THE UNIVERSITY OF SYDNEY

Australian Centre for Robotics

Final Report

iMOVE CRC Project 1-063

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Executive Summary

This final report details the activities and findings of the iMOVE CRC Project 1-063, a collaboration between TfNSW and the Australian Centre for Robotics (ACFR) at the University of Sydney. The project aimed to understand the impact, considerations, and benefits of implementing Cooperative Intelligent Transportation Systems (C-ITS). This research involved comprehensive demonstrations of technologies in various scenarios on NSW roads to inform Connected and Automated Vehicle (CAV) policy for both the research community and TfNSW, aligning with the NSW Government's Future Transport Strategy and TfNSW's Towards Zero vision. The project ran from January 2023 to March 2025.

Key objectives included examining the impact of C-ITS messages on the safety of CAVs and Connected Vehicles (CVs), assessing the benefits of intelligent infrastructure for traffic coordination and perception extension, collaborating with the SCATS team, and supporting the development of technical advice for CAV policy.

The project involved the design, development, and deployment of an Intelligent Roadside Unit (IRSU) at a SCATS-controlled intersection in Chippendale, NSW. The IRSU utilised a lidar for real-time road user detection (vehicles, pedestrians, cyclists) and broadcast this information in the form of European Telecommunications Standards Institute (ETSI) Collective Perception Messages (CPMs) using Dedicated Short-Range Communication (DSRC). The SCATS traffic light was also upgraded to broadcast MAP (topology) Extended Messages (MAPEMs) and Signal Phase and Timing Extended Messages (SPATEMs).

Comprehensive demonstrations were conducted using ACFR CAV/CV in controlled environments, including ACFR lab, Cudal FMTRC, and in live traffic in Chippendale. These demonstrations showcased various C-ITS use cases, including:

- Red Light Violation Warning (RLVW) for both CVs and CAVs using SPATEM information.

- User turn warning for Vulnerable Road Users (VRUs) using SPATEM information.
- User turn warning with pedestrian crossing occupancy detection by integrating CPMs from the ACFR IRSU with SPATEM data.
- Time to green information provided to drivers based on SPATEM messages.

The project also demonstrated automated driving of the ACFR CAV through signalised and unsignalised intersections using a combination of onboard sensors, ETSI messages (SPATEMs, MAPEMs, Cooperative Awareness Messages (CAMs)) exchanged over DSRC, and Human-in-the-Loop (HIL) checks.

The project concluded that C-ITS implementation in urban environments offers significant benefits for safety and traffic efficiency. The demonstrations highlighted the potential of intelligent infrastructure to extend local perception and the ability of C-ITS messages to provide crucial information to both human drivers and automated systems. The integration of Vehicle-to-Everything (V2X) communication enhances perception and decision-making for CAVs, supported by high-accuracy localisation and detailed maps.

The collaboration with SCATS was crucial for the project, enabling the demonstration of Vehicle-to-Infrastructure (V2I) communication and providing valuable data on infrastructure requirements for C-ITS.

The project also emphasised the importance of safety assurance processes, including HIL validation, for on-road trials. The findings contribute to best practices for implementing and testing C-ITS technologies in alignment with ETSI standards, and could also offer transferable insights applicable to cellular V2X systems. The outcomes of the project support the formulation of technical guidance for CAV policy and highlight the essential role of traffic management infrastructure in shaping the future of urban mobility.

Document History

Version	Date	Author(s)	Summary of change(s)
0.1	14/03/25	Mao Shan, Stewart Worrall, Jason Webb, James Ward	Initial draft
0.2	17/04/25	Mao Shan, Stewart Worrall	Updated to incorporate feedback from TfNSW
1.0	7/05/25	Mao Shan, Stewart Worrall	Submitted version (no changes from v0.2)
1.1	2/12/25	Mao Shan	Updated video links

Acronyms

ACFR	Australian Centre for Robotics
ADC	Assumptions, Dependencies and Constraints
AV	Autonomous Vehicle
CAM	Cooperative Awareness Message
C-ITS	Cooperative Intelligent Transportation Systems
CAV	Connected and Automated Vehicle
CPM	Collective Perception Message
CV	Connected Vehicle
DoF	Degrees of Freedom
DSRC	Dedicated Short-Range Communication
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FMTRC	Future Mobility Testing and Research Centre
FoV	Field-of-View
GNSS	Global Navigation Satellite System
HIL	Human-in-the-Loop
IMU	Inertial Measurement Unit
IRSU	Intelligent Roadside Unit
ITS	Intelligent Transportation Systems
MAPEM	MAP (topology) Extended Message
OBU	On-Board Unit
PHL	Project Hazard Log
RLVW	Red Light Violation Warning
RSU	Roadside Unit
SAB	Safety Assurance Board
SAR	Safety Assurance Report

SAE	Society of Automation Engineers
SCATS	Sydney Coordinated Adaptive Traffic System
SFAIRP	So Far As Is Reasonably Practicable
SLAM	Simultaneous Localisation and Mapping
SPATEM	Signal Phase and Timing Extended Message
SREM	Signal Request Extended Message
TfNSW	Transport for NSW
TTC	Time To Collision
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User
PoE	Power over Ethernet
AP	Average Precision
ROS2	Robot Operating System 2

Contents

1

Introduction

1.1 Background

This project, iMOVE CRC Project 1-063, was a collaboration between TfNSW and the Intelligent Transportation Systems (ITS) research group at the ACFR in the University of Sydney aimed at understanding the impact, considerations and benefits of implementing C-ITS. This included using information received from CVs and intelligent infrastructure such as IRSUs and intelligent traffic lights.

The motivation for the project lies in V2X communication technology, which has garnered increasing popularity among researchers in the field of ITS and with automobile manufacturers, as it enables a vehicle to share essential information with other road users in a V2X network. This can be a game changer for both human operated and Autonomous Vehicles (AVs), which would be referred to as CVs and CAVs, respectively. The connected agents within the C-ITS network will be able to exploit the significant benefits that come from sharing information across the network. In this project, the V2X communication is achieved through ETSI ITS-G5 DSRC.

The learnings from the project were gained through comprehensive demonstrations of technologies in various scenarios on NSW roads. These learnings help to inform CAV policy both for the research community and TfNSW, in line with the NSW Government's Future Transport Strategy and TfNSW's Towards Zero vision for a safer road network.

This project commenced on 31 January 2023 and concluded on 31 March 2025.

Details about the research areas the ITS group at the ACFR work in are available online at `http://its.acfr.usyd.edu.au/`.

1.2 Project Objectives

The main aims of the project were to:

- Understand the impact, considerations, and benefits of implementing C-ITS in urban traffic environments, which include examining:
    - the impact of C-ITS messages in improving the safety of CAV and CV and providing redundancy in different contexts
    - benefits/requirements for intelligent infrastructure in traffic coordination and local perception extension in situations such as intersections and blind corners
- Collaborate with the SCATS team on:
    - broadcast and use of MAPEMs and SPATEMs from SCATS' intelligent traffic light
    - broadcast and use of CPMs from ACFR's IRSU
- Support the development of technical advice for CAV policy which include informing:
    - the research community on best practices, safety assurance processes and necessary redundancies in different contexts
    - TfNSW on infrastructure requirements for different contexts, current challenges and standards of C-ITS technologies, various aspects of autonomy in CAVs including V2X communication, localisation, navigation, motion control, and perception.

1.3 Trial Categorisation

Following the reporting guidelines in [1], the metadata categorisation of the CAV trial in this project is presented in Tab. 1.1.

Group	**Category**
Trial type	· AV/CAV technology · Connected communication aspects
Vehicle technology type	· CV · CAV
Vehicle type	· Private passenger vehicle · Test buggies
Society of Automation Engineers (SAE) automation levels	· The vehicle is capable of Level 3 automation, but Level 2 controls were implemented as part of safety measures
Trial stage and type	· Demonstration or proof of concept
Maturity level of the technology being trialled	· Mature: The trial included demonstrations in live traffic in the approved operational area, ready for public interaction · Somewhat mature: The RLVW use case could only be fully tested in a controlled environment
Trial objective types	· Safety
Trial location	· Public roads · Private roads
Operational domain and environmental context (complexity of the location environment)	· City driving on public roads with a lot of interaction with other road users · Closed off roads or private roads and no interaction with other road users
Evaluation type	· Process · Impact
Sensor types used	· Lidar
Communication type	· ETSI G5 (DSRC @ 5.9 GHz) - Vehicle-to-Vehicle (V2V) · ETSI G5 (DSRC @ 5.9 GHz) - V2I
Localisation technology	· Lidar · GPS/RTK-GPS

Table 1.1: Metadata categorisation of the CAV trial in this project.

1.4 Safety Assurance

The Safety Assurance Report (SAR) for this project was developed to demonstrate comprehensive safety hazard identification, analysis, and mitigation activities ensuring safe operations for the trial of C-ITS. The SAR was required to validate that safety risks associated with automated vehicle operations were adequately managed to levels reduced So Far As Is Reasonably Practicable (SFAIRP).

The purpose and scope of the SAR were to ensure hazard identification and risk assessment activities were complete and robust, and to confirm integration of new C-ITS components (e.g., ETSI messages such as MAPEM, SPATEM, and CPM via DSRC) maintained operational safety.

The SAR enabled extension of automated vehicle operations previously established under the trial in iMOVE CRC Project 1-012, which was also a collaboration between the ACFR and TfNSW, and additionally enabled interaction of trial vehicles with upgraded traffic infrastructure, utilising DSRC messages for intersection decision-making. The background information about iMOVE CRC Project 1-012 can be found in Appendix A.1.1.

Key safety assurance activities included:

- Updated the Project Hazard Log (PHL), reflecting operational experience and changes due to DSRC integration.
- Incorporated additional mitigations for managing potential erroneous DSRC data.
- Maintained rigorous HIL processes to validate intersection clearance decisions.

Submitted safety assurance documentation was approved by the TfNSW Safety Assurance Board (SAB) based on the similarity between this project and iMOVE CRC Project 1-012.

The Ministerial Order, which was originally granted during iMOVE CRC Project 1-012, was extended to remain in effect until 30 November 2025 unless revoked earlier.

The detailed safety assurance documentation is presented in Appendix: Safety Assurance.

1.5 Report Structure

This report highlights the project activities that occurred throughout the project. The remainder of the report includes the following.

- Chapter 2: C-ITS design and development
- Chapter 3: Integration with SCATS
- Chapter 4: Demonstrations in controlled environments
- Chapter 5: Demonstrations at the Cudal FMTRC
- Chapter 6: Demonstrations in live traffic
- Chapter 7: Conclusions
- References
- Appendix: Safety assurance

2

C-ITS Design and Development

2.1 Introduction

The C-ITS element that the ACFR was responsible for during this project was an IRSU. Also, a number of changes to the systems on the three vehicles used in the project were required before they could be used in the demonstrations of V2V and V2I connectivity. The changes were focused on adding functionality to send, receive and act upon DSRC messages.

2.2 Intelligent Roadside Unit

The IRSU was designed, fabricated and deployed during the first phase of the project. The IRSU was deployed at the same time as the SCATS' infrastructure upgrade to intersection 4572 in preparation for the second phase of this project.

2.2.1 Sensor Selection

The IRSU deployed to intersection 4572 has two lidars, three RGB cameras, and a DSRC radio. A picture of the sensors is shown in Fig. 2.1. The deployed IRSU is pictured in Fig. 2.7a.

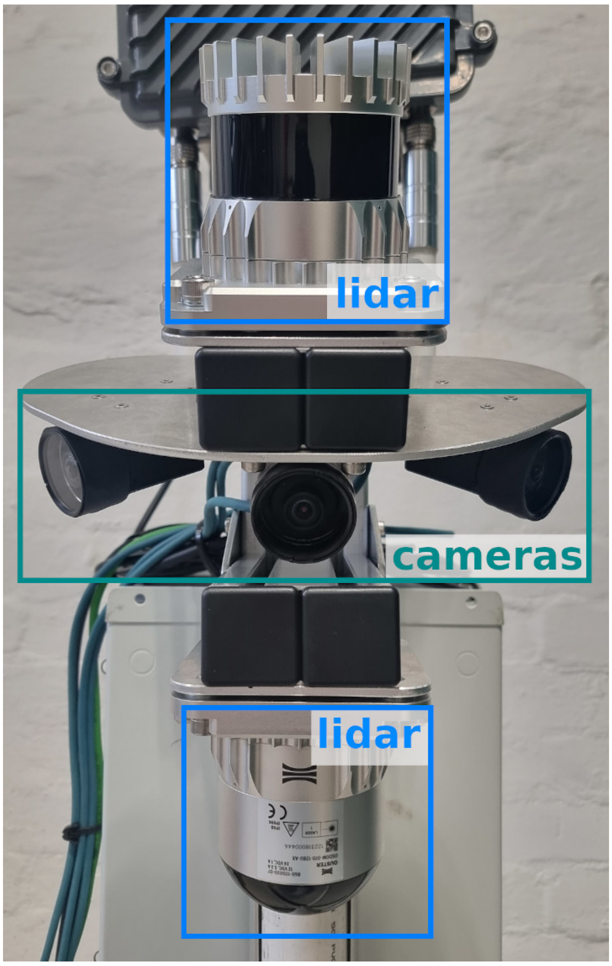


Figure 2.1: Sensor head of IRSU. The lidar on the top is an Ouster OS1-64, and the lidar at the bottom is an Ouster OS-Dome.

Given the use case of the SCATS team for tracking pedestrian movement through and around the intersection, the sensor suite was chosen to provide high-fidelity data within the intersection. This was primarily achieved using the Ouster OS-Dome, a hemispherical lidar sensor with 128 channels of vertical resolution across its entire Field-of-View (FoV). A scan from the deployed unit is shown in Fig. 2.2. This lidar was selected for the task due to its unique scan pattern with the 180° FoV below the sensor, effectively covering all three pedestrian crossings at the intersection. Lidars were selected as the primary road user detection sensor modality because of their strengths, including resistance to light variation and the absence of potential data privacy issues.

Although a single OS-Dome is sufficient to cover a small intersection, as in this case, we recommend installing two or more such lidars at diagonal intersection corners and other types of lidars to cover a larger intersection, or to generate higher-density liar point clouds for improved detection performance. The Ouster OS1-64 lidar was included in the sensor suite to complement the OS-Dome lidar by monitoring beyond the intersection on Abercrombie St, making it more suitable for detecting cars approaching the intersection from the south than for detecting pedestrians at the intersection. However, cost becomes a significant concern for multi-lidar solutions, as lidars have a substantially higher cost compared with other common object detection sensors, such as cameras.

The RGB cameras were included in the sensor suite mainly to monitor environmental and traffic conditions at the intersection. Despite their much lower cost compared with lidars, RGB cameras were not used for model training or road user detection due to data privacy concerns and their reduced performance in low light conditions.

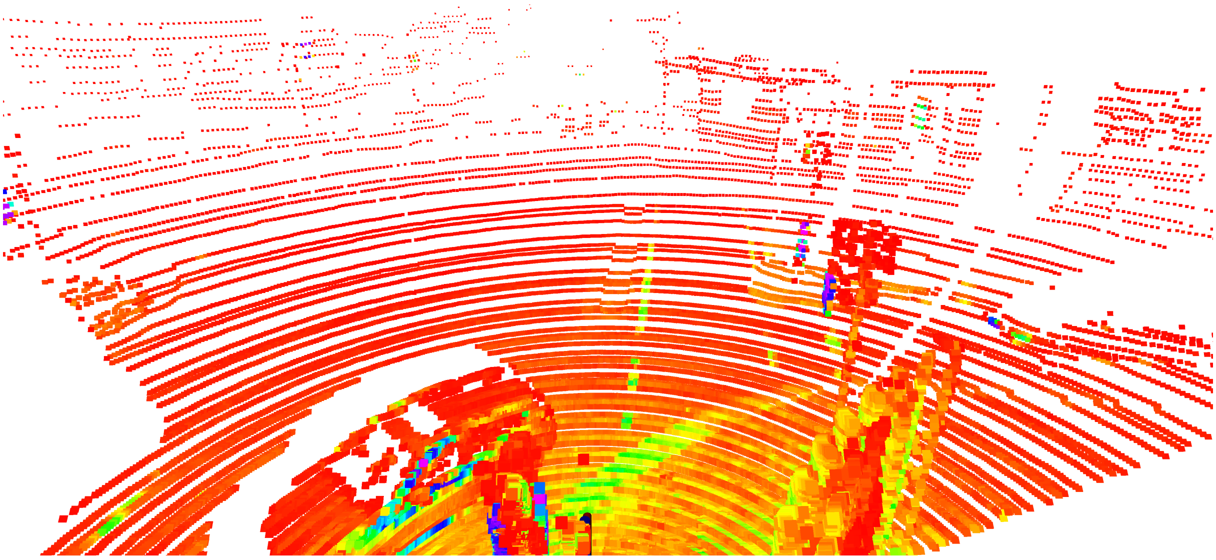


Figure 2.2: Typical pointcloud of intersection from Ouster OS-Dome lidar

A Cohda Wireless Mk5 RSU allows ETSI DSRC messages to be broadcast. These messages contain information that improves situation awareness for drivers and AVs in the scene. The main message type sent by the unit in this trial is the CPM which provides information about what the IRSU can perceive in the traffic scene. Typical information includes target type, motion and classification confidence.

The full system diagram for the IRSU is shown in Fig. 2.3.

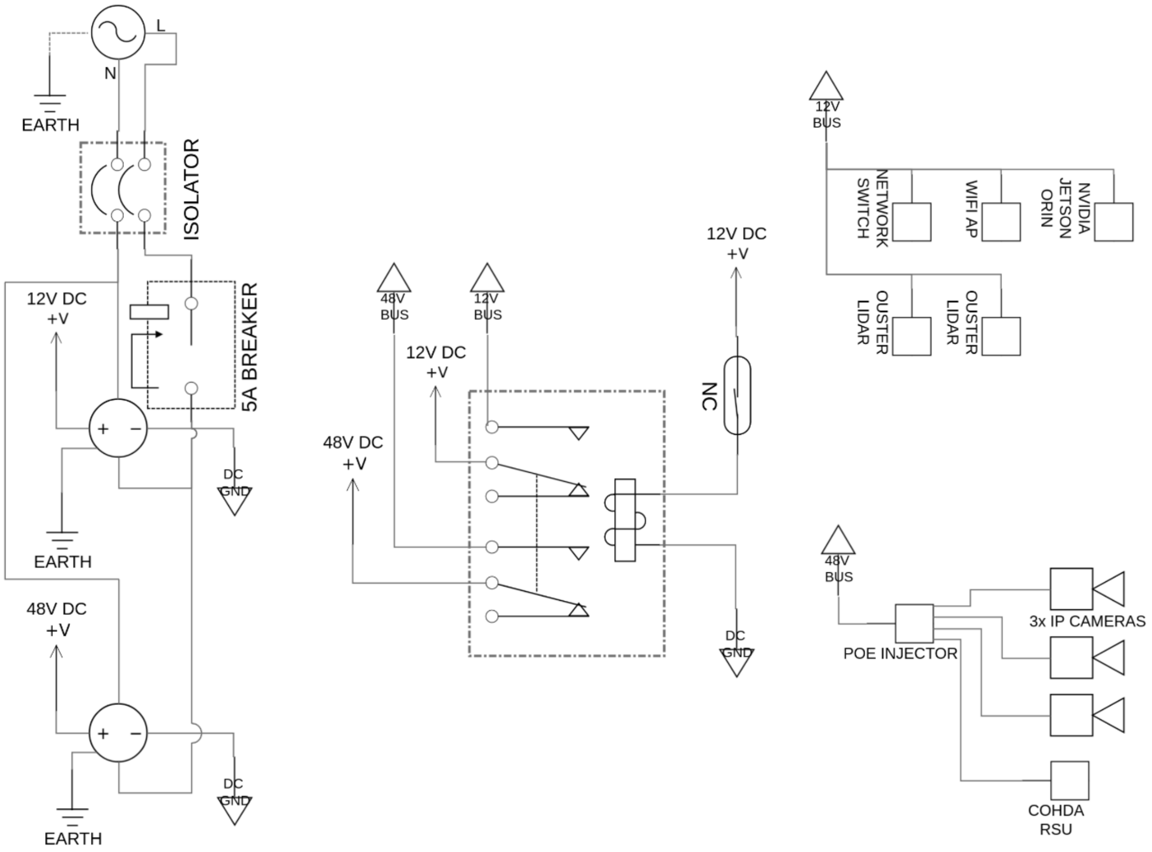


Figure 2.3: Edge compute enclosure wiring diagram

2.2.2 Compute and Other Devices

The volume of data coming from the sensors means that processing must be performed in situ. The combined camera and lidar sensor suite generates approximately 13 gigabytes per minute. It is therefore infeasible to stream this amount data for processing elsewhere in real time.

The edge computing components and network equipment are presented in Fig. 2.4. The system features an NVIDIA Orin 64GB Dev Kit, which serves as the main computing unit for sensory data processing, road user detection model inference, and data logging. A QNAP QSW-2104-2T network switch is used to connect all sensors and the Orin, using 1Gbps and 10Gbps Ethernet connections, respectively. The cameras are powered via a Power over Ethernet (PoE) injector. Network management is provided by a Teltonika RUTX11 industrial router, which also offers dual-band WiFi and 4G LTE cellular connectivity. Additionally, the Orin is connected via Ethernet to the Cohda Wireless Roadside Unit (RSU), which is located outside the edge compute enclosure. The Cohda RSU also receives power via PoE.

When the system is operating, raw sensory data can first be logged to the Orin and then extracted to external computers via the WiFi connection to the system. The extracted data are useful for visualisation, diagnostics, and also in the training and validation of road user detection models.

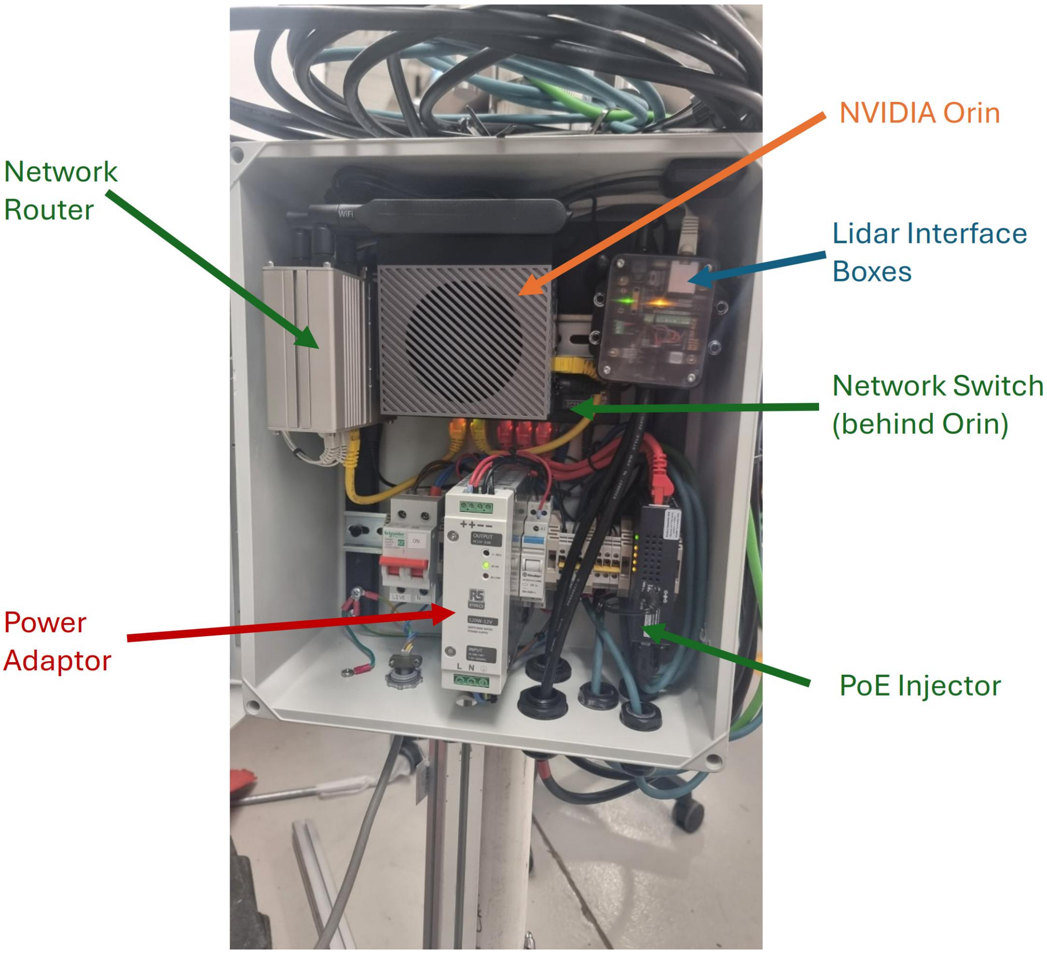


Figure 2.4: Inside edge compute enclosure

2.2.3 Mechanical Design

TfNSW specified a standard CCTV mount, a technical drawing of which is shown in Fig. 2.5, for attaching the IRSU to the traffic light. The ACFR fabricated fixture to connect the sensor head and the compute enclosure to this CCTV pole.

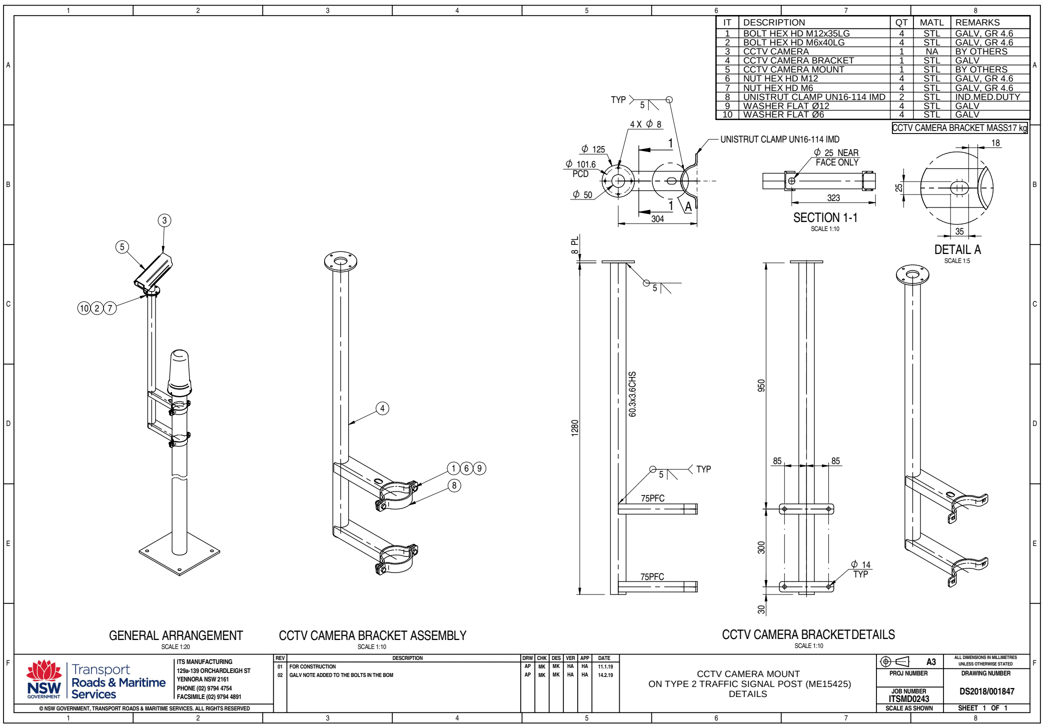


Figure 2.5: CCTV mount

2.2.4 Software Development

The IRSU was delivered to Connect Sydney in September 2023. There were major delays before it was installed on-site, all of which were outside of the control of the ACFR. Between then and when the IRSU was installed in December 2023 the ACFR did not have access to the unit. Software developed during this time could not be validated with real-world data. Work in this area focused on development of processes for data logging, remote access, and system health monitoring. As a key feature of the IRSU, the machine learning based road user detection work and broadcast of CPMs was conducted in 2024, as detailed in Section 2.2.7.

After installation, the ACFR verified that the IRSU is receiving DSRC messages including MAPEM and SPATEM from the SCATS unit, and other messages from the trial vehicles.

2.2.5 Preparation for Installation

In-lab testing commenced once the IRSU was constructed. During this time, the ACFR also created a document with installation instructions for the IRSU. This document was provided to TfNSW and their affiliates to provide details on the various components that make up the IRSU and to walk installers through what is required to deploy and commission the unit. The document was also used to navigate the relevant TfNSW approval processes that were required before the IRSU could be deployed.

To aid in the deployment process, the ACFR procured a post with a similar diameter to the CCTV mount shown in Fig. 2.5 and fastened the IRSU to this post in the ACFR lab, as shown in Fig. 2.6, where it remained until it was delivered with all of the required fasteners to Connect Sydney, who were commissioned by TfNSW to install the IRSU and perform the other required upgrades at intersection 4572.

Figure 2.6: IRSU in ACFR lab

2.2.6 Installation

The IRSU was installed as part of the uplift program for intersection 4572. The IRSU was installed by Connect Sydney in December 2023. The IRSU is mounted on a CCTV mount, which is affixed to a Type 2 post, as shown in Fig. 2.7a, on the North-Western corner of intersection 4572. The RGB cameras of the IRSU are oriented in the direction of North-bound traffic on approach to the intersection along Abercrombie St, as shown in Fig. 2.7b. A wider shot of the intersection is provided in Fig. 2.8 as an example of the orientation of the RGB cameras.

(a)

(b)

Figure 2.7: IRSU deployed at intersection 4572. (a) shows the IRSU affixed to a Type 2 post. (b) shows it installed on the North-Western corner of the intersection.

Figure 2.8: IRSU deployed at intersection 4572, wider shot of the intersection

Fig. 2.9 shows an aerial view of the intersection with different approaches. The northbound approach on Abercrombie St is used in the RLVW scenario and also for right turns onto Meagher St in the user turn warning with occupancy detection scenario. The eastbound approach on Myrtle St and the westbound approach on Meagher St are used in automated driving scenarios.

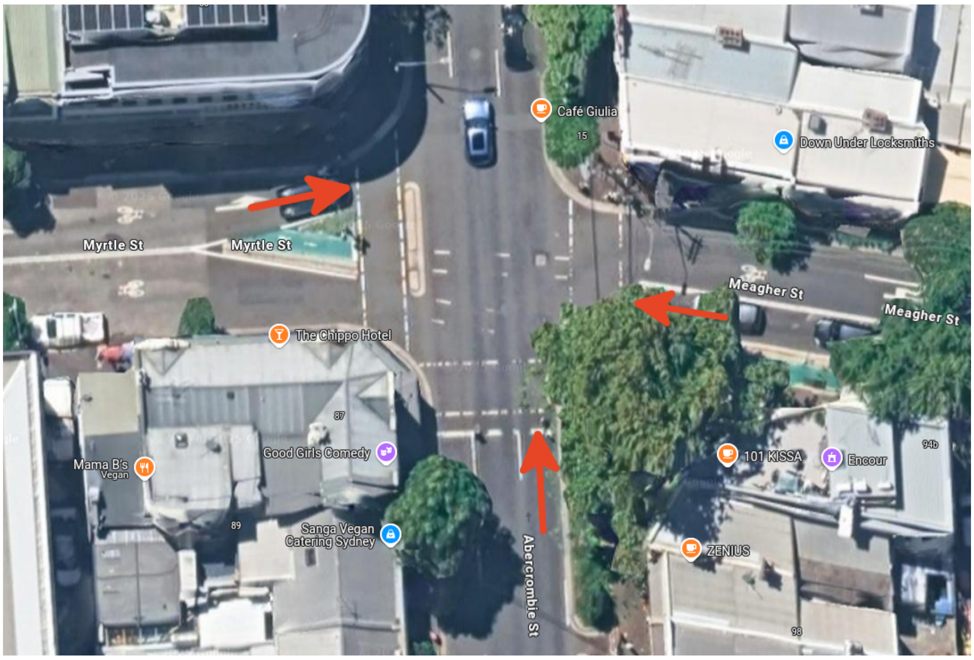
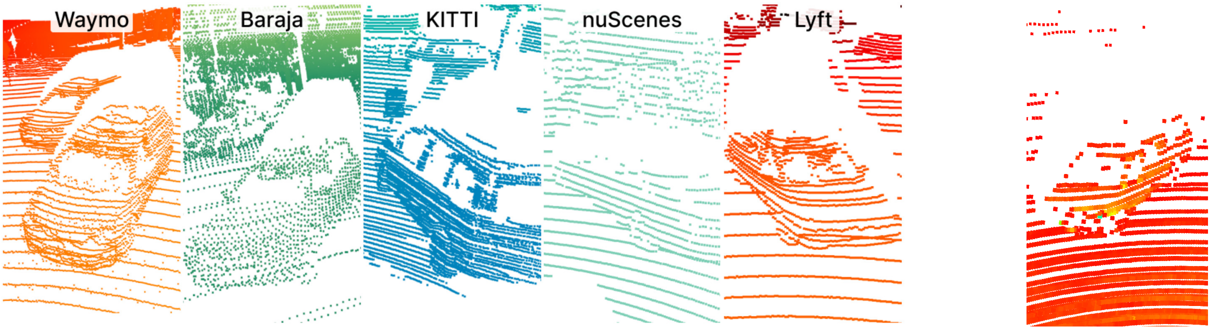


Figure 2.9: Aerial view of the intersection showing different approaches

2.2.7 Road User Detection and CPM

A 3D object classification model based on the lidar point cloud, *PointPillars* [2], was used to detect and classify common types of road users in real time. This includes vehicles, pedestrians, and cyclists. *PointPillars* models pretrained on public datasets are not suitable for intersection 4572, due to the domain shift caused by different traffic environments, lidar scan patterns, and lidar mounting heights and angles. As illustrated in Fig. 2.10, cars can appear significantly different due to the difference in lidar scan patterns and perspectives. This domain shift results in a significant drop in detection performance [3].



(a) (b)

Figure 2.10: Cars in (a) different public datasets [4] and in (b) the lidar scan from the IRSU.

Therefore, the *PointPillars* model deployed on the IRSU was retrained using lidar data collected at intersection 4572 to capture this domain shift. In addition, the data were recorded under different weather and traffic conditions to enhance the diversity of the data. Before retraining, collected data was labelled with 3D bounding boxes for common road users, as illustrated in Fig. 2.11. The labelled data was divided into two subsets for model training and model performance evaluation.

The model retraining was conducted using an open source *PointPillars PyTorch* implementation, available online at `https://github.com/zhulf0804/PointPillars.git`. The code was modified as needed to enable it to process data collected from the intersection for model training. The retrained model was first in *PyTorch* format, and subsequently optimised using NVIDIA *TensorRT*, a high-performance inference optimiser and runtime that delivers low latency and high throughput for deep learning inference on NVIDIA GPUs.

The retrained *PointPillars* model was then deployed to NVIDIA AGX Orin, the edge computer of the IRSU, for real-time road user classification at 10 Hz. Fig. 2.12 presents examples of detected road users from the IRSU.

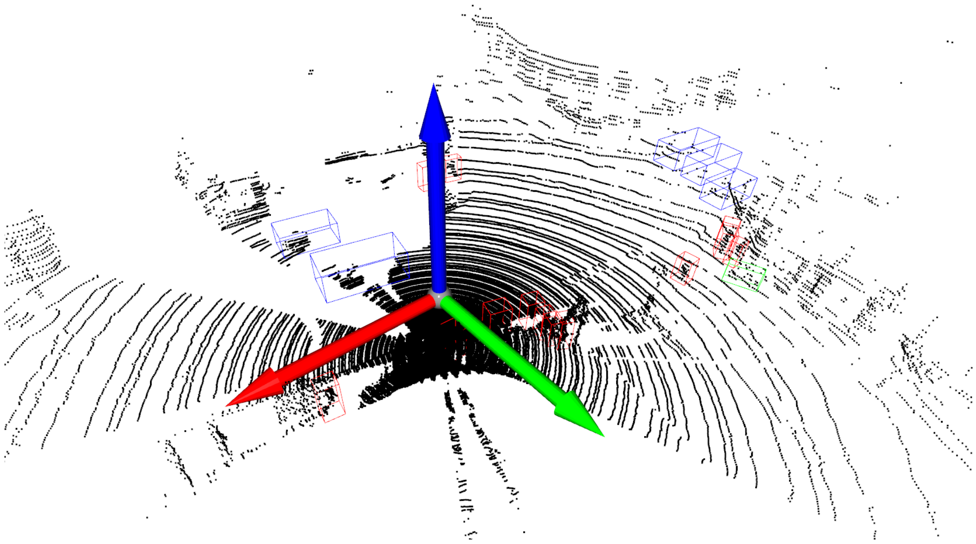


Figure 2.11: Visualisation of lidar pointcloud labels. The vehicles, pedestrians, and cyclists are annotated with 3D bounding boxes in blue, red, and green colours, respectively.

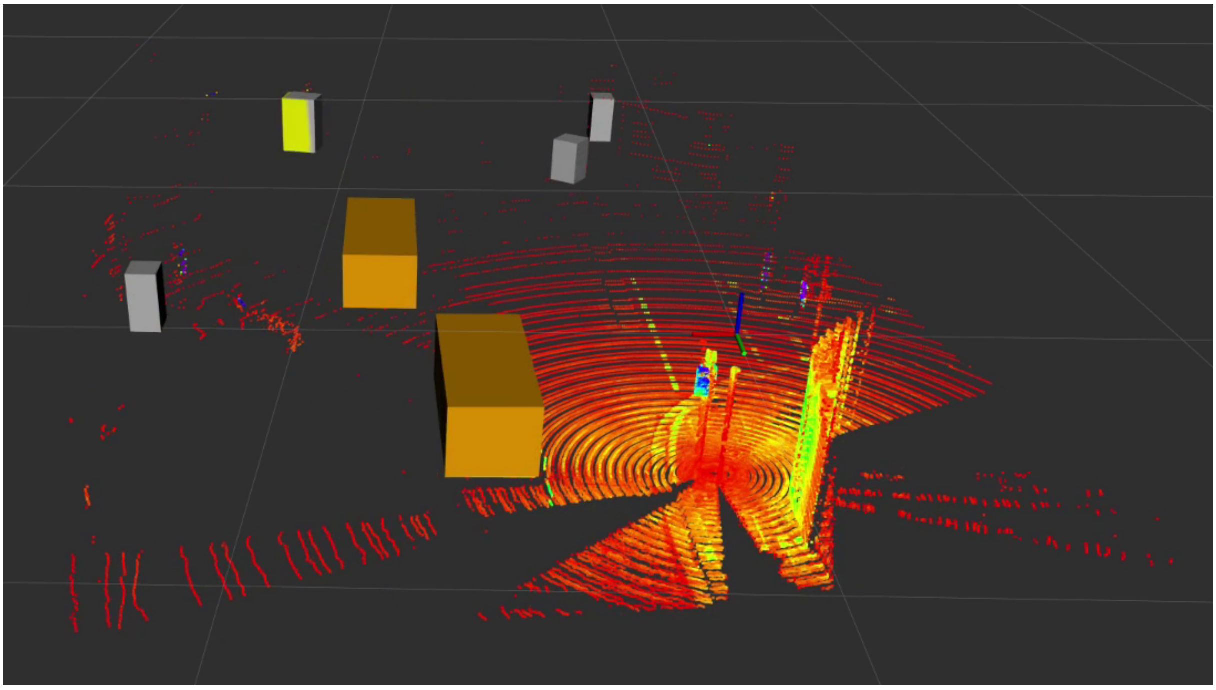


Figure 2.12: Visualisation of real-time road user classification results from the deployed *PointPillars* model. The detected vehicles, pedestrians, and cyclists are visualised as 3D bounding boxes in orange, gray, and yellow colours, respectively.

A short video showing real-time CPM decoding via DSRC is available at `https://youtu.be/ouVjL7ugBLg`.

In the video, and as also shown in Fig. 2.14, 3D bounding boxes in pink represent pedestri-

Metric	**Pedestrian AP@0.5**	**Cyclist AP@0.5**	**Car AP@0.7**
BBOX_BEV	51.19	31.05	59.05

Table 2.1: Model evaluation results. AP stands for Average Precision

ans, with blue representing vehicles. The 2D 'blobs' represent flattened obstacles as observed from an on-board 3D laser scanner.

What appears to be a delay between the 3D bounding boxes and objects from the local perception information is due to the configuration of the IRSU that broadcasts the CPMs over DSRC. The configuration has since been updated, resulting in better alignment between the remote and local information.

Apparent 3D bounding boxes around objects that do not exist are false positive detection. This is due to the initial training of the *PointPillars* model deployed to the IRSU. The model has since been retrained on data collected by the IRSU to account for the domain shift, resulting in less false positives.

The performance of the retrained model was benchmarked using the evaluation subset of the manually labelled data from the intersection, with the results presented in Tab. 2.1. The evaluation metric used was *BBOX_BEV*, which measures the accuracy of estimating bounding boxes from bird's eye view. Note that the results are indicative only due to limited size of evaluation dataset.

To reduce the remaining false positives and to further improve detection performance, additional labelled data from the intersection is generally required for the model training. The observed false positives are partly attributed to the fact that we prioritised pedestrian scenarios during the data collection. This was driven by the need to optimise the model for the use case of user turn warning with pedestrian crossing occupancy detection, as demonstrated in Section 6.2.3. However, this resulted in the under-representation of other road user types in the data, in particular, cyclists, causing a comparatively lower Average Precision (AP) score in Tab. 2.1 and higher false positives for these classes. It is therefore recommended to collect more data and capture a more balanced distribution of different road user types in future data collection to improve overall model performance.

2.2.8 DSRC Integration

The results of the tuned classification model were passed into an ACFR V2X software stack to generate ETSI CPMs. The overall processing pipeline is presented in Fig. 2.13. Further details of this V2X software stack are provided in Section 2.3.5.

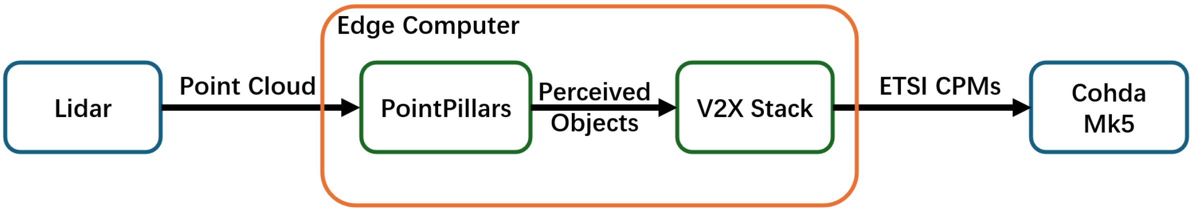


Figure 2.13: The processing pipeline for generating CPMs

The CPM specification can be found in Section 7 of the ETSI Technical Standard 103 324 (V2.1.1), which is available online at: `https://tinyurl.com/bdfk4ffk`.

These CPMs were received by the ACFR test vehicles, decoded, and used to improve the situational awareness of the autonomy stack of the CAV or driver of the CV. Applications using CPMs are described in Chapter 6.

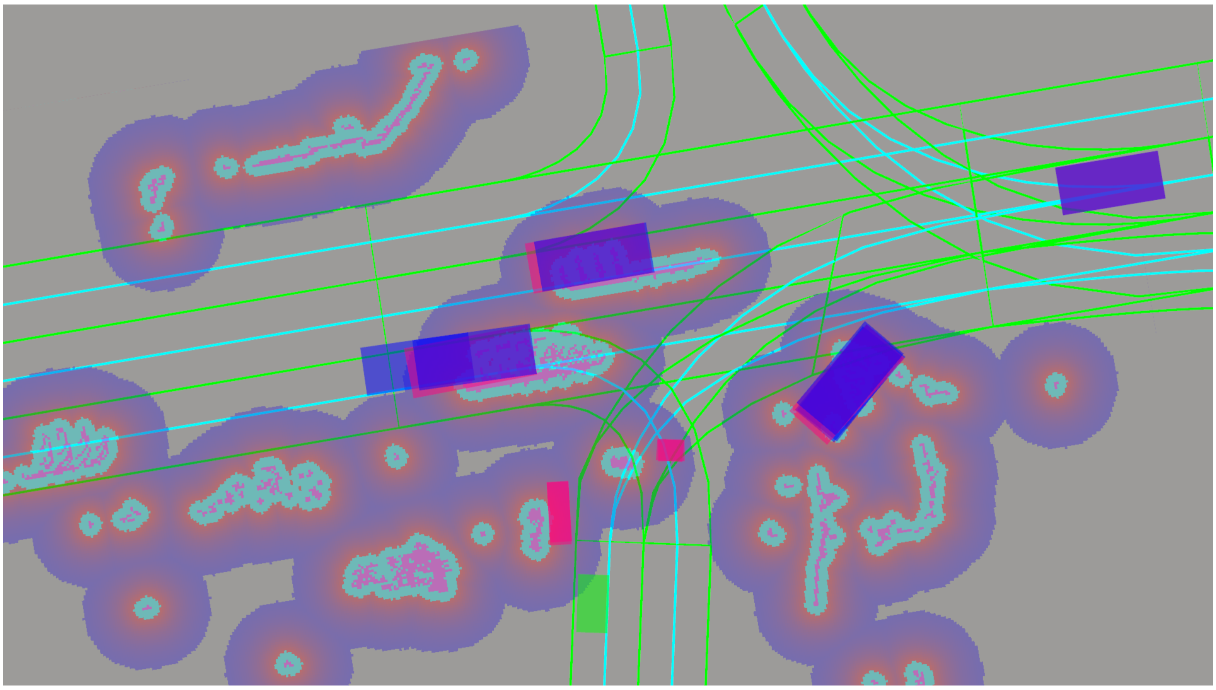


Figure 2.14: Visualisation of traffic participants encoded in CPM. Pink and blue rectangles represent pedestrians and vehicles respectively in the CPMs. The 2D 'blobs' represent flattened obstacles as observed from the lidar mounted on the vehicle

2.3 Connected and Automated Vehicles

2.3.1 Overview

The ACFR team has been conducting research with the CAV used in this project in numerous areas of autonomy since 2017, when platform was built by Applied EV in consultation with the ACFR. The ACFR is responsible for the entire technology stack, including both hardware and software. The CAV uses Robot Operating System 2 (ROS2) as a software "middleware" to support modular design and system integration. The CAV is equipped with a suite of sensors (listed below) and onboard computing capabilities for real-time sensor data processing.

The installed sensors include:

- 1x Ouster OS1-128 REV7, a 128-beam scanning lidar with a 45° vertical FoV and a 360°horizontal FoV for perception, localisation, and mapping.
- 1x Cohda Wireless Mk5 On-Board Unit (OBU) transceiver for communicating in V2X networks.
- 1x Global Navigation Satellite System (GNSS) for high-level (global) localisation.
- 1x 6 Degrees of Freedom (DoF) Inertial Measurement Unit (IMU) for odometry.
- 4x wheel encoders for measuring the rotational speed of the wheels.
- 1x wireless Hetronic e-stop transmitter and receiver for entering/exiting autonomous mode.

The software stack has many components that must work together for the safe operation of the CAV, and to support automated driving through a controlled intersection in this project. Each of the essential components is described in detail in the remainder of this section.

2.3.2 Localisation

Automated driving requires localisation to a high degree of accuracy, typically in the order of centimetres. In order to support this, a new Simultaneous Localisation and Mapping (SLAM) map was created from several manual drives around the operational area. In simple terms, the scene that the lidar can see at a given pose is logged and compared to the view at other poses. An estimate of the vehicle's motion can be calculated from the correspondence between these poses. The resultant map is saved and can be used for future localisation by once again comparing the view by the lidar to stored viewpoints. The particular approach used in this trial is called "graph SLAM" and uses the Google Ceres Solver [[5]] to perform the calculations. A sample of the map is shown in Fig. 2.15.

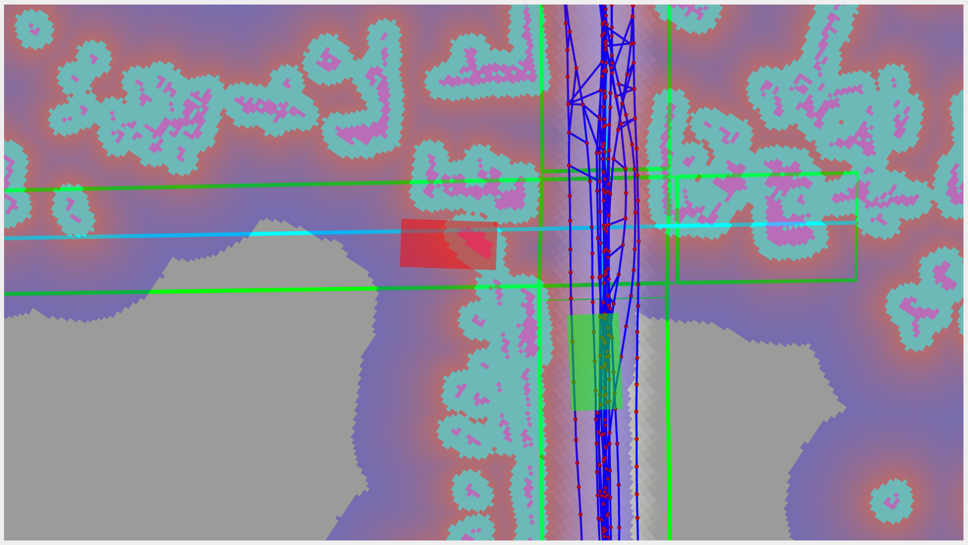


Figure 2.15: Map used for localisation. Red points are recorded poses, and blue lines are associations between poses inferred by the algorithm.

2.3.3 Mapping

Once the SLAM map for the area is created it is possible for the vehicle to know where it is in the world, but it has no information about the particular road rules in effect around it. A *Lanelet2* [6] map of the operational area was created to represent traffic information such as lane positions, one-way roads, intersections, traffic lights, yield points and speed limits. The *Lanelet2* map of the operational area is shown in Fig. 2.16. The *Lanelet2* map does not require updating based on changed traffic conditions, only when there are changes to network attributes such as speed limits.

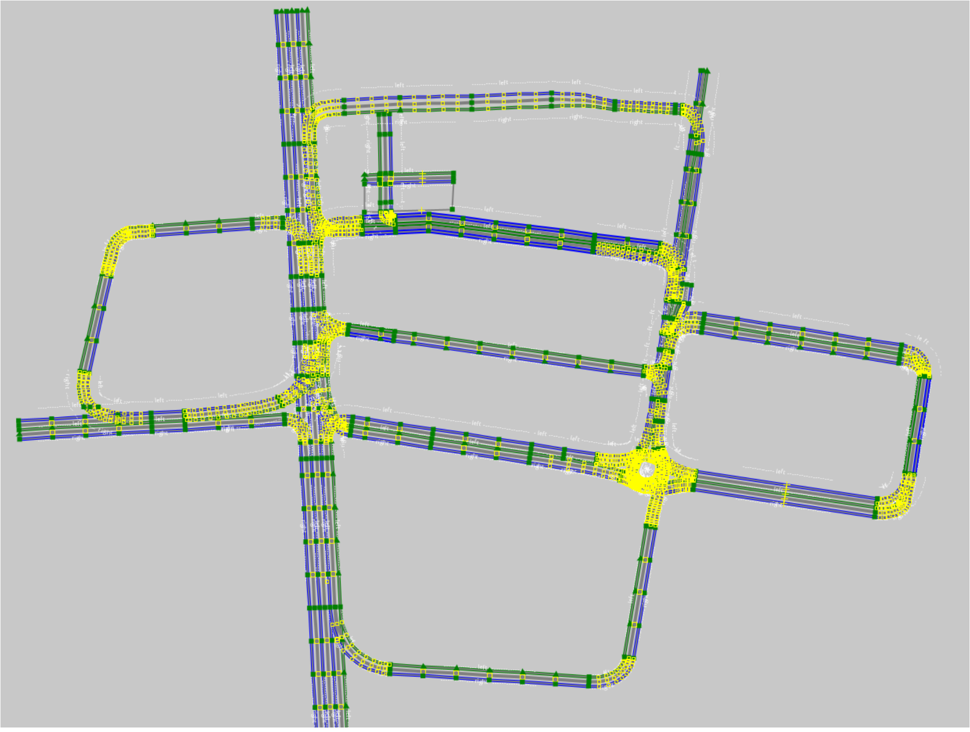
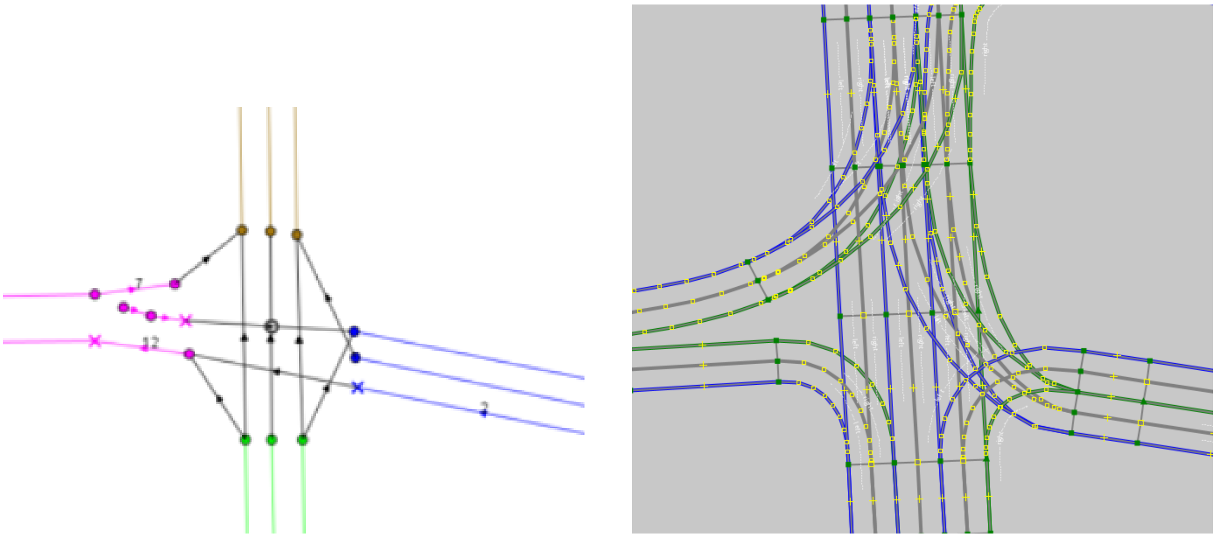


Figure 2.16: *Lanelet2* map of operational area

ETSI MAPEM messages contain geospatial information about the intersection. As can be seen in Fig. 2.17a it is sparse and not suitable for navigation with the precision needed for automated operations. The *Lanelet2* map of the intersection is much more information dense, as seen in Fig. 2.17b. An important part of the development work was developing the functionality to map the intersection connection information in the MAPEM to the driving lane information of the *Lanelet2* map. Without this mapping the vehicle would not be able to correlate its position with the intersection routing graph and therefore would not know which portion of the SPATEM to consider during navigation.



(a) (b)

Figure 2.17: Maps of intersection 4572: (a) MAPEM map, (b) *Lanelet2* map

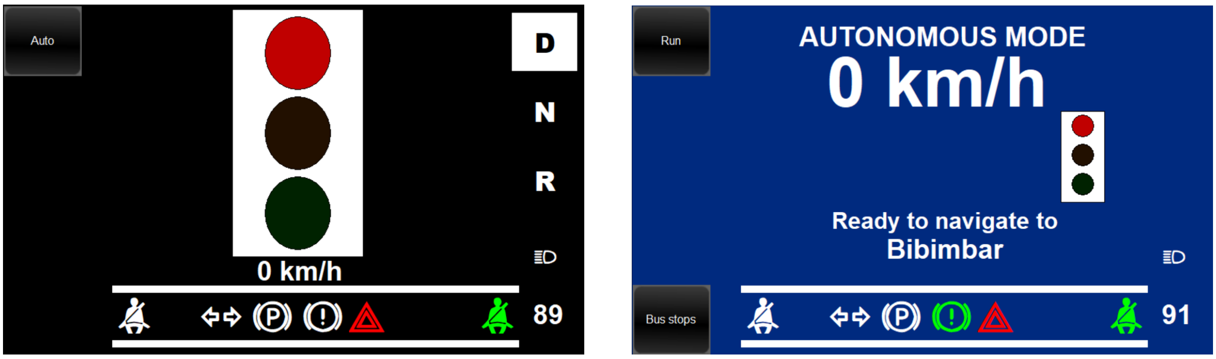
2.3.4 Motion Control

In order to improve the ability of the vehicle to track a path and correct for lateral errors both quickly and smoothly, the lateral control of the vehicle was switched to the controller commonly referred to as a *Stanley controller* [7]. Lateral errors may arise from localisation updates as the vehicle moves through space or they may exist based on the fact that controllers running on real-world platforms do not perfectly track a given path. Longitudinal control of the vehicle was also improved by use of the *Ruckig* [8] motion profiling package to create smooth, jerk-limited speed profiles. Both of these changes lead to much smoother motion and increased comfort for vehicle occupants and other traffic participants.

2.3.5 DSRC Integration

The ACFR team has developed a V2X software stack, which was used in ACFR IRSU, CAV, and CV for encoding and decoding various ETSI DSRC messages. The software stack is primarily a ROS2 extension of *vcits*, an open source library for ETSI V2X messages, available online at: `https://github.com/virtual-vehicle/vehicle_captain_its_lib_c_cxx.git`.

In order to allow the vehicle supervisor to see that DSRC information is being received and is correct, a visual interface was developed. Fig. 2.18a shows SPATEM information when the vehicle is driven in manual mode, and Fig. 2.18b shows the same information in automated mode. In all modes, the screen displays: vehicle speed; vehicle interlock, ancillary and accessory states; battery state of charge. In manual operation the screen also displays: drive direction selection; a traffic light with the current phase when the vehicle is approaching a signalised intersection. In automated operation the screen also displays: vehicle mode; a bus stop selection button; selected bus stop details (if a bus stop has been selected); navigation state; iconography depicting additional signals the vehicle may be waiting on before it proceeds through an intersection - be they CAMs, HIL, SPATEM.



(a)

(b)

Figure 2.18: SPATEM information displayed in (a) manual mode, and in (b) automated mode.

2.4 Connected Vehicle

The Volkswagen Passat operated by the ACFR was included as a CV in the demonstrations to address the use cases of interest to the SCATS team. It was equipped with a Cohda Wireless Mk5 OBU to exchange DSRC messages with other connected agents.

The CAVs had operational restrictions placed on them that proscribe driving through the demonstration intersection by approaching from Abercrombie Street. The Passat had no such restriction. As a full-sized passenger vehicle, the Passat also gave a better idea of what in-cabin driver aids from DSRC would behave like.

3

Integration with SCATS

3.1 Introduction

This project focuses on C-ITS so it was appropriate to engage with groups within TfNSW that are responsible for road network infrastructure. SCATS have been active participants in this project and framed a number of use cases that they wished to explore as part of this project phase.

Throughout the project a number of in-person meetings have occurred between the ACFR and SCATS. Both teams have visited the premises of the other for knowledge transfer. This level of dialogue, both formal and informal, has been very useful for both parties.

3.2 SCATS Use Cases

SCATS were involved in the upgrade of intersection 4572 to enable the broadcast of DSRC messages. Necessary hardware upgrades were performed such that our ACFR vehicles can receive and decode the DSRC messages. The full set of proposed messages were broadcast from SCATS intelligent traffic light, including MAPEM, SPATEM, and CAM.

With the upgraded infrastructure at intersection 4572, a number of use cases for DSRC technology have been demonstrated. As all activities are on a limited trial basis, SCATS instructed that the DSRC messages should not be encrypted to reduce the overhead for implementation and processing.

3.2.1 Red Light Violation Warning

A vehicle approaching an intersection that receives SPATEM messages obtains the time remaining in the current signal phase from these messages. If the next or current phase is red, the vehicle's current speed can be used to determine whether the vehicle will violate the red light. If so, an alert is generated in the vehicle cabin to warn the driver.

In this project, this use case was implemented, tested, and demonstrated by driving the ACFR CV in both a controlled environment at FMTRC and in live traffic on Abercrombie St, Chippendale. The logic behind how RLVW is triggered in these demonstrations is explained in Section 5.1.1. Details are provided in Section 5.1 and Section 6.2.1 for the FMTRC and live traffic demonstrations, respectively.

3.2.2 User Turn Warning for VRUs

When a vehicle is turning through an intersection, the SPATEM will refer to the green signal as either protected or permissive movement is allowed, specifically:

- The permissive state indicates that movement is allowed, but that there may be conflicting traffic including vehicles and pedestrians;
- The protected state indicates that there should not be any conflict.

To help understand these two movement states in SPATEMs, examples at intersection 4572 are provided in Fig. in Section 6.2.2.

Based on the specific configuration at intersection 4572, it is possible to use the protected and permissive states to determine whether the vehicle is turning across a currently active pedestrian crossing. The activation of the crossing can be conveyed as an in-cabin user turn warning for VRUs to the driver.

The user case was implemented, tested, and demonstrated through a CV turning from Abercrombie St to Meagher St at intersection 4572, as elaborated in Section 6.2.2.

3.2.3 User Turn Warning with Pedestrian Crossing Occupancy Detection

Pedestrians crossing at the controlled intersection press the demand button to signal their intention to cross. There is no sensing in the system that can determine whether the pedestrian is still present at the time the traffic lights permit pedestrian crossings, or whether a pedestrian crosses against the lights.

The current approach sees SPATEM being sent to vehicles that include the state of the crossing when movement of the vehicle is across it, but it cannot include information about the actual pedestrians. SCATS are interested in exploring how additional sensing can provide a better understanding of the traffic scene as it relates to pedestrians, and how the ETSI DSRC messages can support transmission of this information.

To implement this use case, research and development work was carried out to enable the ACFR IRSU deployed at intersection 4572 to detect road users in real time and encode and publish results in the form of ETSI CPMs. Readers can refer to Section 6.2.3 for real traffic demonstrations.

3.2.4 Time to Green

Time to green utilises *MovementEvent* information in SPATEMs to deliver information related to an upcoming signal change for vehicles that are stopped at or approaching a red light.

In the case of a vehicle stopped at a red light, preemptive advisory information can be provided to prepare the driver of an imminent green light, thereby reducing delays and ensuring optimal usage of green time. Besides, it helps the vehicle's start-stop system prepare for the upcoming green light, bringing traffic efficiency benefits. Furthermore, this information could be used by CAVs, which may take some time to disengage braking systems in reaction to a green light.

This use case was implemented and tested in the project. It was demonstrated using the ACFR CV as part of demonstrations of other use cases, including the RLVWs at FMTRC in Section 5.1, and user turning warning with pedestrian crossing occupancy detection in live traffic in Section 6.2.3.

3.2.5 Signal Request Messaging

Although outside the scope of the initial project, it was jointly decided to add Signal Request Extended Message (SREM) broadcasts by the vehicles involved in this project. SREM has the potential to improve network demand management by having vehicles requesting particular signal sequences well ahead of their approach to the intersection. This contrasts with the current approach where demand is only signalled by vehicles triggering induction loops as they arrive at the intersection.

Although SCATS will not act on these messages to change the signal phases at intersection 4572, it allows SCATS to receive live data from real vehicles and to explore how this might be integrated into their systems. Essentially, SREMs contain important vehicle information that is not included in CAMs. For instance, when a vehicle is approaching an intersection, it sends a SREM that contains its ingress and egress lanes, determined based on its position and intersection connection information in the received MAPEM. It is also an excellent test to investigate the required parameters of such messages (e.g. positioning accuracy, broadcast frequency, distance from intersection to send request) for them to be useful in a traffic management context.

4

Demonstrations in Controlled Environments

4.1 Introduction

In order to validate the operation of the automated driving system and DSRC messages, it was necessary to test the developed technology first in a controlled environment. A mock intersection was created in the ACFR lab to allow this testing to occur. This was also used for demonstrating the various technologies to visitors to the lab—an important outreach activity for the project.

For this mock intersection, only basic lanes were created virtually, without drawing lane markings on the ground, and a mock traffic light was employed for sending simulated MAPEMs and SPATEMs. This simplified setup for a mock intersection is considered sufficient for a proof-of-concept demonstration of the developed technology. For a more realistic mock intersection, it is recommended to model it after a real-world intersection. This would allow for showing more complicated traffic scenarios, including multiple lanes with lane markings, a mix of virtual and real traffic agents, and a set of traffic lights that closely replicate the signal control patterns of real ones.

4.2 Intersection Mapping

The mock intersection consists of two crossing lanes. The main lane is placed down the main access way of the lab. The Electric Vehicle (EV) with the red logo on the left side of Fig. 4.1 is in the main lane. A secondary lane crosses the main lane. The EV with the black logo on the right side of Fig. 4.1 is in the secondary lane.

Right-of-way is assigned to the secondary lane—an EV in automated mode in the main lane will always yield to the EV in the secondary lane. A traffic light also controls ingress to the intersection along the main lane. Thus, for the EV operating in automated mode to proceed through the intersection it must receive a green light and there must be no vehicle in the secondary lane. If one of these conditions is not met, the EV will wait to proceed.

The corresponding *Lanelet2* map for the mock intersection is shown in Fig. 4.2.

Figure 4.1: Mock intersection. The vehicle on the right of the photo has right-of-way. The mock traffic light can also be seen in the foreground.

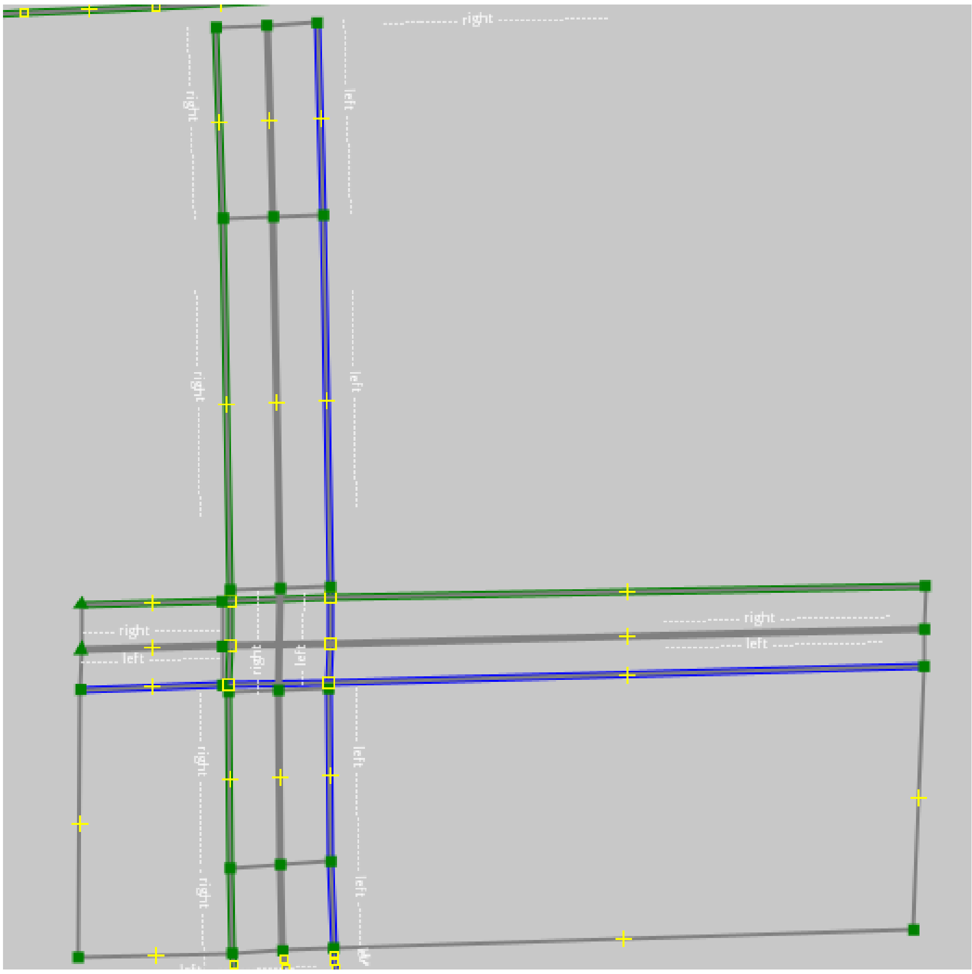


Figure 4.2: *Lanelet2* map of mock intersection

4.3 Traffic Lights

A manually controlled set of traffic lights was created to control the mock intersection. The traffic lights communicate with the EVs using MAPEM and SPATEM messages, in the same way that the intersection used in the road trial does. The mock traffic light unit is shown in Fig. 4.3. The unit contains a Raspberry Pi single-board computer and a Cohda Wireless Mk5 OBU. The computer mimics a traffic controller and encodes simulated MAPEM and SPATEM messages.

Figure 4.3: DSRC-enabled mock traffic lights

4.4 Right-of-Way

Right-of-way decisions rely on vehicle information exchanged by use of CAMs. CAMs are periodically broadcast by connected vehicles and infrastructure within the DSRC range to enhance cooperative awareness and improve safety. Each CAM contains critical status and attribute information of the transmission vehicle, including its current location, speed, and direction.

In the demonstration, upon receiving CAMs, the EV projects the position of other broadcasting vehicles onto the *Lanelet2* map. This projection enables the automation stack within the EV to evaluate the traffic environment and make informed decisions about yielding. Information that the EV is yielding due to received CAM information is displayed to the vehicle supervisor through the screen interface, as shown in Fig. 4.4.

Fig. 4.5 shows the position of the ego vehicle in green and the projected position of a second vehicle in red. The position of the second vehicle is encoded in the CAMs received by the ego vehicle via DSRC.

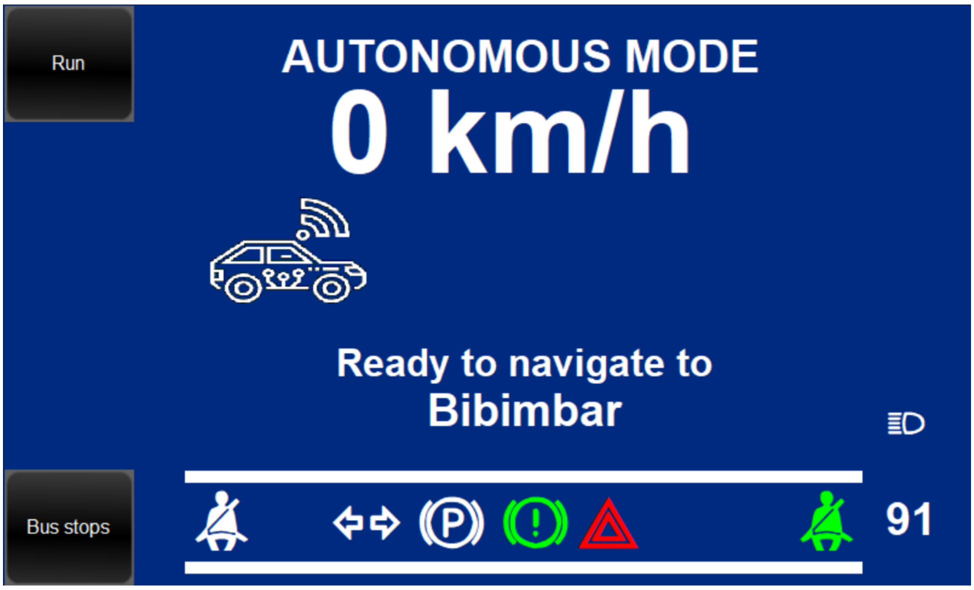


Figure 4.4: CAM information displayed in automated mode

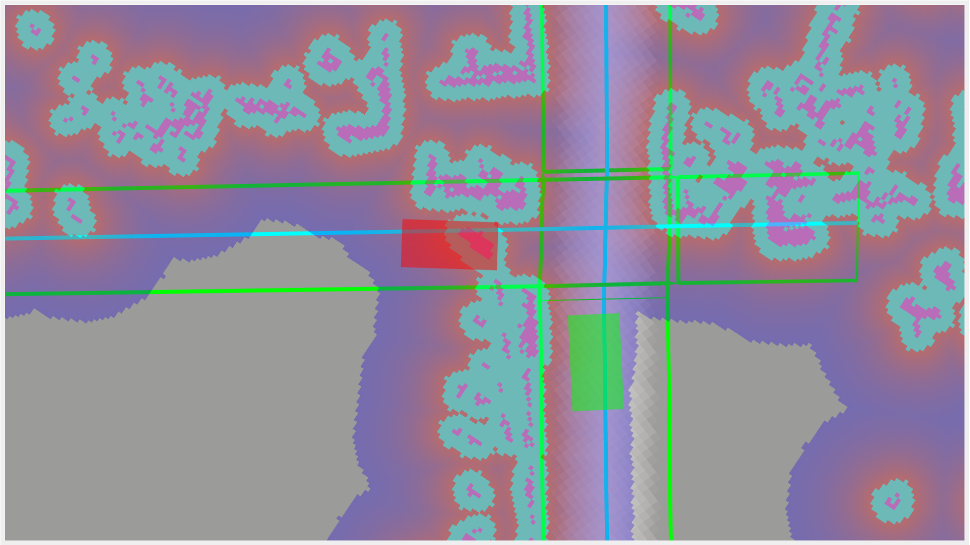


Figure 4.5: CAM information projected into autonomy stack map

4.5 Videos

A video of the EV carrying out numerous scenarios whilst operating in automated mode in the controlled environment of the ACFR lab was captured. A screenshot from one of those scenarios in the video is shown in Fig. 4.6.

The video contains three examples of the vehicle navigating through the mock intersection in automated mode:

- In the first example, the vehicle can be seen to wait at the mock intersection until the vehicle supervisor confirms it is safe to proceed, the DSRC-enabled mock traffic lights transition to green and a second vehicle broadcasting CAMs clears the intersection before proceeding.
- In the second example, the vehicle can be seen to wait at the mock intersection until the vehicle supervisor confirms it is safe to proceed and the DSRC-enabled mock traffic lights transition to green before proceeding.
- In the third example, the vehicle can be seen to wait for a pedestrian to clear the path on more than one occasion, before proceeding through the mock intersection once the vehicle supervisor confirms it is safe to proceed.

The video is available at `https://youtu.be/DC_0FjsL7gQ`.

Figure 4.6: Automated vehicle yielding right-of-way

4.6 Engagement

A large number of groups participated in demonstrations of the technologies developed as part of this project. These demonstrations could not have taken place in live traffic. A controlled environment has great value for education and outreach. One of these activities is shown in Fig. 4.7.

Participants in the demonstrations included people from:

- TfNSW Future Mobility Team
- TfNSW SCATS Team
- TfNSW Cudal FMTRC
- TfNSW Statewide Maintenance and Delivery
- industry
- international robotics research institutes
- The University of Sydney

Figure 4.7: University of Sydney staff learning about CAVs

5

Demonstrations at the Cudal FMTRC

5.1 Red Light Violation Warnings

One of the benefits to demonstrating new and emerging technologies in a controlled environment like the Cudal FMTRC is the ability to conduct tests/demonstrations in the manner they are intended to be tested/demonstrated. This includes being able to violate road rules, such as driving through red lights.

To showcase the utility of RLVWs, we conducted a series of tests with vehicle speeds ranging from 40 km/h to 80 km/h. A demonstration was filmed where representative RLVWs on and off scenarios were tested at 40 km/h. The algorithm we implemented for RLVWs is detailed in Section 5.1.1.

In the first example, the driver of a CV is able to safely come to a stop before entering an intersection when faced with a red light, due to the presence of an in-cabin RLVW, as shown in Fig. 5.1. In the second example, the driver is not presented with a RLVW as the system is not enabled and the driver violates the red light with catastrophic consequences, as shown in Fig. 5.2.

The video is available at `https://youtu.be/p01yb0TM0dk`.

Figure 5.1: An in-cabin RLVW enables the driver of a CV to come to a safe stop

Figure 5.2: A lack of RLVW results in a driver striking a pedestrian after violating a red light

5.1.1 Algorithm

The RLVW algorithm is based on the concept of *Time To Collision (TTC)*. The current speed of the vehicle is used to calculate the time it will take for the vehicle to reach the stop line, assuming a constant speed. If this value is below an empirically derived threshold and the traffic light is currently red or amber, the warning is displayed to the driver. Specifically,

$$TTC = \frac{d}{s}$$

where d refers to the distance between the vehicle current GNSS location and the stop line for the ingress lane, s is the current vehicle speed reading from GNSS.

$$RLVW = \begin{cases} ON & \text{if } TTC < \tau \\ OFF & \text{otherwise} \end{cases}$$

where τ denotes the *TTC* threshold for triggering a RLVW.

Note that *TTC* is a prediction and the calculation is performed based on the assumption of a constant speed model. When the driver is correctly braking to stop for the lights, the speed decreases and the *TTC* increases. If they are not braking, the *TTC* will continue to decrease until it falls below the threshold and the warning is displayed. If the driver accelerates, the *TTC* will decrease more rapidly. In an uncommon case where the driver initially brakes until the warning disappears but then suddenly accelerates, the warning will be displayed again if the calculated *TTC* falls below the threshold.

It is also important to note that this represents one implementation of the RLVW algorithm, which may differ from other implementations.

5.2 Community Day

The ACFR CV and CAVs were demonstrated to the public at the FMTRC Community Day.

The technologies described in the previous sections were demonstrated with members of the public able to ride along in the vehicles, and talk to the researchers about how the systems work. Some photos of the demonstrations are shown in Fig. 5.3, Fig. 5.4, and Fig. 5.5.

Figure 5.3: School student during live automated vehicle demonstration (Supplied: TfNSW)

Figure 5.4: School student during live automated vehicle demonstration (Supplied: TfNSW)

Figure 5.5: Member of the public during live automated vehicle demonstration (Supplied: TfNSW)

5.2.1 Detailed Analysis

The Cudal FMTRC team produced a detailed analysis of the experimental activities undertaken at the Cudal FMTRC, which is provided in a separate report.

6

Demonstrations in Live Traffic

6.1 Automated driving

6.1.1 Operational Area

The operational area for automated driving was a 700 m loop in the Chippendale area as shown in Figure 6.1. The route comprised of public roads, a shared zone on Dick Street, signalised intersections and unsignalised intersections.

The intersections along the route include:

- T-intersection (Dick St & Balfour St),
- T-intersection (Balfour St & Queen St),
- T-intersection (Balfour St & Little Queen St),
- T-intersection (Balfour St & Henrietta St),
- T-intersection (Balfour St & Teggs Ln),
- Roundabout (Balfour St & Meagher St),
- T-intersection (Meagher St & McAlister Ln),
- Four-way intersection (Meagher St & Abercrombie St),
- T-intersection (Abercrombie St & Teggs Ln),
- Four-way intersection (Abercrombie St & Levey St),

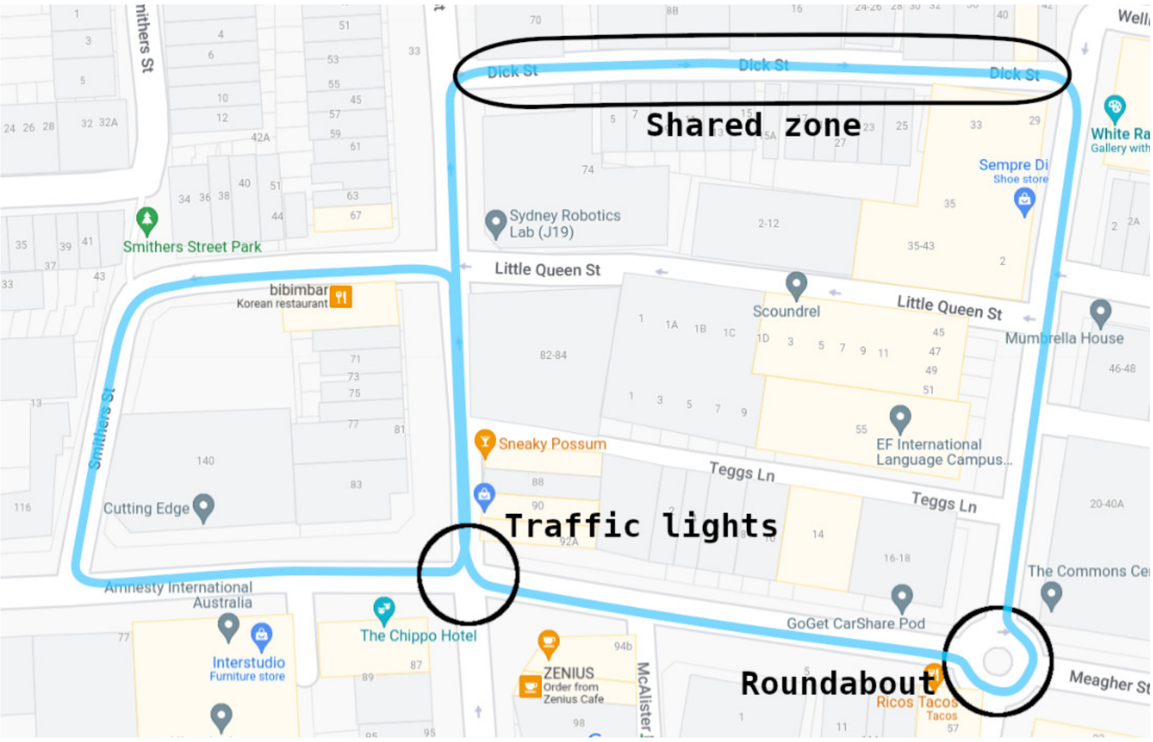


Figure 6.1: Operating area and route for the automated driving.

- T-intersection (Smithers St & Myrtle St),
- T-intersection (Abercrombie St & Dick St).

When travelling through an intersection, either unsignalised or signalised, the CAV determines whether it is safe to proceed into the intersection by combining inputs from three sources: 1) onboard perception sensors, 2) DSRC messages received from other connected agents, and 3) HIL checks from the vehicle supervisor in accordance with TfNSW safety assurance requirements.

The types of DSRC messages the CAV uses depend on the intersection type. For the signalised intersection case, DSRC messages include SPATEMs and MAPEMs from the SCATS network. For an unsignalised intersection, such as a roundabout, the CAV uses CAMs broadcast by other nearby CVs/CAVs to enhance yielding decisions. The demonstrations of each case in live traffic are presented in Sections 6.1.2 and 6.1.4. It should be stressed that DSRC data is one of three key information sources the CAV relies on.

6.1.2 Signalised Intersection

A key focus of this demonstration was the operation of a CAV through a signalised intersection using DSRC messages provided by SCATS. This goal was achieved from both authorised approaches to the intersection.

Prior to the testing in live traffic, the automated driving with the support of the DSRC messages had been well tested in the ACFR lab as a controlled environment. This helped identifying and fixing issues in the automation stack during the development phase. The CAV was also first driven manually in the public traffic to validate various components in the developed software stack, before the automated driving was enabled.

A video showing numerous automated traversals of the intersection from both approaches and a nearby roundabout is available at `https://youtu.be/sp28C1Xty3U`.

A supporting video with annotations to explain what can be observed in the aforementioned video is available at `https://youtu.be/KeHa0RLYC4o`.

In both videos, the CAV can be seen to navigate through the signalised intersection when the traffic light was green. Traffic light information was provided by the SCATS network in real-time and comes in the form of SPATEM and MAPEM data that was broadcast over DSRC. The CAV decoded these messages and, in conjunction with its own localisation information, worked out when it needed to wait at the stop line and when it could proceed into the intersection.

The onboard vehicle supervisor can also be seen to be pressing buttons on the central screen throughout the video. As part of the safety assurance approval granted by TfNSW, the CAV requires a human to confirm when it is safe to proceed into an intersection (both signalised and unsignalised).

The videos also show the vehicle navigating through a roundabout whilst automated. In this context (an unsignalised intersection), the vehicle supervisor performed HIL checks to confirm when it was safe for the vehicle to proceed through the roundabout.

Screenshots from the videos are shown in Fig. 6.2 and 6.3.

Figure 6.2: Automated vehicle approaching intersection from east

Figure 6.3: Automated vehicle approaching intersection from west

6.1.3 Continuous Operation

Although beyond the scope of this project, it was decided to attempt continuous automated driving around the entire authorised figure-8 route of the operational area. This ambitious goal was achieved.

An uncut video of more than two continuous loops is available at `https://youtu.be/yjcK8s4ov8w`.

A shorter video of part of the route is available at `https://youtu.be/r4LURmJXAII`.

In the videos, when multiple presses are seen to be made one after the other, this is the vehicle supervisor selecting the next goal for the CAV to drive to, as once the CAV reached its destination it waited for the vehicle supervisor to select a new goal.

Screenshots from the videos are shown in Fig. 6.4, 6.5 and 6.6.

Figure 6.4: Automated operation along Dick St

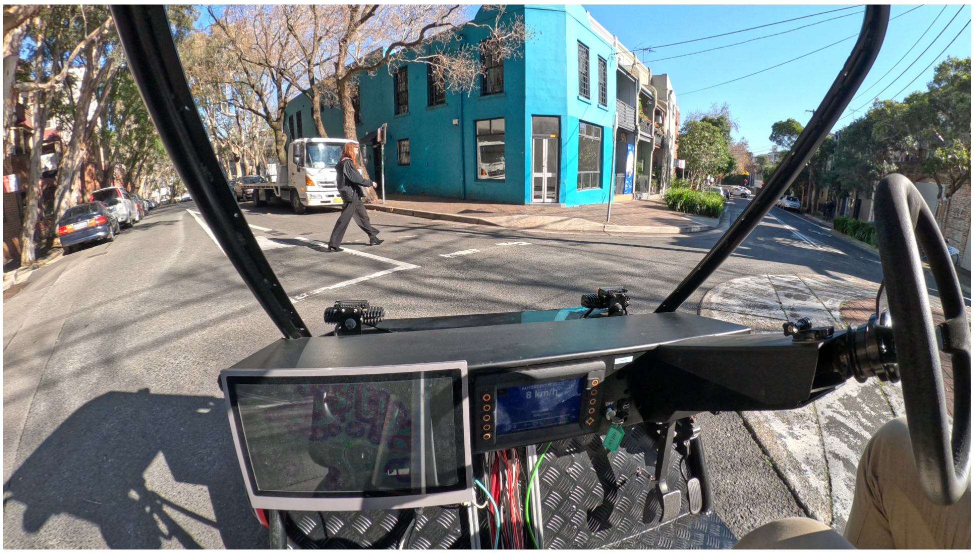


Figure 6.5: Automated operation through roundabout

Figure 6.6: Automated operation along Abercrombie St

6.1.4 Yielding for a CV at a Roundabout

The capability for the CAV was enhanced to enable yielding at an intersection based on data from nearby CVs, and was demonstrated at a roundabout along the approved route.

In this scenario, the CAV approaches the roundabout whilst a CV approaches from the right, where it has right-of-way over the CAV - this right-of-way information is also embedded into the *Lanelet2* map that the CAV uses to navigate.

The CV continually broadcasts CAMs, which the CAV decodes to determine if it should proceed into the roundabout or wait at the stop line for the CV to pass. The southbound lanelet on approach to the roundabout is configured as a *yield* lanelet, whereas the eastbound approach to the roundabout, show in red in Fig. 6.7, is configured as a *right-of-way* lanelet. The CAV will wait at the stop line of the roundabout if a CV is in the *right-of-way* lanelet. Regardless of this, the usual HIL checks are completed.

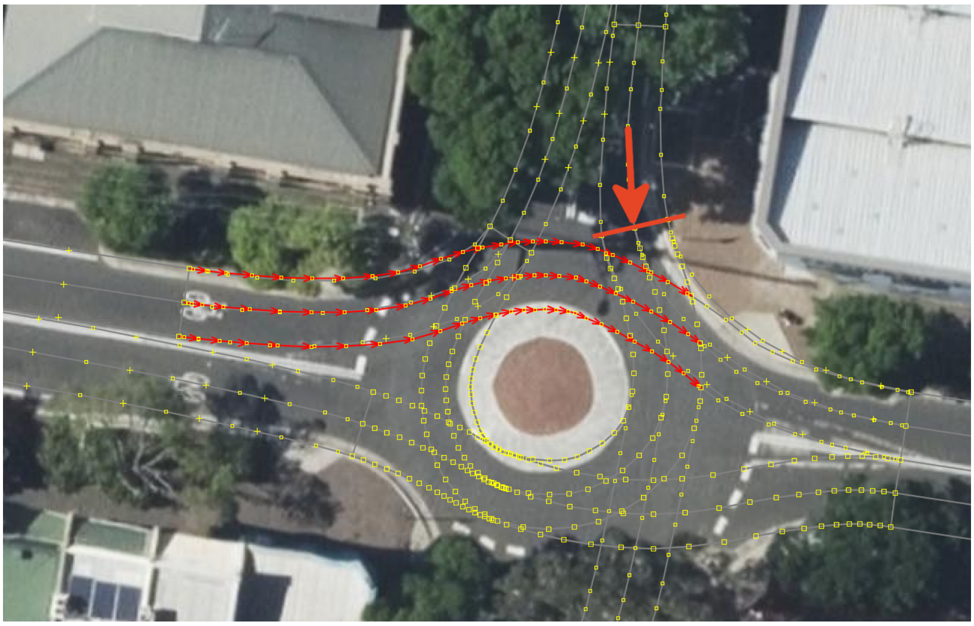


Figure 6.7: Annotated screenshot of the *Lanelet2* map at the roundabout

A video of the CAV navigating through a roundabout whilst yielding for a CV is available at `https://youtu.be/hMTAWh5seKM`.

In this video, the CAV can be seen to navigate through a roundabout. A CV was communicating with the CAV over DSRC. The two vehicles were exchanging position and speed information with each other. This allowed the CAV to determine when it should yield to the approaching CV.

The onboard vehicle supervisor can also be seen to be pressing buttons on the central screen for HIL checks throughout the video to confirm when it was safe to proceed into an intersection (both signalised and unsignalised).

A screenshot from the video is shown in Fig. 6.8.

Figure 6.8: The CAV yielding for a CV at a roundabout

6.2 Manual driving

Two use cases were identified by SCATS as being of interest in the V2I space. These were addressed in the manually driven VW Passat, which is a CV.

6.2.1 Red Light Violation Warning

With information available from SPATEM it is possible for systems in the vehicle to determine whether the vehicle is likely to violate a red light. This is achieved by projecting the vehicle's current motion forward to determine the time at which it will enter the intersection, and checking the signal phase at that time as calculated from the SPATEM.

A video of the vehicle approaching traffic lights with this system is available at `https://youtu.be/VO4Ze9ACVcQ`.

In the scenario shown in the video, a warning was displayed to the driver of the CV on an in-cabin screen when they were approaching a red light, based on the relevant part of the received SPATEM and the vehicle speed information. It is obviously not possible to drive in live traffic in a way that would be likely to violate a red light, so the video shows the CV approaching an already red light. The red light warning persisted until the vehicle stopped moving.

A screenshot from the video is shown in Fig. 6.9.

Figure 6.9: Example of RLVW

6.2.2 User Turn Warning for VRUs

The implementation of user turn warning for VRUs at intersection 4572 used *protected-movement-allowed* and *permissive-movement-allowed* information contained in SPATEMs.

The permissive state indicates that movement is allowed, but that there may be conflicting pedestrian traffic. An example is shown in Fig. 6.10a, where the car is allowed to turn right, but it could conflict with pedestrians because the pedestrian crossing is active. The protected state indicates that there should not be any conflict, as an example in Fig. 6.10b illustrates. Thus, it is possible to determine whether the vehicle is turning across a currently active pedestrian crossing at intersection 4572.

(a) **(b)**

Figure 6.10: Examples of SPATEM states related to turning right from Abercrombie St to Meagher St: (a) *permissive-movement-allowed*, (b) *protected-movement-allowed*

Whilst it is not possible to determine whether a pedestrian is actually on the crossing, the activation of the crossing can be conveyed to the driver. The demonstration in Section 6.2.3 will look further at determining the actual state of pedestrian presence on the crossing.

A video of the vehicle turning across a pedestrian crossing with this system is available at `https://youtu.be/A7fbbKMe9yI`.

In this video, the CV can be seen to navigate through a signalised intersection. Traffic light information was provided by the SCATS network in real-time and came in the form of SPATEM and MAPEM data that was broadcast over DSRC. The CV decoded these messages and, in conjunction with its own localisation information, worked out which parts of which messages were relevant for a particular scenario.

In the scenario shown in the video, a warning was displayed to the driver of the CV on an in-cabin screen when the pedestrian crossing they were turning across was active, based on the aforementioned relevant part of the received SPATEM. Note that this information does not include any details about whether there are any pedestrians using the crossing at a given time, only that the crossing is active.

A screenshot from the video is shown in Fig. 6.11.

Figure 6.11: Driver alerting when approaching active pedestrian crossing

It should be noted that the implementation of this use case using permissive and protected states is possible at intersection 4572 as no vehicle-to-vehicle conflicts exist. This approach was chosen for convenience, however, the SPATEM data provided by SCATS contained *ConnectionManueverAssist* information that would typically be used by a vehicle to determine that a conflicting pedestrian is active. This approach would be required at other intersections where a permissive state may instead result from a conflicting vehicle movement.

6.2.3 User Turn Warning with Pedestrian Crossing Occupancy Detection

In Section 6.2.2, a user turn warning scenario was demonstrated where SPATEM and MAPEM were used in conjunction with vehicle position and speed information to determine whether an in-cabin warning should be displayed.

In this demonstration, the previous demonstration in Section 6.2.2 was iterated to add information to the warning to inform a vehicle occupant if a pedestrian is actually in the pedestrian crossing. In this demonstration, the pedestrian was detected by the ACFR's IRSU. These detections result in CPMs being broadcast, which are then received and decoded by the vehicle. Each CPM contains information about detected objects, including their location relative to the IRSU (x, y offsets and orientation), and the position of the IRSU itself (latitude and longitude). The vehicle uses this information to determine where the detected objects are in its own reference frame.

A video of the vehicle being driven through an intersection with this warning is available at `https://youtu.be/vUUVjXU5X3s`.

This video is comprised of two scenarios.

- In the first scenario, a RLVW was displayed to the driver of the CV on an in-cabin screen when they were approaching a red light, based on the relevant part of the received SPATEM. Note that the warning was only displayed whilst the vehicle was moving and only when the traffic light was red
- In the second scenario, a "Pedestrian Crossing Active" warning was displayed to the driver of the CV on an in-cabin screen when the pedestrian crossing they were turning across was active, based on the relevant part of the received SPATEM. In addition to information decoded from the received SPATEM, the CV also received and decoded CPMs from the nearby IRSU that was perceiving the environment for pedestrians and vehicles. If the crossing was active based on SPATEM information then an alert was displayed. An additional line of text "PEDESTRIAN DETECTED" was added to the alert based on the referenced CPM data.

Screenshots from the video are shown in Fig. 6.12, Fig. 6.13 and Fig. 6.14.

Figure 6.12: Driver alerting when approaching active pedestrian crossing, but no pedestrian in the pedestrian crossing

Figure 6.13: Driver alerting when approaching active pedestrian crossing with a pedestrian in the pedestrian crossing

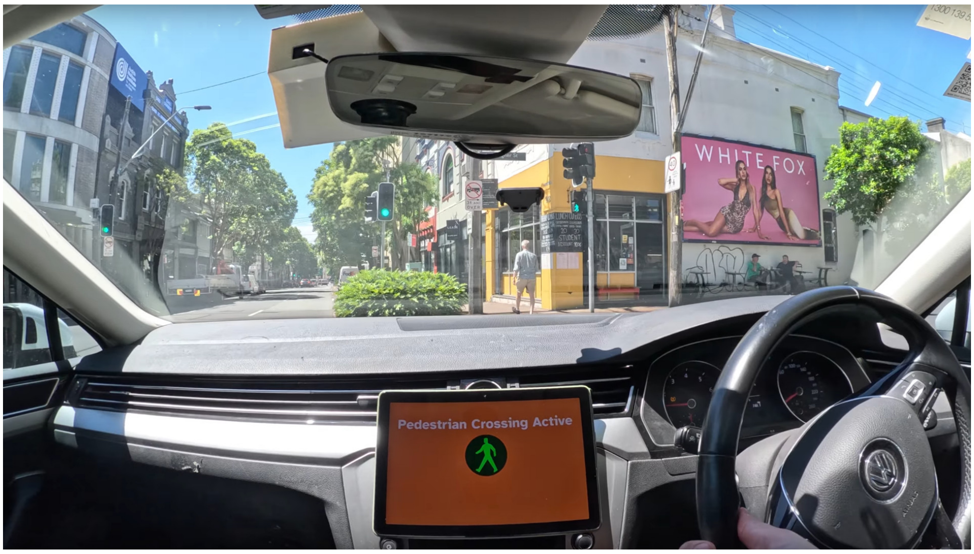


Figure 6.14: Driver alerting when approaching active pedestrian crossing, but the pedestrian has exited the pedestrian crossing

6.2.4 Time to Green

The use case of time to green was demonstrated as part of demonstrations of other use cases, for instance, the RLVW at FMTRC and the user turn warning with pedestrian crossing occupancy detection in live traffic, as presented in Section 5.1 and Section 6.2.3, respectively. In these demonstration videos, the time to green was displayed to the driver when the vehicle was waiting at a red traffic light.

Screenshots from the demonstration videos in Section 5.1 and Section 6.2.3 are presented in Fig. 6.15 and Fig. 6.16, respectively. Both figures show the time to the next phase—green in both cases—on an in-cabin screen. This information helped drivers reduce delays and make better use of the green signal phase.

Figure 6.15: In-cabin time to green information was shown to the driver in FMTRC demonstration

Figure 6.16: In-cabin time to green information was displayed to the driver in live traffic demonstration

7

Conclusions

The two-year-long project successfully concluded that the implementation of C-ITS in urban traffic environments offers significant impacts, considerations, and benefits.

The project first demonstrated the benefits and requirements of intelligent infrastructure for C-ITS. The deployment of ACFR's IRSU at intersection 4572, equipped with real-time road user sensing techniques, demonstrated the capability of intelligent infrastructure to provide a local perception extension. The IRSU could detect and classify road users (vehicles, pedestrians, cyclists) and broadcast this information via CPMs to approaching vehicles. This is particularly beneficial in situations like intersections where the infrastructure's vantage point can offer a more comprehensive view.

Regarding the impact of C-ITS messages on safety and redundancy, the project demonstrated various use cases in different environments including live traffic. RLVW for both CVs and CAVs utilised SPATEMs to determine potential red-light violations and alert drivers. User turn warnings were also implemented using SPATEMs to detect potential conflicts with pedestrians during turns. Furthermore, the project showcased how real-time perception information CPMs from the roadside sensing solution could enhance pedestrian awareness for CVs and CAVs, contributing to safety. A summary of recorded videos for the C-ITS demonstrations is provided in Tab. 7.1.

These demonstrations highlight the potential of C-ITS messages to improve safety by providing drivers and automated systems with crucial information about the surrounding environment and traffic conditions. The integration of information from both the vehicle's own sensors and the infrastructure (through DSRC messages) suggests a form of redundancy that can enhance the reliability and safety of driving.

Furthermore, the demonstrations showcased various aspects of autonomy in CAVs, including the use of V2X communication for enhanced perception and decision-making, high-accuracy localisation using SLAM and detailed maps, navigation incorporating traffic rules from *Lanelet2* maps and signal phase information, and improved motion control for smoother operation.

The project also involved close collaboration with SCATS, a part of TfNSW responsible for the traffic management platform that monitors, controls and optimises the road network. SCATS played a key role in shaping use cases demonstrated in the project. Frequent in-person meetings and site visits facilitated bi-directional knowledge transfer between SCATS and ACFR. SCATS also facilitated the upgrades of DSRC-enabled traffic lights at intersection 4572 in Chippendale. The upgrades enabled ACFR vehicles to receive MAPEM, SPATEM, and CAM messages from the SCATS' software. The messages were broadcast through a DSRC unit sourced from a different vendor than the one used by the ACFR team, validating the interoperability of the C-ITS technology developed in this project.

The successful demonstrations of V2I communication with ACFR IRSU and SCATS intelligent traffic lights provide valuable data on the infrastructure requirements for supporting C-ITS technologies, such as DSRC-enabled traffic lights and roadside perception units. The challenges encountered during the project, such as delays in IRSU installation and the need for domain-specific training of machine learning perception models, offer insights into current limitations and areas for future development.

This collaboration can enable SCATS to explore DSRC-based traffic management, with potential future applications for real-time vehicle interactions and pedestrian safety enhancements. Also, SREMs broadcast by ACFR CAVs allowed SCATS to explore how signal requests from vehicles approaching an intersection could improve traffic demand management. While SCATS is not yet acting on these messages, this serves as a feasibility study for future integration.

For TfNSW, the findings of this project contribute to the development of technical advice for CAV policy, paving the way for safer and more efficient urban transportation systems. The successful integration with SCATS' intelligent traffic lights to broadcast MAPEMs and SPATEMs further demonstrates the crucial role of traffic management infrastructure in coordinating traffic and providing essential signal phase and timing information to CAVs/CVs. The safety assurance processes undertaken for the on-road trials, including hazard identification and mitigation, offer valuable insights. In particular, the safety assurance emphasises the importance of HIL model in enhancing safety. It adds an additional layer of protection, ensuring that a CAV does not rely solely on SPATEM and/or onboard sensors when deciding whether to proceed into an intersection (both signalised and unsignalised).

For the research community, the project provides insights into best practices for the implementation and testing of C-ITS technologies, particularly in urban environments. The demonstrations in various environments highlighted the importance of integrating various information sources (on-board sensors, C-ITS messages) and the need for redundancies to ensure safe and reliable operation in different traffic scenarios. The project adhered to ETSI C-ITS standards for DSRC communication and message types, providing practical experience with these standards. Moreover, the insights and lessons learnt from the project are highly transferrable to cellular V2X based C-ITS.

Environment	**Demonstration Videos**
ACFR lab	Validation of CAV system in controlled environment: `https://youtu.be/DC_OFjsL7gQ`
Cudal FMTRC	Demonstration of CV in-cabin RLVW based on live traffic light information received over DSRC: `https://youtu.be/pO1yb0TM0dk`
Live traffic	Numerous examples of CAV system operating at key intersections in Chippendale: `https://youtu.be/sp28C1Xty3U`
	Annotated video of CAV system operating at key intersections in Chippendale: `https://youtu.be/KeHaORLYC4o`
	Automated laps around Chippendale leveraging live traffic light information received over DSRC: `https://youtu.be/yjcK8s4ov8w`
	A shorter video of CAV driving around Chippendale leveraging live traffic light information received over DSRC: `https://youtu.be/r4LURmJXAII`
	CAV yielding for CV based on DSRC information: `https://youtu.be/hMTAWh5seKM`
	CV in-cabin user turn warning based on live traffic light information received over DSRC: `https://youtu.be/A7fbbKMe9yI`
	CV in-cabin RLVW based on live traffic light information received over DSRC: `https://youtu.be/VO4Ze9ACVcQ`
	CV in-cabin RLVW and user turn warning based on live IRSU pedestrian detection information received over DSRC: `https://youtu.be/vUUVjXU5X3s`

Table 7.1: A summary of demonstration videos in the project

References

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[10] ACFR. *Project Hazard Log*. Tech. rep. Version 2.4. ACFR, 2022 (cit. on pp. 64, 70).

[11] ACFR. *Safety Assurance Plan*. Tech. rep. Version 1.10. ACFR, 2022 (cit. on pp. 64, 71).

[12] ACFR. *Safety Management Plan*. Tech. rep. Version 1.3. ACFR, 2022 (cit. on pp. 64, 71).

[13] ACFR. *Safety Assurance Report*. Tech. rep. Version 0.6. ACFR, 2022 (cit. on pp. 64, 71).

[14] ACFR. *Site Assessment Report*. Tech. rep. Version 0.2. ACFR, 2022 (cit. on pp. 64, 71).

[15] ACFR. *raffic Management Plan*. Tech. rep. Version 0.2. ACFR, 2022 (cit. on pp. 64, 71).

Appendix: Safety Assurance

A.1 Introduction

A.1.1 Background

The previous project, iMOVE CRC Project 1-012, was a collaboration between TfNSW and the ITS research group at the ACFR, the University of Sydney, aimed at establishing real-world future mobility testbeds for CAVs and enabling related research activities and industry developments to be tested in an applied context. The main aims of iMOVE CRC Project 1-012 included the provision of guidelines and recommendations on operating principles for CAVs to operate safely when transitioning between complex environments and functioning as part of an integrated transport network; the delivery of analysis reports to assess the impacts and benefits of CAVs, with particular focus on crowded pedestrian areas; the establishment of multiple real-world testbed sites for evaluating CAVs and emerging C-ITS technologies; and the provision of a flexible, collaborative platform for demonstrating and developing technologies to improve the collective understanding of the physical and digital infrastructure required for the safe integration of CAVs. iMOVE CRC Project 1-012 commenced on 14 November 2019 and concluded on 28 February 2023.

This project, iMOVE CRC Project 1-063, extended the previous work by aiming to understand the impact, considerations and benefits of implementing C-ITS. This included the usage of information received from CVs and intelligent infrastructures such as IRSUs and intelligent traffic lights. iMOVE CRC Project 1-063 commenced on 31 January 2023 and concluded on 31 March 2025.

A.1.2 Purpose of Safety Assurance Report

The purpose of this SAR was to demonstrate that an adequate level of hazard identification and analysis had been conducted to ensure the identification and implementation of appropriate safety requirements that allowed the system to be operated to a level of safety where all identified safety hazards had been eliminated where practicable or the residual safety risks were assessed to be tolerable and mitigated to a level that is reduced SFAIRP through the provision of adequate controls.

A.1.3 Scope of Safety Assurance Report

The scope of this SAR was limited to demonstrating that the activities planned for this project had been objectively managed safe SFAIRP and should progress forward. This SAR was an extension of the safety assurance activities implemented during iMOVE CRC Project 1-012. In this project, the trial vehicle had been further developed to integrate into a C-ITS infrastructure provided by SCATS. The trial vehicle interfaced with traffic lights by receiving SPATEM data provided by SCATS. The mechanism for this integration was an OBU that transmitted and received data via DSRC. The route remained the same.

A.1.4 Assumptions, Dependencies and Constraints

A full log of Assumptions, Dependencies and Constraints (ADC) was provided in the PHL. Changes to the ADCs were captured in the Change Journal of the PHL.

A copy of ADC related to this project is provided below:

- The trial vehicle shall not operate in rain
- The trial vehicle shall not operate in fog
- The trial vehicle shall only operate in areas that have been validated by the trial vehicle's localisation system(s)
- The trial vehicle shall only operate on routes that have been validated for the trial vehicle's capabilities
- The trial vehicle shall not operate in areas with inclination of $15°$ or more

- The trial vehicle shall operate on roads and road-like areas with minimum width of 2.0 meters
- The trial vehicle shall not operate in areas with water over the surface
- The trial vehicle shall only operate during daylight
- The trial vehicle has the maximum capacity of two
- The trial vehicle has a maximum operating range of 50 km on a single charge
- The trial vehicle takes 2-3 hours to charge when connecting to mains power
- The trial vehicle shall operate within the terms outlined by its conditional registration
- VRUs shall have the right of way only in shared zones and pedestrian crossings
- Maximum operating speed of the trial vehicle is 10 km/h in shared zones
- Other vehicles may be present on public roads but are expected to be operating at or below 50 km/h
- All subsystems must be tested in accordance with their test plans as part of pre-deployment activities
- Supervisor performs pre-test checklist prior to commencement of live operations
- The decision the trial vehicle makes when interfacing with other traffic at intersections may be recorded for the purposes of proving the system's maturity
- ACFR to maintain a record of all inducted personnel involved in the trial

A.2 Approval for the Previous Project

Approval to perform automated operations as defined in the relevant safety assurance documents was provided by the TfNSW SAB during iMOVE CRC Project 1-012.

The following documents were provided:

- Concept of Operations [9]

- Project Hazard Log [10]
- Safety Assurance Plan [11]
- Safety Management Plan [12]
- Safety Assurance Report [13]
- Site Assessment Report [14]
- Traffic Management Plan [15]

A Ministerial Approval Order existed for the previous trial. It was granted on 18 August 2020 and was set to expire on 31 December 2023.

A.3 Approval for This Project

A.3.1 Overview

The focus of the extension of the CAV trial in iMOVE CRC Project 1-012 into this project is C-ITS. Specifically, the trial CAV received SPATEM and MAPEM data, and transmitted CAM data. These messages were received and sent via DSRC.

The received MAPEM data were not used in the decision making process and so this additional information had no impact on automated operations.

The CAM data were only broadcast from the trial vehicle, therefore they had no impact on automated operations.

A.3.2 Trial Connected and Automated Vehicles

The trial CAVs used in both iMOVE CRC Project 1-012 and this project approved for automated operations were based on two EVs platforms manufactured by Applied EV Pty Ltd. Fig. 7.1 is a photo of one of the two trial CAVs. The trial CAVs are identical and for simplicity in this document, trial CAV is referred to in the singular. Also, the trial CAV is referred to as the trial vehicle in the remainder of the chapter.

The trial vehicle had a sensor upgrade performed for this project. The roof-mounted

Figure 7.1: Trial CAV

Velodyne VLP-16 lidar was replaced with an Ouster OS1-128 REV7 lidar. The new lidar was located in the same position the old lidar was in. The new lidar increases range, vertical field of view, and the number of horizontal beams (from 16 to 128). This increased performance improved the ability of the sensor to discriminate smaller objects at longer distances. It also improved the swept area immediately in front of the trial vehicle. The way the automation stack processed the information from this sensor was unchanged.

A.3.3 Operating Route

The route approved for automated operations in this project is shown in Fig. 7.2. This was the same route operated on during the iMOVE CRC Project 1-012.

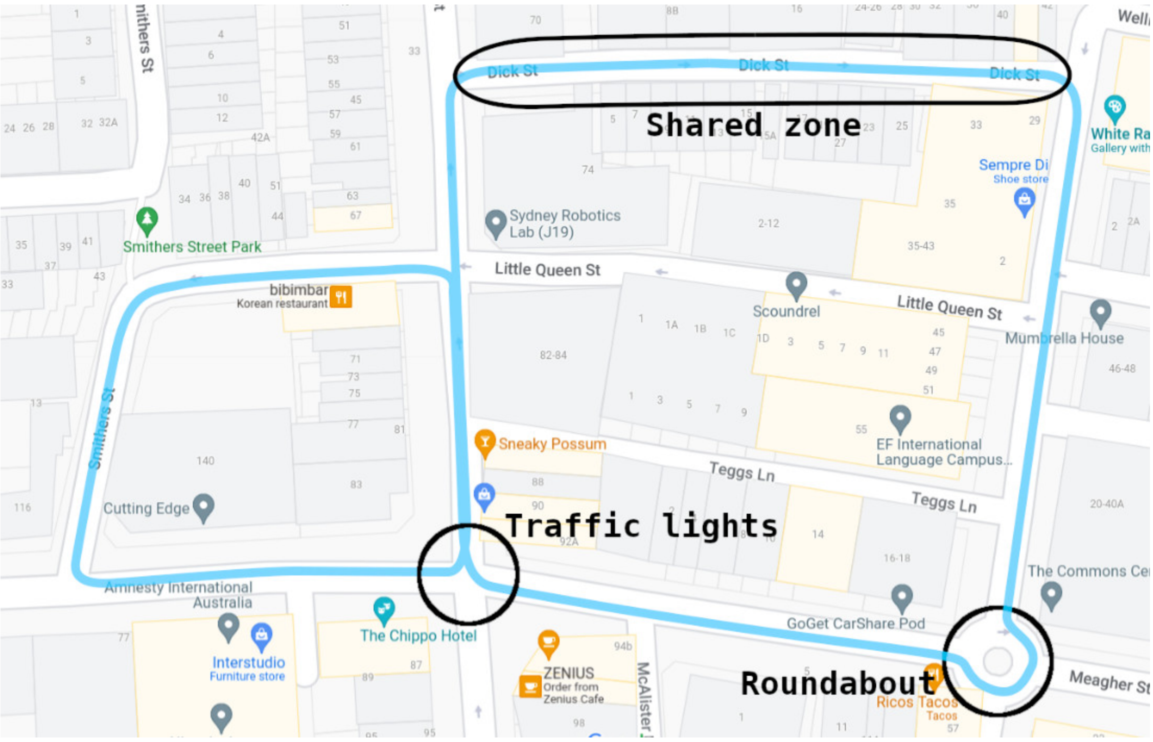

Figure 7.2: Operating route used in both trials

A.3.4 Controlled Intersections

The only change to automated operations was in the way that the trial vehicle interacted with the controlled intersection in the operational area on Abercrombie Street as a result of the inclusion of SPATEM data in the decision making process.

Fig. 7.3 and Fig. 7.4 show the controlled intersection that the trial vehicle interacted with over DSRC. This intersection was upgraded by TfNSW to include an DSRC unit broadcasting SPATEM and MAPEM data.

The previous interaction for when the traffic lights are red on approach was:

- The trial vehicle drives up to the stop line of the intersection
- The trial vehicle stops at the stop line
- The vehicle supervisor gives positive confirmation to the trial vehicle when the traffic lights are green and the intersection is clear (HIL)
- The trial vehicle proceeds if its other sensors indicate that there is a clear path through the intersection

Figure 7.3: Controlled intersection from Myrtle St approach. Trial vehicle turned left onto Abercrombie St

Figure 7.4: Controlled intersection from Meagher St approach. Trial vehicle turned right onto Abercrombie St

The addition of SPATEM data changed the interaction to:

- The trial vehicle drives up to the stop line of the intersection
- The trial vehicle stops at the stop line
- The vehicle supervisor gives positive confirmation to the trial vehicle when the traffic

lights are green and the intersection is clear (HIL)

- The trial vehicle proceeds if its other sensors indicate that there is a clear path through the intersection and the SPATEM data indicates that the traffic lights are green

The previous interaction for when the traffic lights are green on approach was:

- The trial vehicle approaches the intersection
- The vehicle supervisor gives positive confirmation to the trial vehicle that the traffic lights are green and the intersection is clear (HIL)
- The trial vehicle continues if its other sensors indicate that there is a clear path through the intersection

The addition of SPATEM data changed the interaction to:

- The trial vehicle approaches the intersection
- The vehicle supervisor gives positive confirmation to the trial vehicle that the traffic lights are green and the intersection is clear (HIL)
- The trial vehicle continues if its other sensors indicate that there is a clear path through the intersection and the SPATEM data indicates that the traffic lights are green

Use of SPATEM information made the interaction safer because the trial vehicle had knowledge of the traffic light state and would not proceed into the intersection if it was not authorised to do so. Previously, it was only the vehicle supervisor that processed the state of the traffic lights; in this update both the vehicle supervisor and the trial vehicle had to agree that the traffic lights are green.

A.3.5 Mitigating Potential Erroneous DSRC Information

It is possible that the DSRC messages received by the trial vehicle are incorrect or are used incorrectly due to various reasons, for instance, spoofing by a bad actor, and incorrect or highly uncertain vehicle localisation. Problematic localisation can cause the trial vehicle to mistakenly believe it is on a different lane and thus use incorrect subset of SPATEM data.

Another possible but unlikely reason is unintentional misconfiguration due to human error when setting up the SCATS infrastructure, for instance, a mistake in the mapping between signal group IDs and lane-to-lane connections in the MAPEM. This was made negligible through appropriate testing conducted by SCATS prior to field deployment.

Regardless of the cause for incorrect DSRC information, there are two scenarios that the trial vehicle could face when using SPATEM data:

- the trial vehicle believes that the traffic light is green when it is actually red;
- the trial vehicle believes that the traffic light is red when it is actually green.

To address this potential issue, the trial vehicle never relied solely on SPATEM data to decide whether to enter an intersection. The HIL model ensured that the decisions of the trial vehicle were correct before they were acted upon.

If the vehicle believes that the traffic light is green when it is actually red, the vehicle supervisor would not give authority to enter the intersection and the trial vehicle would remain at the stop line. Noting the disparity in SPATEM and traffic light indication, the vehicle supervisor would terminate the test.

In the case where the vehicle interprets a red traffic light when it was actually green, the trial vehicle would not enter the intersection, the vehicle supervisor would notice the disparity and terminate the test.

Overall, the integration of SPATEM information into the decision making process for the trial CAV was designed to fail safe.

A.3.6 Supporting Documents

The addition of DSRC to the automation stack did not change any of the operational conditions of the trial as conducted in iMOVE CRC Project 1-012. It had the effect of providing an additional mitigation for one of the hazards in the PHL (H020 - “The vehicle runs a red light”). In this case the hazard likelihood and consequence were unaffected. Accordingly, all safety assurance documents for this trial remained unchanged except for the PHL.

The PHL had been updated to account for the addition of DSRC and the new focus on C-ITS. The risk ratings for some hazards had been updated in light of three years experience running the trial CAV in the previous project iMOVE CRC Project 1-012.

A.3.7 SAB Approval

Submitted safety assurance documentation was approved by the TfNSW SAB based on the similarity between this project (iMOVE CRC Project 1-063) and the previous project (iMOVE CRC Project 1-012), which was also a collaboration between the ACFR and TfNSW.

A.3.8 Ministerial Order Extension

The Ministerial Order, which was originally granted during iMOVE CRC Project 1-012, was extended to remain in effect until 30 November 2025 unless revoked earlier (previously the Ministerial Order was set to expire on 31 December 2023). This extension was published in Government Gazette No 589 of 18 December 2023.

A.4 Safety Case

A.4.1 Safety Statement

The ACFR continued this trial at the Test Readiness Assurance Gate, Stage 2.

Automated operations during iMOVE CRC Project 1-012 were conducted at the Test Readiness Assurance Gate, Stage 2 and the system operated safely to the point where controls implemented in the relevant TMP were removed towards the later part of that project. A set of compiled evidence was submitted during iMOVE CRC Project 1-012. In addition to this evidence, a video of the trial vehicle performing automated operations along a section of the operational area for this trial extension can be seen here: `https://youtu.be/1q6_-MZ7pPY`.

Therefore, the ACFR continued the extension of the previous trial at the Test Readiness Assurance Gate, Stage 2 based on the extent of similarity between the previous trial and the trial conducted in this project and the scope of the trial extension in relation to the proposed automated operations.

The safety case was objectively demonstrated through the following documents:

- Concept of Operations [9]
- Project Hazard Log [10]

- Safety Assurance Plan [11]
- Safety Management Plan [12]
- Safety Assurance Report [13]
- Site Assessment Report [14]
- Traffic Management Plan [15]

The only documents changed since iMOVE CRC Project 1-012 were this chapter (the SAR) and the PHL. Changes to the PHL are detailed in Section A.3.6.

The trial related safety hazards had been assessed and managed safe SFAIRP, and it had been determined safe to progress forward.

A.4.2 Summary of Acceptability

The engineering safety assurance activities conducted during iMOVE CRC Project 1-012 provided evidence that:

- Safety had been considered an integral part of all configuration management gates.
- All reasonably foreseeable hazards and safety controls had been identified and managed SFAIRP for the current design.
- Residual risks had been identified and operational/procedural controls had been implemented as per the PHL.

These activities had continued through the iMOVE CRC Project 1-063 trial.