Ipswich Connected Vehicle Pilot Safety Evaluation

Summary Report

May 2022

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It is acknowledged that contents of the current report are developed from the study design as was documented in the following project report, Rakotonirainy, A., Schroeter, R., Demmel, S., Larue, G., Zarei, N., Elhenawy, M., Pascale, M., Bond, A., & Haworth, N. (December, 2018). C-ITS Pilot Study Plan Release 5: Milestone Dec 2018, M009c.1. Centre for Accident Research and Road Safety – Queensland (CARRS-Q), QUT.

Executive summary

This report summarises the safety evaluation findings from the Ipswich Connected Vehicle Pilot (ICVP). It is based on analysis of the objective driving data collected from participating drivers from September 2020 to September 2021.

It was hypothesised that receiving a Cooperative Intelligent Transport System (C-ITS) warning on the Human-Machine Interface (HMI) retrofitted in their car would lead to: Lower average speed, Lower celeration and Fewer near crashes. Five C-ITS use cases were tested, Road Works Warning (RWW), Back-of-Queue (BoQ), Road Hazard Warning (RHW), Turning Warning for Vulnerable Road users (TWVR) and Advanced Red Light Warning (ARLW). The warnings were conveyed when drivers were approaching these compromised traffic conditions at an unsafe speed ("scenarios").

Drivers in the treatment group (90%) experienced the safety warnings for six months and no warnings for three months as baseline condition. The remaining 10% of drivers (the control group) did not experience any safety warnings. The analysis focused on comparing the driving profiles with and without warnings during the scenarios.

Safety results from the Pilot

The driving data from the Ipswich Connected Vehicle Pilot (ICVP), a Cooperative Intelligent Transport System (C-ITS) technology pilot, showed positive safety results, overall, demonstrating improved driver behaviour.

The analysis focused on testing if the display of safety warnings via the Human-Machine Interface (HMI) had a significant safety impact on driving behaviour. Overall, most use cases indicated an improved safety outcome as speed and celeration reductions were reported, meaning the drivers might have more control of their vehicle to avoid any potential road hazards.

RWW was highly effective within the roadwork zone, potentially due to the HMI providing both the current roadworks speed limits and an alert when this was exceeded. In the approach to roadworks, the early warning resulted in a lower speed and also significantly greater deceleration (resulting in a higher celeration value) in the treatment group than the control group; the control group tended to not react prior to the roadworks.

ARLW and TWVR improved participants' driving behaviour by alerting participants as they approached traffic signals. A 22% reduction was found in red-light running when participants with and without the ARLW warnings were compared.

The dynamic spatial and temporal nature of BoQ created challenges in providing accurate warnings and in repeatability for the safety analysis. While there was no identified speed difference between the groups, the warnings encouraged smoother travel through the events indicating participants' greater awareness of the risk.

Analysis regarding RHW was limited with so few participants encountering the warning, as a result, the statistical modelling did not yield any conclusive findings on driving behaviour.

South East Queensland (SEQ) crash reduction estimates

The speed results were scaled from the pilot level to the SEQ 100% market penetration level. The principle of Nilsson's power model was used to estimate crash reduction factors for fatal and serious injury types. The crash reduction rates for the individual use cases ranged from 3-11% of the relevant crash types and additionally 22% reduction was determined from the ARLW red-light running analysis. By considering all the use cases which indicated a significant reduction in speed, the overall crash reduction rate with reference to all crashes in the SEQ road network is estimated to be 2-7%.

To provide an overall crash reduction factor for future foundational C-ITS deployment, the estimation of crash reduction factors was extended to include two other use cases unable to be tested on-road and so were tested in a driving simulator instead. These vehicle-to-vehicle use cases were: Slow-Stopped Vehicle (SSV) and Electronic Emergency Brake Light (EEBL). The cumulative reduction was estimated at 5-12%. When including the In-Vehicle Speed (IVS) as a likely early use case which has been assessed in another Australian study (Doecke & Woolley, 2010), the overall crash reduction rate for the fatal and serious injury types is estimated to be 13-20%.

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Brief overview of the Ipswich Connected Vehicle Pilot

Through the ICVP, the Department of Transport and Main Roads (TMR) aimed to build public awareness of C-ITS technology and to validate the safety impact, so that TMR could understand the potential of increased C-ITS uptake. Strategically, the pilot enabled TMR to grow organisational readiness for future widespread deployment in Queensland.

C-ITS technology allows vehicles to 'talk' with other vehicles, roadside infrastructure, and transport management systems in real-time. This provides road users with information or visual warnings, on a dedicated display (i.e., a Human Machine Interface [HMI] as shown in Figure 1), relevant to their current situation.

Figure 1 A Human Machine Interface (HMI) used in the ICVP

To understand the impacts and gather public perspectives of the technology, the ICVP ran between September 2020 and September 2021, involving 355 public participants in Ipswich driving their own vehicles retrofitted with C-ITS technology for a period of nine months. The pilot included a centralised cloud-based service covering 300 square kilometres of road network and 29 TMR-owned signalised intersections in Ipswich, Queensland, Australia.

Data were collected and transmitted through the Vehicle Intelligent Transport System Station (V-ITS-S) installed in participants' vehicles, allowing the analysis team to monitor drivers' responses to the warnings and to estimate the likely impacts on their driving behaviour and crashes. This report presents the study design, the safety measures employed for the evaluation and the findings. Finally, the potential crash reduction factor for each case, assuming 100% market penetration in Southeast Queensland (SEQ), was estimated to inform future investment.

The user perceptions component of this pilot based on questionnaires, interviews, and focus groups occurring over the course of the pilot was documented in *Ipswich Connected Vehicle Pilot - Summary of the Subjective Evaluation Study Findings*. The pilot also conducted a driving simulator study to test the effectiveness of two vehicle-to-vehicle (V2V) warning messages and the findings of the simulator studies are documented in *Ipswich Connected Vehicle Pilot: Summary of the Simulator Study Findings*. It is recommended to read the subjective finding reports and the simulator studies finding reports in conjunction with this summary report, to support or verify findings emerging from the overall study of safety impacts and user perceptions of the ICVP.

Safety information and warnings

Safety information was shown on the HMI only when relevant to the driver (except for in-vehicle speed [IVS], which was always shown).

For example, drivers were shown advanced red-light warnings only if they were driving too fast to stop at an upcoming traffic light (see Figure 2). If the driver was driving at a slower speed, they did not receive this safety warning.

In the ICVP field operational testing (FOT), participants experienced safety information or warnings based on first six different use cases as outlined in Table 1. Two vehicle-to-vehicle (V2V) use cases (as highlighted in orange in Table 1) were developed and tested using the CARRS-Q Advanced Driving Simulator. These use cases were not investigated in the FOT because a valid V2V event would only occur if two participants were travelling within a close distance range to one another; and, thus, it was expected this would not occur frequently on-road.

Figure 2 Example of ARLW message shown before a red light

Table 1 Safety use cases

Safety information		Purpose	Display icon[1]	Audio alert
RWW	Road works warning	Alerts drivers there is a risk they are travelling at an unsafe speed for upcoming road works, giving them time to slow down or change lanes. It also alerts drivers if they exceed the speed limit within the road works.		Single soft "boop"
BoQ	Back of queue	Alerts drivers there is a risk they are travelling at an unsafe speed for an upcoming traffic queue.		None
RHW	Road hazard warning	Alerts drivers that there is a risk they are travelling at an unsafe speed for a hazard up ahead, such as water on the road, road closures or a crash.		None
ARLW	Advanced red-light warning	Alerts the driver that they are likely to violate the red-light at a signalised intersection.		Three quick "beeps" for high warning
TWVR	Turning warning vulnerable road-user	Alerts drivers to pedestrians or bicycle riders potentially crossing at an upcoming signalised intersection.		Single soft "boop"
IVS	In-vehicle speed	Provides drivers with information about the current speed limit.		None
EEBL	Emergency electronic brake light	Alerts drivers there is a risk of a rear-end collision with a vehicle braking hard ahead.		Single "boop" for medium warning and three quick "beeps" for high warning
SSV	Slow/stopped vehicle	Alerts drivers there is a risk of a rear-end collision with a slow/ stopped vehicle ahead.		Single "boop" for medium warning and three quick "beeps" for high warning

[1] Medium warnings (displayed as a warning symbol) informed drivers to prepare for a possible emergency situation. High warnings (with a red background) informed the driver of an emergency situation requiring an immediate reaction.

Study methodology

The primary research question for the safety evaluation was:

Does the system improve road safety?

It was expected the C-ITS warnings produced by the system would result in a positive impact on driving behaviour and consequently, a reduction in the number and severity of crashes. The expected effects on the three surrogate safety measures employed in the evaluation were:

1. **Lower average speed** – the average speed on approach to and/or within use case events would be lower when the HMI was enabled (i.e., when the HMI was on).
2. **Lower celeration** – the value of the celeration on approach to and/or within use case events would be lower when the HMI was enabled. Celeration is defined as the average of absolute acceleration and deceleration values, as an indicator of the smoothness of the drive. The concept is illustrated in Figure 3. A lower value of celeration indicates a smoother driving profile, most likely with less abrupt braking and accelerating over the course of a drive.
3. **Reduced near-crashes** – the likelihood of near-crashes on approach to and/or within use case events would be reduced when the HMI was enabled (i.e., when the HMI was on).

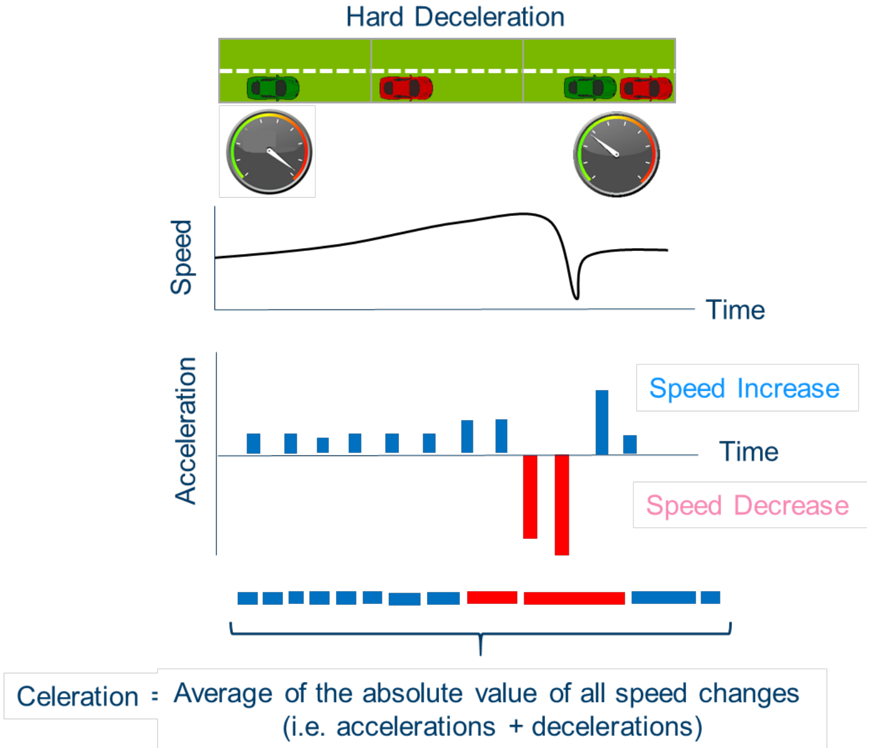

Figure 3 Derivation of the measure of celeration from the driving response

Experimental design

The pilot successfully recruited 355 drivers to participate in the ICVP for a nine-month period. The participants were randomly assigned to different experimental conditions for statistical rigour and comparative purposes. One group of participants drove their own vehicle for six months with the retrofitted C-ITS system to experience the safety warnings (treatment condition) and for three months without the warnings displayed on HMI (baseline condition). Another group of participants was assigned to a control condition whereby no warnings were shown, to account for seasonal effects and balance the driving observations in the baseline condition.

Of the 355 recruited participants, only 349 participants were found to produce sufficient valid objective data for analysis. The number of participants (n) assigned to each cohort and the duration of each condition is shown in Figure 4.

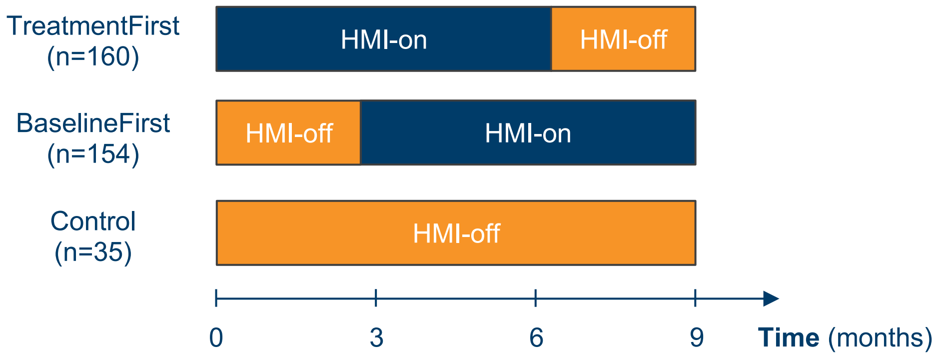

Figure 4 Sample size and duration of experimental conditions

To ensure sufficient driving data were collected, participants were required to drive a minimum of three hours per week within the pilot area. The driving data showed that most participants consistently met this requirement during their nine-months of participation.

Scenario-based assessment

The safety evaluation focused on participants' driving behaviour only within windows where participants encountered a use case event (referred to as a "scenario"). The scenarios generally covered 30 seconds before the warnings were warranted and 30 seconds after the driver had passed by the safety hazards. A single journey could consist of multiple scenarios when driving within the pilot area as illustrated in Figure 5.

For comparative purposes and to increase statistical rigour of the findings, scenarios with (treatment) or without (control/baseline) HMI warnings were included in the safety analyses. The different levels of HMI warning are shown in Figure 5.

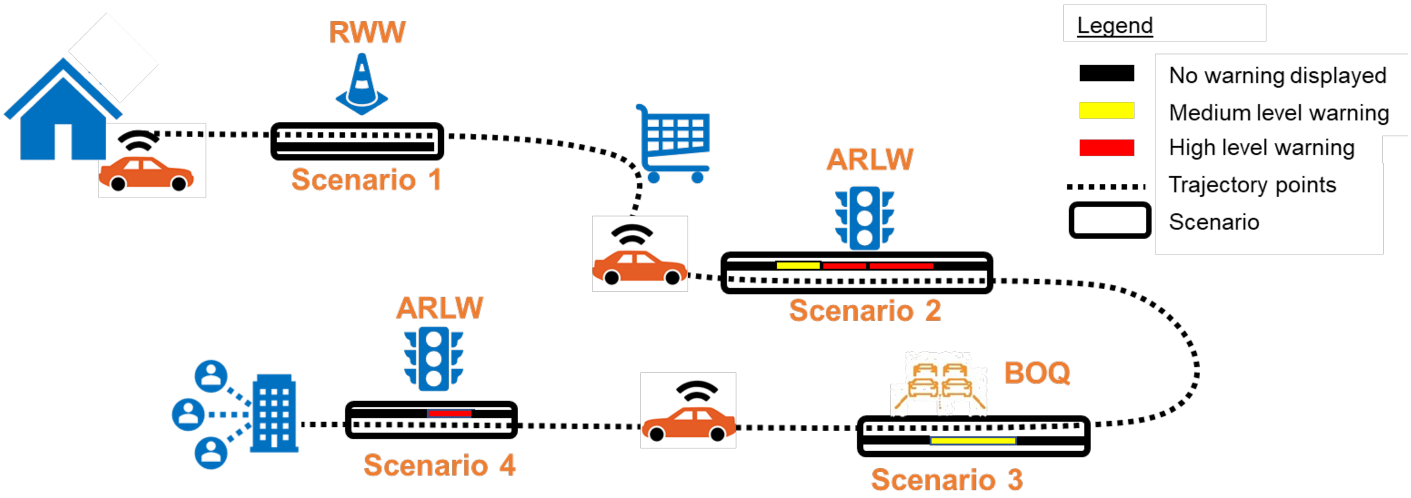

Figure 5 Example of a Treatment participant encountering multiple scenarios in a single journey

Pilot statistics

The safety evaluation only focused on participants' response to the first five use cases listed in Table 1. IVS was not evaluated due to the already large body of existing evidence which has already demonstrated its safety benefit.

For the five use cases being evaluated in the ICVP, there were nine warning messages available for the participants when the driving situation met the safety criteria. The number of safety warnings that were conveyed to the Treatment participants is listed in Table 2.

Table 2 Number of warnings displayed by use case

Use case	Approach warning	Event warning
Road Works Warning	5,820 (Road Work)	13,924 (Reduce Speed)
Back-of-Queue	4,981 (Congestion)	Not applicable
Road Hazard Warning	504 (Hazard)	Not applicable
Turning Warning for Vulnerable Road Users	6,063 (Pedestrian Crossing)	6,821 (Pedestrian Crossing)
Advanced Red-Light Warning	51,818 (Medium) (Red Light) 4,819 (High) (Stop!)	631 (Stop!)

"Approach warning" is defined as the warning given to the participants leading up to the safety hazard, while "Event warning" is displayed when a participant was in the safety conflict zone, for example within the road works zone or beyond the stop bar at an intersection, as is shown in Figure 6.

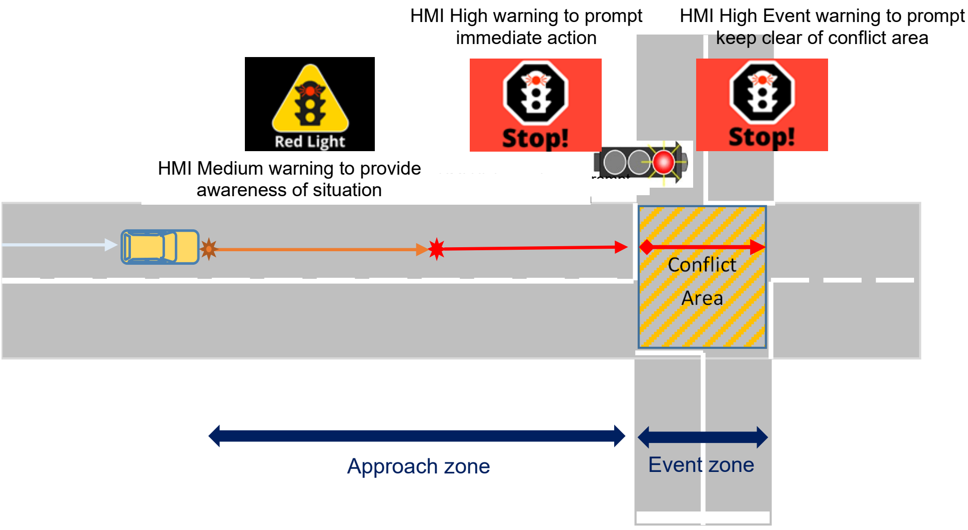

Figure 6 ARLW warning levels and trigger points

Out of the five use cases, the ARLW issued the highest number of warnings as the 29 intersections were permanently activated throughout the FOT, unlike the cellular use cases where the events were only temporary, such as the road works traffic congestions on motorways. The 57,000 ARLW warnings displayed equated to an average of one ARLW warning per participant per day.

Safety impact findings

After the driving data were processed into over 100,000 valid scenarios, the three safety surrogate measures were analysed for the five use cases. Statistical modelling was employed to determine if the individual use cases had a significant impact on the driving speed, celeration and near-crashes. Other environmental factors, such as the prevailing road conditions and participants' demographic characteristics, were also considered in the models.

Average normalised speed

The speed measurements for each scenario were divided by the displayed speed limit to obtain a normalised speed ratio which allows analysis with a combination of different road types. A normalised speed value above 1 means the observed speed exceeded the displayed speed limit.

RWW, TWVR and ARLW showed a beneficial impact on the average normalised speed, with a statistically significant reduction of 1-2% in driving speeds as participants approached the safety event as is shown in Table 3. Although 1-2% change might not be considered "significant" in magnitude, the statistical testing indicated that the reduction was consistently observed across the participants who had the HMI enabled. Road safety research indicates that for every kilometre reduction in impact speed, the risk of serious injury in vehicle crashes reduces, especially in high-speed environments.

The RWW warning within the road works zone was found to reduce speeds by 3.1% reduction for those participants who had the HMI enabled. RWW event warnings could be issued multiple times within the road works zone, serving as continuous reminders when the Treatment participants exceeded the road works speed limit.

BoQ and RHW did not show any significant difference between the participants with or without the HMI enabled. The study was thus unable to draw any conclusive findings due to the variability in conditions found in triggering these two use cases. For BoQ, the dynamic nature of congestion on the motorway context was difficult to capture in the analysis model. For RHW, the low number of scenarios meant that no conclusive findings could be determined.

Table 3 Speed comparison between HMI-on and HMI-off conditions

Use case	Impact of C-ITS warnings on average speed	
	Approach zone	Event zone
RWW	**1.1% reduction**	**3.1% reduction**
BoQ	Nonsignificant change	Not applicable
RHW	Nonsignificant change	Not applicable
TWVR	**1.2% reduction**	Not applicable
ARLW	**1.9% reduction**	Not applicable

What does this mean?

The participants in Treatment group were consistently driving **2.1km/h slower** than those without the warning available.

The speed analysis was generally undertaken in the approach zone because the purpose of the use cases was to increase awareness of drivers through the warning of a changing condition in advance of the event. The increased awareness served as a preventative measure; by contrast, analysing speed in the event zone does not give an indication of the warning effectiveness on safety, given a driver would have already encountered the event. Except for RWW, some road work sites spanned over a few hundred metres (e.g., the Centenary Highway Sumners Road Interchange Upgrade, as shown in Figure 7), so the continual Event warnings were found to be effective in terms of Treatment participants driving below the road works speed limit throughout the site.

Figure 7 RWW displayed on Centenary Highway at Sumners Road Interchange

Average celeration

The average deceleration/ acceleration upon receiving a warning can be an indicator of participants' preparedness for the safety event. If the Treatment group (HMI-On) showed reductions in celeration, these reductions would suggest the warnings had provided them more time to gradually adjust their speed, rather than braking or accelerating abruptly closer to the hazards.

All use cases, except for RHW, showed a statistically significant change in celeration after the Treatment participants received a warning. As shown in Table 4, RWW (in Event zone), BoQ, TWVR and ARLW reported a 0.9-7.9% reduction for the participants with the HMI enabled, suggesting the warnings were effective in minimising aggressive manoeuvres. In contrast, RWW in the Approach zone reported an increase of 4.7%. Investigation of the RWW Approach driving profile revealed that the Treatment participants reacted to the advanced warning by braking prior to the roadworks (compared to the control group who tended to not react in this approach analysis window). This finding was considered a positive safety outcome in that participants were braking prior to the roadworks despite the higher variance in celeration that was recorded in their driving behaviour.

The evidence of a large percentage reduction in celeration, combined with a reduction in average speed, indicated that TWVR could improve driver's awareness of pedestrians' presence as the drivers approached an intersection. Consequently, the drivers could adjust their speed appropriately.

Table 4 Celeration comparison between HMI-on and HMI-off conditions

Use case	Impact of C-ITS warnings on average celeration	
	Approach zone	Event zone
RWW	**4.7% increase**	**3.7% reduction**
BoQ	**2.8% reduction**	Not applicable
RHW	Nonsignificant change	Not applicable
TWVR	**7.9% reduction**	Not applicable
ARLW	**0.9% reduction**	Not applicable

Is an increase necessarily a bad safety outcome?

An increase could be caused by participants correcting their driving in response to the warnings. It might not be a bad safety outcome as they would have reached the event at a safer speed.

Near-crashes

As there were no crashes reported in the proximity of the safety events during the pilot, near-crashes were proposed as a surrogate measure to infer the likelihood of being involved in a crash. A near-crash are generally defined as any circumstance that requires a rapid, evasive manoeuvre by a participant's vehicle to avoid a crash. A rapid, evasive manoeuvre is defined as excessive steering, braking, or accelerating that can cause discomfort to the passengers.

As near-crashes have not previously been used to evaluate any C-ITS applications, three near-crash analysis methodologies which had been applied in other naturalistic driving studies were tested in parallel in the ICVP. The three methodologies employed were kinematic performance thresholds, machine learning models and driving volatility measures. All these methodologies focused on the longitudinal acceleration and deceleration, lateral acceleration and yaw rate logged by the vehicle station.

From these three methods, only BoQ suggested a potential reduction in near-crashes of 30-50% as a result of the HMI being enabled. All other use cases were unable to detect any near-crashes or significant impacts, based on kinematic performance and machine learning methods. There are two main reasons for the lack of near-crashes findings: (1) near-crashes are rare and potentially severe events and by only focusing on small time windows around the warnings, the chance of observing a near-crash is even narrower, and (2) the absence of video footage data to support calibration of the models to local driving conditions.

Additional ARLW observations

Apart from the three key safety measures being tested, the ARLW offered opportunity to investigate other safety outcomes including:

Fewer red-light running instances

As red-light violation is a serious traffic offence and could result in a serious safety outcome, the occurrences of red-light running were compared between the Treatment and Control conditions as an extension analysis. The analysis suggested a positive outcome, with 22% reduction found in red-light running between the two conditions.

Less chance of receiving high-level warning after receiving medium-level warning

Warning escalation is defined as a driver receiving a subsequent high-level "take action" warning after receiving a medium-level "heads up" warning. This could be seen as driver's compliance with the initial warning, as they would slow down attentively to avoid the next level of warning. The analysis revealed a positive outcome, as the participants with HMI enabled were 27% less likely to receive a high-level warning than those without the HMI enabled after they received the medium-level warning.

Potential crash reductions

Converting the safety impact estimates into crash reduction factors assists with community communication regarding the effects of C-ITS. The crash reduction factors were scaled up to reflect the future scenario of when C-ITS being used by all vehicles, therefore assuming a 100% market penetration in Southeast Queensland (SEQ). To this end, the safety evaluation estimated the crash reduction rate for each use case.

Crash reduction by FOT use cases

To estimate a crash reduction rate for each use case, a widely accepted speed scaling model, known as the Nilsson Power Model, was adopted. The main tenet of Nilsson's Power Model is "the safety of the transport system is strongly related to the speed levels in the system". The premise of the model is that a small reduction in speed adopted by the driving population leads to large and measurable reduction in risk.

As only RWW, ARLW and TWVR demonstrated a significant speed impact in the FOT, only these three use cases were scaled for crash reduction estimation. As shown in Table 5, the reduction rates ranged from 3-11%, with the fatal crash type being higher than the serious injuries type, due to the "power" for fatalities being higher. As expected from the speed analysis, RWW in the event zone showed the highest reduction rate for those crashes resulting in fatality or serious injury.

Based on the driving data from the participants, the ARLW warnings could reduce the likelihood of running red traffic signals and thus reduce a potential intersection crash by 22%.

Table 5 Crash reduction rate of FOT use cases

Use case	Estimation method	Crash reductor factor	
		Fatalities	Serious Injuries
RWW (Approach)	Speed scaling model	5.3%	3.0%
RWW (Event)	Speed scaling model	11.4%	6.8%
TWVR	Speed scaling model	6.1%	4.3%
ARLW (Approach)	Speed scaling model	9.7%	5.9%
ARLW (Event)	Red-light running likelihood	22.0%	22.0%

Overall crash reduction for all ICVP use cases

It should be noted that the crash reduction factors reported in Table 5 are only relevant to the crash types which are targeted by the individual use cases. For example, RWWs are expected to be effective in reducing crashes in the proximity or within road works zones, while TWVRs are expected to reduce crashes involving pedestrians at signalised intersections.

This assessment also considered the crash reduction rate of other ICVP use cases that were not evaluated as part of FOT as they were considered likely to be incorporated in future C-ITS implementations. In the simulator study, the Slow-Stopped Vehicle (SSV) and Electronic Emergency Braking Light (EEBL) warnings both reported significant reductions in average speed, ranging from 2.4 km/h to 5.0km/h. The speed reductions were then converted to the crash reduction rates using the Nilsson's power model, resulting in 4.5% to 25.3% crash reductions as shown in the shaded columns in Table 6.

In the Intelligent Speed Assist review undertaken for most states in Australia[2], IVS was reported to reduce the crash rate by 7.7%. As IVS is planned to be available for the entire whole road network, it can be assumed that the reduction rate would be applied to all types of crashes.

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[2] Doecke, S. & Woolley, J.E. (2010) *Cost Benefit Analysis of Intelligent Speed Assist.* Centre for Automotive Safety Research, The University of Adelaide.

In order to determine the overall safety benefits for SEQ, the use case crash reduction factors were applied to the relevant fatal and serious injury crashes within a five-year period (from 1 July 2016 to 30 June 2021). The network-wide crash reductions were provided in ranges. The lower bound values were estimated based on a conservative approach, whereby only the crash types that were specifically targeted by the individual C-ITS use cases were considered. The upper bound values took a broader approach by considering the environment that the C-ITS use case could impose a positive safety impact. For example, the lower bound value for ARLW (Event) was exclusively applied to the crashes with "disobey red traffic light" as a crash contributing factor, while the upper bound value was derived by considering any crashes occurred in the proximity of signalised intersections in the urban area. Table 6 summarises the crash reduction rates for the SEQ road network (refer to the columns with lime green heading in Table 6).

Table 6 Crash reduction rates for the SEQ road network

Use case	Information source	Crash reduction (relevant crash types)		Crash reduction (SEQ network)	
		Fatalities	Serious Injuries	Fatalities	Serious Injuries
RWW (Approach)	ICVP FOT	5.3%	3.0%	0.0%	0.0% - 0.2%
RWW (Event)	ICVP FOT	11.4%	6.8%	0.0% - 0.6%	0.0% - 0.2%
TWVR	ICVP FOT	6.1%	4.3%	0.2%	0.1%
ARLW (Approach)	ICVP FOT	9.7%	5.9%	0.2% - 0.4%	0.4% - 1.0%
ARLW (Event)	ICVP FOT	22.0%	22.0%	1.0% - 5.6%	1.2% - 5.1%
SSV	ICVP Simulator	7.5%	4.5%	0.6% - 1.2%	0.9% - 1.4%
EEBL	ICVP Simulator	25.3%	15.1%	1.4% - 3.6%	2.6% - 4.4%
IVS	Literature	7.7%	7.7%	7.7%	7.7%
			Cumulative total	**11.1% - 19.3%**	**12.9% - 20.1%**

Table 6 shows that three ICVP FOT use cases could cumulatively reduce up to 6.8% of fatal crashes and 6.6% of crashes involving serious injuries. When the vehicle-to-vehicle use cases (SSV and EEBL) are included, the cumulative reduction rates are 11.6% and 12.4% for fatalities and serious injuries, respectively. By including IVS, the overall reduction rates are estimated as 19.3% and 20.1% for fatalities and serious injuries, respectively. It should be noted that including IVS in the assessment does introduce some potential duplication of warning impacts.

In a broader context, with a total of 526 fatalities and 20,826 serious injuries being reported from crashes on the SEQ road network over the five-year period of 1 July 2016 and 30 June 2021, the eight C-ITS use cases implemented in the ICVP could have prevented up to 101 fatalities and 4,198 serious injuries from crashes. This equates to an average of 20 fatalities and 840 serious injuries prevented each year in SEQ.