FIRST STEPS TOWARDS VEHICLE-TO-INFRASTRUCTURE IMPLEMENTATION IN SOUTH AFRICA: A STELLENBOSCH CASE STUDY

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ABSTRACT

This research presents the implementation and evaluation of South Africa's first Vehicle-to-Infrastructure (V2I) communication system. As a proof-of-concept, the study aimed to demonstrate the feasibility of adapting a well-established Right-Hand traffic (RHT) V2I system to local Left-Hand Traffic (LHT) conditions to address congestion, intersection safety, and environmental concerns. The implementation involved developing detailed Intersection Topologies and Virtual Controllers to support real-time traffic signal communication through MAP and SPaT messages. The implemented system integrated two V2I functionalities: Red-Light Countdowns and Green Light Optimal Speed Advisories (GLOSA). Summative evaluations were conducted through test drives, to confirm the system's accuracy and reliability, while outcome evaluations using microscopic traffic simulations assessed its broader impact on traffic and emissions. Results indicated that V2I communication improves vehicle delays, reduces vehicle stops, and enhances traffic flow, particularly under lower congestion levels. The findings demonstrate the feasibility of V2I adoption in South Africa, highlighting its potential to improve urban mobility and support sustainable transport solutions.

Keywords: Vehicle-to-Infrastructure (V2I), GLOSA, Red-Light Countdowns, Virtual Controllers, Intersection Topologies, MAP messages, SPaT messages.

1. INTRODUCTION

1.1 Problem Statement

South Africa's existing transport system currently faces major challenges that need to be addressed to improve the mobility and safety for road users. The 2023 INRIX Global Traffic Survey ranked Cape Town 9th and Johannesburg 26th among the world's most congested cities (Pishue, 2024). Congestion further exacerbates environmental concerns by increasing greenhouse gas (GHG) emissions and fuel consumption (Oladunni et al., 2022). Additionally, intersections in South Africa often become hotspots for crime, particularly hijackings and smash-and-grab incidents, with a 44% rise in hijackings recorded between 2018 and 2022 (BusinessTech, 2023).

1.2 Research Design

This proof-of-concept study explores a potential solution to the highlighted issues through a cutting-edge technology known as Vehicle-to-Infrastructure (V2I) communication. V2I technology enables vehicles to exchange real-time data with roadside infrastructure, such as traffic signals (Arena & Pau, 2019). Often integrated into Connected Autonomous Vehicles (CAVs), this communication technology enhances decision-making by providing pre-emptive traffic signal information.

This novel research project marks a significant milestone as it implements a well-established Right-Hand Traffic (RHT) V2I system in South Africa's Left-Hand Traffic (LHT) conditions; making it the first V2I deployment in Africa. This study was facilitated through collaboration with Traffic Technology Services (TTS), a German V2I Service Provider. Internationally, TTS has already successfully deployed this V2I system in various RHT environments, including the United States of America (USA), Germany, and China.

Once implemented, the system's effectiveness was assessed through two evaluation method: 1) the summative evaluation, which assessed the accuracy and reliability of the implemented V2I system in real-world conditions, and 2) the outcome evaluation, which used traffic simulations to analyse the impact of the V2I system on traffic flow, fuel consumption, and emissions.

The implemented V2I system encompasses two key functionalities: Red-Light Countdown, which provides precise timing for signal changes to enhance driver predictability, and Green Light Optimised Speed Advisory (GLOSA), which recommends optimal driving speeds to minimise stops and maximise throughput at intersections.

1.3 Study Area

Merriman Avenue in Stellenbosch, Western Cape, served as the study area for this investigation. As shown in Figure 1, the V2I system was implemented and simulated at four signalised intersections along Merriman Avenue: Bosman Street, Ryneveld Street, Andringa Street, and Bird Street. This corridor provided a controlled environment to evaluate the technology's effectiveness in the real-world.

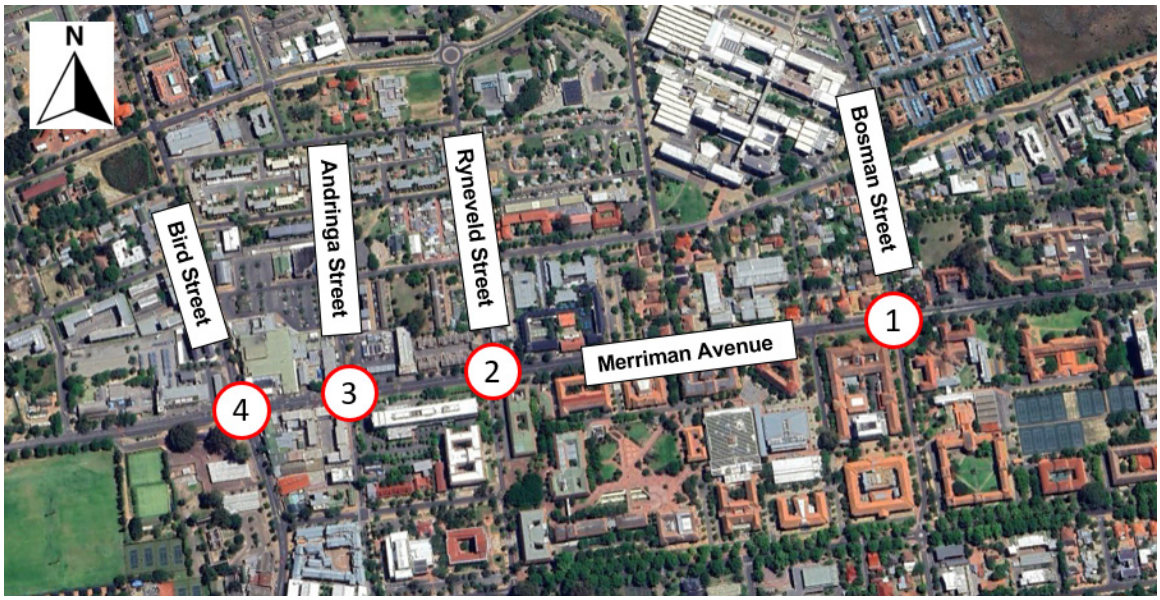

Figure 1: Study area

2. SYSTEM IMPLEMENTATION

The implementation process involved developing Intersection Topologies, setting up Virtual Controllers, and integrating the system's components to facilitate operations. The five main system components were the 1) Intersection Topologies, 2) Virtual Controllers, 3) Centralised Prediction System, 4) SAEJ2735 Messages, and 5) User App.

2.1 Developing Intersection Topologies

The first step was creating detailed Intersection Topologies for each signalised intersection. These Intersection Topologies functioned as digital maps, incorporating critical information such as intersection geometries, dimensions, lane configurations, and permitted vehicle movements. Additionally, each movement was linked to its corresponding signal phase. These digital maps also served as geofences, enabling the system to detect approaching vehicles and correctly associate their position with the relevant signal phase. The geofences were specifically defined for each approaching lane towards an intersection and, as such, there was no overlap between adjacent intersections. To develop these topologies, Google Earth Pro was used to map intersection geometries, while traffic signal timing plans from each intersection's controller provided the essential phasing data.

2.2 Setting Up Virtual Controllers

Virtual Controllers needed to be designed and calibrated to function as digital twins to the in-field traffic signal controllers. Developed specifically for this study, this component precisely replicated the signal timing and phasing logic of each in-field controller, providing a real-time digital representation of existing traffic signal operations. By mirroring the behaviour of in-field controllers, these Virtual Controllers enabled the system to predict upcoming signal changes with precision.

The V2I system was implemented exclusively on fixed-time controllers. Therefore, the signal timing plans provided a reliable basis for establishing the exact predetermined cycle second of each phase transition. This information was instrumental in configuring and calibrating the Virtual Controllers, allowing seamless integration of the V2I system with the existing traffic signal operations.

2.3 System Component Integration

Once the Intersection Topologies and Virtual Controllers were developed and calibrated, these components could be integrated into the Centralised Prediction System. The Centralised Prediction System, developed by TTS, served as the core processing unit of the V2I system. As a cloud-based software component, it was responsible for aggregating data from the Intersection Topologies and Virtual Controllers and applying advanced algorithms to generate standardised SAE J2735 messages. Additionally, the Centralised Prediction System detected when a vehicle entered the geofenced area and identified its designated lane. It then determined the allowed movement for that lane and linked it to the corresponding signal phase. This ensured that vehicles received precise and contextually relevant information via SAE J2735 Messages.

The SAE2735 Messages generated by the Centralised Prediction System used standardised data formats designed specifically for V2I communication. For this case study, two key message types were utilised: MAP messages and Signal Phase and Timing (SPaT) messages.

MAP messages provided detailed intersection geometry information, including the exact layout, lane configurations, and permitted movements. These messages were derived from the developed Intersection Topologies. SPaT messages, on the other hand, conveyed the real-time traffic signal status for each lane or movement within an intersection. SPaT messages included information on whether a traffic signal was red, green or amber along with precise timing details indicating the duration of the current

phase before transitioning. These SpaT messages were derived from Virtual Controllers. Once generated, the Centralised Prediction system relayed these messages to the User App installed into the vehicle.

The final component of the V2I system was the User App. Firstly, the User App collected the vehicle's location data and transmitted it to the Centralised Prediction System, ensuring accurate detection and positioning within the intersection environment. Simultaneously, it received and interpreted SAE J2735 message data. Existing cellular networks (5G) were used to relay information between the User App and the Centralised Prediction System. By combining received data with the vehicle's location, the User App performed complex calculations to facilitate the Red-Light Countdown and GLOSA functionalities through a user-friendly interface. For the GLOSA functionality, the remaining green time and the vehicle's location data were utilised to calculate an optimal speed recommendation for the driver. Additionally, when a signal was red, the remaining time was displayed as a countdown, allowing drivers to anticipate phase changes. For this study, a mobile application developed by TTS was used as the User App component for the system.

Figure 2 shows the concept of operations for the V2I communication system. Through real-time data integration and communication between components, the system accurately relayed signal timings and speed recommendations to approaching vehicles. This seamless exchange of information enabled the Red-Light Countdown and GLOSA functionalities, enhancing driver awareness and traffic efficiency.

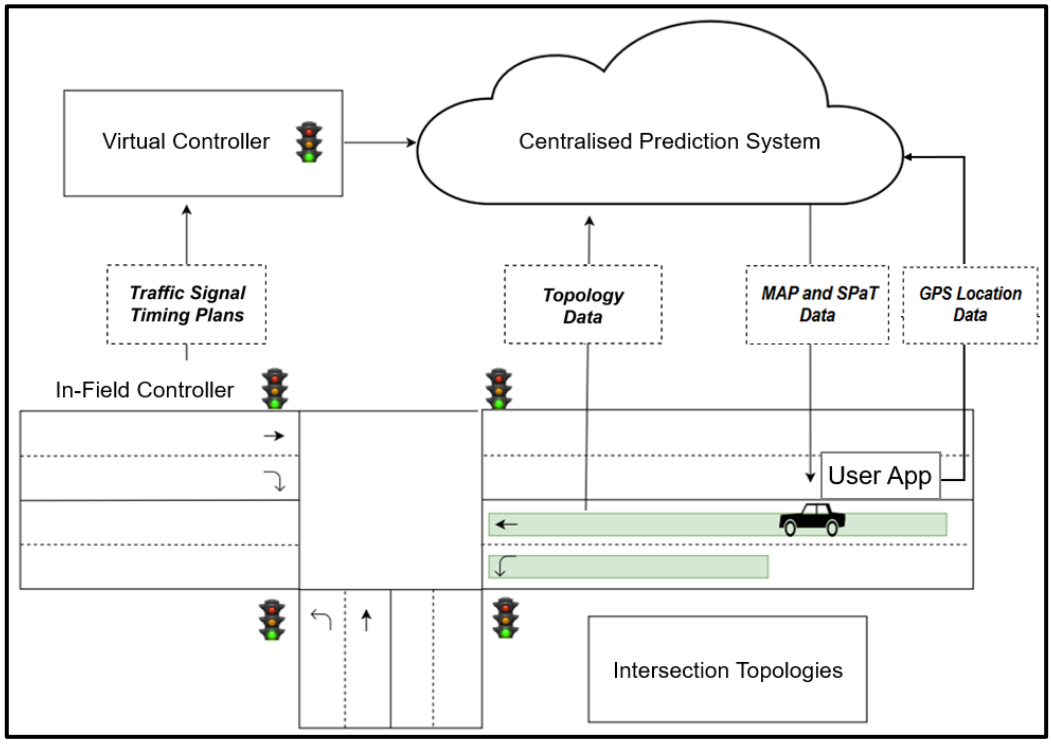

Figure 2: Concept of operations

3. SUMMATIVE EVALUATION

Once implemented, the system's performance was assessed through a series of rigorous test drives to ensure its accuracy and reliability. The summative evaluation confirmed that the system was correctly implemented, met all requirements, achieved its intended

outcomes, and complied with standards necessary for widespread deployment and public use. These evaluations were conducted in two distinct phases.

3.1 Phase One Methodology

This phase focused on assessing the Red-Light Countdown functionality at individual intersections. The primary objective of this phase was to evaluate the system's ability to provide accurate and reliable phasing information to the driver. Additionally, this phase aimed to determine whether the system met key performance requirements that could be quantitatively measured.

To conduct this evaluation, the Red-Light Countdown functionality was activated in the User App before the test drive. The test drives were structured to ensure a comprehensive analysis of system accuracy across different intersections and time periods. Two valid test drives were conducted per intersection for every weekday, covering both the morning and afternoon peak periods. Each test drive required the vehicle to approach the intersection from all four directions, allowing for the collection of complete data across all signal phases.

A key system requirement assessed in this phase was the detection accuracy of the V2I system when the vehicle entered a georeferenced area. Once detected, the User App was expected to display the intersection name, phase numbers (P4, P2, P3), allowed movements, confidence percentages (C98%), and countdown timings (in seconds) as shown in Figure 3. During the test drives, observations were made to confirm that the User App accurately identified the upcoming intersection and correctly displayed the allowed movements and the corresponding phase number for those movements.

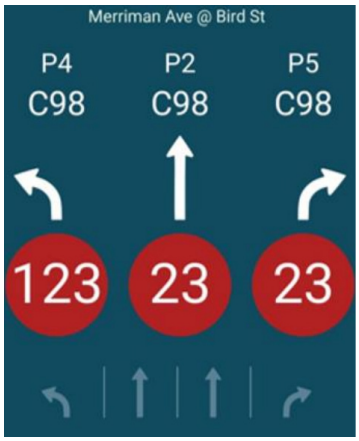

Figure 3: V2I User App Red-Light Countdown display

One of the primary aspects under evaluation was the Red-Light Countdown functionality, which was designed to relay the precise timing of signal phase transitions to the driver. The accuracy of this functionality was assessed by comparing the displayed User App's countdowns with the actual signal changes from the in-field controllers. Any discrepancies between the in-field controllers and the user application countdown were recorded and analysed.

3.2 Test Drive Phase One Results

The summative evaluation of the implemented V2I system's Red-Light Countdown functionality was conducted through extensive test drives to assess its detection accuracy, intersection identification capabilities, and timing discrepancies.

A total of 322 valid observations were recorded across all phase one test drives. The system successfully detected the testing vehicle in 315 out of the 322 cases, resulting in an overall detection accuracy of 97.8%. These results indicate that the geofencing-based detection system performed reliably across the four intersections since approaching vehicles were consistently identified within the designated detection zones. The seven undetected instances could have been due to intermittent cellular connectivity or cases where the vehicle did not fully cross into the designated geofence.

Beyond vehicle detection, the system's ability to correctly identify the upcoming intersection, determine the allowed movements, and display the corresponding signal phase was evaluated. The system correctly identified the intersection approach directions and the associated phase number in 100% of observations. The User App also perfectly relayed the expected phase information, displaying the correct phase number alongside the allowed movements for all observations. Furthermore, the confidence percentage for all displayed predictions averaged 98%, confirming that the system maintained high prediction reliability. The observed high confidence levels reflect the system's capability to provide real-time signal phase data with minimal uncertainty. These results demonstrate that the V2I system's Virtual Controllers effectively replicated in-field traffic signal behaviour, ensuring reliable data.

While the system demonstrated a high degree of accuracy in detection and intersection identification, some timing discrepancies were observed between the Red-Light Countdown displayed on the User App and the actual phase transitions of the in-field controllers. For this study, there was an average network-wide discrepancy was 0.75 seconds, with 80.3% of all observations falling within a deviation of one second or less. Among the tested intersections, the Merriman/Andringa intersection exhibited the most precise countdowns, with an average discrepancy of just 0.14 seconds. This indicates that the system was almost perfectly synchronised with this specific intersection. The Merriman/Bosman intersection recorded the highest deviations, with an average discrepancy of 1.04 seconds. Table 1 shows the average time discrepancy observed for each intersection.

Table 1: Average Red-Light Countdown discrepancies per intersection

Intersection	Unit	Average Time Discrepancy
Merriman/Andringa	s	0.14
Merriman/Bird	s	0.84
Merriman/Reyneveld	s	0.96
Merriman/Bosman	s	1.04
Combined Study Area	**s**	**0.75**

These discrepancies can be attributed to slight inconsistencies in how each intersection's fixed-time controller was synchronised with the Virtual Controllers. Despite these discrepancies, the system's overall performance indicates that it can reliably provide drivers with real-time signal timing information, enhancing anticipation of phase changes.

The observed discrepancies, though minor, highlight areas for future refinement. This could include access to real-time signal controller processing data that would allow the Virtual controllers to synchronise automatically with in-field controllers and, as such, reduce the discrepancies.

The findings from Phase One confirm the system's feasibility for real-world application, demonstrating that Red-Light Countdown functionality can be effectively integrated into South Africa's traffic infrastructure with only minimal adjustments needed to further enhance accuracy.

3.3 Phase Two Methodology

The second phase focused on the GLOSA functionality. This phase adopted a qualitative approach to assessing whether the recommended speeds led to safe, comfortable, and effective outcomes when traversing multiple adjacent intersections. The primary objective was to evaluate how effectively the V2I system could guide vehicles through intersections by providing optimal speed recommendations. Before each phase two test drive, the GLOSA functionality was activated in the User App, and the testing vehicle strictly adhered to the suggested speeds. While phase one focused on individual intersections, phase two expanded to a corridor-level analysis along Merriman Avenue, where the four adjacent intersections were evaluated for the eastbound and westbound traffic directions.

During the phase two test drives, the vehicle encountered a specific GLOSA event for every approach to an intersection based on the signal status. Each of the five possible events (G1, G2, R1, R2 or R3) were associated with an expected outcome as detailed in Figure 4. The recommended speed referred to in Figure 4 was estimated by the system using the time remaining to the next signal change and the distance to the intersection. For every test drive, it was verified whether following the speed recommendation resulted in the intended outcome based on the event encountered.

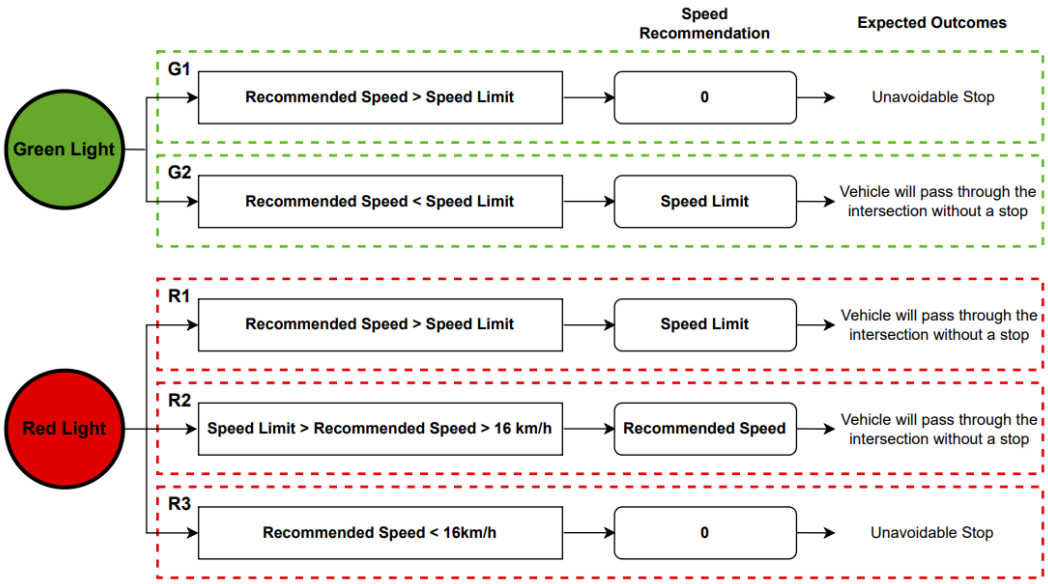

Figure 4: GLOSA events and their expected outcomes

The level of safety was also documented for each phase two test drive and classified as either "Safe" or "Unsafe". A safe event was defined as a scenario where the testing vehicle could either traverse the intersection or come to a stop without any risk. An unsafe event was identified as a scenario where the recommended speeds resulted in any form of risk, such as entering an intersection on a red or amber light. The level of safety classification also considered the practicality of referring to the User App while driving. Specifically, any instance where interacting with the User App detracted from the driving task or posed a potential distraction.

In addition to safety, the driver's perceived comfort was evaluated. Events were classified as "Comfortable", where the recommended speed was easy to follow and provided a smooth driving experience; "Neutral", where the GLOSA functionality had little impact on driving behaviour; or "Uncomfortable", where achieving and maintaining the suggested speed felt difficult or introduced risk. This assessment provided insight into the system's usability.

Finally, system latency was assessed to evaluate the responsiveness of the system's real-time data transmission. The User App generated a prediction request every second while the vehicle remained within the georeferenced area. Latency was measured as the time difference between the request and response, representing the round-trip delay of data between the User App and the Centralised Prediction System. Latency data was collected for each test drive to check that speed recommendations were delivered promptly.

By analysing usability, safety, comfort, and latency, phase two provided a detailed assessment of the GLOSA functionality's real-world applicability. These test drives were critical in determining whether the system could effectively support smoother and safer traffic flow in mixed-traffic environments.

3.4 Test Drive Phase Two Results

The summative evaluation of the implemented V2I system's Red-Light Countdown functionality was conducted through extensive test drives to assess its usability, safety, comfort, and latency.

3.4.1 GLOSA Events and Outcomes

The initial focus was to evaluate whether the recommended speeds from the User App consistently resulted in the anticipated outcomes for all five of the possible GLOSA events. Figure 5 presents the percentage of each GLOSA event encountered during the test drives.

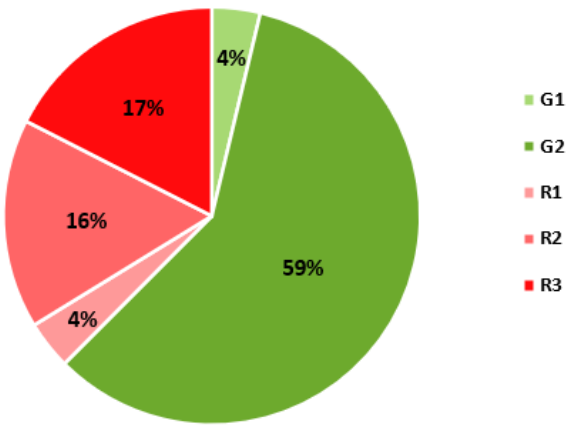

Figure 5: Percentage of GLOSA events encountered

Among the 80 recorded observations, three instances (4%) were classified as G1 events. In these cases, the signal was green at the time of detection, but the vehicle was unable to safely pass through the intersection before the signal turned red. All three G1 events resulted in the expected outcome, achieving 100% accuracy.

The most frequently encountered event type was G2, accounting for 47 of the 80 observations (59%). These events occurred when the signal was green, and the vehicle could safely pass through the intersection while maintaining the speed limit. The system

demonstrated 91.5% accuracy for G2 events, with only four deviations from the expected outcome. In two instances, the User App recommended a travel speed of 60 km/h, but the vehicle entered the intersection just as the signal turned amber. On two other occasions, the vehicle arrived at the intersection as the all-red phase began. These deviations suggest that while the system was generally effective in guiding the vehicle through intersections without requiring unnecessary stops, slight timing refinements might further improve performance.

A total of three R1 events (4%) were recorded. In these cases, the signal was red at the time of detection, but the recommended speed allowed the vehicle to arrive precisely as the signal changed to green, enabling a continuous, uninterrupted movement through the intersection. All three R1 events resulted in the expected outcome, achieving 100% accuracy.

Thirteen R2 events (16%) were observed. These events occurred when the signal was red, but the vehicle was expected to avoid stopping by following the recommended speed, which ranged from 16 to 60 km/h depending on the time remaining before the signal turned green. The system avoided a stop in 11 out of 13 cases (84.6%). In the two cases where a stop was required, the cause was unrelated to system inaccuracies; rather, it was due to queue buildup at the intersection preventing the vehicle from proceeding as anticipated. Excluding these external factors, the system achieved 100% accuracy in predicting the correct outcome for R2 events.

Lastly, 14 of the 80 observations (17%) were classified as R3 events. These events occurred when the signal was red, and a stop was unavoidable, meaning that the GLOSA functionality did not influence the driver's behaviour. As expected, all 14 R3 events resulted in the anticipated outcome, yielding a 100% success rate. The high accuracy across R3 events confirms that the system correctly recognised situations where no speed adjustment was possible.

The combined analysis of all 80 observations demonstrated that the User App's speed recommendations resulted in the expected outcomes in 76 cases, achieving an overall accuracy rate of 95%. The four unexpected deviations observed for G2 events might be attributed to a combination of factors, including system latency, minor calibration offsets in the virtual controllers, GPS inaccuracies, or slight deviations in the testing vehicle's speed during execution. To mitigate these discrepancies, the precision of the virtual controllers could be improved through more rigorous calibration.

3.4.2 Safety and Comfort

The following aspect evaluated was the perceived level of safety and comfort experienced during the test drives. In terms of safety, only four out of the 80 observations (5%) were classified as unsafe, all of which occurred when the testing vehicle entered the intersection during the amber or all-red phases (previously identified as deviations within the G2 event category). These were the only instances in the study where a potential safety risk was recorded and, importantly, none of these events were attributed to driver distraction or difficulty in interacting with the User App. Overall, the system demonstrated a high level of reliability, with 95% of all observations classified as safe. This confirms that the GLOSA functionality effectively aligned with safe driving behaviour.

In terms of driver comfort, the system's speed recommendations were generally well-received. Out of 80 observations, 53 (66%) were classified as comfortable, indicating that the recommended speeds were easy to follow and provided a smooth driving experience. Another 18 observations (23%) were categorised as neutral, primarily

occurring during G1 and R3 events where the system had little to no influence on driving behaviour due to an unavoidable stop. Nine observations (11%) were considered uncomfortable. Four of these were linked to previously mentioned unsafe events where vehicles entered the intersection at an undesirable moment. The remaining five occurred during G2 events, where the system recommended a low speed of 20 km/h, which was impractical in faster-moving traffic.

3.4.2.1 System Latency

The final aspect evaluated during the phase two test drives was the system latency. For the combined test drives, an average latency of 582 milliseconds was recorded. The highest observed latency occurred during the Thursday AM test drives, reaching 914 milliseconds. These results indicate a significantly higher average latency compared to the system's performance in Europe and the USA, where the service provider reports an average latency of less than 100 milliseconds. This suggests that the system's responsiveness under South African conditions is notably slower than in its established regions in the northern hemisphere. The larger latencies observed could be attributed to cellular network-related factors, as the requests and responses from the mobile User App must pass through multiple network hubs, potentially introducing delays.

The findings from phase two demonstrate that the system provided accurate and reliable speed recommendations while maintaining a high level of safety and comfort. Although latency was higher than expected, the system remained effective, again highlighting the feasibility of V2I technology as a potential solution for South Africa.

4. OUTCOME EVALUATION

4.1 Methodology

The outcome evaluation for this study examines the impact of the implemented V2I system on overall traffic conditions and environmental factors through microscopic traffic simulations in PTV Vissim. By modeling various scenarios, the evaluation provides insights into how V2I functionalities influence traffic efficiency and sustainability under different operating conditions.

To accurately simulate the V2I system under local conditions, a microscopic traffic model of the study area was developed in PTV Vissim. This process began with extracting the relevant study section from a previously developed macroscopic model of Stellenbosch in PTV Visum. Once imported into PTV Vissim, the model underwent a comprehensive calibration process to ensure alignment with real-world traffic conditions. This included integrating existing signal phasing data, adjusting traffic volumes based on AM peak conditions (07:00-08:00), and refining vehicle driving behaviour. Additionally, specific modifications were made to accurately represent the interactions associated with the Red-Light Countdown and GLOSA functionalities within the virtual testing environment.

To understand how the V2I functionalities influenced traffic conditions, the following attributes were assessed: 1) average delays per vehicle in seconds, which represents additional time a vehicle spends traveling through a road segment or intersection compared to the time it would take under free flow conditions; 2) queue lengths in meters; 3) vehicle stops; 4) fuel consumption measured in grams; and 5) GHG emissions in grams, specifically carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_x). For the simulations, it was assumed that the drivers would respond instantly and accurately to the User App's recommendations.

The V2I system was also simulated under varying penetration rates to evaluate its impact on overall traffic conditions. This investigation focused on the progressive introduction of V2I-equipped vehicles, assessing how increasing adoption influenced the aforementioned traffic attributes. Six primary scenarios were examined, beginning with a baseline condition of 0% penetration and increasing incrementally by 20% for each subsequent scenario. By comparing these scenarios, the study aimed to identify the penetration rate at which V2I functionalities yielded the most significant improvements, as well as to quantify the benefits associated with each level of adoption.

During the simulations, it became evident that two of the intersections experienced severe congestion due to the high input volumes associated with the AM peak. As a result, the benefits of V2I were less pronounced at these locations compared to the other two intersections with lower congestion levels. To further explore this effect, an additional scenario was introduced at the Merriman/Andringa intersection, where traffic volumes were reduced by 20% to represent an off-peak scenario. This adjustment allowed for an assessment of whether V2I benefits become more prominent in uncongested environments, providing deeper insight into the conditions under which V2I technology is most effective. To investigate this effect, the previously obtained AM peak results at 0% and 100% V2I penetration were used as a baseline. The off-peak period was then simulated at the same penetration levels, and the changes in key attributes between 0% and 100% were documented. Finally, the differences observed in the AM peak were compared to those in the off-peak to determine whether V2I provided greater benefits under lower congestion conditions.

4.2 Simulation Results

The simulation results revealed distinct trends among the evaluated intersections. Firstly, the Merriman/Andringa and Merriman/Bird intersections exhibited minimal improvements across all V2I penetration rates, with traffic patterns remaining largely unchanged as shown in Table 2. This outcome could be attributed to the high congestion levels observed at these intersections, which limit the effectiveness of V2I functionalities. High traffic volumes restrict the ability of vehicles to adjust their speeds in response to GLOSA recommendations or take advantage of Red-Light Countdowns, as movement is constrained by preceding vehicles.

In contrast, the Merriman/Reyneveld and Merriman/Bosman intersections demonstrated substantial benefits from V2I integration as shown in Table 2. Both these intersections showed similar trends. As the V2I penetration rates increased, reductions in critical performance metrics (i.e. vehicle delays, queue lengths, number of stops, fuel consumption, and emissions) became more pronounced. The most significant improvements were observed at a 100% V2I penetration rate, where all investigated attributes experienced their greatest reductions.

The Merriman/Reyneveld intersection demonstrated the most promising benefits, with notable reductions in key performance metrics as shown in Table 2. At 100% V2I penetration, average vehicle delays decreased by 62.6% as the GLOSA functionality enabled vehicles to pass through the intersection efficiently, while the Red-Light Countdowns improved driver anticipation and reduced startup delays. Furthermore, the average number of vehicle stops was reduced by up to 60%, as speed recommendations helped drivers avoid unnecessary stops. This reduction in vehicle stops serves as a solution to the issue of crime in South Africa, as fewer stops would decrease the likelihood of hijackings and smash-and-grab incidents. Similarly, queue lengths saw a substantial 78.7% reduction, as fewer vehicles stopped, preventing excessive buildup at the

intersection. Additionally, fuel consumption and emissions dropped by 22.8% at 100% V2I penetration, as smoother driving patterns reduced the frequency of acceleration and deceleration cycles. These results demonstrate the promising potential of V2I technology to enhance traffic efficiency, reduce environmental impacts, and improve overall intersection performance, particularly when at lower levels of congestion as V2I adoption reaches full penetration.

Table 2: V2I penetration rate simulation results

Merriman Avenue/Bosman Street						
Attribute	**V2I Penetration Rate**					
	0%	**20%**	**40%**	**60%**	**80%**	**100%**
Average Vehicle Delay (s)	36,5	30,1	25,9	22,5	19,2	15,6
Average Vehicle Stops	0,87	0,90	0,86	0,78	0,63	0,45
Average Queue Length (m)	25,9	21,7	19,0	16,5	13,9	9,2
Fuel Consumption and Emissions	61,5	60,3	58,6	57,0	52,7	47,5
Merriman Avenue/Reyneveld Street						
Attribute	**V2I Penetration Rate**					
	0%	**20%**	**40%**	**60%**	**80%**	**100%**
Average Vehicle Delay (s)	21,3	17,6	15,1	13,4	10,5	8,0
Average Vehicle Stops	0,75	0,69	0,61	0,56	0,42	0,30
Average Queue Length (m)	12,3	9,2	7,3	6,0	4,3	2,6
Fuel Consumption and Emissions	61,5	60,3	58,6	57,0	52,7	47,5
Merriman Avenue/Andringa Street						
Attribute	**V2I Penetration Rate**					
	0%	**20%**	**40%**	**60%**	**80%**	**100%**
Average Vehicle Delay (s)	31,3	32,7	34,8	38,6	33,3	34,2
Average Vehicle Stops	1,10	1,20	1,28	1,41	1,20	1,23
Average Queue Length (m)	17,1	16,7	17,0	17,5	14,4	14,8
Fuel Consumption and Emissions	61,5	60,3	58,6	57,0	52,7	47,5
Merriman Avenue/Bird Street						
Attribute	**V2I Penetration Rate**					
	0%	**20%**	**40%**	**60%**	**80%**	**100%**
Average Vehicle Delay (s)	67,7	68,2	67,0	65,4	62,1	58,4
Average Vehicle Stops	1,64	1,77	1,76	1,66	1,52	1,43
Average Queue Length (m)	57,1	60,4	60,4	60,0	58,3	57,0
Fuel Consumption and Emissions	61,5	60,3	58,6	57,0	52,7	47,5

For the simulations, it was assumed that drivers would respond instantly and accurately to the User App's recommendations, which may not always be representative of real-world behaviour. As such, the simulated results might slightly overstate the effectiveness of the system compared to actual conditions.

As mentioned previously, the Merriman/Bird and Merriman Andringa exhibited minimal improvements, and the benefits were less pronounced at these locations compared to the other two intersections with lower congestion levels. To further explore this effect, an additional scenario was simulated at the Merriman/Andringa intersection, where traffic volumes were reduced by 20%. Table 3 shows the percentage change between 0% and 100% V2I penetration observed during the AM peak and off-peak conditions.

Table 3: V2I AM and off-peak simulation results

Percentage Change Between 0% and 100% V2I Penetration for the AM Peak and Off-Peak Conditions at the Merriman/Andringa Intersection		
Attribute	**AM Peak**	**Off-Peak**
Average Vehicle Delay	10%	-50%
Average Vehicle Stops	12%	-56%
Average Queue Length	-14%	-74%
Fuel Consumption and Emissions	-23%	-26%

The simulation results demonstrated that the V2I system was more effective under lower congestion. At the Merriman/Andringa intersection, reducing traffic volumes by 20% led to significantly greater improvements. While the AM peak scenario saw a 10% increase in delays, the off-peak period experienced a 50% reduction. Additionally, vehicle stops reduced by 56% during the off-peak, compared to a 12% increase observed in the AM peak. Queue lengths followed a similar trend, with a 74% reduction off-peak versus 14% reduction during peak hours. Fuel consumption and emissions also reduced slightly from 23% to 26%. These results confirm that V2I benefits are limited in heavy congestion but highly effective in lower traffic conditions, where vehicles can fully utilise the GLOSA and Red-Light Countdown functionalities.

5. STUDY LIMITATIONS

This study was constrained by the unavailability of real-time detector and controller processing data. Obtaining this data required lengthy approvals from Municipal authorities and could not be gathered through alternative means due to financial (and time) constraints. As a result, the system was only implemented on fixed-time traffic signal controllers (not on vehicle actuated controllers). It is also important to note that the summative evaluation was based on a single test driver, introducing an inherent behavioural bias. This limits the generalisability of the results, as different driver behaviours could slightly influence system performance.

6. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated the feasibility of implementing V2I technology in South Africa, particularly within LHT conditions. The summative evaluation confirmed that the existing traffic signal controllers and cellular networks are capable of supporting such advancements. Furthermore, the outcome evaluation highlighted the potential benefits of V2I adoption, including improved traffic flow and reduced GHG emissions. These findings

showcase that this technology could serve as a solution to the research problems. They also indicate that South Africa is well-positioned to integrate V2I technology into its transport infrastructure, leveraging its current capabilities to drive smarter and more sustainable urban mobility.

The results also revealed that the benefits of V2I technology are most pronounced under lower congestion levels. Vehicles were better able to utilise the GLOSA and Red-Light Countdown functionalities when traffic volumes were reduced, leading to significant decreases in vehicle delays, stops, and queue lengths. This suggests that V2I implementation may be particularly effective in optimising traffic efficiency during off-peak periods or in less congested urban areas.

Future efforts should focus on expanding research and pilot projects to assess the performance of V2I technology across diverse traffic conditions and urban environments. A key area for future investigation would be the integration of V2I functionalities with vehicle-actuated signal controllers, which are widely used in South Africa. Implementing V2I on these adaptive controllers would require real-time detector data and controller processing data to accurately predict and synchronise phase changes. Therefore, securing permission to access this data is crucial for enabling large-scale deployment. Collaboration between Government agencies, research institutions, automobile manufacturers and industry stakeholders would be essential in driving the nation-wide adoption of V2I technology and realising its full potential. Furthermore, future research should consider the broader economic impact of deploying V2I systems in South Africa. Larger pilot studies with more users would be necessary to evaluate whether the time savings and reduced vehicle operating costs translate into tangible long-term value and justify the initial capital investment required.

As V2I technology continues to evolve, South Africa has the opportunity to position itself as a leader in connected (LHT) transport systems. By prioritising innovation and strategic implementation, the country could pave the way for a more efficient, safer, and environmentally sustainable transport network.

7. REFERENCES

Arena, F & Pau, G. 2019. An overview of vehicular communications. *Future Internet*, 11(2). Available at: https://doi.org/10.3390/fi11020027.

BusinessTech. 2023. *Shocking number of hijackings in South Africa – these are the worst areas to own a car – BusinessTech*. Available at: https://businesstech.co.za/news/lifestyle/666055/shocking-number-of-hijackings-in-south-africa-these-are-the-worst-areas-to-own-a-car/.

Oladunni, OJ, Mpofu, K & Olanrewaju, OA. 2022. Greenhouse gas emissions and its driving forces in the transport sector of South Africa. *Energy Reports*, 8:2052-2061. Available at: https://doi.org/10.1016/j.egyr.2022.01.123

Pishue, B. 2024. *2023 INRIX Global Traffic Scorecard with Q1 2024 Update.*