings	Markings on the road (signs painted onto the pavement) or changes in road surface (concrete/asphalt) sometimes disengaged lane keeping	• Avoid excessive markings or changes in road surface • Investigate new materials/products designed for improved line marking contrast, wet weather visibility, etc. • Blend changes in road surfaces more gradually • Inform drivers of the capabilities of driver assistance features
Environmental impacts	Lane keeping was sometimes impacted by changes in light on the road surface due to rain, shadows, glare and tunnel portals	• Share data with vehicle manufacturers to refine lane keeping technology • Inform drivers of the capabilities of driver assistance features

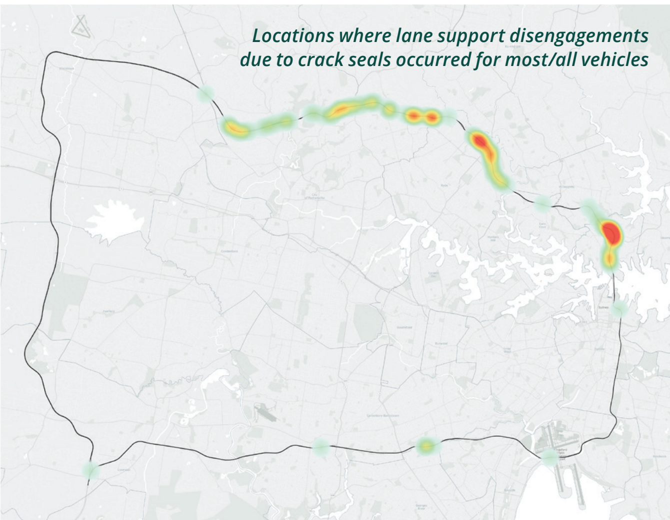
Crack sealing on the road interfered with lane keeping

In some locations on the Sydney Orbital Network, long cracks in the road surface have been sealed with bitumen. These seals on the road are more shiny and reflective than the normal road surface. In some lighting conditions, long seals running along the road can look similar to lines on the road. In some cases, vehicles followed the seal instead of the lane markings and were led out of their lane. In other instances the confusion of the two 'lines' resulted in lane keeping being disengaged. Seals that run across rather than along the road did not seem to impact vehicles.

Seals on the road also impacted automatic lane changing. In some vehicles this feature allows drivers to automatically change lanes when it is legal and line markings are dotted. Seals on the road interfered with this feature by creating the appearance of a solid line where there was none, preventing the vehicle from automatically changing lanes in that location.



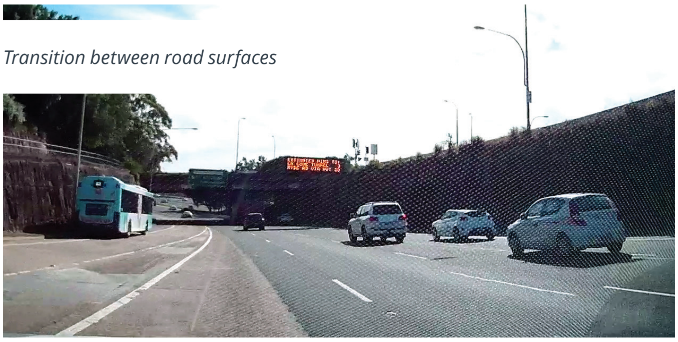
Crack seal along the road surface



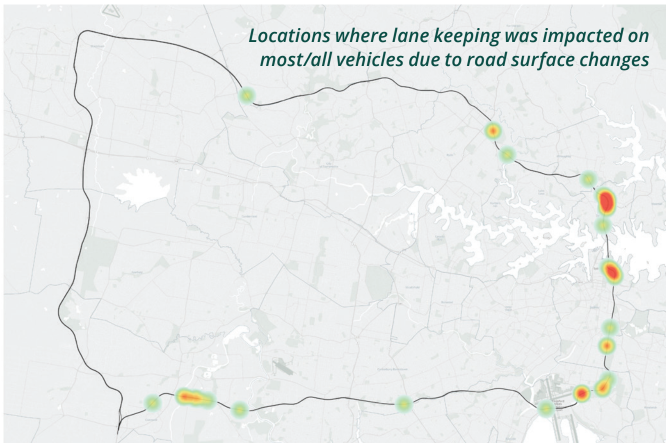
Changes in road surface or road markings

The Sydney Orbital Network includes motorways paved with different materials. In a couple of locations, the roadway transitions from one surface to another.

Transition between road surfaces



It appeared that the difference in contrast between these road surfaces interfered with lane keeping systems, either leading vehicles out of their lane, or disengaging lane keeping.



Other markings on road surfaces also impacted lane keeping. In some locations, signs painted onto the road surface (advising toll zones or other lane information) appeared, on occasion, to interfere with lane keeping, especially at locations where there were already other changes in light conditions, such as coming out of a tunnel portal.

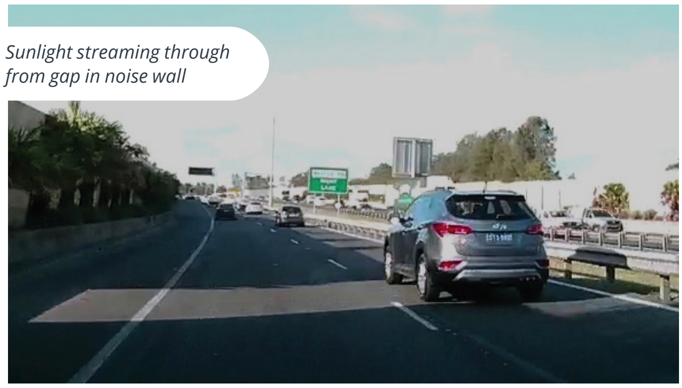
Sign painted on road surface

Environmental impacts

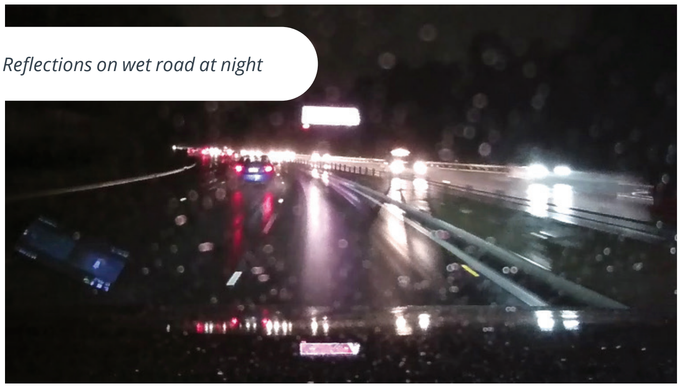
In addition to the road itself, there were also other environmental factors that could lead to changes in the appearance of the road surface at specific locations. In some cases, sudden changes in light and shadow seemed to disrupt lane keeping systems. For example, a shadow cast over the road surface from a tree would contrast strongly against an otherwise uniform road surface. Alternatively, a gap in a noise wall would let through a patch of sunlight on an otherwise shaded road surface. Emerging from a tunnel (or underpass) back into daylight would also sometimes interfere with lane keeping systems.

Extreme weather appeared to have an impact on vehicles, with vehicles unable to see lines during a very heavy downpour. Reflections from oncoming vehicle headlights against a wet road surface at night time also appeared to disrupt lane keeping, making it difficult to distinguish lines from reflections.

Although we might expect these environmental factors to have a similar impact in different regions, we did not observe these results in previous trials. While there was some rain during those trials, there was no heavy downpour. It could be that weather conditions in Sydney are a little different, with more bright sunlight and heavier rainstorms.



Sunlight streaming through from gap in noise wall



Reflections on wet road at night

Speed not limited to signs

Traffic Sign Recognition

Results snapshot

Motorway	Finding	Recommendation
Electronic signs	Some specific sign types, locations and positions were more challenging to read than others	• Review sign type and positioning at problem locations • Investigate electronic sign standards, specifications and design guides (including for consistency), and consider readability criteria and guidelines
Static signs	Static signs applying to specific conditions or locations were incorrectly interpreted as though they applied to the motorway. These included: • signs on buses • signs on parallel roads, in motorway bus lanes, at exit ramps (or advisory signs prior to exit ramps) • signs clarifying speed limit when ESLS is off	• Investigate options to ensure signs remain visible where they apply (on ramps and parallel roads), but less visible from the main motorway • Share data with vehicle manufacturers to refine Traffic Sign Recognition algorithms • Revisit use of static signs explaining conditional speed limits • Explore longer-term options to alert vehicles when signs apply using available connected vehicle communications
Digital maps	Sometimes vehicles identified a change in speed limit where there was none, seemingly following speeds from a digital map	• Highlight to vehicle manufacturers and map providers to help identify causes

New vehicles generally have digital maps that specify the speed limit on a given section of road. As more motorways now use Electronic Speed Limit Signs (ESLS) with varying speed limits a road's current speed limit may not be available in the digital map. Some partially automated vehicles also draw data from Traffic Sign Recognition (TSR) technology, which uses cameras to read physical speed signs as the vehicle drives past. This technology provides vehicles with the primary source of data to help a vehicle determine the current legal speed limit.

Some of the trial vehicles had TSR, which drivers used as guidance in manually setting or adjusting the vehicle speed. In many cases it was not possible to determine from the instrument panel whether the vehicle used a digital map or TSR to determine the speed limit at any particular location.

As with previous trials, in our TSR analysis we noted vehicle responses when a vehicle passed a speed sign requiring a change in speed—for example, going from 60km to 80km. We excluded instances where a vehicle passed a sign showing the same speed displayed on the vehicle's instrument panel because we could not tell if the vehicle had read the most recent sign.

As vehicle automation increases and vehicles begin adjusting their speed automatically, it is critical that vehicles can identify the correct speed.

Alongside these Sydney Orbital Network trials, we collaborated with Austroads in their assessment of ***Implications of TSR Systems for Road Operators***. Several of our findings below relating to speed limits on the Sydney Orbital Network echo findings identified by Austroads across the broader Australian and New Zealand road networks.

Electronic signs

There was a wide variation in vehicles' ability to detect and correctly identify the speed shown on Electronic Speed Limit Signs (ESLSs). Overall though, correct read rates seem to have improved compared to previous trials.

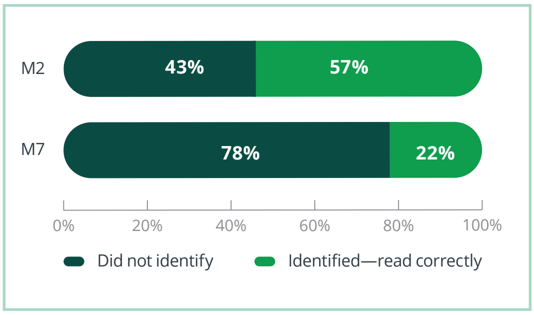
In previous trials, TSR technology varied in its ability to detect and read speed limits shown on the signs (either correctly or incorrectly). In the Sydney Orbital Network trials, vehicles seemed to either read the signs correctly or failed to detect the sign at all. There were very few instances where a sign was detected and incorrectly read. This suggests a rapid maturing of the technology, with far fewer instances where the vehicle would provide incorrect guidance to the driver.

However, ESLS in certain locations seemed more challenging for several of the trial vehicles to read and there were even some signs that all vehicles failed to detect. Also, some signs seemed more likely to be missed when they displayed 100km/hr.

There were also examples where specific vehicles would consistently fail to detect or read a group of signs along a portion of the orbital, despite other vehicles successfully reading those signs.

Figure 2: Read rates for identified signs

Figure 3: Speed limit results on roads with ESLS showing 100km/h

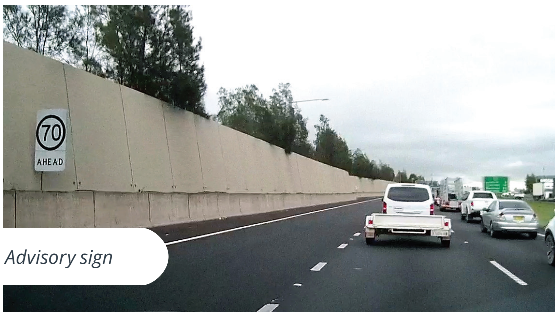


Static signs

Unlike previous trials on motorways, with electronic signs along the whole corridor, the Sydney Orbital Network has a mix of static and electronic signs. In general, the static signs were more accurately read than the electronic signs.

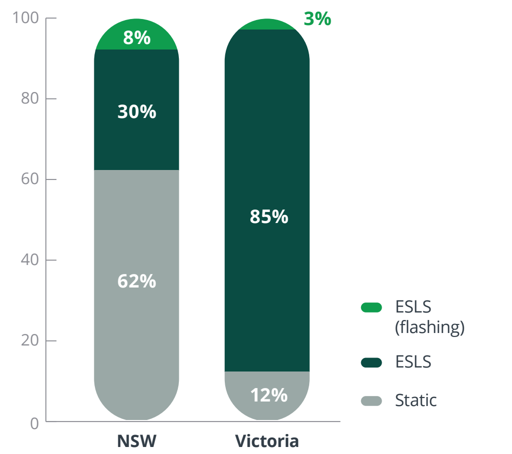
Yet there were several instances in which static signs were read by vehicles as though they applied to the motorway, when the signs actually applied to other locations or situations. For example, static signs on exit ramps (or advisory signs immediately prior to an exit ramp), roads running parallel to the motorway, or 40 km/h bus lanes in the middle of the motorway, were sometimes read by vehicles driving past along the main motorway. Although much rarer, this issue also occurred in reverse, where a vehicle driving on an exit ramp or parallel road would read a sign that actually applied to the motorway.

Speed sign on road parallel to motorway



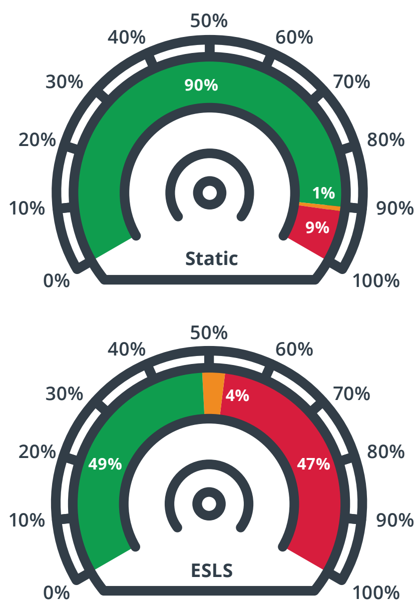
Advisory sign

Figure 4: Proportion of signs by format*



** Electronic signs only recorded when different from previous sign, as explained on page 15.*

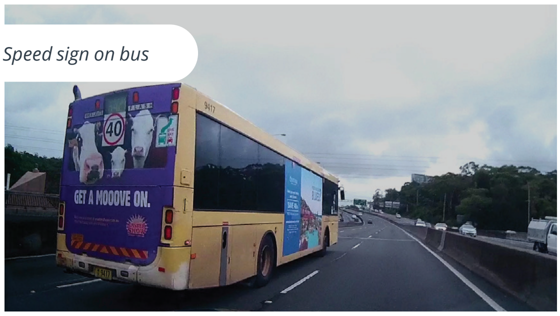
Figure 5: Detection/correct read rate by sign format



Identified sign and read speed ***CORRECTLY***
Identified sign and read speed ***INCORRECTLY***
DID NOT *identify sign*

A similar situation occurred with buses in Sydney, which have 40 km/h speed signs displayed on their back window alongside 'wig wag' orange lights that flash—typically when the bus stops. The signs have text explaining that the speed limit applies when the lights are flashing. Trial vehicles often read the 40km/hr speed signs when a bus was driving on the motorway with its wig wag lights off, and interpreted the sign as applying to the motorway.

Another type of static sign displayed a speed limit together with text explaining the conditions in which it applied. For example, near a gantry with electronic signs, a static sign explains that the speed limit is 100 km/h if the electronic sign is blacked out. This type of sign seemed confusing to trial vehicles, which sometimes read the 100 km/h symbol on the static sign even though the electronic sign was active and showing a different speed.



Speed sign on bus

Conditional sign

Digital maps

In some cases, vehicles would detect a change in speed limit even though there was no speed limit sign displayed in that location, presumably by referencing a digital map with speed limit data.

This seemed to happen in locations where imprecise GPS could confuse the vehicle, such as tunnels and emerging from underpasses. In another example, a vehicle showed a reduced speed limit and even slowed down to this reduced limit without driver intervention at a location that had previously undergone long-term roadworks. The roadworks had since been completed and there were no longer any reduced speed limit signs displayed on that section of the motorway, yet the vehicle seemed to be following outdated data from a digital map.

An underpass where digital map issue occurred

Tunnel vision

Lane Keep Assist

Results snapshot

Motorway	Finding	Recommendation
Shoulder and line markings	• Some tunnels have very narrow/non-existent shoulders, with line markings right against the tunnel wall. Specific tunnels or locations with no line markings created challenges for some vehicles • Faded/dirty disrupted lane keeping, especially in tunnels	• Factor into future tunnel design wherever possible • Consider increasing frequency of cleaning dirty lines in tunnels • Repaint clear edge line markings alongside all tunnel walls if necessary
Electronic signs	ESLS on tunnel walls seem more difficult to detect	• Further investigate readability of ESLS in tunnels • Factor into future tunnel design as per current guidelines and specifications

Shoulder and line markings

The Sydney Orbital Network includes a number of different types of tunnels. Across the broader Sydney motorway network there are other major tunnel projects in progress and several further tunnels planned for future development.

Compared with tunnels in previous trials, some of the tunnels in the Sydney Orbital Network have very narrow or even non-existent shoulders, where the line marking at the edge of the lane is right up against the tunnel wall/barrier with no gap. As long as there were good quality line markings this was not necessarily a problem for vehicles' lane keeping, but placing trust in the vehicle systems was a little disconcerting for drivers given the small margins.

In some cases edge line markings appeared faded or dirty, impacting lane keeping. There were various locations where this occurred, but some tunnels seemed particularly susceptible to dirty line markings. Further investigation is required, however this issue may be due to dust becoming trapped and accumulating on the sides of the tunnel.

There were also some locations where the line markings along the edge of the tunnels disappeared, which interfered with lane keeping.

Faded/dirty edge lines on the left

Location where lane keeping was impacted on most/all vehicles due to faded/dirty lines

Electronic signs

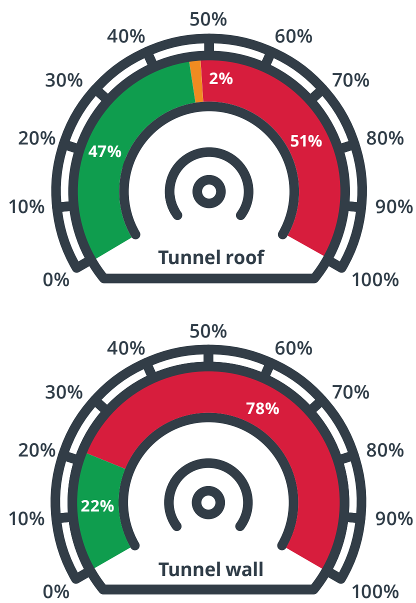
In previous trials, ESLS in tunnels proved particularly challenging, with almost none of the tunnel signs identified or correctly read. Around the Sydney Orbital Network, ESLS in tunnels were identified or read more often than in previous trials, yet these signs still proved less accurate than electronic signs on the open road, which warrants further investigation.

In previous trials, all of the electronic signs in the tunnel were small-format signs on the wall of the tunnel.

Around the Sydney Orbital Network, ESLS in tunnels are positioned on walls and overhead. Overhead signs were detected and read with similar accuracy to those on the open road. Yet signs on tunnel walls were significantly more difficult to detect and read than those overhead.

This should be less of an issue in future, as current specifications require overhead signs.

Figure 6: Chart comparing ESLS detection/read rate in tunnels for overhead vs wall mounted sign



Identified sign and read speed ***CORRECTLY***
Identified sign and read speed ***INCORRECTLY***
DID NOT *identify sign*

Twists and turns in the road

Lane Keep Assist

Adaptive Cruise Control

Results snapshot

Motorway	Finding	Recommendation
Sharp curves	Some vehicles struggled to maintain lane keeping while taking sharper curves or dips in the road	• Advise drivers of the limitations of driver assistance features • Investigate further at specific locations

Sharp curves

In some locations around the Sydney Orbital Network, tight bends in the road created difficulties for lane keeping. Some vehicles seemed to drift to one side around these bends. In other cases, drivers would be unsure as to whether the vehicle would take the curve on its own. There were also some specific bends in the road where many different vehicles would disengage lane keeping in the same area.

A specific example occurred at one location where there was an unusual alignment with a dip and bend in the road together. Several vehicles had issues with lane keeping at this location, warranting closer investigation.

Blinkered vision: CAVs can’t see everything

Lane Keep Assist

Results snapshot

Motorway	**Finding**	**Recommendation**
Bollards	Permanent bollards separating lanes sometimes interfered with lane keeping	• Advise drivers of the limitations of driver assistance features • Review approach for attaching bollards to road surface • Avoid combining different objects and changes to road surface or markings in close proximity

Bollards

One interesting feature of the Sydney Orbital Network is the use of bollards to separate motorway lanes. While motorways tested in previous trials used bollards as part of the traffic management during roadworks, in Sydney there are locations where bollards are a permanent device used to separate the traffic into the appropriate lane and prevent lane changing.

In some instances, these bollards appeared to disrupt the lane keeping in the trials vehicles, either on their own or in combination with other changes (signs and/or road surface conditions) such that the vehicles were required to navigate multiple sudden changes in the road environment at the one location.

Although less common than bollards, there were also similar examples of other lane separation devices such as a raised strip of concrete which also affected lane keeping in vehicles.

Permanent bollards

Discussion

The Sydney trial built on the findings of previous trials by highlighting where findings were consistent across Sydney and Melbourne, and by identifying new findings unique to the Sydney Orbital Network.

The combined data from both trials, captured via our purpose built app, is useful in highlighting patterns of vehicle behaviour towards road infrastructure.

While details of how individual vehicles responded during the trial have been provided to the relevant vehicle manufacturer, it is the collective findings that will further help vehicle manufacturers, road operators and governments prepare road infrastructure to support automated vehicles.

It is important the trial recommendations be considered within the context of a rapidly developing automated vehicle industry. In future, it is likely that further developments in vehicle technology or sophisticated vehicle-to-vehicle/infrastructure communication features may address some of the challenges identified in our trial.

While some recommendations should be acknowledged and monitored to see if they are addressed through industry innovation, we recommend two practical changes be considered and implemented now, these include:

- Increasing frequency of cleaning lines in tunnels
- Conducting further trials of new materials/products designed to improve line marking contrast and wet weather visibility.

Results from our previous trials have already formed inputs into ongoing industry review, and we will continue to work with industry to share our latest results.

Trial recommendations will also be considered as part of Transurban's road operational reviews, and in the design of new roads.

Next steps

The trials on the Sydney Orbital Network have been an important step in preparing the state for increasing vehicle automation. Building on this, Transport for NSW is continuing to trial vehicle technology on the NSW regional network, to help identify new findings specific to regional roads.

Now is the time for industry to trial vehicles in as many different environments as possible, introducing new technologies as they are made available. Since completing the Sydney Orbital Network trials we have commenced trials of partially automated vehicles on our motorways in Brisbane.

While features tested in partially automated vehicles are becoming increasingly available in new cars across all price ranges, highly automated vehicles use different technologies and will likely encounter different issues with our road environments.

Alongside continuing trials of partially automated vehicles, our ongoing trial program is also incorporating more highly automated vehicles and connected vehicle communications.

We look forward to sharing further details of these trials as they become available, and welcome further industry collaboration to support the arrival of these exciting new technologies.

Glossary

ACC

Adaptive Cruise Control builds on standard cruise control functions and maintains a set speed and following distance to the car in front

Autonomous driving mode

A combination of LKA, ACC and TSR (where applicable) that assists the driver with steering and speed control

CAV

Connected and automated vehicle

Digital map

Maps used for automotive navigation systems with coordinates and other data about the roads and surrounding environment

Driver-assistance features

Partial automation features that assist drivers in some elements of driving

GPS

Global Positioning System

High precision maps

3D maps which vehicles can compare against what their sensors 'see', to help pinpoint their exact location

I2V

Infrastructure to vehicle

Identify a traffic sign

Where a vehicle detects a traffic sign exists

Line marking

Lines used on a road surface to provide guidance and information to drivers and pedestrians—commonly to delineate lanes

LKA

Lane Keep Assist, reads lane lines and proactively intervenes with the steering of the vehicle to ensure that it does not unintentionally leave the lane

Map providers

Providers of digital maps to the vehicle manufacturers e.g. HERE Maps, TomTom etc.

Radar

A system for detecting the presence, direction, distance, and speed of objects, by sending out pulses of radio waves which are reflected off the object back to the source

Read a traffic sign

Where a vehicle identifies and correctly reads the speed sign and illustrates the speed on the instrument panel

Toll point/gantry

Elevated structure above the road which monitors vehicles underneath for billing purposes

TSR

Traffic Sign Recognition—camera technology that detects and reads traffic signs and displays them in the vehicle

V2V

Vehicle-to-vehicle

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