Centre for Accident Research & Road Safety - Queensland

Cooperative and Highly Automated Driving (CHAD) Safety Study

Work Package 2: C-ITS / AV INTEGRATION, BENEFITS EVALUATION

August 2023

Dr Muhammad Hussain, Dr Gregoire Larue
Dr Sepher Ghasemi, Djamel Benrachou
Dr Sebastien Demmel, Prof Andry Rakotonirainy
Prof. Sébastien Glaser

iMOVE
Queensland Government

research.qut.edu.au/carrsq
CRICOS 00213J
MAIC
QUT

INTENTIONALLY BLANK

Acknowledgements

This research is jointly funded by the Department of Transport and Main Roads (TMR), Queensland University of Technology, iMOVE Australia and supported by the Cooperative Research Centres program, an Australian Government initiative.

TABLE OF CONTENTS

INDEX OF TABLES

INDEX OF FIGURES

ACRONYMS

AD	Automated Driving. All driving tasks are being carried out by ADS, including steering, brake, and acceleration.
AVs	Automated Vehicles
ADS	Automated Driving System
CAVs	Cooperative Automated Vehicles
CHAD	Cooperative and Highly automated Driving
C-ITS	Cooperative Intelligent Transport Systems
DENM	Decentralised Environmental Notification Message
ETSI Standard	European Telecommunications Standards Institute Standard TS 103 301 V1.1.1 and TS 102 894.2 V1.2.1
FoV	Field of View
IEEE	Institute of Electrical and Electronics Engineers
SPaTEM	Signal Phase and Timing Extended Message

TMR	Queensland Department of Transport and Main Roads
V2I	(communication) Vehicle to Infrastructure
V2X	(communication) Vehicle to Everything
VRU	Vulnerable Road User
ZOE2	Level 4 CAV prototype vehicle used for this project

1 INTRODUCTION

1.1 PROJECT SUMMARY

The iMove Cooperative and Highly Automated Driving (CHAD) Safety Study (iMOVE project 1-008) has delivered a cooperative and automated vehicle (CAV) prototype research platform (ZOE2, pictured in the cover page) with local expertise, to deliver a comprehensive safety study that will inform government policy and direction.

This project is part of the Queensland Department of Transport and Main Roads' (TMR) CHAD Pilot intended to prepare for the arrival of CAVs to improve safety, mobility, and environmental benefits on Australian roads. There are several reports to show the CAVs have potential to reduce crashes due to the human error significantly. However, this technology may also introduce new safety challenges. This project focuses on safety impacts/implications of introducing CAVs on Australian roads and is divided into four work packages:

- Work package 1: Driving task transition in AVs
- Work package 2: C-ITS and AV integration, and benefits evaluation (this report)
- Work package 3: Australian safety challenges for CAVs in the dynamic road environment
- Work package 4: Public awareness and demonstrations.

Published reports for each work package are available on iMOVE's website (Safely deploying automated vehicles on Australian roads (imoveaustralia.com)). This report summarises findings of the Work package 2 and focuses on integration and safety evaluation of using existing Cooperative Intelligence Transportation System (C-ITS) technologies in Automated Vehicle (AV). The safety evaluation mainly focuses on the added safety benefit of using CAVs compared to AVs.

Detailed methodologies and associated studies for the work package 2 are outlined in a series of unpublished reports prepared for the Department of Transport and Main Roads (TMR) including:

1. Dr Sepehr Ghasemi, Prof Sébastien Glaser, Dr Sébastien Demmel, Dr Andy Bond, Prof Andry Rakotonirainy – Technical report – C-ITS performance, June 2020
2. Dr Muhammad Hussain, Dr Gregoire Larue, Dr Sepehr Ghasemi, Djamel Benrachou, Prof Sébastien Glaser – D2.5.1b Key findings report (Use Case A), May 2021
3. Dr Muhammad Hussain, Dr Gregoire Larue, Dr Sepehr Ghasemi, Prof Sébastien Glaser – D2.5.1b Key findings report (Use Case B), Oct 2021

1.2 STUDY OBJECTIVES

The project endeavours to overcome the degradations in the motion and perception of the AV which caused due to the impacts on the field of view (FoV) potentially due to severe weather conditions, existence of obstructing objects and road geometry. These degradations are expected to reduce the safety on roads. Therefore, this study aims to explore the safety benefits of C-ITS technologies in AVs.
At the beginning of this work package, it is assumed that the C-ITS technology will provide trustworthy information of the dynamic environment to support AV to make robust decisions thus improving safety outcomes. This assumption was made as C-ITS or vehicle-to-everything V2X information in fully automated

vehicles will help overcome the limitations of the sensors' view by extending its view to improve AV's decision making for safer outcomes.

Two use cases were selected for exploration utilising C-ITS messages already developed and implemented by TMR as part of Ipswich Connected Vehicle Pilot (Connected Vehicle Pilot: Safety and user perceptions evaluation (imoveaustralia.com)). These are:

- **Use Case A**: Explores integration of C-ITS messages pertaining to occluded pedestrian at a signalised intersection. In this use case, the AV will need to take into account the traffic light phase, duration (when applicable) and existence of an occluded pedestrian and improve its behaviour at the intersection for improved safety outcomes.
- **Use Case B**: Explores a roadworks use case where the C-ITS message will provide an alternate path to manoeuvre through the roadworks or obstructed area much earlier than the AV's own sensor's detect road works, thus potentially improving safety outcomes. This use case has applicability on roads with limited number of lanes, or when the road configuration has completely changed impacting AVs operating design domain limitations.

1.3 USE CASE A: CAV IN PEDESTRIAN CROSSING AT SIGNALISED INTERSECTION (CAV-PCSI)

This use-case looks at the prototype CAV algorithms to consider deceleration when a pedestrian's presence in the crossing is indicated within the Signal Phase and Timing Extended Message (SPaTEM). CAV-PCSI intends to reduce unexpected AV stops/harsh braking and test-driver takeover and support a smoother deceleration profile while considering the vehicle behind to avoid rear-end crashes. All messages are supported by the European standard C-ITS communication.

The CAV-PCSI use case in this study is not intended to include the behaviour of other similar use cases such as:

1. Attempt to warn surrounding cooperative driver/vehicles of an event,
2. Cooperative use of information from other V2V (Vehicle to Vehicle) connection to assess potential red-light conflict based on the movements of other vehicles.

1.4 USE CASE B: CAV IN ROADWORKS (CAV-RW)

In this use case, the study aims to understand the safe speed for the AV to be harmonised with traffic and how to adapt to ETSI standard C-ITS message for the automated driving. In such a roadworks scenario, an AV requires information such as roadworks speed limit, number of lanes and road geometry for handling the driving task. The C-ITS information for this use case is provided to AV via a Decentralised Environmental Notification Message (DENM).

The DENM message used for this use case contained the required information for safe driving such as the driveable path, speed limits and road geometry to facilitate safe automated driving. This information was provided by following the Abstract Syntax Notation One (ASN.1) specification published by ETSI.

1.5 STUDY PHASES

The study was carried out in four phases.

Phase 1: *In-vehicle integration*. In this phase, C-ITS messages were designed and integrated in the framework of the CAV prototype to modify the CAV's behaviour. The system was tested in the Mt. Cotton testbed. The success criteria are related to the technical integration of the system in the vehicle such as:

- C-ITS-related criteria: distance to communication (D_{com}), message received/message emitted (T_{lat}), the latency of processing (T_{proc}), the number of lost messages (N_{drop}).
- Content description criteria: messages correctly managed/number of received messages.

The in-vehicle integration was tested at the Mt Cotton Test track successfully. (see Figure 2 for the Use Case A and Figure 4 for the Use Case B)

Phase 2: *Setup the simulation environment*. To generate a statistically significant comparison database, Monte Carlo-based microsimulation was fed by real-word condition parameters gathered in Phase 1. The CAV functionality was prepared for operation in full AV mode on a simulated route in a pilot area. Two sets of scenarios were conducted for each parameter i) AV with C-ITS integration and ii) AV without C-ITS integration. This methodology aligns with current investigation on CAV when the market penetration of this technology is too low to provide statistically significant results.

Phase 3: *Event based scenario assessment.* The aim of this phase is to enable an evaluation of the increased performance of automated response to the selected C-ITS use cases. The trial scenario database gathered in phase 2 is used to classify events into the failure and success. To do that, specific criteria and definition of success are developed. For the use case A, simulations are informed by behavioural data collected at an intersection close to Kelvin Grove and for the use case B, safety related criteria are extended to a secondary evaluation, given the conservative behaviour of AVs.

Phase 4: *An Impact evaluation*. A safety/performance-related impact evaluation was undertaken considering the likelihood of near-crash events (frequency) and the behaviour modification (effect). The expected output of this safety evaluation is an assessment of frequency (reducing the number of failure scenario by integrating C-ITS) and the effect measured indicators (i.e. the safety improvement by comparing surrogate safety measures of each hypothesis) for each selected use case. It was anticipated that the output of the safety evaluation will reveal safety benefits of using CAVs as well as limitations of deploying this technology in real-world condition.

1.6 STUDY LIMITATIONS

It is important to note the following limitations which are applicable to the use case A (CAV – PCSI).

- Since the inception of these use cases and the subsequent efforts to implement the logic in the ZOE2 and in the simulator for safety evaluation, significant developments have taken place in the field of Assumptions in Safety related models for Automated Driving Systems. Specifically, the IEEE Standard Association has recently introduced a new standard, namely IEEE 2846-2022, which outlines a minimum set of assumptions and scenarios aimed at enhancing the safety-related models in the decision-making process for Automated Vehicles. It is important to note that these assumptions were not incorporated into the modelling the decision-making process of AV/CAV behaviour during this study.

  Considering the potential implications, if these assumptions were integrated into the decision-making process of the AV, it is anticipated that the outputs for the tested scenarios would yield different results in terms of primary outcome measures (success) and secondary outcome measures (induced deceleration and speed differences). Consequently, it is reasonable to anticipate that the measured safety benefits attributed to the CAV in comparison to the AV would likely reduce or diminish. Therefore, it is recommended to consider extending the scope of this study to fully understand the impact of the latest industry standards. In the meantime, the findings contained in this report should be considered as true at the time of AV behaviour data collection, that is 2021.

- The CAV may demonstrate better capabilities in regulating its speed if the green light duration was known via C-ITS communication. The implemented C-ITS solution at Mount Cotton test track was not providing green light duration information which meant the decision mechanism, in the CAV, has to deal with ambiguity (unknown green phase duration) while approaching the signalised intersection. This issue could have been solved by communicating the green light duration via SPaTEM.

2 CAV IN PEDESTRIAN CROSSING AT SIGNALISED INTERSECTION (CAV-PCSI)

2.1 DESCRIPTION OF THE SCENARIO

Figure 1 illustrates CAV-PCSI use case. In this scenario, the perception system of the CAV is constrained by the presence of other objects (e.g., obstructed view by a truck driving straight). As a result, the detection of vulnerable road users (VRU) occurs relatively late, which hinders the generation of a safe driving behaviour.

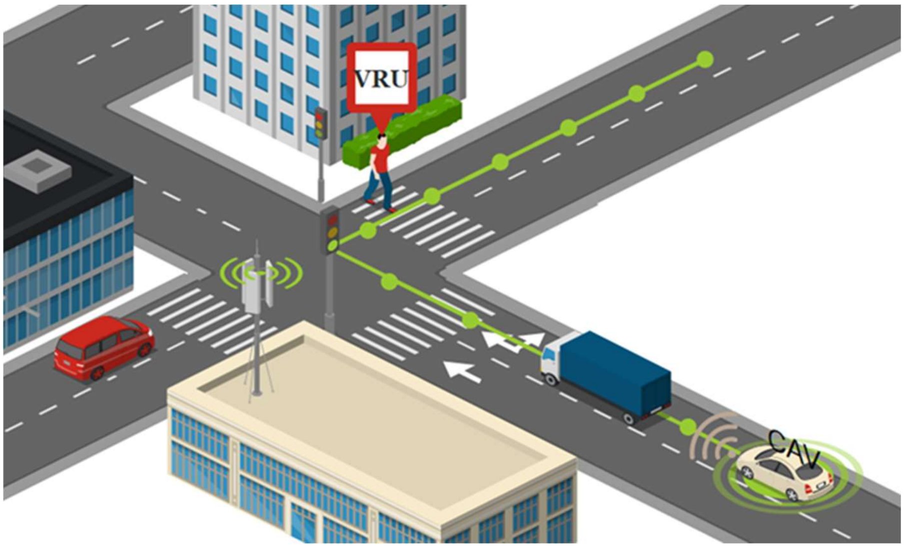

Figure 1 CAV Field of View obstruction

To address this limitation, the C-ITS comes into play by providing complementary information to the CAV. It offers spatial and temporal data related to the intersection. Furthermore, the MAPEM module establishes a zone within which a pedestrian is expected to be present in the intersection, while the SPATEM module furnishes information about the existence of VRUs within the pedestrian crossing area. These enhancements contribute to the CAV's ability to exhibit safer behaviours.

Several components were developed to integrate CAV-PCSI algorithm in ZOE2 platform; including components to read the relevant signal group, calculating the distance to traffic light and optimiser. Since the computational demand of stochastic optimisation is high, instead of implicitly solving the problem, we explicitly found off-line solutions for different combinations of the inputs and record them as a table. Algorithms in ZOE2, consider information contained in the solution table and calculate the target velocity. The initial tests at the Mount Cotton test track showed the effectiveness of the proposed method. Following these effectiveness tests there was still further development and integration of the CAV-PCSI algorithm required to be integrated in the ZOE2 to capture vehicle behind behaviour and provide an explicit solution for the optimiser.

A safe heuristic was implemented by knowing the yellow signal phase is a constant 4 seconds. The proposed heuristic considers the amber phase at the beginning of the red light, and if it is not safe to stop, the CAV approaches the amber signal. The safety feature of this heuristic is avoiding harsh brakes for either CAV or vehicles behind. The proposed algorithm ensures avoiding harsh brakes to stop for an amber light or approaching a red signal by controlling the CAV velocity. The simulation results show that the proposed heuristic is always obeying the rules; however, due to the lack of knowledge about the remaining time for the green phase[1], the driving velocity is further reduced compared to knowing the remaining time of the green phase.

Several data collection runs were carried out using ZOE2 at Mount Cotton test facility (Figure 2), and as per section 1.5, simulation and modelling was carried out.

Figure 2 Traffic Light intersection area at Mt cotton, obstructed visibility on the left side for the CAV

2.2 FINDINGS

The evaluation criteria were set early in the project. Findings against each criterion are tabled below.

Table 1 Findings from CAV-PCSI use case

	Hypothesis	Finding	Comment
1	CAVs reduce the likelihood of crashes and near crashes in intersection compared to AVs	Verified, subject to the information contained in the comment column	Crash likelihood improved by 20%. Crash severity also reduced. It is important to note these benefits may likely reduce or diminish as explained in the 'Study limitations' section 1.6 of this report.
2	Likelihood of crashes and near crashes with VRU on intersection decreased	False	Both CAV and AV manage to stop before a crash with VRU. CAV has the advantage of being able to regulate its speed in advance and minimise the need for harsh braking (refer to the hypothesis 3).

[1] The implemented C-ITS solution at Mount Cotton test track was not providing green light duration information which meant the decision mechanism, in the CAV, has to deal with ambiguity (unknown green phase duration) while approaching the signalised intersection.

3	Likelihood of rear-end crashes and near crashes on intersection decreased	Verified, subject to the information contained in the comment column	Likelihood of rear end crashes on intersection decreases by around 20%. Crash severity is also reduced. It is important to note these benefits may likely reduce or diminish as explained in the 'Study limitations' section 1.6 of this report.
4	The communication quality has impact on reducing the likelihood of crashes and near crashes on intersection.	False	No impact observed, the C-ITS message is able to be accumulated and checked in advance.
5	Smooth velocity profile is achievable by using CAVs	Verified	The smooth velocity profile has been demonstrated on the test track. Results in the simulation also shows less harsh acceleration variations.
6	Frequency of occurrence entering conflicting zone during yellow phase decreased	False	Strategies to decide on entering the conflict zone does not differ between AV and CAV. The decision to enter in the conflict zone is decided based on the safe deceleration to stop before the traffic light. Knowing the remaining green phase would help to better plan a strategy in advance for a smoother drive.
7	Number of times entering the conflict zone and harsh brake due to the late VRU detection decreased.	Verified	The CAV produces less harsh braking compared to AV before stopping. Although, CAV sometime generates a harsher braking (still safe) due to the speed/proximity of the following vehicle, this harsh braking behaviour will further reduce if the remaining green light phase is known (refer to section 1.6).

3 CAV IN ROADWORK (USE CASE B – CAV-RW)

3.1 DESCRIPTION OF THE SCENARIO

Figure 3 illustrates CAV-RW use case. In this scenario, the AV's sensors will detect roadworks and associated speed limits by its sensors and make a judgement to merge in the adjacent open lane. The opportunity for a safe merge (time) can be improved by providing C-ITS message earlier than the AV's sensors can detect roadworks, potentially providing safety benefit.

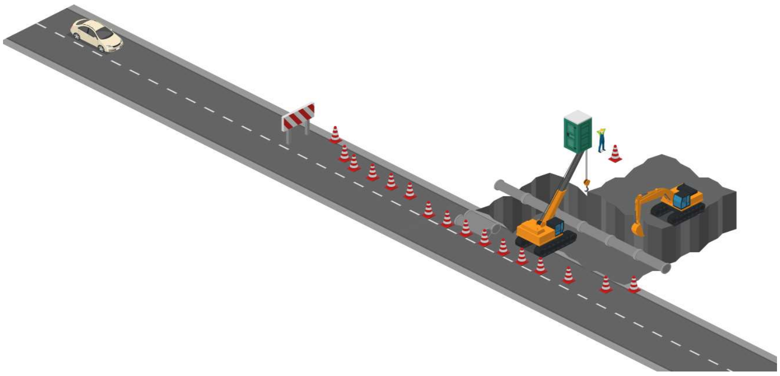

Figure 3 Roadworks scenario

To address this scenario, the study collected data capturing AV behaviour by only relying upon its sensors and then provided the AV with a C-ITS message (DENM) complying with ETSI standard.

Understanding a safe speed in automated driving is one of the first principals of controlling an AV. Not only the safe speed needs to be harmonised with the traffic, it also needs to take into account the C-ITS message for automated driving. An AV requires low-level information from infrastructure such as speed limit, number of lanes and road geometry for handling the driving task. While the DENM messages implemented as part of the Ipswich Connected Vehicle Pilot are well designed for a human driver to inform them about the unusual/unsafe events in the road networks, this message needs to be supplemented with added information for automated vehicles. The DENM message for the use case was developed containing the driveable path, speed limits and road geometry to facilitate safe automated driving.

Algorithms were developed and implemented in ZOE2 to allow decision making in real time considering information contained in the DENM message rather than simply relying on the pre-defined parameters, such as onboard maps. This is important as a roadworks configuration can drastically change the road infrastructure. For example, in a simple scenario, a lane can be obstructed, and the traffic must merge into an adjacent lane (see Figure 3). An extension to this scenario is when a new path created completely outside of the existing road infrastructure, such as outside the road shoulder. In this case, it is challenging for the AV to navigate with its onboard maps alone, while in automated mode. DENM will provide further information allowing the AV to define a new path outside of its onboard maps.

Several data collection runs were carried out using ZOE2 at Mount Cotton test facility (Figure 4), and as per section 1.5, simulation and modelling was carried out. During the data collection runs ZOE2 assessed safe gap between vehicles and safely merged into the adjacent lane.

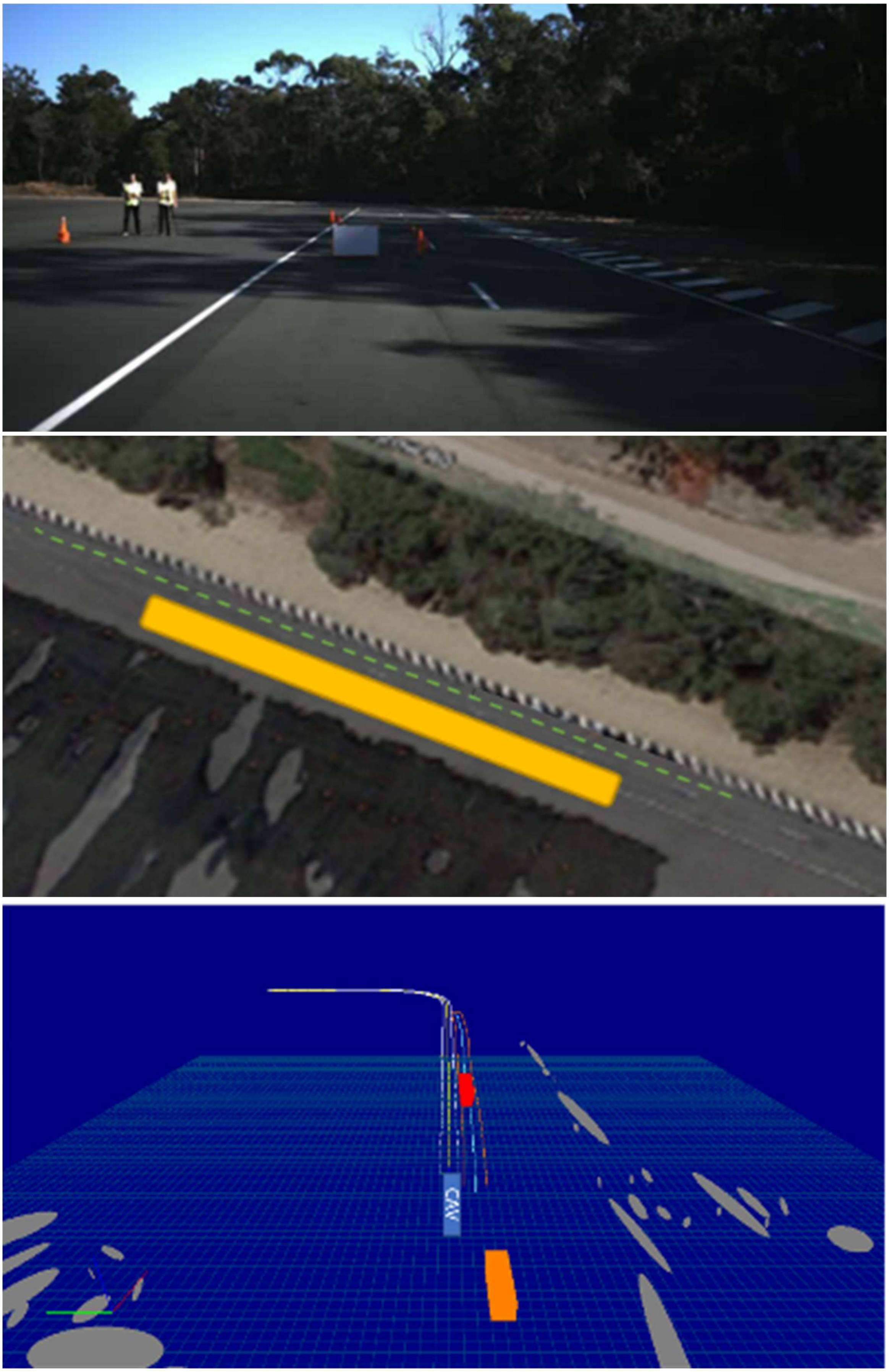

Figure 4 Roadwork area at Mt cotton, obstructed lane and alternate path in the bird's eye view and new trajectory by ZOE2

3.2 FINDINGS

The evaluation criteria were set early in the project. Findings against each criterion are tabled below.

Table 2 Findings from CAV-RW use case

	Hypothesis	Finding	Comment
1	The likelihood of crashes and near crashes on roadworks zone will decrease for CAV	False	No crashes were recorded in the simulation environment. The Automated Vehicles (without the connectivity component) adopts a conservative behaviour during the lane change. As a result, the lane change decision does not create large overall deceleration, and no crash. CAV has a more aggressive behaviour to achieve the lane change, but a trade-off between the success rate and the aggressiveness can be achieved, maximising the benefit for the CAV and other vehicles. This leads to larger deceleration during the lane change, and no crashes.
2	Reduce number of time CAV blocked in closure lane	Verified	The introduction of communication drastically increases the success of lane change for CAV with respect to AV.
3	CAV will have higher likelihood of speed limit compliance in the roadworks zone	False	The AV and CAV both equally complied with the speed limit as long as the speed limit signs are visible, or AV's maps are up to date.
4	The communication quality has impact on reducing the likelihood of crashes and near crashes.	False	No impact measured on this criterion.
5	In the case of lane closure, CAV will have "better" or "earlier" orderly change of lane before the location of lane closure	Verified	Using communication, the lane change occurs earlier. The longer the range of communication, the earlier the lane change occurs benefitting the overall traffic flow.

6	CAV will have improved time to collision and headway by providing enough gap for lane change	Depends on the strategy	Strategies to decide on lane change differ between AV and CAV. AV is using mutual benefit evaluation, while CAV has a more aggressive behaviour. It results in shorter gap and lower headway. However, the trade-off between the success rate and the gap can be adjusted to improve the benefit.

INTENTIONALLY BLANK