Article│ Received 22 August 2024; Accepted 21 October 2024; Published 26 October 2024
https://doi.org/10.55092/aias20240007

Developing a Machine Intelligence Quotient (MIQ) for evaluating autonomous vehicle intelligence: A conceptual framework

Mehdi Cina[1], Ahmad Rad[1,*] and Abdol Rasul Rasuli[2]

[1] Autonomous and Intelligent Systems Laboratory, School of Mechatronic Systems Engineering, Simon Fraser University, Surrey, BC V3T 0A3, Canada

[2] DyMo Technology Corp, Vancouver Canada

[*] Corresponding Author; E-mail: arad@sfu.ca.

Abstract: This paper presents a methodology to quantify the Machine Intelligence Quotient (MIQ) for autonomous cars. MIQ integrates multi-dimensional categories—Physical, Cognitive, and Functionality Intelligence attributes—to evaluate vehicle intelligence in a comprehensive manner. By focusing on the harmony of these facets with human cognitive and decision-making processes, MIQ provides a transformative approach to understanding and enhancing autonomous vehicle technology. This framework not only offers an empirical method for intelligence assessment but also sets a visionary benchmark, advocating for advancements that parallel human-like intelligence in future autonomous systems.

Keywords: autonomous vehicle intelligence; Machine Intelligence Quotient (MIQ); cognitive computing in vehicles; Advanced Driver Assistance Systems (ADAS); intelligent vehicle systems; human-centric vehicle technology

1. Introduction

The complex quest to understand, quantify, and measure intelligence, biological as well as artificial, has remained a compelling endeavor in the scientific community, particularly in the last bicentennial period. Essential to this exploration was the iconic work of Alan Turing in the mid-20th century. Often termed the father of computer science, Turing introduced the Turing Test as a pioneering empirical measure of machine intelligence [1]. This test envisioned an assessment where a human evaluator would engage in conversation with a machine designed to produce human-like responses. If the evaluator found it challenging to discern between the machine and a human interlocutor, the machine would be said to have successfully demonstrated human-equivalent intelligence [1]. Groundbreaking as Turing's test was, it did not escape critique. Scholars opined that it placed undue emphasis on the machine's ability for imitation, often sidelining the essence of genuine intelligence [2]. Recent systematic reviews underscore the significant role of AI to enhance autonomous vehicle safety, and emphasize on the development of metrics that evaluate the adaptive and integrative aspects of intelligence in these systems. Nascimento *et al.* provide a comprehensive analysis of AI's role in advancing autonomous vehicle safety, featuring the need for robust evaluation metrics [3]. Additionally, Di and Shi explore AI-guided driving policy learning in mixed autonomy settings, illustrating the evolution of control strategies as autonomous vehicles integrate into human-dominated traffic, further supporting the critical need for adaptive evaluation frameworks [4]. As technological landscapes evolved, the Turing Test's emphasis on human-like mimicry appeared increasingly narrow, revealing its limitations in addressing a broad spectrum of intelligence assessment applications [5]. François Chollet's critique on evaluating AI solely based on human-like capabilities further underscores this limitation, suggesting a broader spectrum of intelligence attributes [6]. In the last two years, however, with the advent of Generative AI such as ChatGPT, Bing, Bard, *etc.*, machines are closer as ever to understand human sentiment and are becoming adept in natural language processing.

On a separate direction yet related scope, Intelligence Quotient (IQ) tests were developed in early 20th century and are still quite popular. The IQ test is aimed mostly at measuring an individual mathematical skills, memory, spatial perception, and language abilities. The IQ is calculated as the ratio of mental age (MA) over chronological age (CA). Inspired by Minsky's concept of a "society of mind," which suggests that intelligence emerges from the interaction of non-intelligent components, our study proposes a composite Machine Intelligence Quotient (MIQ) that reflects the multifaceted nature of AI systems [7]. The question of developing a counterpart intelligence index for machines, however, has been conspicuously overlooked. The notion of MIQ was coined by Zadeh in two papers in 1994 [8,9]. Zadeh envisioned that the development of fuzzy logic, neural networks, and soft computing would lead to consumer products (microwave ovens, household appliances, cameras, *etc.*) with higher MIQ, yet he did not articulate further as to how such a quotient could be quantified. Bien *et al.* [10] proposed a method to calculate MIQ employing Sugeno and Choquet fuzzy integrals and applied it to an elevator group control system. Park *et al.* [11] proposed an Intelligence Task Graph (ITG) to estimate MIQ. However, the quest for MIQ has not been pursued to a level that it deserves. With the advent of AI and its presence in all aspects of modern societies, we argue that it is high time the MIQ is revisited and be included as an essential attribute in different consumer products and intelligent systems. For examples, MIQ is listed in washing machines from different manufactures to indicate as a performance and functionality index to aid consumers for decision making about their intelligent functionalities. Within this context and the modern era's surge in autonomous vehicle technology, as a testament to human ingenuity, there is a pressing need for a comprehensive system to assess 'intelligence' in autonomous vehicles such as driverless cars or advanced driver assist systems. These vehicles, blending the marvels of engineering and artificial intelligence, have transitioned from mere theoretical constructs to real-world applications, capturing the interest of scholars, automotive industry stakeholders, and the general public alike [12]. However, this rise has also necessitated the development of a comprehensive system to assess the 'intelligence' of these machines. Despite preliminary attempts [13], existing methodologies often do not capture the full spectrum of challenges associated with assessing vehicular intelligence. Whereas an array of methodologies exist for assessing the intelligence of autonomous vehicles, they often focus narrowly on specific technical capacities such as sensor accuracy, navigation abilities, and response times under controlled testing conditions. These evaluations typically overlook how these systems perform in unstructured environments and real-world unpredictability. Notably, traditional metrics fail to account for the vehicle's overall adaptability, learning capability, and holistic integration of its systems when faced with dynamic driving scenarios. Such gaps highlight the need for a comprehensive evaluation framework that not only assesses individual components but also considers the vehicle's intelligence as an integrated whole in realistic settings. This oversight in existing methodologies emphasizes the importance of developing a more robust metric like the MIQ, which aims to bridge these gaps by offering a multi-dimensional and detailed approach to evaluating vehicle intelligence, closely mirroring the complexities of human cognitive processes. The multifaceted nature of intelligence in the context of autonomous vehicles demands a more nuanced approach [14]. To address this demand, this paper revisits MIQ and presents a comprehensive, adaptable, and forward-thinking mechanism, designed to holistically assess the intelligence of vehicles. It aims to provide a more detailed, multifaceted understanding of vehicular intelligence, crucial for advancing the field and enhancing the integration of these vehicles into our daily lives. As we delve into the intricacies of assessing machine intelligence in autonomous systems, it is imperative to define key terms that will guide our analysis and discussions throughout this paper.

(1) Intelligence: We adopt Pei Wang's definition of intelligence as "the capacity of an information-processing system to adapt to its environment while operating with insufficient knowledge and resources" [15]. This perspective aligns with our exploration of machine intelligence in autonomous systems, underpinning the necessity for adaptability and resource efficiency in complex, unpredictable environments.
(2) Autonomous Cars: We refer to vehicles that perform tasks requiring human-like intelligence—including but not limited to navigation, localization, perception, and decision-making—without human intervention. This operational independence is crucial for the application of MIQ in assessing the capability of these systems to handle real-world complexities autonomously.
(3) Machine Intelligence Quotient (MIQ): This metric, developed specifically for our research, quantifies the intelligence of autonomous systems by evaluating their physical, cognitive, and functional capabilities. The MIQ framework is crucial in benchmarking the intelligence of these systems against standardized criteria, facilitating a deeper understanding of their operational effectiveness.
(4) Hybrid Intelligence: A fusion of human and artificial intelligence that leverages the strengths of both entities to achieve complex goals. This concept is vital for developing co-evolutionary systems where human insights and machine efficiency are integrated, enhancing the decision-making processes within autonomous systems.

(5) Co-evolutionary Hybrid Intelligence: Describes the ongoing, mutual enhancement of human and machine intelligence, emphasizing continuous adaptation and learning. This dynamic interplay is central to our study's aim of developing a sustainable, adaptable framework for intelligence assessment in autonomous vehicles.

The rest of the paper is organized as follows: Section 2 presents related work, setting the context for this study. Sections 3.1 and 3.2 introduce the MIQ, explaining its purpose and conceptual framework. Section 4, along with its subsections 4.1 to 4.3, explores categorization and measurement of vehicle intelligence. Section 5 lists the research objectives and hypotheses. Sections 6.1 and 6.2 examine the mathematical representation of MIQ. Section 7 and its subsections 7.1 and 7.2 detail a case study on the 2024 Hyundai Palisade. Section 8 provides an analysis and implications of the study's findings. Section 9 is dedicated to a comprehensive discussion on MIQ and autonomous intelligence. Finally, Section 10 concludes the paper and proposes future research directions.

2. Related work

Intelligent vehicles have commanded significant attention and focus from the researchers and car manufacturing industries over the past few years. The emergence of machine learning as a dominant force in numerous sectors, including vehicular technology, has led to rigorous academic and industrial discourse. Akata *et al.*'s research on label-embedding techniques for image classification introduces a sophisticated method for enhancing machine learning models, which is particularly relevant for autonomous systems that rely on visual data for navigation and decision-making [16]. Though, some scholars have expressed concerns regarding the robustness and "legibility" of autonomy that relies heavily on machine learning paradigms [17]. The critique often revolves around the predictability, transparency, and accountability of systems trained on vast datasets without explicit consideration for every possible scenario. In parallel, there has been a reinvigoration of the notion of Strong AI in the form of Artificial General Intelligence (AGI) and its yet unknown implications to human societies [18]. Liu et. al. [19] discusses the "standard intelligence model", which unifies AI and human characteristics to address AI threats and tests AI systems' intelligence quotients. In exploring the cognitive architectures that underpin both human and artificial intelligence, Smith's extensive research provides a comprehensive framework for understanding the complexities of cognitive processes [20]. Recent studies have increasingly focused on the human-centric evaluation of autonomous vehicles, emphasizing trust, transparency, and situational awareness. Haspiel *et al.* explored the dynamics of trust in automated vehicles through user interaction, highlighting the importance of clear and timely explanations from the vehicle to its users [21]. Hewitt *et al.* developed a model assessing public acceptance of self-driving cars, emphasizing key factors that influence trust and public adoption [22]. Furthermore, Atakishiyev *et al.* detailed the integration of explanations into vehicle interfaces to enhance user trust and situational awareness [23]. Another segment of academia posits that the field of vehicular autonomy is overly reliant on computer vision techniques, suggesting that true autonomy should encapsulate a broader range of sensors and decision-making paradigms [24]. The MIQ framework, devised in response to these challenges, synthesizes these varied insights to propose a robust, multidimensional metric that quantifies vehicle intelligence across three critical pillars: Physical, Cognitive, and Functional. This framework not only captures the robustness of hardware and the agility of machine learning algorithms (PI) but also assesses the vehicles' sensory interpretations and decision-making processes (CI) in complex, real-world environments, thus addressing the criticisms concerning the opacity and unpredictability of AI-driven systems. Furthermore, by integrating measures of functionality intelligence (FI), the MIQ considers the vehicle's ability to apply these cognitive processes in real-time operational scenarios, thereby responding to the need for a more comprehensive evaluation tool that bridges theoretical research and practical applications in vehicular autonomy. However, amidst these debates and discussions, there is a growing consensus that the advancements in machine learning, especially those related to intelligent system assessment, need to be synergized with practical applications in vehicular autonomy. This study, therefore, endeavors to bridge this gap, introducing a robust method to evaluate the intelligence of autonomous vehicles. Within this landscape; there is a pressing need to arrive at metrics to quantify machine intelligence. In response, the studies reported in this paper aims to provide a standardized and comprehensible means to assess, compare, and benchmark vehicular intelligence, offering stakeholders a clearer vision of the state-of-the-art and guiding future innovations.

3. MIQ: An overview

3.1. Purpose and significance of MIQ

Here, we suggest that the MIQ marks a transformative step in the design and development of future autonomous vehicles. This innovative concept serves as a crucial metric, designed to standardize the evaluation of a vehicle's intelligence, a task that has grown increasingly complex with the rapid advancements in automotive technology. MIQ addresses a critical gap in the existing methodologies, which often lack a comprehensive view, focusing instead on isolated aspects of vehicle performance. By introducing a unified and holistic approach, MIQ provides a more accurate and refined assessment of autonomous vehicles' capabilities. The significance of MIQ extends beyond mere measurement; it is a tool that facilitates meaningful comparisons across different autonomous vehicles and systems. This standardization is essential for manufacturers, enabling them to benchmark their vehicles against industry standards and competitors. Furthermore, MIQ plays a crucial role in guiding research and development within the industry, offering insights that drive innovation and improvement in vehicle intelligence. Moreover, the implementation of MIQ has profound implications for consumer safety and regulatory compliance. For consumers, MIQ offers an objective measure of a vehicle's intelligence, enhancing trust and confidence in autonomous technology. From a regulatory perspective, MIQ aids in establishing clear standards and benchmarks, ensuring that vehicles not only meet technological thresholds but also adhere to safety and intelligence criteria.

3.2. Conceptual framework of MIQ

The conceptual framework of MIQ is rooted in the understanding that the vehicle intelligence is a complex amalgamation of various components. This framework categorizes vehicle intelligence into three fundamental types: Physical Intelligence (PI), Cognitive Intelligence (CI), and Functionality Intelligence (FI). Each type is quantified using specific measurable attributes that capture their respective contributions to overall vehicle intelligence. PI, for instance, includes crucial aspects like Infotainment System Quality and Software Efficiency, focusing on the vehicle's tangible technological robustness and operational effectiveness. In measuring PI, we employ metrics such as system response time and uptime to gauge the reliability and efficiency of the vehicle's hardware and software. Each category reflects a different aspect of intelligence, collectively contributing to the vehicle's overall capability.

In the PI category, features like Infotainment System Quality assess user interface and system responsiveness, while Software Efficiency evaluates the speed and reliability of onboard software systems. CI, on the other hand, involves the vehicle's ability to perceive and interpret its environment. This includes Advanced Driver-Assistance Systems (ADAS), sensor accuracy, environmental awareness, and data processing capabilities. CI is quantified through performance measures such as object recognition accuracy, sensor fusion efficacy, and latency in data processing, which are critical for safe and intelligent vehicle operations. In the context of CI, Decision Making refers to the analytical processing and interpretation of data, enabling the vehicle to make informed decisions about its driving strategy. Guo *et al.* outlines critical factors and metrics for assessing drivability and safety, highlighting the importance of robust and interpretable data analysis systems in autonomous driving [25]. FI represents the vehicle's decision-making and operational abilities. This includes its capacity to make real-time decisions, adapt to new situations, and execute complex driving maneuvers autonomously. FI is assessed by testing the vehicle's ability to execute decisions under various simulated conditions, measuring factors like decision accuracy, adaptability to changing scenarios, and execution time of maneuvers. It's in this category that Decision Making's role in executing selected actions and maneuvers in real-time scenarios becomes evident. The integration of these measurements provides a comprehensive view of a vehicle's intelligence, combining qualitative assessments with quantitative data to benchmark against established standards. Therefore, while CI encompasses the cognitive aspect of decision-making—the 'thinking' process—FI embodies the practical application of these decisions—the 'doing' part. Figure 1 visually represents the conceptual framework of the MIQ, detailing the distinct yet interconnected roles of PI, CI, and FI. In the framework, PI pertains to tangible technological robustness like Infotainment System Quality and Software Efficiency, essential for the operational effectiveness of the vehicle. CI deals with the vehicle's capability to perceive and process environmental data, which is critical for intelligent decision-making. FI, meanwhile, applies these cognitive evaluations in real-world scenarios, demonstrating the vehicle's ability to execute decisions effectively. The attributes for each category is not exhaustive and other features could be added. Nevertheless, the figure serves as a foundational guide, illustrating how PI, CI, and FI synergistically contribute to the overall intelligence of an autonomous vehicle. It also helps in visualizing the multi-layered structure of MIQ, providing a clear representation of how these distinct aspects of intelligence are integrated and assessed. This detailed approach to quantifying each intelligence component ensures that the MIQ framework not only assesses but also provides actionable insights that can drive improvements in vehicle design and functionality.

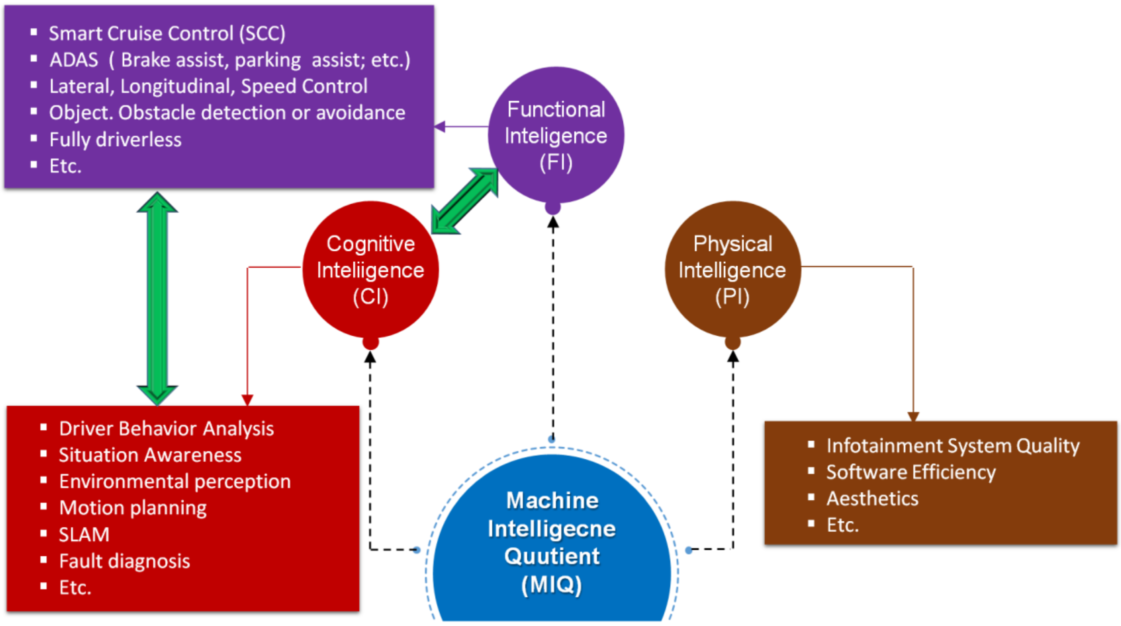

Figure 1. MIQ—The conceptual diagram of the presented intelligence analysis method.

As a visual aid, Figure 1 illustrates these concepts in the MIQ framework, showing how PI, CI, and FI synergistically contribute to an autonomous vehicle's intelligence. It particularly illuminates the dual role of Decision Making in both CI and FI, emphasizing its importance in a holistic assessment of vehicle intelligence.

3.2.1 Hybrid intelligence and co-evolutionary systems in MIQ

Within the dynamic domain of artificial intelligence, the MIQ framework innovatively integrates Hybrid Intelligence and co-evolutionary systems, aligning directly with our research objectives to quantify the intelligence of autonomous vehicles. The groundbreaking notion of a driverless car is a paradigm shift advocating a measured morphing of the car from an electro-mechanical manually operated vehicle into an autonomous robot whereby the role of the human driver is being redefined from the sole controller to a member of a complex human-robot collaborative system. Within this context, hybrid Intelligence synthesizes human cognitive capabilities with advanced AI technologies, enabling systems that capitalize on the combined strengths to excel in problem-solving and decision-making. This synergy is indispensable in autonomous vehicles, facilitating rapid and effective decisions across diverse operational scenarios. Co-evolutionary Hybrid Intelligence encapsulates the ongoing interaction and mutual enhancement between human and artificial intelligence elements within these systems. This interaction fosters a continuous evolutionary cycle of learning and adaptation, enhancing both the performance and versatility of the system. Such a framework is essential for developing cognitive architectures that emulate complex human thought processes, ensuring our vehicles not only execute predefined tasks but also dynamically adapt and evolve in response to new challenges and environmental stimuli.

Implications for cognitive architectures. Embedding Hybrid and Co-evolutionary Intelligence within the MIQ framework enhances its compatibility with advanced cognitive architectures designed to replicate human cognitive processes. These processes, encompassing perception, decision-making, learning, and memory, are crucial for the autonomous systems assessed by the MIQ. The integration of human insights and adaptive AI technologies underpins the development of intelligent systems that are not only operationally effective but also capable of continuous learning and adaptation. This approach substantiates the mathematical models used in MIQ, where the weighting and sensitivity analyses are designed to reflect the composite intelligence of the vehicle, fostering an environment where artificial systems reach and potentially exceed human cognitive abilities in specific contexts. By focusing on these integrative and evolutionary aspects, the MIQ framework is positioned not merely as a metric for intelligence assessment but as a strategic tool for advancing intelligent system design. This ensures that autonomous vehicles are assessed on their ability to perform and adapt, reflecting the sophisticated interplay of various intelligence metrics outlined in our research. This holistic approach aligns with the cutting-edge research on hybrid and co-evolutionary intelligence systems, offering a robust foundation for future advancements in autonomous vehicle technologies [26-29].

3.2.2 Integration of Auto-Poetic systems and conflicting structures

The notion of autopoiesis, initially introduced by Maturana and Varela and further elaborated by Lefebvre, provides a critical lens through which we can examine the self-sustaining and self-regulating capabilities of autonomous systems [30,31]. This concept is particularly relevant to autonomous vehicles, which are designed to operate independently, learning from and adapting to their environment without external intervention. The MIQ framework seeks to embody this principle by incorporating a specialized metric that evaluates the vehicle’s capacity for maintaining operational integrity and adapting to unforeseen conditions autonomously. In addition to autopoietic capabilities, our framework addresses the complexities of conflicting structures within intelligent systems. Such conflicts, especially prevalent in autonomous vehicles, often involve competing priorities such as the trade-offs between safety and efficiency or passenger comfort *versus* adherence to traffic regulations. The MIQ methodology integrates a detailed analysis of how these dilemmas are managed by the vehicle’s decision-making algorithms. This not only assesses the outcomes but also scrutinizes the decision-making processes, providing a comprehensive view of the vehicle’s ability to achieve operational harmony and intelligence efficiency. This integrated approach within the MIQ framework enables a holistic evaluation of autonomous vehicles, moving beyond traditional performance metrics to assess their inherent intelligent capabilities and sustainability. By including these dimensions, the MIQ is positioned as a robust and adaptive tool, well-suited for the complexities of modern intelligent systems in dynamic and often unpredictable real-world environments. This methodology ensures that the MIQ remains relevant and effective for benchmarking the intelligence of autonomous systems, supporting ongoing advancements in vehicle technology and AI applications.

4. Categorization and measurement of vehicle intelligence

4.1. Physical Intelligence (PI)

In the context of MIQ, PI is a critical category that focuses on the vehicle's hardware and software aspects. This includes an evaluation of the vehicle's sensory hardware, computing units, and the robustness of its physical components. The reliability and durability of these components are paramount, as they form the foundation upon which the vehicle operates. Additionally, software efficiency is a key aspect of PI, involving the examination of the algorithms and programming that drive the vehicle's operations. Assessing PI involves rigorous testing of the vehicle's physical systems under various conditions to evaluate their performance, reliability, and resilience.

4.2. Cognitive Intelligence (CI)

CI within the MIQ framework refers to the vehicle's ability to perceive, interpret, and respond to its environment. This encompasses the vehicle's sensory systems, such as cameras, radar, and LIDAR, and their ability to accurately capture and interpret external information. CI also involves assessing how well the vehicle processes this information to understand its surroundings—a critical factor in autonomous navigation. Integration with cognitive systems such as ACTR would substantially contribute to CI. Omeiza *et al.* survey current explanations in autonomous driving, presenting methodologies that enhance the interpretability of AI decisions [32]. Additionally, Atakishiyev *et al.* offer a comprehensive overview of explainable AI applications in autonomous driving, highlighting the necessity for integrating explanations into the human-machine interface to foster trust and improve situational awareness [33]. The evaluation of CI includes testing the vehicle's environmental perception capabilities, such as its ability to detect and react to obstacles, interpret traffic signals, and understand road conditions. This also extends to assessing the vehicle's interaction with human drivers, particularly in how it adapts to their behaviour and provides necessary feedback or assistance. The accuracy, speed, and reliability of these cognitive processes are crucial metrics in determining a vehicle's CI score.

4.3. Functionality Intelligence (FI)

FI is perhaps the most dynamic aspect within the MIQ framework. It assesses the vehicle's decision-making abilities and its effectiveness in executing complex functions autonomously. This includes evaluating how the vehicle reacts in real-time to various traffic scenarios, its problem-solving capabilities, and its adaptability to changing conditions. Testing for FI involves creating a series of controlled scenarios and simulations to assess the vehicle's autonomous functions. This includes its ability to navigate complex environments, make safe and effective decisions in emergency situations, and learn from new experiences to improve future performance. The vehicle's operational efficiency, particularly in executing driving tasks and adapting to new challenges, is a key measure of its FI.

5. Research objectives and hypotheses

In this study, the focus is on developing a robust framework for the MIQ to assess the intelligence of autonomous vehicles. The research is tailored to encapsulate the details of autonomous technology, integrating various intelligence aspects that these advanced vehicles exhibit. The specific objectives and hypotheses set to guide this research are summarized in Table 1.

Table 1. Research objectives and hypotheses with validation approaches.

Objective No.	Research Objective	Associated Hypothesis	Validation Method
Objective 1	To define and conceptualize the three-fold intelligence in MIQ.	The three-fold intelligence in MIQ (PI, CI, and FI) provides a holistic measure of a vehicle's intelligence.	Conceptual analysis through literature review and expert consultations to refine the definitions of PI, CI, and FI.
Objective 2	To assess PI of autonomous vehicles.	Higher PI in vehicles corresponds to greater hardware and software quality, ensuring optimal performance and safety.	Experimental testing of hardware and software components in controlled environments, using metrics like system response times.
Objective 3	To understand and evaluate CI in vehicles.	Advanced CI enhances adaptability and interaction with the environment.	Field tests and sensor performance evaluations, particularly focusing on environmental perception and data processing capabilities.
Objective 4	To gauge the FI of vehicles.	The level of FI directly affects the vehicle's operational effectiveness in complex scenarios.	Simulations and operational tests in varied driving conditions to assess decision-making processes and response efficacy.
Objective 5	To formulate the MIQ using PI, CI, and FI metrics.	The MIQ formula provides a reliable and standardized measure of vehicle intelligence, facilitating comparisons and benchmarking.	Application of the MIQ framework to validate its reliability and standardization across different contexts.

6. Mathematical representation and analysis of MIQ

6.1. Mathematical representation of MIQ

The calculation of the MIQ is a key aspect of our framework, incorporating a mathematical model that thoroughly evaluates the intelligence of autonomous vehicles. This model utilizes a weighted formula, taking into account the sensitivity values of each intelligence category: PI, CI, and FI. To enhance reproducibility and ensure that the MIQ model can be consistently applied across different studies, detailed specifications on how each sensitivity value is derived are provided. In determining the MIQ, we first focus on the sensitivity values for each intelligence category and their subsequent weighted contributions. This approach ensures a refined assessment, reflecting the complex nature of vehicle intelligence.

(1) *Sensitivity Values:* The sensitivity value for each category (PI, CI, and FI) is derived as the average of its subfactor analysis. This means each category's sensitivity, S_{PI}, S_{CI}, and S_{FI}, is calculated using Equation 1:

$$\mathrm{S_{PI}} = \frac{\sum \mathrm{S_i}}{\mathrm{N}}, \mathrm{S_{CI}} = \frac{\sum \mathrm{S_i}}{\mathrm{N}}, \mathrm{S_{FI}} = \frac{\sum \mathrm{S_i}}{\mathrm{N}} \tag{1}$$

Here, S_i represents the sensitivity of the i^{th}subfactor within each category. The sum of sensitivities $\sum S_i$ for each subfactor is divided by N, the number of subfactors, to get the average sensitivity for that intelligence type. This method ensures that each sensitivity value accurately reflects the performance of subfactors in a standardized manner, allowing for consistent and meaningful comparisons across different vehicle assessments.

(2) *Weighted Formula:* The overall sensitivity, S_{total}, which forms the basis of the MIQ score, is determined using Equation 2:

$$S_{total} = \frac{\alpha_{PI} S_{PI} + \alpha_{CI} S_{CI} + \alpha_{FI} S_{FI}}{\alpha_{PI} + \alpha_{CI} + \alpha_{FI}} \tag{2}$$

In this equation, α_{PI}, α_{CI}, and α_{FI} are weighting coefficients for PI, CI, and FI, respectively. These coefficients are assigned based on their relative importance and reflect the contribution of each intelligence type to the overall MIQ. The coefficients are determined based on expert consensus or empirical data, reflecting the relative impact of each intelligence category on the overall vehicle intelligence. The choice of these coefficients is crucial as it reflects the varied significance of each intelligence factor.

In refining the MIQ's mathematical representation, special attention was given to the determination of sensitivity values and weighting coefficients, which are essential for the reproducibility of the framework. Sensitivity values for each intelligence category—Physical, Cognitive, and Functional Intelligence—are computed using a standardized approach where the performance metrics of each subfactor are aggregated and normalized. This process is detailed in Equation 1, where S_{PI}, S_{CI} and S_{FI} are calculated by averaging the normalized performance scores of the respective subfactors. The normalization process adjusts the raw data to a uniform scale, thereby mitigating the influence of outlier values and ensuring that the sensitivity scores accurately reflect the operational effectiveness of the vehicle features under varied conditions.

The weighting coefficients, α_{PI}, α_{CI}, and α_{FI} , integral to the computation of the overall MIQ score, are derived through a structured expert assessment. This involves a panel of interdisciplinary experts who evaluate the relative importance of each intelligence category based on their expertise and current industry standards. The assessment utilizes a quantitative scoring system outlined in Equation 2, where experts rate each category's impact on overall vehicle intelligence. The scores are then statistically analyzed to achieve a consensus, ensuring that the weight assigned to each category reflects its true significance in the broader context of autonomous vehicle capabilities. This rigorous method enhances the transparency and adaptability of the MIQ, facilitating its application across different vehicle assessments and contributing to its scientific robustness.

The final MIQ score is calculated by applying Equation 3, which scales the total sensitivity to a value analogous to human IQ scores:

$$MIQ = 160. S_{total} \quad (3)$$

This equation multiplies the total sensitivity score by 160, aligning the MIQ score with the scale typically used for human intelligence quotients. The choice of 160 as a multiplier ensures that the MIQ score is reflective of the percentage of objects or functions correctly detected by the vehicle, scaled in a manner comparable to human IQ evaluations. Furthermore, the MIQ architecture, as illustrated in Figure 1, is versatile and applicable across various types of vehicles, including autonomous, semi-autonomous, and non-autonomous models. This flexibility allows for a comprehensive assessment of vehicle intelligence, irrespective of the level of autonomy. The MIQ model evaluates autonomous vehicles using PI and FI metrics, while traditional vehicles are assessed using FI and CI metrics. Semi-autonomous vehicles, which incorporate features from both spectrums, are evaluated using all three intelligence categories: FI, CI, and PI.

In conclusion, the mathematical representation of MIQ offers a rigorous and systematic approach to evaluating the intelligence of vehicles. By carefully balancing the contributions of Physical, Cognitive, and Functional intelligence and aligning the scoring with human IQ scales, the MIQ provides a thorough and scientifically robust tool for understanding and comparing the intelligence of various vehicle systems. This detailed approach ensures that the MIQ is both reproducible and adaptable, providing a reliable method for assessing vehicle intelligence across different contexts and studies. It not only contributes to the advancement of autonomous vehicle technology but also sets a precedent for future research and development in the field.

6.2. Weighting scheme and sensitivity analysis

The weighting scheme in the MIQ formula plays a central role, as it defines the relative importance of each intelligence category. A panel of experts from various fields related to autonomous vehicle technology is typically used to assign these weights $\alpha_{PI}, \alpha_{CI},$ and α_{FI} based on a constant and standard value, reflecting the significance of each category in the overall intelligence assessment of the vehicle. This method involves several rounds of surveys where experts provide their input on the relative importance of each category, which is then statistically analyzed to reach a consensus. Sensitivity analysis forms an integral part of the MIQ formulation. In this context, sensitivity refers to the accuracy with which the vehicle detects and responds to various objects or functions within its environment. Each sensitivity measure, ranging between 0 and 1, is vital in evaluating the vehicle's performance in specific tasks and its responsiveness to stimuli. The outcomes of these analyses are crucial for fine-tuning the MIQ model, ensuring that it accurately reflects the vehicle's operational capabilities and adaptiveness in real-world scenarios. The aggregation of these sensitivities, weighed appropriately, culminates in the MIQ, offering a comprehensive assessment of the vehicle's intelligence. This mathematical representation and the accompanying weighting and sensitivity analysis offer a systematic and rigorous approach to evaluating vehicle intelligence. By aligning the MIQ score with human IQ scales and considering the contributions of different intelligence types, this methodology provides a thorough and scientifically robust tool for comparing various vehicle systems. It contributes notably to the advancement of autonomous vehicle technology and sets a standard for future research and development in the field.

7. Experimental design for S values—case study: 2024 Hyundai Palisade

The 2024 Hyundai Palisade, with its integration of cutting-edge autonomous and semi-autonomous features, stands as an exemplary model for the application of the MIQ framework. This vehicle, emblematic of modern automotive advancements, offers a rich array of technologies and systems that align perfectly with the MIQ's analytical dimensions. By leveraging the diverse capabilities of the Hyundai Palisade, this case study aims to thoroughly apply and validate the MIQ framework, providing a comprehensive and tangible assessment of vehicle intelligence. The experimental design structured for this purpose systematically addresses each intelligence category outlined in MIQ: PI, CI, and FI. These categories, encompassing a wide range of vehicle attributes and capabilities, are critical in painting a complete picture of the vehicle's intelligent behaviour and performance. The S values, (S_{PI}, S_{CI} and S_{FI}), or sensitivity values, are crucial in this analysis as they quantify the effectiveness and accuracy of the Palisade's features within these intelligence domains. For PI, the experiments focus on the tangible, hardware aspects of the vehicle, including its robustness, technological infrastructure, and cybersecurity measures. CI experiments investigate the vehicle's sensory and data processing capabilities, assessing how it perceives, interprets, and interacts with its environment and the driver. Lastly, FI experiments are geared towards evaluating the Palisade's decision-making abilities and operational efficiency, particularly in scenarios that demand autonomous control and response. This experimental design, therefore, is not only about assessing the presence of various features but also about critically evaluating their performance, integration, and contribution to the overall intelligence of the Hyundai Palisade. By thoroughly calculating the S values across these three intelligence categories, this case study aims to provide a detailed understanding of the MIQ in the context of a modern, sophisticated autonomous vehicle.

7.1. Experimental design for S values

The application of the MIQ framework to the 2024 Hyundai Palisade involves a comprehensive experimental approach to evaluate the vehicle's intelligence across three distinct categories: PI, CI, and FI. This section details the experimental design tailored to the specific features of the Palisade, aiming to derive precise sensitivity values (S values) for each intelligence category. The experiments are structured to assess the key attributes of the vehicle that significantly contribute to its overall intelligence quotient.

Experimental framework. The experimental design is based on a series of practical tests, each focused on a particular feature of the Hyundai Palisade that aligns with the definitions of PI, CI, and FI within the MIQ model. For instance, the ‘Software Efficiency’ test involved measuring the response time of the vehicle’s onboard systems under various operational conditions, thereby assessing the efficiency and reliability of the software.

Methodology. Each experiment is designed to be as controlled and repeatable as possible, ensuring the reliability and validity of the results. The methodology includes:

(1) *Setting up controlled environments* for testing, where variables can be systematically manipulated and observed.

(2) *Defining clear evaluation criteria* for each test, based on the expected range of results, to ensure consistent assessment across trials.

(3) *Conducting multiple trials* for each experiment to account for variability and enhance the robustness of the findings.

(4) *Gathering and analyzing data* from each test, using both quantitative measures (like response times, accuracy percentages) and qualitative observations (like system robustness under stress).

To further illustrate the quantification process, table 2 presents detailed calculations of S values for two specific features—Software Efficiency and Navigation-Based Smart Cruise Control (NSCC)—serving as examples of how data is processed and sensitivity values are derived across different evaluations within our experimental framework.

Table 2. Detailed calculation of S values for software efficiency and navigation-based smart cruise control.

Feature	Iteration	Raw Data (s)	Normalized Score	Comment
Software Efficiency	1	1.2s	0.60	Normalized Score = 1 − (1.2s / 3s)
	2	1.4s	0.53	Normalized Score = 1 − (1.4s / 3s)
	3	1.1s	0.63	Normalized Score = 1 − (1.1s / 3s)
	4	1.5s	0.50	Normalized Score = 1 − (1.5s / 3s)
	5	1.6s	0.47	Normalized Score = 1 − (1.6s / 3s)
	6	1.3s	0.57	Normalized Score = 1 − (1.3s / 3s)
	7	1.4s	0.53	Normalized Score = 1 − (1.4s / 3s)
	8	1.2s	0.60	Normalized Score = 1 − (1.2s / 3s)
	9	1.3s	0.57	Normalized Score = 1 − (1.3s / 3s)
	10	1.5s	0.50	Normalized Score = 1 − (1.5s / 3s)
	Average S Value	-	**0.55**	Calculated from Normalized Scores
NSCC	1	1	1.00	Successful adaptation
	2	1	1.00	Maintained distance
	3	0	0.00	Failed to adjust speed
	4	1	1.00	Handled bends smoothly
	5	1	1.00	Adjusted well in construction zone
	6	0	0.00	Did not reduce speed in time
	7	1	1.00	Navigated complex intersection

Table 2. *Cont.*

Feature	Iteration	Raw Data (s)	Normalized Score	Comment
	8	1	1.00	Maintained safe following distance
	9	0	0.00	Struggled with lane changes
	10	1	1.00	Effective performance
	Average S Value	-	**0.70**	Calculated from Scores

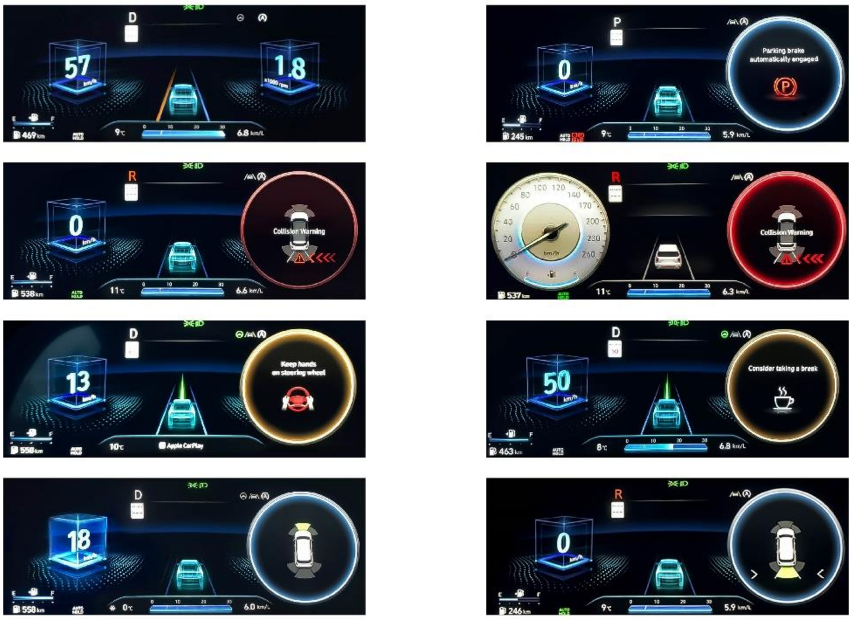

Figure 2. Display of key features in the 2024 Hyundai Palisade.

To illustrate the practical implementation of these features, Figure 2 displays the instrument cluster of the 2024 Hyundai Palisade, showing several key systems, including Lane Following Assist and safety functionalities. This visual representation exemplifies how the vehicle integrates advanced technologies into its user interface, contributing to its overall intelligence quotient.

Goals and expected outcomes. The primary goal of these experiments is to accurately quantify the performance of each feature within the PI, CI, and FI categories. The expected outcomes include a set of S values that reflect the effectiveness, reliability, and sophistication of the Hyundai Palisade's various intelligent features. These values will be essential in calculating the overall MIQ score for the vehicle, offering an empirical and detailed understanding of its intelligence. Table 3 summarizes the results of our experimental evaluations. For each feature within the categories of PI, CI, and FI, we have calculated the average S values. These values are derived from the normalization process of raw performance data. Each S value represents the average of normalized scores from multiple iterations, ensuring a comprehensive evaluation of feature effectiveness. For clarity, 'Average S values' reflect individual assessments for each feature rather than a cumulative total sensitivity which would encompass an aggregated score across multiple features or categories. These values are indicative of the performance and effectiveness of each feature, as assessed through our rigorous experimental process.

Table 3. S value assessment for 2024 Hyundai Palisade MIQ evaluation.

Intelligence Type	Feature	Experiment Description	Average S Value
Physical Intelligence (PI)	Infotainment System Quality	Evaluation of response time and user interface quality	0.57
Cognitive Intelligence (CI)	Software Efficiency	Testing for speed and reliability of onboard software systems	0.55
	Driver Behaviour Analysis and Situation Assessment	Monitoring and analysis of driver behaviour for safety and comfort	0.80
	Environmental Perception and Situation Awareness	Sensor testing in diverse conditions for accurate environmental mapping	0.80
	Decision Making	Assessing decision-making in urban traffic scenarios	0.90
Functionality Intelligence (FI)	Smart Cruise Control (SCC)	Assessing the effectiveness and reliability of adaptive cruise control systems	0.80
	Lane Following Assist (LFA)	Evaluation of lane keeping capabilities under various driving conditions	0.90
	Highway Driving Assist (HDA)	Testing highway-specific features like speed adaptation and lane changing	0.90
	Navigation-Based Smart Cruise Control (NSCC)	Analyzing the integration of navigation data with cruise control	0.70
	Parking and Safety Systems	Assessing the efficiency and reliability of parking aids and safety features	0.90

These experimental results provide valuable insights into the strengths and areas for improvement within the Hyundai Palisade's various intelligent systems. The high S values in certain features, particularly within the Functionality Intelligence category, demonstrate the vehicle's advanced capabilities in autonomous driving and safety systems. Conversely, the areas with lower S values, such as some aspects of Physical Intelligence, suggest opportunities for further enhancement in user interface and system responsiveness. This comprehensive assessment of the Palisade's intelligence not only illustrates its current capabilities but also guides future advancements in vehicle technology.

Detailed S value assessment for 2024 Hyundai Palisade in MIQ evaluation

This comprehensive analysis leads us to Table 4, which encapsulates the S Value assessment for the 2024 Hyundai Palisade, integral to its MIQ evaluation. Covering the three intelligence categories—PI, CI, and FI—this section details the methodology, experimental framework, and the resulting S values derived from this comprehensive analysis.

Table 4. S value assessment with iterations for 2024 Hyundai Palisade.

Intelligence Category	Feature	Iterations (Raw Data)	S Value (Normalized Average)
Physical Intelligence (PI)	Infotainment System Quality	1.2s, 1.3s, 1.1s, 1.4s, 1.5s, 1.3s, 1.2s, 1.1s, 1.4s, 1.5s	0.57
	Software Efficiency	1.2s, 1.4s, 1.1s, 1.5s, 1.6s, 1.3s, 1.4s, 1.2s, 1.3s, 1.5s	0.55
Cognitive Intelligence (CI)	Driver Behaviour Analysis and Situation Assessment	1, 0, 1, 1, 1, 1, 1, 1, 0, 1	0.80
	Environmental Perception and Situation Awareness	1, 1, 1, 1, 0, 1, 1, 0, 1, 1	0.80
	Decision Making	1, 1, 1, 1, 1, 1, 0, 1, 1, 1	0.90
Functionality Intelligence (FI)	Smart Cruise Control (SCC)	1, 1, 0, 1, 1, 1, 0, 1, 1, 1	0.80
	Lane Following Assist (LFA)	1, 1, 1, 0, 1, 1, 1, 1, 1, 1	0.90
	Highway Driving Assist (HDA)	1, 1, 1, 1, 1, 1, 0, 1, 1, 1	0.90
	Navigation-Based Smart Cruise Control (NSCC)	1, 1, 0, 1, 1, 0, 1, 1, 0, 1	0.70
	Parking and Safety Systems	1, 1, 1, 1, 1, 1, 0, 1, 1, 1	0.90

$$S_{category} = \frac{\sum S_i}{N}$$

where $\sum S_i$ is the sum of the sensitivity scores for all features within a category, and N is the number of features in that category.

Based on the data from Table 4:

For PI:

(1) Features: Infotainment System Quality (0.57), Software Efficiency (0.55)

(2) $S_{PI} = \frac{(0.57+0.55)}{2} = \frac{1.12}{2} = 0.56$

For CI:

(1) Features: Driver Behaviour Analysis (0.80), Environmental Perception (0.80), Decision Making (0.90)

(2) $S_{CI} = \frac{(0.8+0.8+0.9)}{3} = \frac{2.5}{3} = 0.83$

For FI:

(1) Features: Smart Cruise Control (SCC) (0.80), Lane Following Assist (LFA) (0.90), Highway Driving Assist (HDA) (0.90), Navigation-Based Smart Cruise Control (NSCC) (0.70), Parking and Safety Systems (0.90)

(2) $S_{FI} = \frac{(0.8+0.9+0.9+0.7+0.9)}{5} = \frac{4.2}{5} = 0.84$

(3) Therefore, the average sensitivity values for each intelligence category are:

$$S_{PI} = 0.56$$
$$S_{CI} = 0.83$$
$$S_{FI} = 0.84$$

7.2. MIQ expert assessment

The MIQ framework for the 2024 Hyundai Palisade includes a critical component known as the MIQ Expert Assessment. This process involves gathering insights from industry experts to determine the weighting coefficients (α_{PI}, α_{CI}, α_{FI}) for each intelligence category—PI, CI, and FI. These alpha values are fundamental in calculating the MIQ, reflecting the relative importance assigned to each category in the vehicle's overall intelligence assessment.

Expert panel selection and questionnaire development. To ensure a comprehensive assessment, we assembled a diverse panel of experts from fields such as automotive engineering, artificial intelligence, and human-machine interaction. This diversity provided a breadth of perspectives crucial for a holistic evaluation of autonomous vehicle technology. A detailed questionnaire was developed to capture these experts' insights into the significance of each intelligence category. This questionnaire included scales from 0 (not important) to 10 (extremely important) ensuring a thorough capture of expert opinions. In the process of conducting the MIQ expert assessment for the 2024 Hyundai Palisade, a range of ratings was collected from the panel of experts. These ratings, crucial in assigning the alpha values for each intelligence category, were interpreted according to a predefined significance scale. This scale helped in quantitatively categorizing the importance that experts placed on each feature of the vehicle. Table 5 outlines this rating scale, offering a clear understanding of how the numerical ratings correspond to the level of significance as perceived by the experts.

Table 5. Expert rating significance scale.

Rating Range	Significance
0-2	Very Low
3-4	Low
5-6	Moderate
7-8	High
9-10	Very High

This scale was instrumental in interpreting the expert ratings, which were then used to determine the weighted significance of each feature in the MIQ framework. Higher ratings indicated a greater perceived importance of a feature, influencing its weight in the overall MIQ calculation.

Administration of the questionnaire. The questionnaire was administered to the expert panel through a combination of online and in-person methods, depending on the availability and preference of the participants. Sufficient time was given to allow for thoughtful and considered responses, and follow-up discussions were conducted where necessary to clarify responses or gather additional information.

Data analysis and alpha value determination. Once the responses were collected, the data was analyzed to determine the alpha values for each intelligence category. This process involved:

(1) *Compiling and reviewing responses:* All quantitative and qualitative data from the questionnaire were compiled and reviewed to understand the experts' perspectives.
(2) *Calculating average ratings:* The average rating for each intelligence category was calculated based on the numerical scores provided by the experts.
(3) *Assigning alpha values:* These average ratings were then used to assign the alpha values (α_{PI}, α_{CI}, α_{FI}). The values were normalized to ensure that their sum equaled 1, maintaining the balance in the MIQ calculation.

Incorporation into the MIQ framework. The alpha values derived from the expert assessment were incorporated into the MIQ formula for the 2024 Hyundai Palisade, ensuring that the final MIQ score reflected not only empirical data from the sensitivity tests but also expert opinion on the relative importance of each intelligence category. This approach added a layer of depth and validity to the MIQ assessment, grounding it in both quantitative analysis and industry expertise. For each feature, we will follow a systematic process to assess its intelligence quotient. Let's take a hypothetical feature of the 2024 Hyundai Palisade, such as its advanced collision avoidance system, to illustrate this process:

Identification: First, we identify the feature—in this case, the advanced collision avoidance system.

Operational testing: We conduct a series of tests to evaluate how this feature operates under various conditions, including city driving, highway conditions, and in different weather scenarios.

Performance measurement: The performance of the feature is measured based on its responsiveness, accuracy, and reliability. For instance, we assess how effectively and quickly the collision avoidance system reacts to unexpected obstacles.

Sensitivity calculation: Based on the performance data, we calculate the sensitivity value (S) for this feature. This involves analyzing the percentage of objects or functions detected correctly by the system.

Expert assessment results: The culmination of this expert assessment process is summarized in Table 6, presenting the average expert ratings for each feature within the PI, CI, and FI categories. These ratings, when translated into alpha values, provide a detailed understanding of each category's significance and impact on the overall MIQ score for the Palisade.

Table 6. Expert assessment results for 2024 Hyundai Palisade MIQ evaluation.

Intelligence Type	Feature	Average Expert Rating
Physical Intelligence (PI)	Infotainment System Quality	7.4
	Software Efficiency	6.8
Cognitive Intelligence (CI)	Driver Behaviour Analysis and Situation Assessment	8.4
	Environmental Perception and Situation Awareness	8.4
	Decision Making	9.0
	Smart Cruise Control (SCC)	8.2
Functionality Intelligence (FI)	Lane Following Assist (LFA)	6.8
	Highway Driving Assist (HDA)	9.2

Table 6. *Cont.*

Intelligence Type	Feature	Average Expert Rating
	Navigation-Based Smart Cruise Control (NSCC)	8.0
	Parking and Safety Systems	8.6

These results demonstrate a noteworthy appreciation for the vehicle's advanced features, particularly in the areas of FI and CI, indicating recognition of their importance in the overall intelligence of the Palisade.

Comprehensive expert assessment of MIQ features for the 2024 Hyundai Palisade

Building on this assessment, Table 7 provides a detailed overview of the expert assessment results for the MIQ evaluation of the 2024 Hyundai Palisade. This table collates the average expert ratings for each feature, offering a detailed understanding of their perceived importance across the PI, CI, and FI categories.

Table 7. Full expert assessment results.

Intelligence Type	Feature	Sub-Feature	Expert 1 Rating	Expert 2 Rating	Expert 3 Rating	Expert 4 Rating	Expert 5 Rating	Average Rating
Physical Intelligence (PI)	Software Efficiency		6	7	8	6	7	6.8
	Infotainment System Quality		7	8	9	7	6	7.4
Cognitive Intelligence (CI)	Driver Behaviour Analysis and Situation Assessment		9	8	7	9	9	8.4
	Environmental Perception and Situation Awareness		8	9	10	8	7	8.4
	Decision Making		9	9	8	10	9	9.0
Functionality Intelligence (FI)	Autonomous Driving Features	Smart Cruise Control (SCC)	9	8	9	8	7	8.2
		Lane Following Assist (LFA)	7	6	8	7	6	6.8
		Highway Driving Assist (HDA)	10	9	9	10	8	9.2
		Navigation-Based Smart Cruise Control (NSCC)	8	7	8	9	8	8.0

Table 7. *Cont.*

Intelligence Type	Feature	Sub-Feature	Expert 1 Rating	Expert 2 Rating	Expert 3 Rating	Expert 4 Rating	Expert 5 Rating	Average Rating
	Parking and Safety Systems	Rear Cross-Traffic Collision-Avoidance Assist (RCCA)	9	8	7	9	10	8.6

Physical Intelligence (PI): The features are Software Efficiency and Infotainment System Quality.

(1) Average Rating for PI $= \frac{(6.8+7.4)}{2} = 7.1$

Cognitive Intelligence (CI): The features are Driver Behaviour Analysis and Environmental Perception.

(2) Average Rating for CI $= \frac{(8.4+8.4+9.0)}{3} = 8.6$

Functionality Intelligence (FI): The features are SCC, LFA, HDA, NSCC, RCCA.

(3) Average Rating for FI $= \frac{(8.2+6.8+9.2+8.0+8.6)}{5} = 8.16$

Next, we calculate the total average rating across all categories:

$$\text{Total Average Rating} = 7.1 + 8.6 + 8.16 = 23.86$$

Now, we calculate the alpha values:

$$\alpha_{PI} = \frac{7.1}{23.86} = 0.30$$
$$\alpha_{CI} = \frac{8.6}{23.86} = 0.36$$
$$\alpha_{FI} = \frac{8.16}{23.86} = 0.34$$

These alpha values are the normalized weights for each intelligence category, indicating their relative importance in the overall MIQ calculation.

7.3. Ethical considerations in AI and autonomous vehicle Decision-Making

As we advance the MIQ framework to more closely mirror human intelligence, it becomes imperative to address the ethical dimensions that accompany increased decision-making capabilities in autonomous systems. While MIQ primarily assesses computational intelligence akin to human IQ, ethical decision-making—often associated with emotional intelligence (EQ)—is not currently captured by MIQ but is equally crucial for the holistic evaluation of autonomous vehicles. The integration of ethical considerations into AI systems goes beyond mere compliance with predefined ethical principles and protocols; it involves embedding a deeper understanding of morality directly into the decision-making processes. This requirement is particularly acute in scenarios where autonomous vehicles may face decisions with significant moral implications, such as accident avoidance maneuvers that pose ethical dilemmas regarding potential harm to different parties.

Incorporating Emotional and Moral Intelligence: Future enhancements of the MIQ should consider elements of emotional and moral intelligence, which are vital for making ethical decisions. Research in AI ethics has highlighted that high IQ does not necessarily equate to good decision-making and that moral and ethical competencies are essential for preventing harm and ensuring fairness [34]. Therefore, expanding MIQ to include these dimensions could lead to more comprehensive assessments of autonomous intelligence.

Relation to General AI and Deep Learning: The relationship between deep learning, a core component of modern AI, and human-like intelligence includes the potential for these systems to learn ethical behaviours if properly guided by frameworks that incorporate ethical training data and objectives [35]. As such, the evolution of general AI should be guided by robust ethical frameworks that not only respect legal standards but also adhere to higher moral standards traditionally associated with human society.

8. Analysis and Implications

In the comprehensive MIQ evaluation of the 2024 Hyundai Palisade, the synthesis of experimental S values and expert alpha assessments has painted a detailed picture of the vehicle's intelligence. The data indicates a robust performance in the FI domain, particularly in advanced autonomous features like HDA and SCC, as reflected in their high S values. These results highlight the Palisade's proficiency in complex, real-world driving scenarios, spotlighting its cutting-edge autonomous capabilities. Conversely, certain aspects within PI and CI echo the human pursuit of continual learning and adaptation. The lower S values in these domains suggest avenues for enhancing user interface, system responsiveness, and environmental perception, aligning with evolving expectations in a digitally integrated world. These human-inspired findings exhibit the vehicle's potential to evolve, akin to human cognitive growth, emphasizing the need for vehicles to be not only technically efficient but also adaptable and intuitive in various conditions.

The significance of these findings is further reinforced by the expert assessments. The calculated alpha values offered a refined perspective on the relative importance of each intelligence category. The alpha values were determined as α_{PI}= 0.30, α_{CI}= 0.36, and α_{FI}= 0.34, reflecting the proportionate significance of each category in the MIQ framework. These values were instrumental in deriving the final MIQ score. The average sensitivity values for each intelligence category were calculated as S_{PI} = 0.56 for Physical Intelligence, S_{CI} = 0.83 for Cognitive Intelligence, and S_{FI} = 0.84 for Functionality Intelligence. Applying these in the MIQ formula resulted in a total sensitivity (S_{total}) of 0.7524, leading to an MIQ score of 120.38 for the Palisade.

$$S_{total} = \frac{\alpha_{PI}S_{PI} + \alpha_{CI}S_{CI} + \alpha_{FI}S_{FI}}{\alpha_{PI} + \alpha_{CI} + \alpha_{FI}} = 0.7524$$

$$MIQ = 160.S_{total} = 120.38$$

This score encapsulates a balanced assessment across the physical, cognitive, and functional domains, indicating both the strengths and potential improvement areas of the vehicle.

9. Discussion

This study's exploration of the MIQ for autonomous vehicles unveils a significant stride in harmonizing machine functionality with human-like decision-making and cognitive processes. Reflecting on SAE's autonomy levels, a vehicle at Level 5, which represents full autonomy, would ideally achieve an MIQ score of 160. This benchmark aligns with the aspiration of Vision Zero (a quest for zero traffic accidents and fatalities) [36] and advocating for autonomous cars that are not only technologically advanced but also emulate human cognitive and decision-making capabilities. Drawing on Zadeh's envision [8,9], the MIQ framework transcends mere technical proficiency and merges with artificial intelligence. It provides a holistic assessment that emphasizes the importance of CI in future vehicles. A vehicle's ability to recognize problems, assess their severity, and make critical decisions reflects a level of "thinking" akin to human intelligence. This aspect is crucial in differentiating between human drivers and autonomous cars. In this evolving landscape, the MIQ framework emerges as a key tool. It not only evaluates but also guides the development of autonomous vehicles towards achieving higher levels of intelligence and safety. As we envision vehicles operating at Level 5 autonomy, the goal extends to designing vehicles that not only navigate roads but also make decisions and adapt in a manner comparable to human drivers. This vision, inspired by Zadeh's insights, places a significant emphasis on the decision-making context, asserting that vehicles achieving Level 5 autonomy should exhibit a form of intelligence that closely mirrors human cognition and judgment.

Thus, the MIQ framework, as proposed and elaborated upon in this paper, stands as a pioneering approach. It sets a novel benchmark in the assessment of autonomous vehicles, emphasizing a human-centric approach in their design and functionality. However, there are inherent limitations in this framework that need addressing to enhance its effectiveness and applicability. The current framework may not fully account for the dynamic and unpredictable nature of real-world environments where autonomous vehicles operate. Future research should focus on incorporating more adaptive algorithms that can handle unexpected situations and non-standard conditions.

This methodology, while acknowledging the current gaps and levels of subjectivity, lays the groundwork for future advancements. It opens up avenues for more objective and comprehensive evaluations of CI in autonomous vehicles, contributing prominently to the field's advancement towards safer, more intelligent, and human-like autonomous driving experiences.

9.1. Theoretical and philosophical considerations of AI

While the MIQ framework endeavors to mirror the complexities and adaptability inherent in human intelligence, it is crucial to distinguish between the capabilities of current AI systems and the nuanced cognitive abilities of humans. Contrary to the implications of the strong AI hypothesis, which posits that machines might one day possess human-like consciousness and cognitive capacities, our framework operates under the understanding that AI exhibits forms of intelligence that are fundamentally different from human intelligence [35,37]. AI systems, including those in autonomous vehicles, are essentially tasks based and operate on algorithms and learned data (pattern matching), lacking the consciousness and emotional context that characterize human intelligence [38]. Therefore, the proposed MIQ framework should not be interpreted as equating AI capabilities directly with human thinking but rather as a tool for assessing specific aspects of intelligence that are practical and measurable within the confines of technology [39]. To further refine the MIQ framework, future studies should explore integrating qualitative assessments that consider the ethical and emotional dimensions of intelligence, ensuring a more holistic approach to autonomous vehicle evaluation. Furthermore, the philosophical implications of comparing AI to human intelligence necessitate a cautious approach. Acknowledging these differences helps prevent the overestimation of AI's capabilities and underscores the importance of ethical considerations in AI development [40]. By clarifying these distinctions, we aim to contribute to the ongoing dialogue on the appropriate applications and expectations of AI technology, ensuring that our research supports informed and responsible advancements in the field.

10. Conclusion and future directions

This paper's exploration of the MIQ as a metric for autonomous vehicle intelligence reflects a substantial stride in aligning machine performance with human cognition and behavioural patterns. The MIQ framework, with its facets of Physical, Cognitive, and Functionality Intelligence, mirrors the complexities and adaptability inherent in human intelligence. This alignment is a testament to our endeavor to infuse human-like understanding and responsiveness into autonomous systems, a goal that resonates with the foundational aspirations of artificial intelligence, as illustrated by Turing's work. Future research should focus on further integrating human behavioural insights into the MIQ framework. This includes developing evaluation methods and machine learning algorithms that not only assess, but also emulate human cognitive processes in various environmental contexts. Optimizing the weighting coefficients within MIQ would further enhance this human-centric approach, ensuring that autonomous vehicles not only exhibit high levels of intelligence but also demonstrate an understanding akin to human perception and decision-making. One should be cautious to draw parallel with the computation of IQ which is an objective process. We are aware that the computation of MIQ as outlined here has elements of subjectivity. However, we argue that the process here is the first iteration and we are already looking into the next revision that involves the CI component in order to substantiate the computation of MIQ. If we benchmark a human driver and his/her ability to drive in diverse situations; we can design a metric for CI that takes into all "capabilities" in driving scenarios and calculate an objective S value. This could include driving in standard roads, congested and not structured environments, ability to localize (SLAM embedded system), or decision making (ACT-R) capability. Having that said, we suggest that the proposed system is a sensible and rational method to address MIQ in the context of autonomous vehicles. In the future direction of our research, we aim to explore how components of moral and emotional intelligence can be quantified and integrated into the MIQ framework. This exploration will be crucial for developing autonomous systems that are not only intelligent but also capable of making morally sound decisions in complex real-world scenarios. Ethical training for AI, as discussed by authors in [33], along with integration with machine emotional intelligence models, should inform the development of these new components.

Concluding, the MIQ framework marks an important juncture in the evolution of autonomous vehicles, transcending technical capabilities to embrace a more human-centric approach. This shift is crucial as we navigate towards an era where vehicles are not just tools, but partners in mobility, reflecting the complex intelligence and adaptability that define human cognition and behaviour. As the field progresses, the integration of human-inspired intelligence in vehicles will undoubtedly be a cornerstone in shaping the future of autonomous vehicle technology.

Conflicts of interests

The authors declare no conflict of interest.

Ethical statement

The study was performed in accordance with the Declaration of Helsinki and approved by Simon Fraser University Ethics Committee (Approval Number: 30001815, Approval Date: July 10, 2023).

Authors' contribution

Conceptualization, Mehdi Cina and Ahmad Rad; methodology, Mehdi Cina, Ahmad Rad; software, Mehdi Cina; validation, Mehdi Cina, Ahmad Rad, and Abdol Rasul Rasuli; formal analysis, Mehdi Cina, Ahmad Rad; investigation, Mehdi Cina, Ahmad Rad; resources, Ahmad Rad; data curation, Abdol Rasul Rasuli; writing—original draft preparation, Mehdi Cina; writing—review and editing, Ahmad Rad; visualization, Mehdi Cina; supervision, Ahmad Rad; project administration, Ahmad Rad. All authors have read and agreed to the published version of the manuscript.

References

[1] Turing AM. Computing machinery and intelligence. *Mind* 1950, 59(236):433–460.

[2] French RM. Subcognition and the limits of the turingtest. *Mind* 1990, 99(393):53–65.

[3] Nascimento AM, Vismari LF, Molina CBST, Cugnasca PS, Camargo JB, *et al*. A systematic literature review about the impact of artificial intelligence on autonomous vehicle safety. *IEEE Trans. Intell. Transp. Syst.* 2019, 21(12):4928–4946.

[4] Xuan D, Rongye S. A survey on autonomous vehicle control in the era of mixed-autonomy: From physics-based to AI-guided driving policy learning. *Transp. Res. Part C Emerg. Technol.* 2021, 125:103008.

[5] Moor JH. The status and future of the turing test. *Mines Mach.* 2001, 11(1):77–93.

[6] Chollet F. *Deep learning with python*, 2nd ed. New York: Simon and Schuster, 2021, pp. 504.

[7] Minsky M. *The society of mind*, New York: Simon & Schuster, 1988, pp. 336.
[8] Zadeh LA. Fuzzy logic, neural networks, and soft computing. In *Fuzzy sets, fuzzy logic, and fuzzy systems: Selected papers by Lotfi A Zadeh*. Binghamton: World Scientific Publishing Co Pte Ltd, 1996, pp. 775–782.
[9] Zadeh LA. The role of fuzzy logic in modeling, identification and control. In *Fuzzy sets, fuzzy logic, and fuzzy systems: Selected papers by Lotfi A Zadeh*. Binghamton: World Scientific Publishing Co Pte Ltd, 1996, pp. 783–795.
[10] Bien Z, Bang WC, Kim DY, Han JS. Machine intelligence quotient: Its measurements and applications. *Fuzzy Sets Syst.* 2002, 127(1):3–16.
[11] Park HJ, Kim BK, Lim KY. Measuring the Machine Intelligence Quotient (MIQ) of human-machine cooperative systems. *IEEE Trans. Syst. Man Cybern. Part A Syst. Humans* 2001, 31(2):89–96.
[12] Todd L. *Autonomous vehicle implementation predictions*. Victoria: Victoria Transport Policy Institute, 2017, pp: 22.
[13] Bringsjord S, Schimanski B. What is artificial intelligence? Psychometric AI as an answer. In *Proceedings of the 18th International Joint Conference on Artificial Intelligence*, Acapulco, Mexico, 2003, pp. 887–893.
[14] Biswas A, Wang HC. Autonomous vehicles enabled by the integration of IOT, edge intelligence, 5g, and blockchain. *Sensors* 2023, 23(4):1963.
[15] Wang P. On defining artificial intelligence. *Journal of Artificial General Intelligence* 2019, 10(2):1–37.
[16] Akata Z, Perronnin F, Harchaoui Z, Schmid C. Label-embedding for image classification. *IEEE Trans. Pattern Anal. Mach. Intell.* 2015, 38(7):1425–1438.
[17] Amodei D, Olah C, Steinhardt J, Christiano P, Schulman J, *et al*. Concrete problems in AI safety. *arXiv* 2016, arXiv:1606.06565.
[18] Blili-Hamelin B, Hancox-Li L, Smart A. Unsocial intelligence: A pluralistic, democratic, and participatory investigation of agi discourse. *arXiv* 2024, arXiv:2401.13142.
[19] Liu F, Shi Y, Liu Y. Intelligence quotient and intelligence grade of artificial intelligence. *Ann. Data Sci.* 2017, 4(2):179–191.
[20] Smith BC. The foundations of computing. In *Computationalism: New directions*. Cambridg: MIT Press, 2002, pp. 23–58.
[21] Haspiel J, Du N, Meyerson J, Jr. Lionel PR, Tilbury D, *et al*. Explanations and expectations: Trust building in automated vehicles. In *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*. Chicago, pp. 119–120.
[22] Hewitt C, Politis I, Amanatidis T, Sarkar A. Assessing public perception of self-driving cars: The autonomous vehicle acceptance model. In *Proceedings of the 24th International Conference on Intelligent User Interfaces*, California, USA, 17–20 March 2019 pp. 518–527.
[23] Atakishiyev S., Salameh M., Goebel R. Incorporating explanations into human-machine interfaces for trust and situation awareness in autonomous vehicles. In *2024 IEEE Intelligent Vehicles Symposium (IV)*, Jeju Island, Republic of Korea, 2–5 June 2024, pp. 2948–2955.

[24] Chen CLP., Liu Z. Broad learning system: An effective and efficient incremental learning system without the need for deep architecture. *IEEE Trans. Neural Networks Learn. Syst.* 2018, 29(1):10–24.

[25] Guo J, Kurup U, Shah M. Is it safe to drive? An overview of factors, metrics, and datasets for driveability assessment in autonomous driving. *IEEE Trans. Intell. Transp. Syst.* 2019, 21(8):3135–3151.

[26] Goertzel B, Wang P. Adaptive algorithmic hybrids for human-level artificial intelligence. In *Advances in artificial general intelligence: Concepts, architectures and algorithms*. Amsterdam: IOS Press, 2007, pp. 94.

[27] D Helbing. *Social self-organization: Agent-based simulations and experiments to study emergent social behavior*, 1st ed. Berlin: Springer, 2012.

[28] K Warwick. *Artificial intelligence: The basics*, 1st ed. London: Routledge, 2012.

[29] Harari YN Homo Deus. *A brief history of tomorrow*, 1st ed. London: Harvill Secker, 2016.

[30] Maturana HR Varela FJ. *Autopoiesis and cognition: The realization of the living*, 1st ed. Dordrecht: Springer Science & Business Media, 1991.

[31] Lefebvre VA. The fundamental structures of human reflexion. *J. Soc. Biol. Struct.* 1987, 10(2):129–175.

[32] Omeiza D, Webb H, Jirotka M, Kunze L. Explanations in autonomous driving: A survey. *IEEE Trans. Intell. Transp. Syst.* 2021, 23(8):10142–10162.

[33] Atakishiyev S, Salameh M, Yao H, Goebel R. Explainable artificial intelligence for autonomous driving: A comprehensive overview and field guide for future research directions. *IEEE Access* 2024, 12:101603–101625.

[34] Arrieta AB, Díaz-Rodríguez N, Ser JD, Bennetot A, Tabik S, *et al*. Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. *Inf. Fusion* 2020, 58:82–115.

[35] Russell S, Norvig P. *Artificial intelligence: A modern approach*, 3rd ed. New Jersey: Prentice-Hall, 2010.

[36] Johansson R. Vision zero—implementing a policy for traffic safety. *Saf. Sci.* 2009, 47(6):826–831.

[37] Searle JR. Minds, brains, and programs. *Behav. Brain Sci.* 1980, 3(3):417–424.

[38] Dennett DC. *Consciousness explained*. Boston: Little, Brown and Co., 1991.

[39] Pfeifer R, Bongard J. *How the body shapes the way we think: A new view of intelligence*, 1st ed. Cambridge: MIT press, 2006.

[40] Wallach W, Allen C. *Moral machines: Teaching robots right from wrong*. New York: Oxford University Press, 2008.