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AV Safety Assessment Framework – Stage 1: Physical-Based Testing for Functionality Capability of AV

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ABSTRACT – *This paper presents a comprehensive physical-based assessment methodology tailored for autonomous vehicles (AVs) within Malaysian driving scenarios under the safety assessment framework. The study investigates the potential requirement to conduct the first level of safety assessment for autonomous vehicles based on international standards. This study discusses a detailed evaluation of sensor functionality and a case study analysis to validate the proposed assessment criteria. The outcome of this study addressed the critical need for localized testing based on Malaysia's unique driving conditions, which is essential for enhancing AV safety and performance. Therefore, the Smart Campus Autonomous Vehicle (SCAV) developed by Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) is used as a case study for the physical-based assessment. The proposed physical assessment methodology is classified as Stage 1 assessment which evaluates the effectiveness of AV in assessing and improving sensors capability to ensure the vehicle's safety to perform self-driving capability. The findings affirm the framework's potential as a foundational tool for advancing the safety testing and deployment of autonomous vehicles in Malaysia, ensuring they meet local and international safety standards.*

KEYWORDS: Autonomous Vehicle (AV), safety assessment, physical-based testing

1. INTRODUCTION

Autonomous vehicles (AVs), or self-driving cars, represent a significant advancement in transportation technology, promising increased safety, efficiency, and convenience. This technology has been proposed to reduce traffic congestion and minimize unwanted road accidents due to human negligence (Wei et al., 2023). It can be noted that this self-driving technology was proposed by Mitsubishi in the early ’90s, called Adaptive Cruise Control (ACC), to provide a warning to the driver about oncoming objects (Winner et al., 1990). Later, the technology evolved by controlling the longitudinal distance between the ego-vehicle and the frontal traffic vehicle by adjusting the speed of the ego-vehicle. Then, other technologies such as Lane Keeping Assistance System (LKAS), Forward Collision Warning System (FCW), Blind Spot Detection (BSD), Autonomous Emergency Braking (AEB), pedestrian detection/avoidance, and traffic sign recognition. All these technologies are categorized under one main technology, the Advanced Driving Assistance System (ADAS), which can be seen in most Level 2 automated vehicles (Ng & Ng, 2021). The main role of ADAS is to prevent deaths and injuries by reducing the number of car accidents and the serious impact of those that cannot be avoided. This technology was adopted to develop an autonomous driving system (ADS) that allows vehicles to operate without any human input. The ADS technology is proposed for Level 3 to Level 5 automation of vehicles with advanced features such as sensor fusion technology using multiple sensors to minimize blind spot zones, enhance vehicle perception and handling capability, and Artificial Intelligence based ADS system to adapt to traffic rules and road conditions (Tang et al., 2021).

Despite the integration of technologies into vehicles, certain countries still face road accident issues. Some developers have self-certified these vehicles before putting them on the road to build trust in the technologies among the public. However, concerns have been raised about the safety of vehicles due to road accidents in Western countries that have caused injuries to road users. The focus on deploying vehicles as public transportation services in some countries has intensified these concerns. These incidents have prompted some bodies and government agencies to prioritize ensuring vehicles' safety and ability to adapt to local traffic conditions and road networks. Consequently, countries like the United Kingdom and Germany are developing safety testing frameworks tailored to their road networks and driving scenarios. Singapore stands out in the ASEAN region for its progress in creating milestone assessments for vehicles to ensure their safe deployment within the country. Drawing inspiration from efforts made by developed nations, this study proposes a safety assessment framework for vehicles with multiple evaluation stages. This research explores an evaluation method designed for the driving conditions in Malaysia, considering local traffic patterns, road structures, and environmental elements during the initial evaluation phase.

2. RELATED STUDY FOR AV REGULATIONS AND STANDARDS

Autonomous vehicles (AVs) are designed with advanced sensors, artificial intelligence, and control systems that enable them to navigate and operate without human intervention. As these technologies advance, developing and implementing robust testing standards have become crucial for ensuring AVs' safety, reliability, and public acceptance. Several requirements to ensure the safety of the AV technology before actual deployment on the road are the AV regulations, testing standards, and dedicated routes for testing the AV capability of autonomous vehicles. In terms of AV regulations, it can be noted that several countries, both in Western and Asian regions, are already making significant efforts to develop regulations for AV safety testing. In 2017, the Singapore government, through the Land Transport Authority (LTA), introduced Road Traffic Rules for AVs to regulate AV trials and developing Technical Reference (TR) 68 for the safety testing of autonomous vehicles along with the Centre of Excellence for Testing and Research of AVs-NTU (CETRAN) (Land Transport Authority, 2019).

Meanwhile, in 2020, NHTSA launched Automated Vehicle Transparency and Engagement for Safe Testing, referring to the early publication of the Federal Automated Vehicles Policy in 2016 (NHTSA, 2021). On the other hand, in 2022, the European Union (EU) published AV regulations to focus on minimizing deaths and serious injuries on European Union (EU) roads by introducing state-of-the-art safety technologies as standard vehicle equipment (Greg et al., 2022). Besides, EU regulations are also used to enhance the competitiveness of EU vehicle developers in the global market by providing the EU legal framework for automated and fully automated vehicles. In the United Kingdom, a new act, namely the Automated Vehicle (AV) Act, was enacted in 2024 to set the target for AV deployment by 2026 in the UK. The act aims to enhance the autonomous vehicle industry and improve road safety by minimizing human error. In Japan, a new amendment to the Road Traffic Act was published in 2022. The amendment mainly emphasizes approval for Level 4 AVs. The previous act allows for Level 3 driving, where self-driving is allowable with human drivers to handle the AVs in emergencies (Greg et al., 2022). Besides, the Korean government also took a huge initiative to expand the AV regulation based on the Future Vehicle Industry Development Strategy in 2019 by proposing safety standards for Level 3 and Level 4 as well as establishing an insurance system for autonomous vehicles and its performance verification process (Seungbum et al., 2024). Extensive development for AV regulations has been initiated in China since 2021. The government established a law, "Administrative Measures for Road Testing and Demonstration Application for Autonomous Vehicles", in 2021 (Greg et al., 2022). Based on the law, most provinces and cities in China have published their regulations for road testing for AVs. In Malaysia, a new policy called National Automotive Policy (NAP) 2020 was published to focus on connected and automated vehicles. Based on the policy, a new guideline, namely "Guideline for Public Road Trials of Autonomous Vehicles has been proposed by the Ministry of Transport to conduct the safety testing of autonomous vehicles with several locations as the testbeds (Aparow et al., 2022).

One important aspect to consider for self-driving cars is the set of testing criteria. Testing standards play a role in ensuring the safety of vehicles for multiple reasons. Primarily, they create a safety benchmark that guarantees these vehicles can function safely in various scenarios and environments. These standards help minimize risks linked to using vehicles, such as accidents caused by system malfunctions or unexpected behaviors in settings. This directly relates to both technological barriers that influence the acceptance of self-driving cars. A study conducted by Cartenì et al. (2020) suggests that addressing these barriers could increase acceptance and willingness to use shared vehicle (SAV) services. Moreover, testing standards boost consumer confidence by ensuring autonomous vehicles undergo evaluations and meet safety requirements. They also promote innovation and competition within the industry by providing guidelines for manufacturers and developers (Yuen et al., 2020). Across the globe, different countries and regions have. Implemented testing standards for autonomous vehicles are often tailored to their specific regulatory frameworks and safety priorities, as highlighted by Koopman and Wagner (2016). Organizations like the National Highway Traffic Safety Administration (NHTSA, 2021) offer testing guidelines in the United States. Implementing vehicles (AVs) covering data recording, crash safety, and cybersecurity. Similarly, the European Union has put frameworks focusing on vehicle safety, environmental regulations, and collaborative cross-border testing. Asian countries like Singapore, Japan, and South Korea have taken steps to set AV testing standards to integrate AVs seamlessly into inter-city transport systems. Meanwhile, China's standards prioritize performance and regulatory adherence to keep pace with its progress in AV technology. Different countries such as the United States (SAE J3016), Germany (VDA Level 3), and China (GB/T 33594) have established their AV testing criteria encompassing safety, cybersecurity measures, and human-machine interaction protocols.

It can be noted that autonomous driving technology has rapidly evolved, with significant investments from automotive companies and tech giants. Despite these advancements, ensuring the safe deployment of AVs remains critical. Various assessment frameworks have been proposed globally, but localized testing still needs improvement for specific regions, especially for developing countries such as Malaysia. The lack of region-specific assessment frameworks may lead to safety and performance issues when AVs are deployed in diverse driving environments. Malaysia's unique driving scenarios necessitate a tailored approach to AV assessment. Therefore, this study aims to adopt and integrate international standards in developing a new safety assessment framework for autonomous vehicles with several stages of safety assessment methodology. Among several assessment stages, physical-based testing for autonomous vehicles focusing on AV functional capability is focused on in this study. The remainder of the paper is organized as follows: Section 3 describes adopting international standards for the safety assessment of autonomous vehicles. Meanwhile, Section 4 addresses the proposed safety assessment framework for autonomous vehicles based on Malaysian driving scenarios. Section 5 focuses on the physical-based assessment methodology, using SCAV as the sample test platform for the analysis. Section 6 addresses the basic requirements for cybersecurity analysis for the AVs before completing the 1st stage of the assessment, and the last section describes the conclusion of this study.

3. ADOPTION OF INTERNATIONAL STANDARDS FOR THE DEVELOPMENT OF A SAFETY ASSESSMENT FRAMEWORK FOR AUTONOMOUS VEHICLE

In the development process of the safety assessment framework for autonomous vehicles, certain international standards have been reviewed and adopted in this development stage. The safety assessment framework is proposed to conduct verification and validation testing for autonomous vehicles using the scenario-based testing methodology. Thus, this study analyzed the existing standards to explore the potential requirement to evaluate the capability of the AV before on-road deployment in developing countries such as Malaysia. One of the first international standards adopted in this framework is the ISO 26262:2018. ISO 26262:2018 focuses on functional safety for road vehicles, including model-in-the-loop (MIL), software-in-the-loop (SIL), and hardware-in-the-loop (HIL) testing (ISO, 2018). Then, ISO 21448:2022, which is called Safety of The Intended Functionality (SOTIF), has been analyzed in this study. These standards address safety aspects related to the intended functions of AVs, especially those not covered by ISO 26262, such as safe behavior in the absence of faults. The other international standards reviewed in this study focus on the ISO 3450x series, such as ISO 34501, ISO 34502, ISO 34503, and ISO 34504. These standards are mainly used for the definition of the vocabulary for test scenario (ISO 34501, 2022), specification for operational design domain (ODD) (ISO 34503, 2023), test scenario classification (ISO 34504, 2024), and scenario-based evaluation framework

(ISO 34502, 2022). Besides, several British Standard International (BSI) focusing on virtual simulation testing, human-machine-interface, and remote operation have been adapted in this reviewed process. Moreover, ISO/TR 4804 has been explored in this study to emphasize the safety and testing of AVs related to cybersecurity, including safety objectives and a testing framework for validation and verification processes (ISO 4804, 2020). Along with international standards, Malaysian standards, namely Next Generation Vehicle (NxGV) – Terminology, Automated and Connected Vehicle (AACV), have been reviewed for adoption. This document mainly focuses on the terminology and definition of the next-generation vehicle for automated vehicles, and this terminology has been used for the safety assessment framework. It can be noted that these standards help ensure that AVs are tested rigorously and consistently, promoting safer and more reliable autonomous driving technologies. These testing standards are crucial for AVs' current safety and functionality and play a pivotal role in shaping the future landscape of autonomous transportation, ensuring that technological advancements are matched with robust safety and regulatory frameworks.

While the existing literature and guidelines offer a basis for testing and evaluating vehicles (AVs), a notable need remains to bridge the gap in incorporating all necessary standards into developing a safety assessment framework. This is particularly important for conducting assessments of AVs, especially in real-world scenarios that mirror specific driving conditions found in Malaysia. Many standards, including those from ISO and regional regulatory bodies, are primarily crafted for applicability across settings. However, these standards must also consider the obstacles presented by driving conditions like those in Malaysia, which encompass varying road infrastructure, unpredictable weather patterns, and intricate urban traffic scenarios. Furthermore, further research is required to integrate these assessments into a framework tailored to various regions while upholding strict safety and performance criteria. Closing this gap is essential for establishing regional testing standards that guarantee the safe and dependable deployment of global AVs in Malaysia. Therefore, an integrated standard framework has been embraced based on adjusted international standards, as suggested by Aparow et al. (2024a). Aparow et al. (2025). Additionally, the team at Automated Vehicle Engineering System (AVES) has incorporated the Malaysian Road Scenario Database (MaRSeD) by Aparow et al. (2023) into their framework to focus on traffic situations and road conditions for driving in Malaysia. The AVES research team has evaluated both MaRSeD and the standardized framework integration working on establishing a safety evaluation system for self-driving vehicles at the University of Nottingham Malaysia (2023), as detailed in the following section.

4. PROPOSED SAFETY ASSESSMENT FRAMEWORK FOR AUTONOMOUS VEHICLE

The safety assessment framework has been created based on the standards, which are under review as discussed in the previous section. This framework serves as a guide to evaluate the safety and performance of vehicles according to road and traffic conditions aligning with international and national standards. It consists of four stages for assessing the vehicle's performance before its actual deployment in real-world settings. Each assessment stage is developed by incorporating standards related to the evaluation criteria within an integrated standard framework. In this stage, the fundamental functionality of the vehicle operating in self-driving mode is assessed using international standards like ISO 26262 and ISO 21448. This involves evaluating sensor functionality conducting hazard analysis and risk assessment (HARA) and monitoring the safety operators' actions during vehicle operation. The aim is to comprehend the safety mechanisms integrated into these vehicles by developers for testing and deployment purposes. This stage evaluates the vehicle's performance based on its system description and capabilities. The primary goal is to ensure the car can drive itself on routes, interact with passengers for Level 3 and Level 4 cars, and have safety features like emergency braking, an emergency button, or the ability for a safety operator to take control if needed.

As for the second stage, the vehicle behavior analysis is evaluated under the safety assessment framework. In this stage, the vehicle behavior assessments are divided into simulation-based and physical-based testing for the autonomous vehicle. Standard driving capability within the defined operational design domain of the deployment area (e.g. national testbeds as defined in the Malaysian AV Guideline), such as driving at a constant speed, left turn junction, right turn junction, lane change, driving in the center of the lane, cruising speed, deceleration condition, sudden braking from constant speed and other essential driving conditions are evaluated in this stage. The vehicle's behavior is tested via a simulation platform using the ADS by the developers. Then, similar driving profiles are tested in the physical environment within the ODD. Then, specific behavior will be used for fidelity assessment to ensure the validity of the autonomous vehicle between simulation and physical testing. Thus, testing criteria from the Society of Automotive Engineers (SAE) based on ISO 3888, ISO 4138, and ISO 21994 are used for the validation purposes for the autonomous vehicles. A double lane change test using ISO 3888 and a J-Turn test using ISO 4138 is conducted for the lateral behavioral testing. Meanwhile, ISO 21994 is used for longitudinal behavioral testing, such as sudden acceleration and braking test conditions.

Meanwhile, the third stage is evaluated based on scenario-based testing methodology for the autonomous vehicle. The vehicle is tested using simulation and physical-based testing by integrating the advanced driving simulation profile such as a 3D environment, virtual vehicle model, sensor simulation, road network, traffic scenario, and third-party controller integration such as ADS. In this stage, ISO standards such as ISO 21448, ISO 34501, ISO 34502, ISO 34503, and ISO 34504 are adopted in the testing framework. ISO 21448 is mainly used to categorize the potential scenarios based on the hazard level in Malaysian driving scenarios and classify them based on the hazard conditions defined in ISO 21448.

Then, the ISO 3450x series is used in scenario-based safety testing to define the ODD specification, scenario behaviors, assessment evaluation criteria, and scenario categories. For the scenario description and classification, the MaRSeD approach has been used in this assessment stage (Aparow et al., 2024b). All the potential test scenarios are designed and developed using a Human-Machine-Interface (HMI) simulated platform for the safety assessment. AV developers must evaluate their ADS performance based on the proposed test scenarios (Aparow et al., 2023). HMI-based simulation platform has been integrated into the assessment stage to evaluate the safety operator’s behavior during critical test scenarios. Then, several test scenarios are selected for the fidelity assessment of the ADS system using the physical testbeds as proposed in the Guidelines for Public Road Trials of Autonomous Vehicles as published by the Ministry of Transport.

As for the final assessment stage, the autonomous vehicle is assessed in terms of cybersecurity assessment. As for the cybersecurity evaluations, the ISO standards, such as ISO 4804 and ISO 21434, have been adopted for designing the testing process, which has been adopted based on the automotive cybersecurity verification and validation approach. The main aim of cybersecurity is to represent the perception-level requirements associated with multiple threat test scenarios. Cybersecurity testing focusing on system vulnerabilities to cyber threats such as jamming, denial-of-service attacks, and malicious code injection, affecting the integrity of AV as one whole system, is explored in this stage. Similar to the previous assessment stage, simulation-based and physical-based testing are explored in this assessment stage. Specification-based testing, commonly known as compliance testing, is explored to ensure the developed system aligns with design specifications.

Meanwhile, regulation-based testing focusing on verification of the regulations and standards at national or international levels, such as UNECE R155 and UNECE R156, is also adapted in this assessment stage. Another testing approach is Fuzz testing, which exposes security vulnerabilities by injecting non-valid or unpredicted data. This is conducted simultaneously during vulnerability scanning by automatically identifying and assessing system weaknesses. A detailed description was included in Aparow et al. (2024a) and Aparow et al. (2025). Based on the four stages, the safety assessment framework is developed to evaluate the performance of autonomous vehicles. A safety assessment platform using a 6 DOF motion platform integrated with simulation software and integration with HMI and external controller is developed for the safety assessment of autonomous vehicles, as shown in Figure 1.

5. DEVELOPMENT OF BASIC PHYSICAL-BASED TESTING

In this section, one case study of autonomous vehicle platforms has been investigated as a benchmark case study to evaluate the effectiveness of the proposed physical-based testing. The first platform used in this study is the Smart Campus Autonomous Vehicle (SCAV). The SCAV is developed by a research team from Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA). SCAV is an autonomous vehicle developed from the ground up approach, and the primary aim is for research and education for university students. In this case, the SCAV is a functional prototype that should address its essential safety aspect for autonomous navigation tests. Figure 2 shows the SCAV platform, which researchers at Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) developed for research and development purposes in autonomous vehicle technology. The SCAV is equipped with various sensors and computers for computing advanced algorithms such as path planning and control and 3D LiDAR perceptions, enabling it to effectively perform autonomous driving tasks (Vinayak et al., 2023; Yong et al., 2023; Habeeb et al., 2022; Yee & Zakaria, 2022).

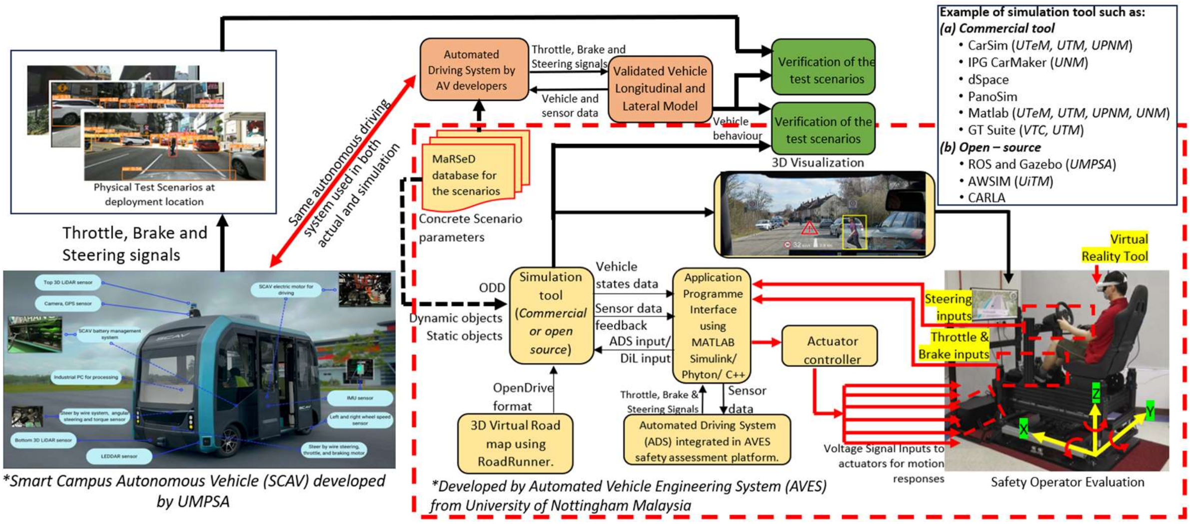


FIGURE 1: System configuration safety assessment platform for autonomous vehicle for Malaysian driving scenario

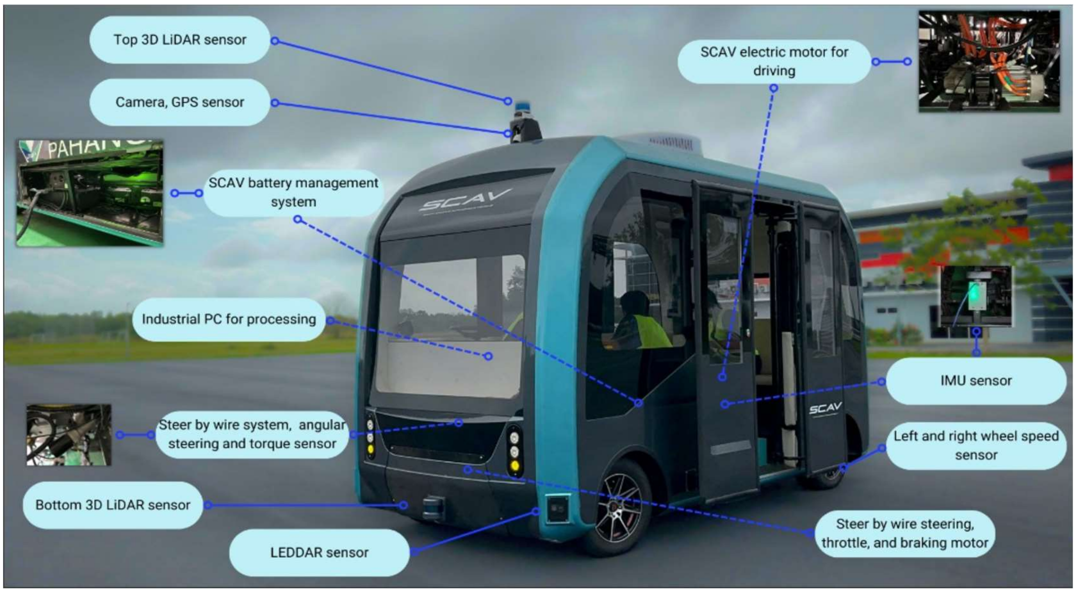


FIGURE 2: Smart Campus Autonomous Vehicle (SCAV) by Universiti Malaysia Pahang Al-Sultan Abdullah as a test case physical assessment framework (UMPSA, 2021)

5.1 Assessment Criteria for Functional Testing

For Level 1 physical testing, data submission will be evaluated based on three performance matrices:

a) Not Meeting Requirements (0) - NMR
b) Basic Requirements Achieved (1) - BARA
c) Very Good Requirements Achieved (2) - VGR

To complete the Level 1 physical testing guidelines, the vehicle under testing must achieve at least 80% of the BARA. The achievement is calculated based on the following method:

$$NMR\_weightage = 0 \tag{1}$$

$$BARA\_weightage = 1 \tag{2}$$

$$VGR\_weightage = 2 \tag{3}$$

$$Total\ case\ aspect,\ N = \sum Number\ of\ aspects \tag{4}$$

$$Total\ BARA\ Score\ Marks,\ M = N * BARA\_weightage \tag{5}$$

$$BARA\ percentage,\ \% = \frac{\sum BARA\ physical\ test\ score}{M} \times 100 \tag{6}$$

$$(BARA + VGR)\ percentage,\ \% = \frac{\sum BARA + \sum VGR\ physical\ test\ score}{M} \times 100 \tag{7}$$

The percentage score must be at least 80% to achieve the Level 1 requirement. (BARA + VGR) scores that exceed 80%, indicate that the system in the test is in a good condition for the autonomous safety framework Level 1 test. The VGR value indicates how many percent of the assessments are above the standard of the basic requirements. For the proposed physical assessment Level 1 framework, SCAV will be assessed based on the following:

a) Assessment criteria 1: Minimum specifications of sensors
b) Assessment criteria 2: Sensor's detection range and capability
c) Assessment criteria 3: Measurement of the platform sensors

5.2 Assessment Criteria 1: Minimum Specifications of Sensors

Assessing the minimum specifications of sensors in basic testing for AVs is crucial to ensure that these vehicles can reliably perceive and interact with their environment. Sensors are the primary means an AV detects obstacles, reads road signs, identifies lane markings, and navigates through various traffic conditions. We can verify that the sensors meet the necessary standards to function effectively in diverse and dynamic driving scenarios by establishing and evaluating the minimum specifications, as mentioned in the case aspects. This assessment helps as a gatekeeper to ensure that at least a relevant autonomous sensor is used in the development.

The detailed calculation has been included in the Appendix section of this study. Based on the calculation, the total BARA + VGR percentage exceeds 80%, which indicates that the minimum specifications are good for SCAV to be operated in autonomous operations. This serves as a fundamental indicator before assessing the sensor's detection. The minimum specifications of sensors used in the vehicle for physical-based assessment are described in Table 1.

5.2 Assessment Criteria 2: Sensor's Detection and Capability

Assessing a sensor's detection and performance is crucial in testing vehicles (AVs) to guarantee that the vehicle can accurately perceive its surroundings and react effectively. Detection involves the sensor's capacity to recognize and distinguish objects, barriers, and road characteristics. By examining these factors, we can ensure that the AV sensors are strong and adaptable enough to handle the intricacies of real-world driving. This evaluation helps validate that the AV can understand its environment, make informed choices, and uphold safety and efficiency standards across driving conditions.

The detailed calculation has been included in the Appendix section of this study. Based on the calculations, the combined BARA and VGR percentages exceed the 80% threshold, indicating that the vehicle surpasses the minimum requirements for Basic Requirements Achieved (BARA). This means the SCAV meets the necessary safety standards for sensor detection in physical assessments. The sensor's detection physical assessment used in the vehicle for physical-based testing is described in Table 2.

TABLE 1: Minimum specifications of sensors' physical assessment

Case Aspect Number	Physical Specification Aspects	Description	SCAV System	Remarks
1	Max. Temperature	Sensors should be able to work at least 60 degrees Celsius to ensure reliability in various environmental conditions.	All sensors in SCAV use industrial-grade sensors.	Very Good Requirements achieved (2)
2	IP65 Rating	Sensors must be IP65 rated, ensuring they are at least splash-proof and resistant to dust and debris ingress.	SCAV uses IP-rated sensors. However, some parts of the SCAV body are not IP-rated or splash-resistant.	Basic Requirements achieved (1)
3	ROHS Compliance	All sensors must comply with ROHS standards to ensure they are environmentally friendly and free from hazardous substances.	All components are ROHS compliant.	Very Good Requirements achieved (2)
4	Emergency Button	A dedicated emergency button should be installed to allow immediate manual intervention in case of emergencies or system failures.	There is a dedicated emergency stop button to stop the system. Steer-by-wire steering has backup mechanical linkage steering to overwrite the control during an emergency.	Very Good Requirements achieved (2)
5	Wiring Safety	Wiring must adhere to safety standards, with no exposed power wires. Proper fusing and grounding should be implemented, along with adequate shielding for sensor signal wiring to prevent interference.	All cables are properly covered and grounded. However, some parts of the wiring are exposed minimally for debugging purposes.	Basic Requirements achieved (1)
6	Proposed Sampling Rate	Depending on speed requirements, a proposed sampling rate should be established.	Every sensor has an established sampling rate which can be checked individually in the configuration parameters file.	Very Good Requirements achieved (2)
7	Fire Extinguishers	Fire extinguishers should be readily accessible in the vehicle to mitigate the risk of fire-related incidents.	Fire extinguishers are readily inside SCAV during testing.	Very Good Requirements achieved (2)
8	Vehicle Identification in Auto Mode	When the vehicle is in autonomous mode, it should be easily identifiable, potentially through beacon lights or relevant indicators to alert other road users.	SCAV's double signal lights flash to indicate it is in operation during the testing. Two escort vehicles will notify the road users about the testing.	Very Good Requirements achieved (2)

TABLE 2: Sensor's detection physical assessment

Case Aspect Number	Sensors Detection Physical Assessment	Description	SCAV System	Data Collections Evaluation
1	Traffic Signs and Signals	To adhere to traffic rules and regulations, sensors should identify and understand traffic signs, signals, and lights.	The SCAV system's navigation mainly uses LIDAR-based speed sensors, IMU, and GPS. The camera is not used for navigation, mainly for object and sign classifications.	Basic Requirements achieved (1)
2	Roadside Infrastructure	Sensors should detect and recognize roadside infrastructure such as traffic lights, pedestrian crossings, and speed bumps to navigate safely.	LIDAR is used for 3D object classification, including roadside classifications, and the camera is for moving obstacles.	Very Good Requirements achieved (2)
3	Obstacles	Sensors must detect static obstacles, such as parked cars, barriers, and road debris, and dynamic obstacles, such as pedestrians, cyclists, and other vehicles.	Sensors detect obstacles. 3D LIDAR can detect cars, pedestrians, trucks, and vans. Barriers are not classified currently. However, they can be detected during the SLAM process. No classification is made for cyclists.	Basic Requirements achieved (1)
4	Road Lanes	Sensors should be able to detect and interpret road lane markings, accurately determining the vehicle's position within the lane and navigating accordingly.	SCAV navigation is mainly LIDAR-IMU-based navigation. Therefore, the lane marking has not been detected yet.	Not Meeting Requirements (0)
5	Road Edges	Sensors should identify the boundaries of the road, including curbs, shoulders, and medians, to maintain proper alignment and avoid collisions.	SCAV detects road edges and boundaries during the mapping and localization process.	Very Good Requirements achieved (2)
6	Other Vehicles	Sensors must detect nearby vehicles, including their position, speed, and direction of travel, to enable safe interaction and avoid collisions.	Another vehicle detection method is 3D LIDAR detection.	Basic Requirements achieved (1)

7	Pedestrians and Cyclists	Sensors must detect and track pedestrians and cyclists near the vehicle to ensure safety and avoid accidents.	SCAV is not able to detect the cyclists. However, the detection is considered obstacle detection in general.	Basic Requirements achieved (1)
8	Traffic Flow	Sensors should monitor traffic flow, including vehicles' speed and direction, to make informed decisions about lane changes, merging, and intersections.	SCAV operates in a controlled environment. It can detect the speed of other vehicles using 3D LIDAR detection. However, it cannot predict or make informed decisions about lane changes and merging, and it is still being researched.	Not Meeting Requirements (0)
9	Environmental Conditions	Sensors should assess environmental factors such as light, visibility, and weather conditions to adjust driving behavior and ensure safe operation.	SCAV cannot predict the weather environment and only operates in good weather conditions. SCAV researchers are currently researching to estimate harsh rain conditions based on LIDAR machine learning classifications.	Not Meeting Requirements (0)

5.3 Assessment Criteria 3: Measurement of the Platform Sensors

The next stage involves the measurement of the platform sensors, which is Stage 3 of the physical assessment process. The detailed calculation is included in the Appendix section of this study. Meanwhile, Table 3 addresses the measurement of platform sensors for the SCAV. During this stage, data from sensors such as cameras, LiDAR, radar, GPS, and speed sensors can be collected and recorded to ensure they function as intended. In the Level 1 assessment, addressing all the technical difficulties and complexities of algorithms or case studies is unnecessary. It is sufficient to verify that the sensors are operating correctly. Figures 3 to 10 show the example of the measurement of platform sensors during testing to ensure that the sensors work during testing and development.

TABLE 3: Measurement of the platform sensors

Case Aspect Number	Sensor's Detection Physical Assessment	SCAV System	Remarks	Data Collections Evaluation
1	Camera	 **FIGURE 3:** Camera detection algorithms in the SCAV system	The camera is working and able to classify lanes.	Basic Requirements achieved (1)

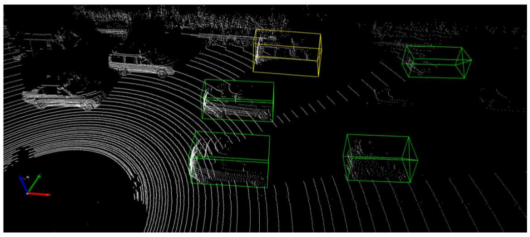
<table>
<tr><td>2</td><td>LiDAR</td><td>


FIGURE 4: 3D classification object detection using LiDAR sensor in SCAV system

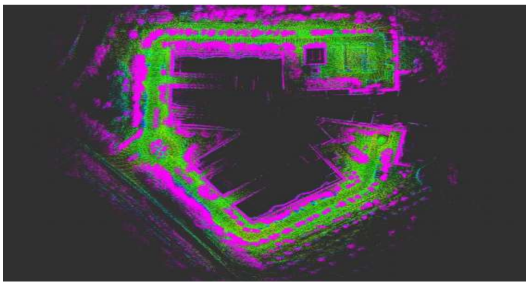


FIGURE 5: 3D mapping environment in SCAV system

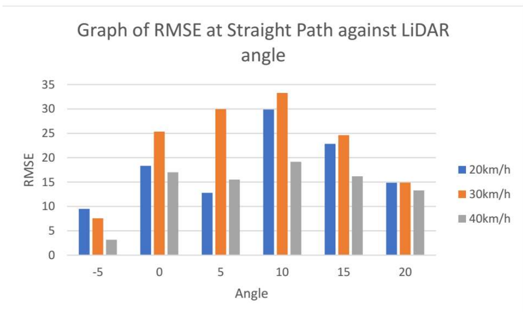
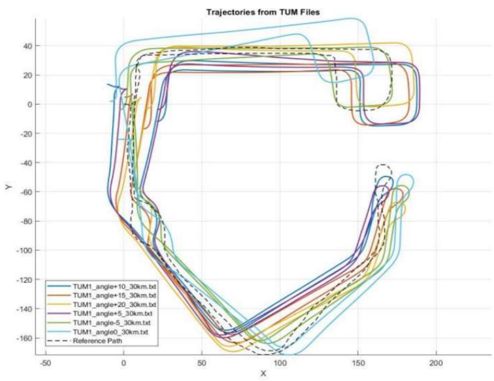
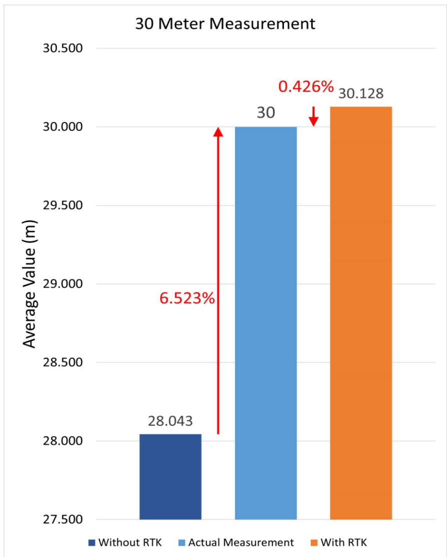
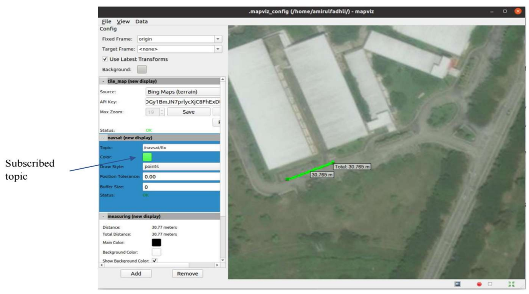
FIGURE 6: Actual map before mapping by SCAV system
</td><td>LIDAR is working and can do 3D point cloud detection, mapping, localisations, and obstacle detection.</td><td>Very Good Requirements achieved (2)</td></tr>
<tr><td>3</td><td>Wheel speed sensors</td><td>


FIGURE 7: RMSE error for LIDAR detection concerning vehicle's velocity (the vehicle velocity is using two-wheel speed sensors)
</td><td>Wheel speed sensors are well calibrated.</td><td>Very Good Requirements achieved (2)</td></tr>
</table>

4	IMU	IMU data is fused to generate the trajectory with wheel speed sensors.  **FIGURE 8:** The trajectory can be calculated using the IMU sensor, wheel speed sensors, and sensor fusion	IMU sensor is well-calibrated with sensor fusion techniques and sensor filtering techniques.	Very Good Requirements achieved (2)
5	GPS	 **FIGURE 9:** The performance comparison of the sensor GPS with RTK and without RTK  **FIGURE 10:** SCAV trajectory movement from maps view in MapViz software from GPS sensor reading	GPS data is tested with RTK and without RTK to compare the performance of the positing detection.	Very Good Requirements achieved (2)

The platform measurements sensor equipped in the SCAV obtained the score of BARA+VGR as 100%. It indicates that the current equipped sensors are working as intended with a high score. The total three scores for three assessments can be summarized in Figure 11 below:

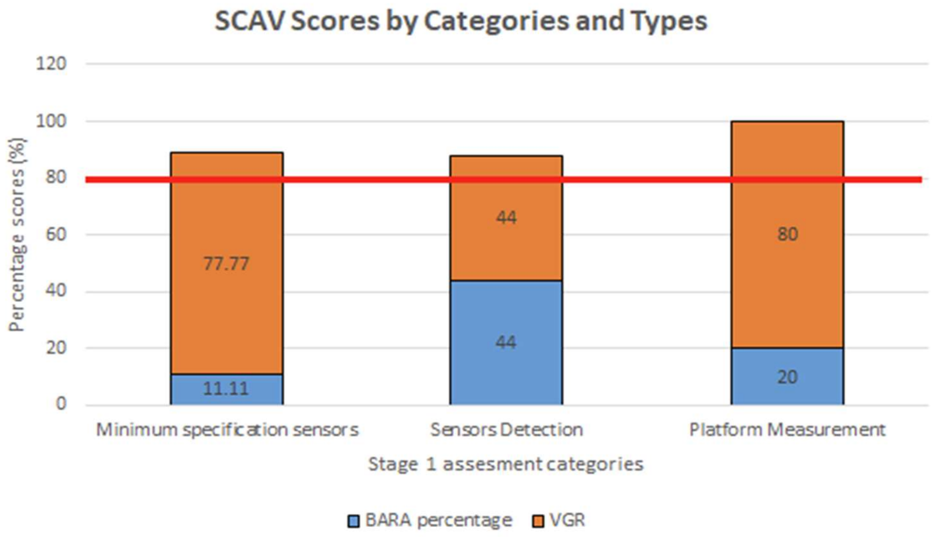


FIGURE 11: Summary of the physical assessment results for Level 1

From Figure 11, the combined BARA + VGR percentages are consistently high, exceeding the 80% threshold. Although the BARA scores are relatively low due to a shift towards the VGR categories, the sensor detection category shows a higher BARA score than others. It indicates that the SCAV meets approximately 44% of the minimum requirements for the sensor detection test. Despite the BARA + VGR score being 88%, the same as in category 1 (minimum specification sensor), this demonstrates that in the sensor detection category, the SCAV does not achieve a higher score in the Very Good Requirements domain. The calculator indicated a need for additional improvements to enhance the vehicle's safety.

6. FUTURE WORKS ON CYBERSECURITY REQUIREMENTS FOR STAGE 1 ASSESSMENT

A possible future work should involve developing a cybersecurity evaluation process for the AV developers during the initial assessment phase. This would involve designing a survey to gauge developers' preparedness and knowledge of cybersecurity risks and the effectiveness of their risk mitigation strategies. The survey will include adherence to security frameworks and policies, methods for assessing threats and managing risks, data protection and privacy measures, and the strength of incident response and recovery plans. It will also assess developers' adoption of software development practices, their handling of security risks in third-party relationships and supply chains, and the impact of their cybersecurity training programs. This approach aims to establish an understanding of each developer's readiness in terms of cybersecurity and provide recommendations to enhance the overall security of autonomous vehicle systems.

7. RECOMMENDATION FOR AV ASSESSMENT

From the Stage 1 physical-based testing, a higher stage of safety assessment can be constructed using a similar approach. The developer or authorities can expand the safety assessment by focusing on vehicle behavioral validation, simulation-based testing, safety operator behavior assessment, cybersecurity, and others. The evaluation is to provide or give awareness on the safety aspect of the vehicle under test, which will help the developer to have a safety mindset when developing the autonomous vehicle. Meanwhile, local authorities can consider adopting the functional assessment methodology for future AVs who want to deploy their vehicle at national testbeds. Moreover, the developed safety assessment framework for autonomous vehicles can be used for future testing of autonomous vehicles in Malaysia, designed by adopting international and national standards.

8. CONCLUSION

The initial phase of evaluating the Smart Campus Autonomous Vehicle (SCAV) for operations involves a physical assessment framework. This assessment method calculates the vehicle's readiness by combining the percentages of Basic Requirements Achieved (BARA) and Very Good Requirements (VGR), serving as a benchmark against predefined standards. In a case study, the SCAV consistently surpasses the 80% threshold set by the framework showcasing its ability to meet the criteria for safe autonomous driving. Despite its performance, there are areas, particularly in sensor detection, where improvements are needed to boost Basic Requirements Achieved (BARA) scores. This suggests that while the SCAV is generally well-prepared, enhancements are required in certain aspects to enhance its performance. The framework's role in pinpointing these improvement areas emphasizes its importance as a tool for assessing capabilities and shaping advancements in autonomous vehicle technology. By refining testing procedures and aligning vehicle systems with this framework, stakeholders can ensure that autonomous vehicles like the SCAV meet and exceed safety and operational standards in real-world scenarios. This hands-on evaluation will serve as the analysis for the phase of testing the newly created safety assessment framework, as detailed in Section 4.

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Appendix I. Calculation for Minimum Specification of the Sensors

The score for the SCAV in Table 1 for the minimum specification of the sensors can be calculated as follows:

$$NMR\_weightage \ = \ 0$$

$$BARA\_weightage \ = \ 1$$

$$VGR\_weightage \ = \ 2$$

$$Total\ case\ aspect,\ N \ = \ 8$$

$$Total\ BARA\ Score\ Marks \ = \ 8\ *\ 1 \ = \ 8$$

$$BARA\ percentage,\ \% \ = \ \frac{2}{9} \times 100 \ = \ 11.11\%$$

$$(BARA \ + \ VGR)\ percentage,\ \% \ = \ \frac{2+6}{9} \times 100 \ = \ 88.88\%$$

Appendix II. Calculation for Sensor Detection Range and Capability

From Table 2, the total case aspect number, N is 9. Using the formula, the Table 2 score can be calculated using the following calculations:

$$NMR\_weightage \ = \ 0$$

$$BARA\_weightage \ = \ 1$$

$$VGR\_weightage \ = \ 2$$

$$Total\ case\ aspect,\ N \ = \ 9$$

$$Total\ BARA\ Score\ Marks \ = \ 9\ *\ 1 \ = \ 9$$

$$BARA\ percentage,\ \% \ = \ \frac{4}{9} \times 100 \ = \ 44\%$$

$$(BARA \ + \ VGR)\ percentage,\ \% \ = \ \frac{4+4}{9} \times 100 \ = \ 88\%$$

Appendix III. Calculation for Measurement of the Platform Sensors

From the measurement of the platform sensors, the score can be calculated as follows:

$$NMR\_weightage \ = \ 0$$

$$BARA\_weightage \ = \ 1$$

$$VGR\_weightage \ = \ 2$$

$$Total\ case\ aspect, N \ = \ 5$$

$$Total\ BARA\ Score\ Marks \ = \ 5 * \ 1 \ = 5$$

$$BARA\ percentage, \% \ = \ \frac{1}{5} \ \times \ 100 \ = \ 20\%$$

$$(BARA \ + \ VGR)\ percentage, \% \ = \ \frac{1 \ + \ 4}{5} \ \times \ 100 \ = \ 100\%$$