Journal of Knowledge Learning and Science Technology
ISSN: 2959-6386 (Online)
2024, Vol. 4, No. 3, pp. 188–199
DOI: https://doi.org/10.60087/jklst.v3.n4.p188

Review

Model Based Systems Engineering for Sustainable Autonomous Vehicle Design and Development

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Abstract

Model Based System Engineering (MBSE), introduced in the 2000s, has become a cornerstone for automobile companies like BMW, Toyota, and others prominently involved in the development of autonomous vehicles. MBSE is a unique systematic approach that uses designs and architecture instead of traditional document-centric methods. While the integration of MBSE in autonomous systems shows great promise for system development, there are still drawbacks due to the process of its complex integration. Currently, the engineering community is shifting its approach in systems engineering from document-based system engineering to MBSE. The shift has provided numerous advantages, one example being the enhancement of safety and security using Systems Modeling Language (SysML). Additionally, the continuous verification and validation of the system allowed by MBSE ensures that communication protocols meet real-time constraints. This study aims to address how MBSE can be used in autonomous vehicle development to improve functionality, secure connectivity, vehicle certification and enhance trust/confidence. Additionally, exploring how to overcome challenges such as streamlining existing requirements, test identification, navigating multi-perspective simulation, and improving vehicle-to-vehicle (V2V) communication. By using practical and multi-dimensional methods, formalisms, and applications, the future of MBSE shows great potential as a fundamental component to support effective, collaborative, and successful autonomous development environments.

Keywords

MBSE, Modeling and Simulation Framework, V2V Communication, Systems Engineering, MIL (Model-in-the-Loop), Multi-Scale Modeling, Complex Adaptive System of System, Autonomous Vehicle Technology

1. Introduction

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Received: 03-08-2024; **Accepted:** 20-09-2024; **Published:** 25-12-2024

Journal of Knowledge Learning and Science Technology
ISSN: 2959-6386 (Online)
2024, Vol. 4, No. 3, pp. 188–199
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The concept of self-driving cars emerged in the 1920s and 1960s when remote-controlled cars were operated using radio. Over the years this concept grew more advanced in terms of technology and network. In the 2000s MBSE gained traction within the automotive industry as companies started exploring its potential for improving the design process. A notable breakthrough in the 2010s was when Google, now known as Waymo [1] began a self-driving car project, leading to significant advancements in autonomous technology. In 2015, Tesla introduced its Autopilot system [2], a semi-autonomous driving feature that was a major success in convincing the masses that autonomous cars are the future of the automobile industry. At the same time, major automobile industries like BMW and Toyota began publicly stating that they used MBSE to develop their autonomous systems [3]. By the year 2022, there was a widespread adaptation of MBSE tools in automotive companies. By the year 2023, the automobile industry has adopted MBSE for system design, integration, communication, navigation, and simulation [4,5].

To excel in the field of autonomous vehicles there are some key areas which require consideration. Firstly, innovation and reliability must be balanced as advancements in AI algorithms and sensor technology increase along with the rise of safety concerns in diverse operational conditions. Secondly, getting hands-on connectivity to prevent cyber threats such as malware and hacking remains a major concern. Along with that, meeting standard certification requirements to build user confidence is also essential. ISO 26262 for functional safety by the International Organisation for Standardization may be essential to foster user confidence in autonomous vehicle technology [6,7,8]. Additionally, Vehicle to Vehicle (V2V) communication is one of the vital aspects of autonomous vehicle technology which enables real-time data exchange between vehicles allowing for improved situational awareness and coordination [9]. Model-Based Systems Engineering (MBSE) acts as the backbone of autonomous vehicle technology by offering guidance at various stages of development, whether it's code generation or big data integration [5]. Furthermore, through use of advanced SysML within MBSE streamlines system integration. Paying a look into these areas is also important for heading out of the complications and ensuring a safe and sound future for autonomous vehicle development [10].

Autonomous technology can be improved with the use of MBSE, as it offers more advanced technological model-based system engineering. It does this through increases in available computing power and reduced costs in sensing and computing technologies [11]. Advancements in efficiency, secure connectivity, vehicle certification, and trust/confidence are needed for autonomous models, and MBSE has the potential to fulfill these requirements. MBSE can incorporate aspects of system specification, design, and validation, improving the consistency, speed, and functionality of the overall system. It can enhance the safety and security of automotive vehicles through the SysML system model, allowing for the early detection of safety hazards and security threats. MBSE can support continuous verification and validation by ensuring reliable V2V communication through precise specification and management of requirements[12]. The autonomous industry can use MBSE for more efficient complex system development, as it continues to play a key role in the future of urban transportation systems [13].

MBSE has potential in both safety/security and building confidence in the autonomous vehicle industry. Confidence in terms of technicality allows reliable vehicle-to-vehicle communication and streamlining pathways towards automating the industry. Enhancing the safety and security perspective of autonomous vehicles enables the improvement of quality and consistency of requirements and test specifications of complex autonomous systems. The pathways toward safety/security and other applications are summarized in Figure 1. Here in our review, we focus on different challenges that arise in the development of autonomous vehicles spanning issues such as functionality, secure connectivity, vehicle certification, and trust. Our focal point is the utilization of Model Based System Engineering to face these challenges head-on. Through a comprehensive review of previous literature, we aim to provide possible solutions to these challenges, focusing on the potential of MBSE in molding the landscape for more efficient autonomous vehicle development [14].

2. Discussion

2.1. Shift Towards Model Based Systems Engineering

In recent years there has been a shift from traditional document-based system engineering to model-based system engineering. The traditional document-based approach is stable and predictable, but it doesn't incorporate stakeholders as an integral part of system development and analysis. The document-based approach also relies heavily on text-based documents to analyze system requirements, design, and validation of autonomous vehicles Therefore, utilizing an MBSE based approach can meet the challenges of developing systems having characteristics including but not limited to sustainable development, adaptiveness, human integration and systems with an approach of utilizing intensive technology [15]. One of the main advantages of MBSE is its holistic approach to the system by incorporating aspects of system specification, design and validation, and management of the configuration of the target system. MBSE illustrates a real abstraction of the system starting from the design phase and continuing to the system life-cycle phase thus ensuring the system's reliability for an extensive period. MBSE combines multiple stakeholders' views of interdisciplinary backgrounds in the system development, ensuring better communication between all the stakeholders and also enhancing their understanding of the system. By embodying this approach MBSE also improves the consistency, traceability, and effectiveness of the system [14].

The automobile industry has increasingly adopted MBSE to address the growing complexity of modern vehicles. As cars have gone from mechanical systems to sophisticated entities encompassing electronics, software, and complex technology that enables communication, the need for an integrated approach to system design and management has become important. MBSE allows the integration of these different components by making a framework that helps to capture different interactions between systems. This method is especially helpful in developing an autonomous vehicle where safety, reliability, and intercommunication between various systems of a vehicle are very important. Through the MBSE technique, manufacturers of autonomous vehicles can enhance the development process, and improve traceability inside the vehicle and its compliance with regulatory standards which ultimately results in the development of higher-quality vehicles [16].

Autonomous vehicles depend upon specific coordination between components of hardware and software, real-time data processing, and complex algorithms. MBSE helps those requirements by offering an in-depth and executable model of the automobile's structure and behavior. Through simulation and validation of these models, engineers can identify and address errors early in the development phase which reduces the threat of high-priced errors. Additionally, MBSE allows the implementation of integration and testing of various components of the system, making sure that the adjustments in one part do not adversely affect the overall performance of the entire system. The autonomous vehicles developed by way of pursuing this strategy can attain better levels of performance, accuracy, and protection [17].

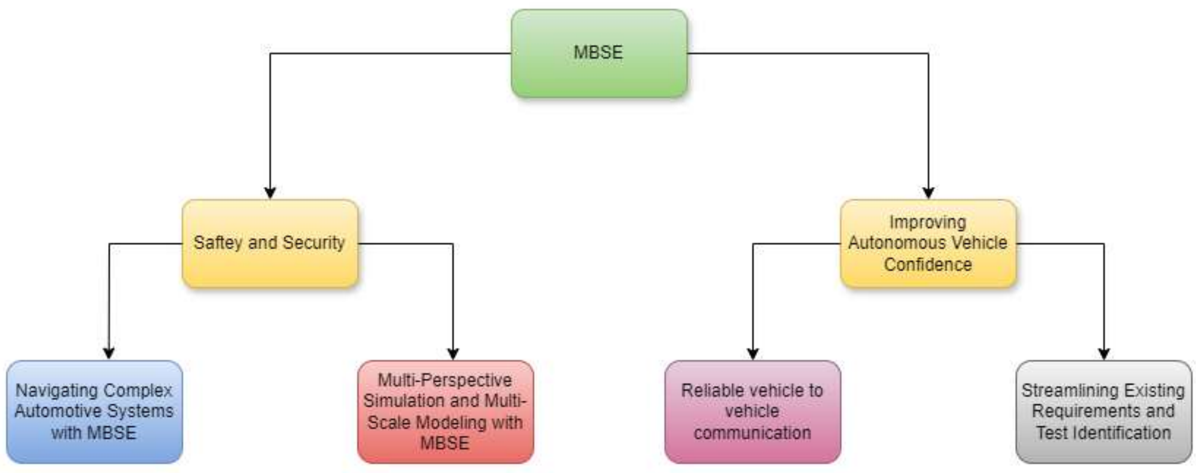

Figure 1. *MBSE approach towards efficient and reliable autonomous vehicle.*

2.2. Safety and Security in Autonomous Vehicle Development

MBSE can enhance the safety and security of automotive vehicles by allowing early detection of safety hazards and security threats by developing a SysML system model. The SysML model is designed and developed in the early architectural development phase. This incorporation of SysML in the early design phase results in an early discussion between the different stakeholders regarding the classification of security and safety aspects. The authors elucidate the early detection of security and safety threats prone to an autonomous vehicle in three phases. The first phase identifies the security threat from a black box perspective by incorporating user stories, and the second phase refines threats detected in the first phase using the strategy of white box which assigns a critical value to each function of the vehicle in terms of its security/safety level, and the third phase prioritizes the threats refined in the second phase to create a SysML model that can be used by stakeholders in the workshop to early on mitigate the security/safety threats to an autonomous vehicle [18].

AI can identify and predict potential threats to the security of a vehicle by analyzing patterns in the overall performance of the vehicle and reading sensor data. Based on that data the machine learning algorithms can provide real-time decision making to combat the threats early on. This ultimately improves vehicle navigation and avoids hazards prone to weak security. Furthermore, through advanced mapping and analyzing environmental data MBSE models integrating AI can protect against hacking and unauthorized access which interns result in security-efficient vehicles [19].

2.3. Reliable Vehicle-to-Vehicle (V2V) Communication

By ensuring reliable V2V communication, MBSE can enable precise specification and management of requirements by creating detailed architectural models. Through this, MBSE can support continuous verification and validation, ensuring that communication protocols meet real-time constraints and that security measures are effective. It can help facilitate interoperability and integration across different vehicle models and manufacturers by providing a single source of truth for all stakeholders. Additionally, efficient V2V communication can help MBSE identify and mitigate risks early in the development process, ensuring the reliability and safety of the Inter Vehicle Communications (IVC) system. By managing the entire lifecycle, MBSE can ensure systematic updates and continuous improvement of the communication systems in autonomous vehicles. MBSE can be utilized in the context of reliable V2V communication through detailed architectural models for autonomous vehicles' IVC systems. It emphasizes the different components needed in an architectural model and the process after that including simulation, analysis, documentation and communication, interoperability and integration, and lastly, risk management in ensuring precise specification and management of requirements as shown in Figure 2 [12,20].

2.4. Streamlining Existing Requirements and Test Identification

By facilitating good working environments through the use of models, MBSE allows engineers to be able to easily identify the area of the issue and where they can potentially improve. The way that MBSE does this is by promoting collaboration using Agile Systems Engineering (ASE). ASE is a type of engineering where each part of work is broken down and sent to groups of people to work on to encourage productivity and efficiency. When working on multiscale system engineering, communication is essential; and made much easier with a shared understanding of the system so potential conflicts can be identified. This can also help mitigate delays in work and cost overruns, boosting the quality of the final product. MBSE enables multiple stakeholders to work on the same model allowing feedback and smooth transaction of information. In addition to improving communication, MBSE increases the efficiency of engineering tasks such as documentation and validation making everything more organized and easy to understand for everyone involved.. By increasing efficiency, engineers can in turn focus their attention to more essential aspects such as analysis or system design [22]. Simplifying the navigation of complex vehicle systems in autonomous vehicles can be achieved through a user-centric approach. This involves designing intuitive user interfaces that provide clear, real-time information and leveraging advanced technologies like artificial intelligence (AI) for personalized recommendations. Using MBSE tools for simulation ensures reliability and modular designs allow for easy updates. Comprehensive, accessible documentation and effective feedback mechanisms further enhance user experience. Practical examples include Tesla's user-friendly Autopilot interface and Waymo's detailed simulations for refining autonomous driving systems. This approach makes advanced vehicle systems more accessible and user-friendly. Simplifying the navigation of complex vehicle systems, especially in the context of autonomous vehicles, can greatly

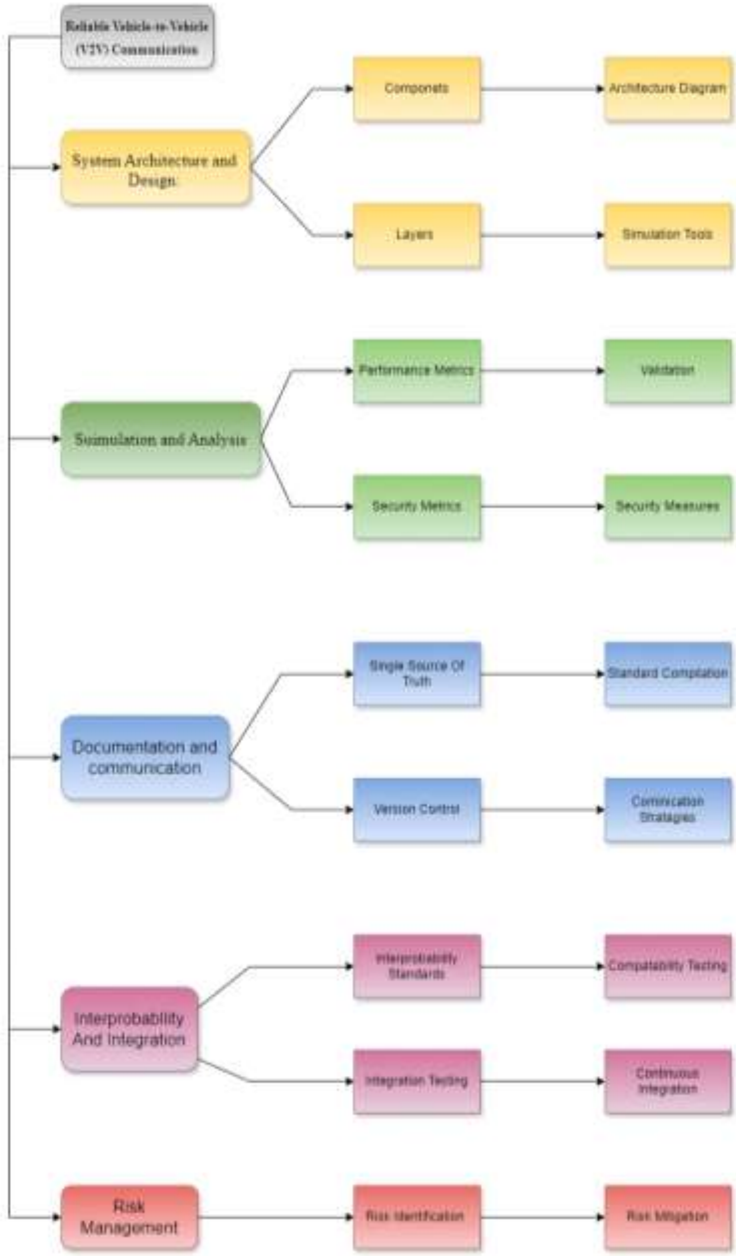

Figure 2*. The different actors and their interactions with an MBSE system in an engineering project.*

benefit from a user-centric approach. This involves designing systems prioritizing ease of use, intuitive interfaces, and seamless integration of various subsystems [23,24].

2.5. Navigating Complex Automotive Systems with MBSE

The use of SysML ensures that all stakeholders have a clear understanding of system requirements in the early stages of the development of autonomous vehicles. The detailed analysis and specification of functional requirements of the system allowed by the MBSE ensures that all system components follow the desired performance criteria. Potential risks associated with the system can be identified early in the development phase with the help of modeling and simulation of various components of the system.MBSE enables the integration of various subsystems in a system which in turn provides a clear framework on how the different components should interact with each other. The specification of tests of system requirements facilitates a thorough validation process for each component of the system. The use of models and standardized languages such as SysML enhances better communication between engineers, designers, and other stakeholders which in turn reduces the communication gap and improves the confidence of various entities. Comprehensive traceability of system requirements through design, testing, and implementation of system components ensures that all changes are documented and their impacts are identified throughout the system life-cycle [25].

2.6. Multi-Perspective Simulation and Multi-Scale Modeling with MBSE

Complex system simulation and multi-scale modeling have been playing an unparalleled role in understanding, predicting, and controlling diverse and complex systems. Concerning MBSE, its current state is still tied to traditional systems engineering and needs to expand to incorporate complex systems simulation and engineering practices. To understand its relevance, M&S (Modeling and Simulation) represents a core capability in today's engineering world and is needed to address complex engineering challenges of systems. M&S methodology can work together with MBSE to provide growing capabilities to help develop and implement models of Complex Adaptive System of Systems (CASOS). To bridge the gap between these ideologies, the Discrete Event System Specification (DEVS) formalism with a holistic construct called the Modeling and Simulation Framework (MSF) offers a solution and provides a base for which the relation between the model and simulator can connect and that can specify the simulation protocol between the system as a whole to ensure they support complex systems engineering. Figure 3 explains the process in which M&S can be implemented within the DEVS formalism using MSF. The DEVS formalism can be used to connect M&S and MBSE using MSF for the best increased result. Without the support of integrated simulation capability and the potential for closer unification between M&S and MBSE, knowledge gaps in engineering such complex systems would create difficulties in the structure and innovation of the system overall, thus reinstating the importance of simulation and modeling roles in MBSE [22,25].

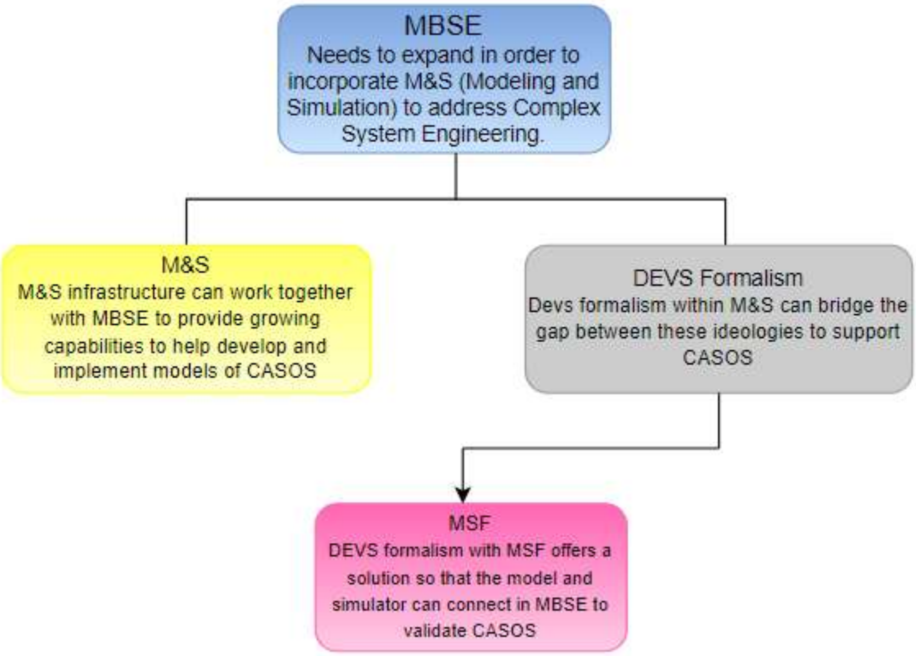

Figure 3. *MBSE in the context of improving multiscale modeling and simulation.*

2.7. Improving Autonomous Vehicle Confidence with MBSE

The development of a subsystem by using MBSE allows users to create a digital system to test autonomous technology. This can lead to the verification and validation that the system in question provides safety for the user. Diagrams created by MBSE provide different views and perspectives of one system, making testing autonomous technology easier, faster, and more cost-effective [26]. A survey in 2024 by AAA Auto Club asked drivers whether they trusted, were unsure about, or were afraid of autonomous technology. Out of the people surveyed, only 9% trusted self-driving vehicles while 25% were unsure and 66% were afraid of them. The improvement of these technologies through the use of MBSE could lead to an increase in driver trust in autonomous technology. There is currently a low rate of trust among drivers towards self-driving vehicles, and new advancements in the field will result in confidence increasing [27].

Current validation methods are primarily automatic and manual. Automatic validation includes simulations such as Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), Processor-in-the-Loop (PIL), and Hardware-in-the-Loop (HIL). These processes are parts of MBSE that also fall into this category, with their creation of a system of diagrams that can be used to validate and verify autonomous technology [28,29]. MIL testing and simulation can be used to validate individual or integrated models or modules in a developmental environment. SIL is used to verify software, algorithms, control loops, and other system elements through simulation. If any results in SIL are bad, it is necessary to go back into MIL. Once the first two steps are completed, the next step is PIL. PIL, also known as FIL (FPGA-in-the-loop) testing is used to run the embedded software, algorithms, control loops, and other system elements as a closed-loop simulation on the processor. Once the first three steps are complete, the final round of testing is HIL. HIL testing involves running simulations before connecting the processor to the hardware. Any problems in HIL testing would require it to be run again or would require the tester to revisit the first 3 stages [28]. These 4 stages as a part of MBSE will verify and validate autonomous systems. They provide many advantages such as time and lower costs over other methods of validation such as manual testing. Figure 3 shows the order of the processes and the functions that they carry out.

2.8. Potential and Challenges of Utilizing MBSE

Increasing trends in implementing MBSE in the automobile industry are primarily due to its potential benefits of incorporating multiple stakeholders' views in the development, validation, and life cycle phase of autonomous vehicles allowing them to mitigate various errors. This is done by detecting them early in the design phase and as a result, enhancing the overall efficiency of the vehicles. While security and safety is one of the key concerns in the development and analysis/validation of autonomous vehicles, MBSE improves these concerns by utilizing a model called SAVE based on the SysML modeling technique. By incorporating this technique, MBSE enhances collaboration and communication between interdisciplinary stakeholders by allowing early discussion of problems of safety and security. However, this methodology is only tested in automobile workshops. It is yet to be implemented in the workshops with industrial participants. Likewise, this model has yet to be implemented to analyze complex industrial systems.

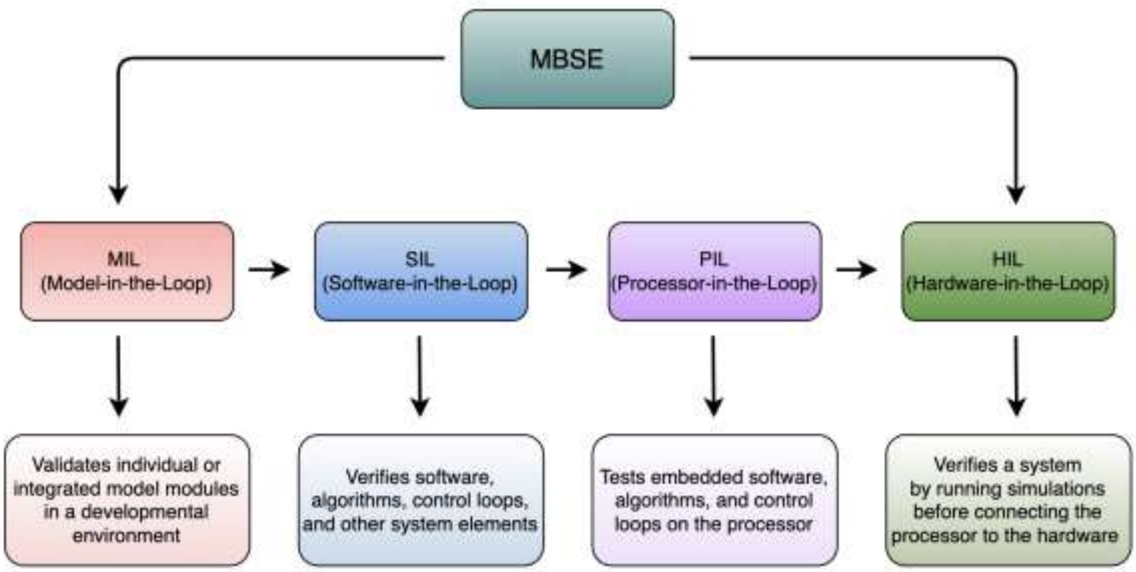

Figure 4. *Various mechanisms involved in the validation and verification of autonomous technology.*

Nevertheless, MBSE holds a promising future in the development of automobiles by allowing the detection of security and safety hazards early in the system design phase. Additionally, interoperability, integration, and system architecture are crucial factors when it comes to V2V communication in the context of MBSE, but they are also the most complex in terms of upgradation due to regulatory and compliance issues and concerns in terms of security and privacy. The continuous evolution in the interoperability structure makes it hard for systems to keep up. Maintaining and updating interoperability standards is a continuous process as new technologies emerge but can be solved by developing and adopting universal standards advancing cybersecurity measures. Creating comprehensive simulation tools and carrying on many tests with different conditions can help strengthen cybersecurity measures. To add on, streamlining existing requirements of automobiles and enhancing their test identification is also achieved by MBSE allowing engineers to work on projects simultaneously and find issues in the system without much interference. The cooperation of stakeholders working on the same model is improved by implementing the ASE technique which results in reducing the risk of miscommunication. Alongside improving cooperation and communication between various stakeholders, the efficiency of the system is also augmented by allowing them to work on more significant problems as a whole. Although communication/collaboration and efficiency of the system are enhanced, the risk of a snowball effect occurring during the process is also very high. MBSE can significantly improve the reliability of the work and trust between the workers by bringing up constructive feedback thereby improving its overall performance. Among the discussed factors, the feedback mechanisms and integrations of advanced technologies need to be worked on the most. These play a vital role in quick reaction times for the vehicle, for instance, the reaction time of an average human is 250 milliseconds and advanced autonomous cars have a response time of 830 milliseconds as of today. This illustrates how even the smallest time gap can cause catastrophic damage to safety and security. Hence continuous integration of the latest technology and making the feedback systems is essential.

Moreover, to address the challenges of complex engineering systems, M&S methodology is implemented. M&S methodology leads to the closing of knowledge gaps and the elimination of the danger of cascaded failures helping support the design and testing of CASOS models. This in particular is done by enabling exhaustive parameter evaluation and advanced experimentation. However, current MBSE practices must extend to incorporate M&S within a holistic approach to contribute to complex systems engineering. Also, M&S still has to evolve to support CASOS and its multi-dimensional and uncertain nature [30]. Furthermore, embodying various methodologies such as MIL, SIL, PIL, and HIL, provides a cost-effective and fast way to validate and verify autonomous technology. MIL is implemented early in the development process, SIL allows software and code to be tested, PIL can detect overflow conditions and casting errors, and HIL can identify higher-level system integration problems. Altogether, the use of these multiple different stages and techniques for validation and verification allows for safer autonomous technology which ultimately increases the confidence level of autonomous vehicles. Despite this, integrating various tools/techniques to improve vehicle confidence can be challenging as it increases the complexity of the system which leads to stability issues. Still, MBSE promises a good application in improving vehicle confidence by adding different strategies and techniques to enhance the overall efficiency of the vehicle.

Application	Method	Major Findings
Enabling early detection of errors(security and safety) [18]	SAVE	Incorporating the method called “SAVE” using SysML allowed the stakeholders to detect safety and security errors early in the system architecture design phase. This improved the system understanding by enhancing the communication among the stakeholders and ensured the safety/security of the vehicle.
Reliable Vehicle-to-Vehicle (V2V) Communication [12][31]	System Architecture and Design:	Create detailed architectural models for autonomous vehicles' inter-vehicle communication (IVC) systems. Ensures precise specification and management of requirements.

	Simulation and Analysis:	Simulate system behavior to verify and validate communication protocols and security measures. Ensures that communication protocols meet real-time constraints and that security measures are effective.
	Documentation and Communication	Provide a single source of truth for all stakeholders, ensuring a unified understanding of the system's design and requirements. Facilitates clear documentation and communication among all parties involved.
	Interoperability and Integration	Provide a single source of truth for all stakeholders, ensuring a unified understanding of the system's design and requirements. Facilitates clear documentation and communication among all parties involved.
	Risk Management:	Identify and mitigate risks early in the development process to ensure the reliability and safety of the IVC system. Helps in early risk identification and mitigation, ensuring the reliability and safety of the IVC system.
Improves communication between workers and efficiency [22]	Agile Systems Engineering (ASE)	Enabling workers to work together simultaneously using models, processes, and assignments can be done with more efficiency. With a higher efficiency rate, stakeholders can turn their heads to more pressing issues such as analysis or system design.
Navigating Complex Automotive Systems with MBSE[34]	Test-Driven Scenario Specification (TDSS)	The TDSS approach uses automated tools to identify contradictions and inconsistencies in the system in the development phase which enables continuous refinements of both the requirements and tests. This approach enhances the efficiency of the validation process which allows the integration of comprehensive stakeholders' requirements which ultimately leads to the development of higher-quality systems that meet the intended goals.
	Scenario-Based Requirements Engineering	This approach integrates both functional and non-functional requirements which ensures comprehensive analyses of all requirements. The use of detailed scenarios helps determine hidden requirements and edge cases, leading to more potential and complete specifications which in turn improves communication and collaboration between system stakeholders, developers, and testers.
MBSE integration with Modeling and Simulation (M&S) [22]	DEVS formalism with Modeling and Simulation Framework(MSF)	Improved the viability of concepts and provided a visual way to better represent system components and the connections between them. Thus, improving communication about system artifacts among stakeholders as well as strengthening testing and verification.

Improving Autonomous Vehicle Confidence with MBSE [28]	MBSE	MBSE (Model-based Systems Engineering) uses diagrams to create virtual systems. This can be used to verify and validate autonomous technology. 4 parts of MBSE include MIL, SIL, PIL, and HIL.
	MIL	MIL (Model-in-the-Loop) testing is used to verify and validate software by testing individual or integrated model modules in a development environment. MIL is early in the development process, allowing developers to identify and correct errors at the start of development.
	SIL	SIL (Software-in-the-Loop) testing is used to test embedded software, algorithms, control loops, and other system elements. It allows software and code to be tested without needing to also test the hardware and finish the product.
	PIL	PIL (Processor-in-the-Loop) testing is used to run the embedded software, algorithms, control loops, and other system elements as a closed-loop simulation. This step ensured that the hardware could run the software. PIL can detect overflow conditions and casting errors due to the code being executed on the MCU (Micro Controller Unit).
	HIL	HIL (Hardware-in-the-Loop) testing is run simulations before the processor is connected to the hardware. HIL can identify higher-level system integration problems by enabling the tester to intentionally cause problems to see how the system reacts.

Table 1. *Summary of all the applications of MBSE discussed above and their major findings.*

3. Conclusion

Primarily, this study aims to address how MBSE can integrate with autonomous vehicle development to improve functionality, secure connectivity, vehicle certification and lastly trust/confidence and also how to overcome a few challenges we are facing in these factors. MBSE, as stated by the International Council on Systems Engineering (INCOSE), can support systems requirements, design, analysis, simulation, verification, and validation activities to enhance complex autonomous models [32]. This paper illustrates how MBSE can work on certain aspects such as streamlining existing requirements and test identification, multi-perspective simulation, and more to address and uphold the growing complexity of modern vehicles. By using and practicing the multi-dimensional methods, formalisms, and applications discussed in this article, the future of MBSE shows great potential as a fundamental component to support effective, collaborative, and successful autonomous development environments.

Currently, this study believes that MBSE plays a clear and significant role in the design, simulation, and integration of various systems of autonomous vehicles. Though MBSE is an essential tool in terms of designing and simulation, it also has many drawbacks in terms of its complexity and steep learning curve. To showcase MBSE's full capability, sophisticated and improved tools, and a comprehensive understanding is needed across multiple branches to make it effective. The integration of MBSE will require more extensive training for employees and more resources must be available to implement it. An adoption strategy to combat this issue is an introduction to MBSE and slowly building the knowledge and skill of employees to use MBSE in models. Additionally, this would aid the integration of this technology. MBSE also raises concerns about its cost-effectiveness in licensing, ethical and social implications, and cybersecurity as well as its capability to keep up with the growing CASOS models. Security concerns are often also brought up, as supporting different levels of access can lead to configuration issues [33]. An additional point to mention is that integrating MBSE with other systems requires considerable time and effort, unlike other tools which require a high amount of capital. MBSE can be improved upon despite these faults with rapid advancements in technology to support aspects such as V2V communication security and infrastructures. Through considerable research and implementation, MBSE shows great promise for efficient system development in the current stage of technological advancements in the autonomous industry.

Conflicts of Interest

The authors declare no competing financial interests or conflicts of interest.

Author Contributions

H.R. data curation, methodology. H.T. validation, writing-review & editing. S.H. writing- original draft, methodology, formal analysis. E.D. visualization, data curation, writing-review & editing.

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