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Framework for field evaluation of signal cooperative intelligent transport system use cases as based on the Ipswich Connected Vehicle Pilot

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Abstract

Cooperative Intelligent Transport Systems (C-ITS) have the potential to greatly increase traffic safety on roads. To ensure C-ITS implementation is effective, the equipment within the ecosystem must communicate using standardised, available and reliable messages that can be trusted for use in end-user warnings. If the warnings displayed to the end-user are incorrect, untimely or inappropriate the system may have the reverse effect on user safety instead.

Queensland Department of Transport and Main Roads (TMR) identified the need for government investment in C-ITS roadside stations (R-ITS-S) and through the Cooperative and Automated Vehicle Initiative's (CAVI) Ipswich Connected Vehicle Pilot (ICVP) installed and studied the performance of the equipment as part of a larger behavioural study. This paper describes a framework created for the assessment of R-ITS-S suitability against ten key criteria, with a focus on reuse in future Australian deployments of C-ITS, projects and pilots. These criteria were proposed after reviewing current literature of European and U.S standards and guidelines.

The assessment criteria within the framework includes: 1) **Roadside Coverage** – the effective range of the roadside unit (RSU); 2) **Availability** –the percentage of time the RSU and its substituent components are operational; 3) **Reliability** – a sub-category of availability, finding the Mean-Time-Between-Failures (MTBF), Mean-Time-To-Repair (MTTR) and the total number of failures; 4) **Latency** –the total time for communicating messages between sent and received timestamps; 5) **Usability** – the accuracy of the MAP Extended Message (MAPEM) file transmitted by the RSU with respect to the road centreline; 6) **Security** – the percent of security certificates that fail under conditions where it is expected that certificates should be passed; 7) **Refreshment Rate** – the assessment of updated signal statuses between the field processor and RSU; 8) **Classification Correctness** – the assessment of how correct the presented signal use case messages are; 9) **Integrity** – the assessment of instances where the integrity of the system is compromised; and 10) **Conformance** – a judgement of the conformance of the ICVP against the European standards.

1. Introduction

As intelligent transport systems (ITS) continue to rapidly develop on a global scale, road transport authorities are responsible to ensure that state-of-the-art technologies are deployed on public roads and that they meet minimum operational requirements. These requirements aim to protect all road users that directly or indirectly interact with the new technologies. Early implementation of ITS has combined multiple ITS devices to provide the user with real-time information on the traffic environment. Cooperative intelligent transport systems (C-ITS) have been explored over the last decade, with increasing development and deployment by government and industry leaders in Europe and in the US. With original equipment manufacturers (OEM) looking to bring C-ITS vehicles to public roads, it is important for road transport authorities in Australia to validate the impacts and benefits of C-ITS applications and user perceptions. To support this objective, the Queensland Department of Transport and Main Roads (TMR) commenced a large-scale C-ITS pilot in Ipswich as part of its broader Cooperative and Automated Vehicle Initiative (CAVI). The Ipswich Connected Vehicle Pilot (ICVP) is the largest Australian trial of C-ITS technologies, with over 350 public participants, set up to test how such technologies would operate on Australian roads and to gain lessons for the future development and deployment of such technologies. As the initial deployment of the ICVP comes to a close during 2021, TMR is looking to review the performance metrics of the ICVP.

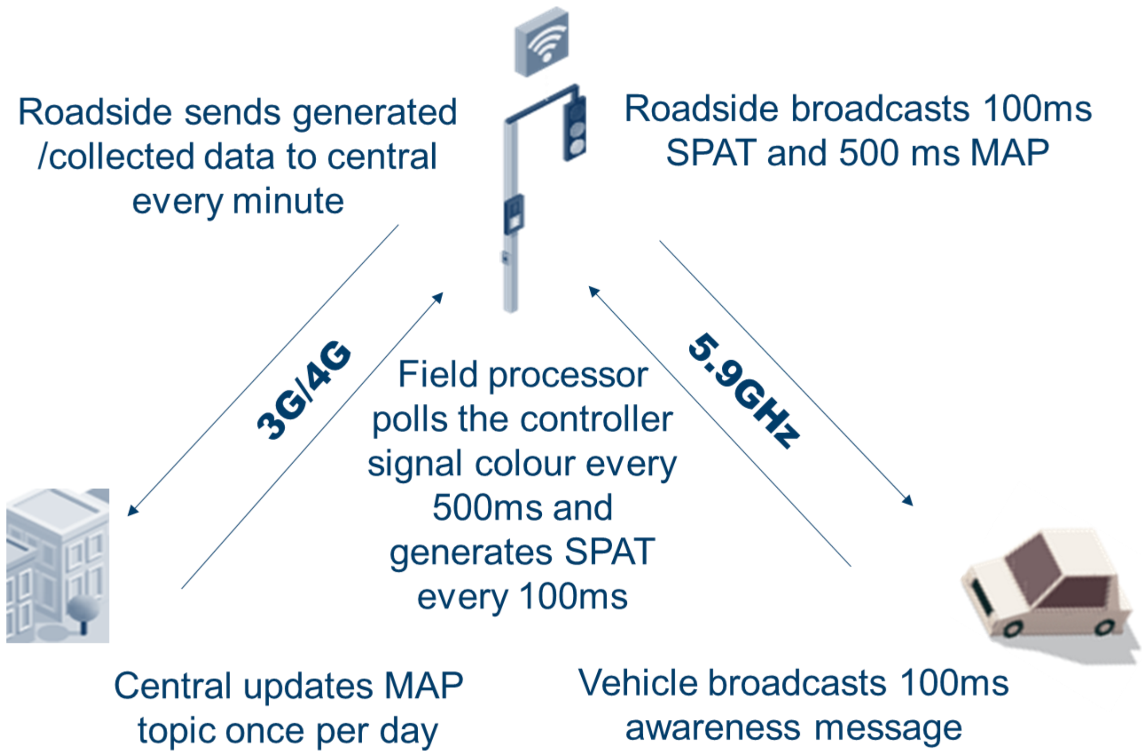
It is important for TMR to critically analyse and understand the performance of the ICVP equipment to ensure that the development of the technologies continues and that it is mature for broader deployment on public roads. C-ITS will become increasingly important as connected automated vehicles (CAV) are introduced on public roads. It will enable CAVs to "hear" and "speak" to other vehicles or infrastructure and help improve their performance and safety. AV implementation is not discussed further in this paper, however, could be a future beneficiary of the outputs of the proposed C-ITS assessment framework.

The current use cases involved in the ICVP include:

- In-vehicle Speed (IVS)
- Advanced Red-Light Warning (ARLW)
- Road Hazard Warning (RHW)
- Back-of-Queue (BoQ)
- Turning Warning for Vulnerable Road users (TWVR)
- Road Work Warning (RWW)

These use cases have varying safety applications and differing system architectures, using cellular or ITS-G5 communications. ITS-G5 is a communication medium, similar to Wi-Fi, enabling secure and standardized messages to be sent and received between C-ITS devices within the protected 5.9GHz bandwidth. This paper will focus on the vehicle to infrastructure (V2I) use cases, ARLW and TWVR, which make use of the ITS-G5 5.9GHz communication medium. Figure 1 ICVP System Architecture (C-ITS-F, R-ITS-S, V-ITS-S) below shows how major components within the system communicate.

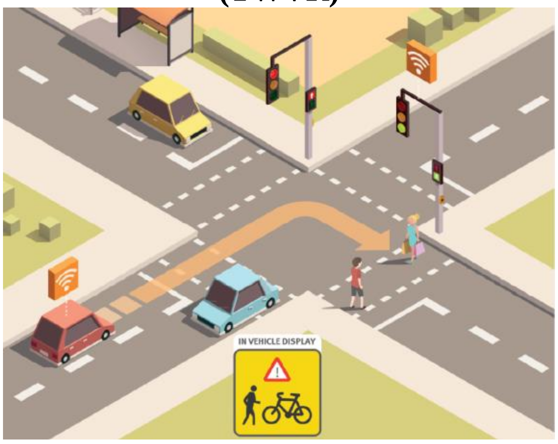
Figure 1 ICVP System Architecture (C-ITS-F, R-ITS-S, V-ITS-S) *(Source: TMR)*



2. Use Cases

The signal V2I use cases are intended to address some critical safety scenarios, namely; red light compliance and vulnerable road user awareness at intersections. If the vehicle intelligent transport system station (V-ITS-S) receives untimely or incorrect messages from the R-ITS-S, the ARLW/TWVR warning to the driver may result in an incorrect or ill-informed decision about the true state of an intersection. This may lead to the respective vehicle entering the conflict zone of a signalised intersection at an inappropriate time, or a future state could impact the safe operation and reaction of AV. These could both lead to incidents resulting in serious injury or death as well as a loss of trust in the roadside equipment by the vehicle. This emphases the importance of ensuring the R-ITS-S is operating at a satisfactory level. Examples of how ARLW/TWVR use cases operate within the ICVP can be found in Table 1 ICVP C-ITS V2I Use Cases.

Table 1 ICVP C-ITS V2I Use Cases

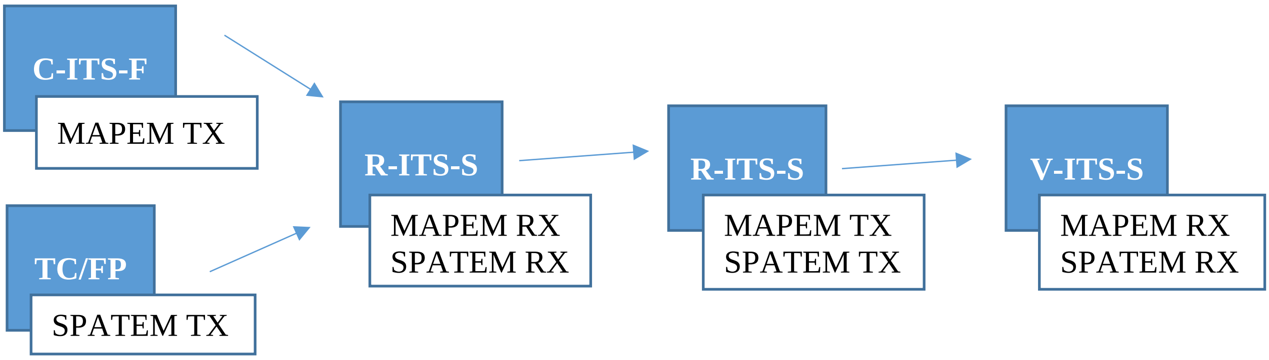
Use Case Name and Graphic	Use Case Description and Features
Advanced Red Light Warning (ARLW)  ***(Source: TMR)***	**Description**: Alerts the driver that they are likely to violate the red light at a signalised intersection. **Vehicle Interface**: R-ITS-S → V-ITS-S **Vehicle Communications**: ITS-G5 **Message Format**: MAPEM and SPATEM (ETSI TS 103 301) **Data Source**: The lamp/display colour is indicated by the Traffic Signal Controller. The intersection layout is sourced with a surveyed positioning correction.
Turning Warning Vulnerable Road User (TWVR)  ***(Source: TMR)***	**Description:** Alerts the driver that they are likely to conflict with a pedestrian or cyclist at a signalised intersection. TWVU is based on the pedestrian signal call button. **Vehicle Interface:** R-ITS-S → V-ITS-S **Vehicle Communications:** ITS-G5 **Message Format:** MAPEM and SPATEM (ETSI TS 103 301) **Data Source:** SPATEM – Traffic controller, MAPEM – TMR database

This paper presents a framework to assess the performance of C-ITS infrastructure within the CAVI ICVP context. The framework has been scoped to assess the R-ITS-S interactions that involve the signal use cases. It can be applied to future pilots and projects that utilise the ICVP infrastructure or similar models within Australia.

The CAVI ICVP is comprised of three main components, the cloud-based central intelligent transport system facility (C-ITS-F), R-ITS-S and the V-ITS-S. The signal use cases rely on the R-ITS-S sending signal phasing and timing extended messages (SPATEM) and MAP extended messages (MAPEM) to the V-ITS-S. The European Telecommunications Standards Institute (ETSI) has defined these messages and their applications. SPATEM is sent by the R-ITS-S at 10Hz, whereas the MAPEM is sent twice a second. The SPATEM contains information about the current signal state of the intersection, regarding all relative signal groups. The MAPEM contains the intersection's geographical layout, with stopping bars, lane centre lines and the connection between the signal state and the lane. The V-ITS-S interprets the MAPEM and SPATEM to assess the situation based on the trajectory and signal information, and if relevant, will provide a warning to the driver. The visual/audible warning is delivered to the driver via the human machine interface (HMI), whereby the driver takes evasive or alternative action.

Figure 2 C-ITS message flow within the ICVP (ARLW/TWVR) below illustrates the flow of messages, transmitted (TX) and received (RX), for the signal use cases.

Figure 2 C-ITS message flow within the ICVP (ARLW/TWVR)



These communications require a low latency medium, which current 3G/4G cellular communications do not meet, hence the interface between the V-ITS-S and the R-ITS-S is the ITS-G5 5.9GHz interface. This allows for fast communication speeds within the range of the intersection, at the cost of significantly reduced range in comparison to the cellular communications utilised within the other cloud-based use cases.

C-ITS vehicles entering an intersection require timely and relevant messages for the appropriate signal use cases. The impacts of untimely or unavailable signal use case messages may be more profound with the possibility of vehicles unknowingly entering intersection conflict zones without a warning. Although this may be an extreme example, it highlights the importance of ensuring that the signal use cases are operating at an acceptable standard for participants to confidently respond.

3. Methodology

This paper proposes a framework to assess the performance quality of the ICVP. The performance criteria proposed in this paper were developed following a comprehensive literature review of European and US standards and guidelines. The bespoke criteria were developed to effectively assess key components of the R-ITS-S performance.

After the bespoke criteria were defined, metrics were sourced by TMR's recommendation or using relevant references. The criteria listed in this paper are not exhaustive and new bespoke metrics and definitions may need be created. A summary of the bespoke performance criteria has been tabulated in Table 2 Summary of performance criteria

Table 2 Summary of performance criteria

Criteria	Standard Definition	Proposed Definition	Analysis Method	Metric	Standard/Guidelines Referenced
Roadside Coverage	Percentage of the road network and/or selection of road classes, where stationary, connected C-ITS stations operate.	The radio signal range (coverage) from the R-ITS-S antenna.	Investigate the geographical range of the R-ITS and build an effective performance radius of the R-ITS analysed. Determine the radio frequency range, measured by the V-ITS-S' CAM location associated with the nearest SPATEM received time.	Roadside Range = 300m where speed limits are 60 kph, and 500m where speed limits are < 60kph	EU EIP SA 4.1: Determining Quality of European ITS Services (p.32)
Availability	Average availability for all operating connected data senders, including the communication chain up to the data receiver.	Is defined as the time percentage a (content provision) service is offered. Where the content provisions are the components of the R-ITS-S (TC, FP, CISCO router and RSU).	Investigate the percentage uptime, measured by MAPEM TX and SPATEM TX metrics, depending on which metrics are active will define which content provision service is available or not. The availability will account for SPATEM 'unknown' states.	Availability > 99.5%	EU EIP SA 4.1: Determining Quality of European ITS Services (p.33, 52)
Reliability (sub-category of availability)	Reliability – Mean-Time-Between-Failure and as Availability.	The MTBF (Mean-Time-Between-Failure), MTTR (Mean-Time-To-Repair) and total number of failures.	Investigate the three characteristics outlined by the reliability conditions, MTBF, MTTR, the total number of failures of the R-ITS (TC, FP, CISCO router and RSU).	Statement of observation based on results of the investigation.	U.S. Department of Transportation: Roadside Unit (RSU) Standard v1.0 (p.127)
Latency	Total time for communicating messages between (a) a timestamp at a C-ITS sender and (b) a timestamp at a C-ITS receiver.	Is defined as the total time for communicating messages between timestamps for	Internal: Assess the internal latency of the R-ITS-S between SPATEM Rx and SPATEM Tx. External: Assess the latency between the R-ITS-S	Timeslip < 100ms, Internal < 100ms,	EU EIP SA 4.1: Determining Quality of European ITS Services (p.35)

Criteria	Standard Definition	Proposed Definition	Analysis Method	Metric	Standard/Guidelines Referenced
		internal and external processes	(SPATEM Tx) and the V-ITS-S after the internal timestamp (SPATEM Rx).	External < 300ms	
Usability	Mapping accuracy shall be within 0.5m from the centre of lane. The accuracy is a measurement of the perpendicular distance from the node to the centre of the lane.	The accuracy of the MAPEM lanes compared to the most frequently travelled paths, determined by V-ITS-S' CAM locations.	Investigate the accuracy of the manually created MAPEM lanes compared to the normalised V-ITS-S positional location. Determine the percentage length of MAPEM lane within the buffered paths.	95%ile of the CAM vehicle positioning within 0.5m of the MAPEM lanes	Vehicle-to-Infrastructure Consortium: SPaT Challenge (p.18)
Security	[The] preservation of confidentiality (that information is not made available or disclosed to unauthorized individuals, entities, or processes), integrity (accuracy and completeness) and availability (accessible and usable on demand by an authorized entity) of information.	Is defined as the percent of security certificates that fail under conditions where it is expected that the certificates should be passed.	Investigate the performance of the R-ITS-S security function by assessing the message failures compared to legitimate messages.	The C-ITS' message integrity function does not unduly interfere with the availability of legitimate messages (effective packet loss no greater than 10%).	ISO/IEC 27000:2018 (p.12)
Refreshment Rate	Time interval for refreshing / updating the status reports coming from a data sender.	Is defined as the time interval for refreshing / updating the signal statuses as sent by the FP to the R-ITS-S.	Investigate the time interval between successive timestamps and the 95th percentile of time intervals between consecutive messages as contained in the SPAT message.	No more than ±1% of SPAT should be > 100ms per consecutive SPAT message.	EU EIP SA 4.1: Determining Quality of European ITS Services (p.53)
Classification Correctness	Percentage of messages with erroneous information, as	Is defined as the percentage of	Investigate the number of ARLW HIGH EVENTs that	Statement of observation	EU EIP SA 4.1: Determining Quality

Criteria	Standard Definition	Proposed Definition	Analysis Method	Metric	Standard/Guidelines Referenced
	reported by a data sender, out of the total number of messages.	messages that were displayed incorrectly for ARLW and TWVR signal use cases.	were presented as a false positive to the participant. Investigate the number of TWVR HIGH EVENTs.	commenting of results based on the investigation.	of European ITS Services (p.42)
Integrity	The roadside unit (RSU) needs to protect data integrity, at rest and in transit, and detect and notify the traffic management system (TSM) of integrity losses. This ensures that the data an RSU transmits is the same as the data the RSU receives from a local field device or back-office system and that it is not corrupted or used in a way it was not intended to.	Is defined as the number of instances where the SPATEM / MAPEM has been compromised by the version number identification.	Assess occurrences where the SPATEM/MAPAM has been compromised by the version number.	The version number should match between SPATEM and MAPEM sent by the R-ITS-S.	U.S. Department of Transportation: Roadside Unit (RSU) Standard v1.0 (p.24)
Conformance	To claim "Conformance" to this standard, the manufacturer shall minimally fulfill the mandatory requirements as identified.	Is defined as the conformance to the European Standards specified by the European C-Roads and the C2C CC.	Assess the differences between the ICVP and the European C-ITS standard specifications for SPATEM and MAPEM.	Statement of observation commenting of results based on the investigation.	U.S. Department of Transportation: Roadside Unit (RSU) Standard v1.0 (p.50)

3.1 Roadside coverage

The standards define roadside coverage as, "Percentage of the road network and/or selection of road classes, where stationary, connected C-ITS stations operate." (European ITS Platform, 2020, p.32). This paper develops a new metric to fit the scope of this project, analysing the effective range of the R-ITS-S. The range of the R-ITS-S is the distance the R-ITS-S can effectively send the SPATEM/MAPEM. It is important that the R-ITS-S has a radio range that can reasonably service the V-ITS-S to allow for timely signal-based messages. The messages can be affected by line-of-sight as the messages are sent over ITS-G5 communications. The messages must be received in a timely manner by the V-ITS-S to present the relevant warning to the participant. This ensures that the participant will have enough time to react to the warning and respond accordingly. Roadside coverage is defined as needing a minimum effective range of 300m for roads with a speed limit of 60 kph, and a minimum effective range of 500m for roads with a speed limit greater than 60 kph (Automotive Requirements for SPaT and MAP, CAR 2 CAR Communication Consortium, 2020)

Metric: The R-ITS-S should have a minimum effective range of 300m from the intersection, for 60 kph roads. For roads with a speed limit greater than 60 kph the R-ITS-S should have a minimum effective range of 500m.

3.2 Availability

The standards define availability as, "Average availability for all operating connected data senders, including the communication chain up to the data receiver." (European ITS Platform, 2020, p.33). This framework will use this definition to assess the availability of the R-ITS-S and its subcomponents: the traffic controller (TC), field processor (FP), router and RSU. The availability of a R-ITS-S begins with the TC, where the TC sends basic (Boolean) logic to the FP of the intersection signal state through a serial connection. The FP then sends SPATEM via the router to the RSU through a physical connection. If any of these four components are not operational the system becomes unavailable, as the R-ITS-S will not be broadcasting messages to the V-ITS-S. It is important that the R-ITS-S is available to send messages to the V-ITS-S otherwise the ARLW and TWVR use cases will not operate. This paper defines availability as the percentage of MAPEM transmitted and SPATEM transmitted, over the expected number to be sent, respectively. These metrics will be compared against the metric outlined for the advanced quality criterion with availability greater than 99.5% (Table 4: Requirements Table for C-ITS Quality Criteria EU EIP SA 4.1: Determining Quality of European ITS Services, 2020).

Metric: The R-ITS-S should not be inactive for more than 7.2 minutes within a given day or be inactive for more than 99.5% of the pilot life.

3.3 Reliability

The standards define reliability as "Mean-Time-Between-Failure." (U.S Department of Transportation, 2021, p.127). This paper uses this definition and expands on the concept of Mean-Time-Between-Failures by defining Mean-Time-To-Repair and the total number of failures as additional metrics for reliability. Reliability is a sub-category of the ‘availability’ analysis, building on the previously stated ‘availability’ assessment criteria. This analysis will create an understanding of how often and for how long the system is unavailable, rather than a total measure of unavailability. This is an important measure to better understand the performance of the R-ITS-S, helping understand when and why a station becomes unavailable, possibly being used to find common reasons and timelines for R-ITS-S unavailability. This measure should be assessed by measuring the times in between working operation and the frequency of operational failures. These can be found through identifying when the system is inoperative, finding average times for how long it takes for the R-ITS-S to be fixed and for how long it takes before the station is operational again. These metrics will then be compared against the TMR performance requirements and specifications.

Metric: This will be a statement of observation commenting on results based on the investigation, as the reliability of the RSU may not be within the hands of TMR but rather outages may occur beyond TMR's control.

3.4 Latency

The standards define latency as, "Total time for communicating messages between (a) a timestamp at a C-ITS sender and (b) a timestamp at a C-ITS receiver." (European ITS Platform, 2020, p.35). This paper will continue with this definition through the assessment of the internal and external latency of the R-ITS-S. The internal latency is defined as the time between when the RSU receives the SPATEM message from the FP and when the RSU transmits the SPATEM message to the V-ITS-S. The external latency is defined as the time between when the R-ITS-S transmits the SPATEM message and when the V-ITS-S receives the SPATEM message and internally timestamps the message as received. The communication speed between the R-ITS-S and the V-ITS-S is the speed of light but the timestamp of the message can otherwise be bottlenecked by the internal processes of each respective station. Latency is important to assess as it can be a defining factor in forming a timely message or untimely message. The internal latency will build a picture of how long the internal processes of the RSU take, possibly being affected by other computational factors. The external latency will build a picture of how internal processes may affect the task priority of the V-ITS-S. Latency can be measured by finding the difference between the respective timestamps for internal and external latencies, where there is a common reference clock between the two timestamps. These metrics can then be compared against the TMR performance requirements and specifications.

Metric: Timeslip should not exceed 150ms, internal latency should not exceed 100ms, external latency should not exceed 300ms.

3.5 Usability

The standards define usability as, "Mapping accuracy shall be within 0.5m from the centre of lane. The accuracy is a measurement of the perpendicular distance from the node to the centre of the lane." (Vehicle-to-Infrastructure Consortium: SPaT Challenge, p.18). For this paper, the definition will be altered to assess the usability of the MAPEM files sent by the R-ITS-S. The MAPEM file is what the V-ITS-S uses to define the boundaries of the conflict zone of the intersection. It is also used to define what lane the vehicle is in, assigning the vehicle to a signal group for the SPATEM. If the MAPEM files are incorrect, the participant will receive an incorrect or untimely presented message for the real-time traffic conditions of an intersection. Currently, the MAPEM files are manually created through a geospatial program. This analysis seeks to assess how accurate the manually generated MAPEM files are against normalised vehicle trajectory data. If vehicles are frequently stopping past the stop bar or vehicles are positioned on the edges of the defined lanes, it is likely that the MAPEM files are marginally incorrect. This criterion will be judged against the requirement by V2I Consortium as supported by the U.S. Department of Transportation, "The accuracy for the map shall be within 0.5 m." (Vehicle to Infrastructure Consortium – SPaT Challenge, 2017, p.18)

Metric: The accuracy of the MAPEM should be within 0.5m.

3.6 Security

The standards define security as, "[The] preservation of confidentiality (that information is not made available or disclosed to unauthorized individuals, entities, or processes), integrity (accuracy and completeness) and availability (accessible and usable on demand by an authorized entity) of information." (ISO/IEC 27000:2018, 2018, p. 12). This paper will expand the analysis of system security by investigating certificate operations. Using the following definition as the reference for analysis, "the percent of security certificates that fail under conditions where it is expected that the certificates should be passed."

ICVP uses certificates to validate the legitimacy of messages sent/received by ITS stations, through a public and private key authentication process. The system becomes unavailable when the security fails under scenarios where it is expected that the system would otherwise accept the provided certificates. If the security process fails, the message will be ignored, and the respective C-ITS station will then need to wait until it receives the next validated message to continue with the C-ITS use case. Therefore, it is important for the MAPEM/SPATEM to properly pass security checks to reduce unnecessary latency in the system and to ensure messages are received in a timely manner. To assess security, the percentage of failed security certificates that should have passed will be found. This should be done by filtering out failed certificates because the station is out of range (or on the edge of the range of the system) from each other and by filtering out the first second of inter-station communications to eliminate the "sec-fail" flag (where the first message between ITS fails security as the stations are exchanging public keys). These metrics can then be compared against the TMR performance requirements and specifications.

Metric: There are no real defined requirements for security processes, but the security of the system should not impact the signal use cases. Therefore, the security certifications should not reduce the effective range of the R-ITS-S below the roadside coverage requirements. This is maintained by ensuring the security certificates do not increase the packet loss between R-ITS-S and V-ITS-S communication to greater than 10% (90% of packets received by a V-ITS-S should pass security certification within the effective R-ITS-S range).

3.7 Refreshment Rate

The standard defines refreshment rate as, "Time interval for refreshing / updating the status reports coming from a data sender." (European ITS Platform, 2020, p.53). This project will analyse the refreshment rate of SPATEM messages sent between the FP and R-ITS-S, updating the R-ITS-S with SPATEM information based on the TC status. The FP updates the signal status once every 500ms, with the R-ITS-S interpreting the status every 100ms. The metric will measure the frequency of R-ITS-S updates and signal state information every 100ms. It will also look at the delay recorded between the FP and the R-ITS-S. This will gauge the relevant SPATEM information being transmitted by the R-ITS-S. As per the TMR requirements, the R-ITS-S should update SPATEM messages every 100ms, and the delay between the FP and the R-ITS-S should not exceed 30ms.

Metric: Refreshment rate should have a count of 10 per second (100ms per message) and the delay between FP and V-ITS-S should not be greater than 30ms.

3.8 Classification Correctness

The standard defines classification correctness as, "Percentage of messages with erroneous information, as reported by a data sender, out of the total number of messages." (European ITS Platform, 2020, p.42). This project will assess the classification correctness of the ARLW and TWVR events as presented by the V-ITS-S. This measure is slightly outside of the original scope of the project as it is not directly measuring the performance of the R-ITS-S but is rather commenting on the incorrect presentation of the ARLW/TWVR messages to the participant. Under certain shared lane scenarios, where a single lane has both a through movement and a turning movement, the V-ITS-S can present a false positive warning to participants. This occurs when the through movement is red, but the turning movement is green for the single shared lane. For the ICVP the V-ITS-S are not equipped with the capability to know for certain what movement a V-ITS-S will make during a shared lane scenario. Therefore, it assumes that the participant will always take the through movement by design. This causes the V-ITS-S to present the participant with a warning indicating the driver has entered the intersection conflict zone incorrectly when the participant can turn through the green turning movement. Although the system is working as expected, this form of classification correctness still causes an impact on the participant and could have a negative impact on system safety.

These metrics will then be compared against the TMR performance requirements and specifications, with consideration that the system cannot currently predict the movements of the vehicle without the addition of machine learning trajectory prediction or the implementation of the V-ITS-S recording the vehicles indicator state and reacting accordingly.

Metric: This will be a statement of observation based on the investigation. This criterion will be assessed within reason and with reasonable justification.

3.9 Integrity

The standard defines integrity as, "The RSU needs to protect data integrity, at rest and in transit, and detect and notify the TMS (RSU management) of integrity losses. This ensures that the data an RSU transmits is the same as the data the RSU receives from a local field device or back-office system and that it is not corrupted or used in a way it was not intended to." (U.S Department of Transportation, 2021, p.42). This definition will be slightly altered to assess if the messages sent out by the R-ITS-S have been compromised by mismatched message version numbers. When the MAPEM or SPATEM version is updated the version number of each message must be incremented together regardless of which message has been updated. If either message has a differing version number, the V-ITS-S should not accept the message as it should be considered that one of the messages is of an outdated version number. Although during the ICVP, mismatched version numbers are still accepted by the V-ITS-S and used. This may comprise the integrity of the system (as the V-ITS-S does not check the version number of the messages but just records the version number of the messages). Therefore, it should be assessed if the MAPEM/SPATEM messages have been compromised by the version mismatch under this definition and do the compromises have a profound impact on the operation of the system.

Metric: SPATEM and MAPEM should consistently have the same version number, the version number should not mismatch.

3.10 Conformance

The standard defines conformance as, "To claim 'Conformance' to this standard, the manufacturer shall minimally fulfill the mandatory requirements as identified." (U.S Department of Transportation, 2021, p.50). This is a U.S. standard definition and the definition itself will be used to analyse the conformance of the ICVP against the European standards (European C-Roads and the C2C CC). It must be noted that for this criterion the project will only be compared to the European Standards. It must also be considered that the documents that the ICVP are to be measured against were created after the inception of the CAVI ICVP. Therefore, it is expected that there will be variation between ICVP operations. With these considerations in mind, comparisons will be made against the conformance of the ICVP C-ITS system against the European C-ITS network. The European standards that the ICVP will be assessed against are the Automotive Requirements for SPaT and MAP as written by the Car 2 Car Communication Consortium and the European handbook for MAPEM and SPATEM creation as written by C-ROADS.

Metric: This will be a statement of observation commenting on results based on the investigation. This criterion will be assessed within reason and with reasonable justification with the inclusion of whether the variance between systems impacts safety.

4. Discussion

The framework proposed by this paper has created a template for future research projects to use as a measure to assess the performance of future C-ITS pilots and projects based within Australia. The bespoke criteria were directly developed for the ICVP context.

As this paper only proposes a framework for the assessment of the performance of the R-ITS-S, more research should be completed in the future to also create frameworks for the assessment of the C-ITS-F and the V-ITS-S. As this technology continues to develop, all components of the system should be scrutinized to ensure the mature development of C-ITS. When creating such frameworks, it should be considered that C-ITS technologies are complex and intricate systems with many factors that may affect the 'availability' be beyond reasonable control.

Although this research only considers the design of two out of the six use cases and the utilisation of one of the three major components. This leaves a gap of knowledge for future works to create similar frameworks for the assessment of the cellular use cases (IVS, RWW, RHW, BoQ). Through the analysis of C-ITS technologies and the development of C-ITS technologies, road transport authorities will confidently be able to support the deployment of C-ITS across public roads. Ensuring that the end users' safety is not compromised by the system.

This framework could be turned into a tool or set of dashboards that could output results based on input data. The framework could also be used to assist future development and deployments for both interoperability, performance and harmonisation against standards. This could be plug tests, pilots, OEM testing or government deployment.

5. Conclusion

With the rapid growth of C-ITS technologies, there is a responsibility to ensure that the equipment is deployed and operates in a mature, reliable and safe manner enabling its use by the public. This is only achieved through a continual improvement mindset with the critical evaluation of current and future works, with recommendations and lessons iterating to improve ongoing pilots/projects, of which this performance framework can start to facilitate. This leads to the mature and holistic development of technologies endorsed by the governing jurisdictions. To ensure the proper development of such C-ITS technologies governing bodies must ensure that more assessment criteria, such as the one presented in this paper, are created. These performance requirements must be scrutinised before the safety of the public is compromised by poorly available and unreliable systems. If the systems are left to be immature and undeveloped the end-users may suffer rather than benefiting from the development of C-ITS technologies.

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Appendix

Table 3 List of abbreviations

	Expansion	Definition
ARLW	Advanced Red-Light Warning	The C-ITS use case for red light warnings.
ANCAP	Australasian New Car Assessment Program	An assessment program for crash testing new vehicles to be sold in Australia.
AV	Autonomous Vehicle	A 'self-driving' vehicle, with little to no human input depending on the level of autonomy.
BoQ	Back of Queue	The C-ITS warning for drivers approaching congestion on a high-speed road.
CAVI	Cooperative and Automated Vehicle Initiative	The TMR team running the ICVP.
C-ITS	Cooperative Intelligent Transport System	The cooperative vehicle technologies being tested by the ICVP.
C-ITS-F	Central Intelligent Transport System Facility	The Central Station used as a base of communications for many applications of C-ITS.
DENM	Decentralised Environmental Notification Message	The message type with vehicle traces for BoQ, RWW, RHW use cases.
FP	Field Processor	The field processor interprets and transforms the TC messages.
G5	G5 Network (AKA DSRC – Dedicated short range communications)	The 5.9 GHz Wi-Fi communication system which the V-ITS-S and R-ITS-S use to communicate.

	Expansion	Definition
ICVP	Ipswich Connected Vehicle Pilot	The C-ITS pilot TMR is running in Ipswich.
ITS	Intelligent Transport System	The industry that C-ITS falls under.
IVS	In Vehicle Speed	The in-vehicle speed use case.
MAPEM	Map Extended Message	The message type sent from the R-ITS-S that carries the intersection geometry.
RHW	Road Hazard Warning	The C-ITS warning for drivers approaching a hazard on a road on a high-speed road.
R-ITS-S	Roadside Intelligent Transport System Station	The roadside station attached to the intersection. Also known as the RSU.
RSU	Roadside Unit	The roadside station attached to the intersection. Also known as the R-ITS-S.
RWW	Road Work Warning	The road work warning C-ITS use case.
SPATEM	Signal Phase and Timing Extended Message	The message type sent from the R-ITS-S that carries the signal phasing information.
TC	Traffic Controller	The signalized intersections traffic controller.
TMR	Queensland Department of Transport and Main Roads	The body for which this research is conducted by and the orchestrators of the CAVI ICVP.
TWVR	Turning Warning Vulnerable Road user	The C-ITS use case for pedestrian warning when a vehicle is turning at a signalised intersection.
V2I	Vehicle to Infrastructure	Communications between a C-ITS vehicle and C-ITS infrastructure.
V2V	Vehicle to Vehicle	Communications between C-ITS vehicles.
V-ITS-S	Vehicle Intelligent Transport System Station	The vehicle station attached to the participants vehicle which receives and displays the C-ITS messages.