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INTEROPERABILITY IN AN ELECTRIFIED PAVEMENT SYSTEM:

A MODEL-BASED SYSTEMS ENGINEERING PERSPECTIVE

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Master's Program in Industrial Engineering

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Dean of the Graduate School

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2022

DEDICATION

Thank you, God, for giving me the strength to achieve this goal. To my parents for inspiring me to never give up no matter what the circumstances, mom you were and will be my example of always moving forward, I hope one day I can give you back everything you have done for me. To my grandma Elena, wherever you are, I dedicate this achievement to you. You were always there for me and taught me to be a good person, thank you for all the love you gave me in life. I love you with all my heart and soul.

My gratitude to all those who have been part of my life and have led me to become the person that I am, and the person which I aspire to become.

INTEROPERABILITY IN AN ELECTRIFIED PAVEMENT SYSTEM:

A MODEL-BASED SYSTEMS ENGINEERING PERSPECTIVE

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BEATRIZ IRENE SOTO

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Industrial, Manufacturing & Systems Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

December 2022

ACKNOWLEDGEMENTS

I would like to extend my gratitude to my mentor and advisor, Dr. Sergio Luna Fong, for guiding me through this research process, for believing in me, and for providing me with an exceptional example of constant work. His constant motivation, guidance, support and advice helped me achieve this goal. I thank him for believing in my potential and trusting me by giving me the opportunity to be one of his master's research students. Also, I would like to express my gratitude to the faculty and staff at UTEP's Center for Transportation Infrastructure Systems (CTIS) for the countless opportunities I have received over my period at UTEP. Thank you, Dr. Nazaria, Dr. Tirado, and the soon to be PhD candidate Hector Cruz and Kamaleen Santos for your guidance, expertise, and support to conduct this work. In addition, I cannot thank enough to all members of the NSF ERC ASPIRE community for the professional and economic support I have received while pursuing my master's degree. This project has opened my eyes in so many ways that I am blessed to have been part it. Finally, I would also like to recognize and thank all the professors of my courses throughout the master's degree, and the University of Texas at El Paso for providing me with important and valuable tools and resources to be able to develop professionally and achieve this goal.

ABSTRACT

In a 2021 statement provided by The White House, (The White House, 2021), the Biden administration announce the goal for electric vehicles to account for 50% of new vehicle sales in the United States by 2035. In addition, the legislation allocates a budget of $7.5 billion to build out a national network of EV chargers along highway corridors to facilitate long-distance travel and within communities to provide convenient charging where people live, work, and shop. This investment will support the President's goal of building a nationwide network of 500,000 EV chargers to accelerate the adoption of EVs, reduce emissions, improve air quality, and create good-paying jobs across the country.

The transformation towards a holistic electrified transportation system where systems such as power, highway, data and information, vehicles themselves, and consumers synergistically collaborate to achieve a common goal introduces new opportunities and challenges to the transportation domain. In addition, the characteristics of resulting system-of-systems can be considered through the lens of cyber-physical systems (CPS) where a set of components, networks, data storage, analytics methods, and human beings interact in the context of transportation to provide an electrified service to communities. This thesis contributes to the body of knowledge by 1) exploring current challenges in electric vehicles as CPS, and 2) understanding how model-based principles can assist the development of complex projects such as the interoperability between electric vehicles, highways, and power systems. For this thesis in particular, applied to a case study of an Electrified Pavement System.

The research presented in this thesis was conducted in two phases. Phase 1) a grounded theory methodology was implemented to identify the challenges of electric vehicles as they are considered CPS. Results from this study indicated the need to explore efforts in Interoperability, Integration, Understanding, Sustainability, and Security of EVs. Consequently, Phase 2) presents a Model-Based Systems Engineering (MBSE) model developed in 3DS No Magic System of Systems Architect, also known as Cameo, to inform researchers and practitioners how digital

engineering models could be effective methods to promote collaboration among systems and stakeholders. The scope of the model is limited to a pavement system, and it is planned to be expanded to additional systems in the future.

Overall, the findings of this research will enable decision makers to better understand how digital engineering models can be translated to cost-effective solutions by minimizing verification and validation schedule, decreasing costs across the lifecycle, and increasing overall system performance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1. MOTIVATION

Governments across the globe recognize the need to decrease current levels of CO_2 emissions due to current air pollution and greenhouse gases coming from the same sources, reducing greenhouse gas emissions in an effort to stop climate change would help reduce air pollutants. Reducing these air pollutants, would improve air quality and benefit human health. While investigating strategies to reduce such levels, policy makers identified that an electrified vehicle fleet can be one of the top strategies to reduce carbon emissions as electric vehicles (EVs) are known to reduce transportation emissions, promote low-carbon mobility, and an overall cleaner environment (Debnath et al., 2021). Therefore, policies to explore the introduction, adoption, and production of electric vehicles (EVs) have been implemented resulting in EVs are becoming more widely available (Rezvani et al., 2015).

From 2012 to present, the sales of EVs have been doubling every one to two years in the United States, where the highest market share of vehicles is found in the state of California (Archsmith et al., 2022). Western U.S. states lead the way when it comes to electric vehicle registrations, with California accounting for over 28% of the nation's overall count in 2021. On a per-100,000-person basis, California also leads the field, with 5,694 vehicles registered per 100,000 people last year, followed by Washington (4,279) and Oregon (4,013) (Gilligan, 2022).In 2019 alone, the sales of electric vehicles reached 2.1 million units in the world, with a 90% concentration of sales mainly in China, Europe and the United States.

Figure 1 below shows us how sales of new plug-in electric vehicles, including all-electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs), nearly doubled from 308,000 in 2020 to 608,000 in 2021. EV sales accounted for 73% of all plug-in electric vehicle sales in 2021. EV sales grew by 85% from 2020 to 2021, while sales of PHEVs more than doubled, with an increase of 138% over the previous year. The rapid growth in plug-in electric vehicle sales from 2020 to

2021 is remarkable in the context of overall light-duty vehicle sales, which increased by only 3% during the same period (Minos, 2022).

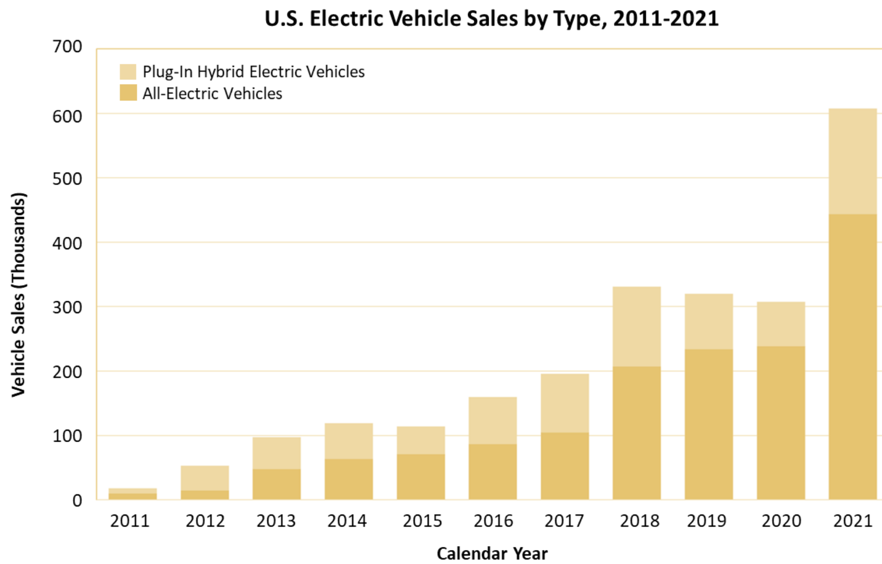


Figure 1. U.S. Electric Vehicle Sales 2011-2021. (Minos, 2022) (Adapted from the original)

In addition, the market is expected to be increasing. For example, Debnath et al., 2021 state that by 2025, about 200 new electric vehicle models will be introduced to the United States alone, many of which are in the sport utility vehicle (SUV) segment. To complicate matters further, many segments such as the transportation sector, which represents the largest source of greenhouse gas emissions in the United States, already aspire to reach a 100% electric transportation, while several countries and states have declared their intention to ban sales of gasoline cars in the future (Archsmith et al., 2022).

According to The White House (The White House, 2021), the Biden administration has set a goal for electric vehicles to account for 50% of new vehicle sales in the United States by 2035, with more than 20 countries planning to phase out internal combustion engine vehicle sales in the next 10 to 30 years (Afridi, 2022). Considering a holistic perspective, to achieve the end goal, Rezvani et al., 2015 indicate the importance of understanding how consumers perceive EVs and what potential drivers and barriers exist between this adoption and the consumer. It is necessary to understand the factors influencing consumer's intentions to buy an EV. Similarly, Debnath et al., 2021 argue for the need of significant EV policies and funding sources to support national and state efforts.

1.1.1. Electric vehicle infrastructure

Governments and some private companies have been building public charging infrastructure for several years, resulting in more than 200,000 stations of various types around the world. The state of the charging infrastructure varies greatly from one country to another, as well as from one city to another (Hall & Lutsey, 2017) for which it is necessary to review its current situation.

A study conducted by the Office of Energy Efficiency & Renewable Energy of the United States Government Department of Energy, found that approximately 400 DCFC (fast direct current charger) corridor charging stations as shown in Figure 2 (spaced 70 miles apart in average) are necessary to provide convenient access for BEV (Battery Electric Vehicle) drivers throughout the U.S. Interstate system. (Wood et al., 2017)

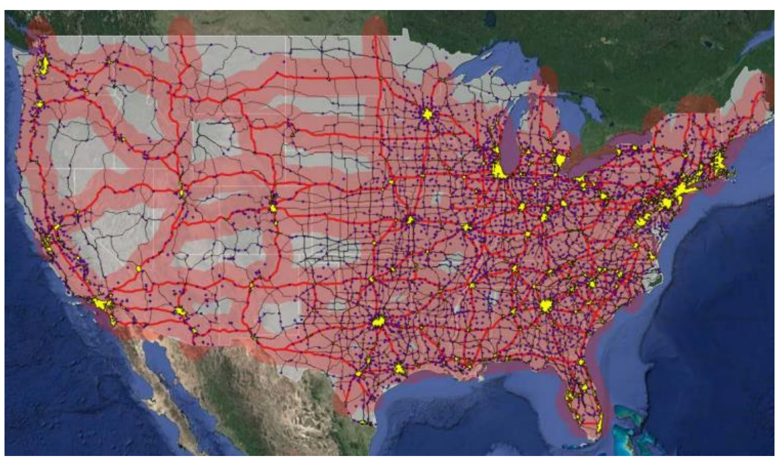


Figure 2. Approximate BEV driving coverage enabled by providing DCFC stations along the U.S. Interstate System. (Wood et al., 2017)

Such estimated coverage enabled by DCFC stations in this scenario is visualized in Figure 2 with red buffers located around the interstate network, each with a 70-mile radius.

According to data from the Federal Highway Administration (FHA) of the United States Department of Transportation, it was announced that the Biden-Harris administration approved the first 35 state plans to build an electric vehicle charging infrastructure on 53,000 miles of highways, among the 35 states for this plan are: Arizona, Ohio, Arkansas, Oklahoma, California, Massachusetts, Oregon, Colorado, New Mexico, Tennessee, Wisconsin, among others. (U.S. Department of Transportation, 2022)

Due to what has already been mentioned above, the high adoption of the electric vehicle that has picked up in recent years will require a generalized development of public access charging infrastructures (Afridi, 2022). Furthermore, because EV adoption is not automatic, methods will be needed to understand how to integrate these electric charging infrastructure systems, so that stakeholders can understand, interpret, and transform the information that is shared within them, addressing and understanding existing risks before developing an electrified transport network. As well as understanding within these systems, how the essential processes for their development will be carried out efficiently, for example: system design, support, standardization, validation, verification and, above all, how to communicate and integrate within the system, is That is, how to achieve a more interoperable system.

1.2. PROBLEM STATEMENT

Last September, 14 of this year, The Federal Highway Administration (FHA) of the United States Department of Transportation, announced that the Biden-Harris administration approved the first 35 state plans to build an electric vehicle charging infrastructure on 53,000 miles of highways in different states of the USA (Transportation U. D., 2021).

The high adoption of electric vehicles that has rebounded in recent years is requiring a widespread development of infrastructure for electric vehicles, in addition to leading to the emergence of Cyber Physical Systems (CPS). Multiple domains including healthcare, automotive, manufacturing, emergency management, power distribution, and transportation, seek to take advantage of its features and capabilities. Expected benefits include emergence of new systemic capabilities, enhanced strategic decision-making process through near-real time data monitoring, increase system level resiliency and robustness, enhance safety and security, among others. While there are obvious advantages to leveraging CPS, there are challenges and risk that organizations must consider and address before they fully take advantage of their benefits.

In chapter 2 the current challenges in electric vehicles such as CPS were explored, and they were identified in about 150 articles consulted in the literature on issues related to electric transportation systems, that 21% of the challenges they face, are of interoperability within their systems, processes and organizations.

Currently there are solutions to interoperability problems in general within systems. There are organizations that organize their information and data in software's that help them keep the information available and updated, but nevertheless it is carried out in a very general way, where the information is available but limited to being only viewed by specific people, that is say, there is no interaction between stakeholders-system, which for example, does not allow visualizing changes made or emergence of new specifications in real time.

Despite the efforts of these organizations for the development and integration of electric transportation systems for this specific case, it is important to mention that for systems of this magnitude it is easy to get lost in such a large amount of information, that changes in the system or modifications that are important and relevant to other parts of the system run the risk of not being informed or of not reaching the right people, Due to the above, it can be considered as a focus of attention, the way in which the information is flowing and how available it is for stakeholders

In chapter 3 of this thesis, a solution is proposed that understands how, through a digital engineering tool, model-based principles can help the development of complex projects such as interoperability between electric vehicles, roads and energy systems. For this thesis in particular, applied to a case study of an Electrified Pavement system, as a reference point for future applications in other systems.

In general, the difference between existing solutions and this proposed solution to the interoperability problem is: 1) The solution is proposed for more complex systems (electrified pavement systems) and 2) the findings of this research will allow decision makers better understand how digital engineering models can be translated into cost-effective solutions by minimizing the verification and validation schedule, lowering costs throughout the life cycle, and increasing overall system performance.

1.3. OBJECTIVE

The general objective of this research is to contribute to the domain of electrified transport by identifying the existing challenges in cyber-physical systems in social and technical perspectives. To do so, the study aims to identify the greatest challenges during the development and research of electrified transportation systems, in addition to proposing a model-based solution to the most recurring challenge: Interoperability.

The specific objectives of this research are formally expressed by the following research questions to better understand the main objective.

1. According to the literature consulted, what are the most recurrent challenges within Cyber-Physical Systems in the sector of electrified transportation systems?
2. How can a model-based systems engineering (MBSE) solution solve interoperability within a system architecture?
3. What benefits are claimed in the literature associated with the use of model-based digital engineering tools and solutions?

This thesis addresses these questions through the use of grounded theory, and model-based systems engineering.

First, in Chapter 2, a systematic method of data collection and analysis was implemented to allow interoperability issues in EV to be addressed through the lens of CPS. From the analysis of multiple electric vehicles such as CPS and literature, it follows that electric vehicles present 5 main challenges: Interoperability, Integration, Understanding, Adoption and Sustainability, Interoperability as main problem with 21% recurrence.

The impact of interoperability on the integration of electric vehicles focuses on the complexity of the interactions between the information systems in terms of procedures, applications, infrastructure, and data. To take advantage of EV further research efforts are needed to address the current methods used and a focus on selective aspects of interoperability, effective communication, data exchange and decision support.

In chapter 3, a digital model was proposed to create a pavement system that supports interoperability between components and stakeholders. This model is based on Model-Based Systems Engineering (MBSE), because this methodology focuses on the creation and exploitation of models as the main way of exchanging information.

Whit this model, it is also intended to propose a digital copy of how the system is connected in order to reduce labor costs, increase performance and support the delivery schedule. A model would allow us to visualize the system as a whole in real time, in addition to facilitating the joint and orderly management of all the information. In addition, this model is intended to be a basis for future models in any type of system where the challenge of interoperability is to be resolved.

CHAPTER 2: EXPLORING THE CHALLENGES OF CPS IN ELECTRIC VEHICLES

2.1. AN ELECTRIC VEHICLE AS A CPS (CYBER PHYSICAL SYSTEM)

2.1.1. Cyber Physical Systems

The term Cyber-Physical Systems has its origins in the US when the National Science Foundation (NSF) held its first CPS related workshop in 2006. The initiative called for a "new generation of engineered systems that are highly dependable, efficiently produced, and capable of advanced performance in information, computation, communication, and control.". (Monostori, et al., 2016) A year later, the discipline generated significant interest after it was reported by the President's Council of Advisors of Science and Technology (PCAST) as top priority issue to ensure US industrial competitiveness

Following the NSF initiative, it can be deduced that CPS are multidisciplinary in nature. These systems result from the intersection of multiple domains including but not limited to engineering, computer science, science, social sciences, education, business, among others. With such scalability and supporting backgrounds, it is understood that CPS definitions may vary across domains. Therefore, to understand the mental model of CPS among a diverse set of stakeholders, Table 1 presents definitions of CPS from government organizations, industry, and academic articles.

Table 1. CPS Definitions

Author	CPS Definition
NIST (National Institute of Standards and Technology)	"CPS comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic."
E.A. Lee	CPS, computational and physical resources that are strictly interconnected: embedded computers and communication networks govern physical actuators that operate in the outside world and receive inputs from sensors, creating a smart control loop capable of adaptation, autonomy, and improved e - ciency. Such systems are commonly and broadly defined as cyber-physical systems (Lee E. , 2008)
National Science Foundation	"…engineered systems that are built from, and

	depend upon, the seamless integration of computation and physical components.”
	Cyber-physical systems integrate sensing, computation, control and networking into physical objects and infrastructure, connecting them to the Internet and to each other.
Institute of Electrical and Electronics Engineers	“A CPS is composed of a collection of devices interacting with each other and communicating with the physical world. It integrates computation and communication aspects together with control and monitoring techniques.”
INCOSE SEBoK	(1) Cyber-Physical Systems (CPS) are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. (Lee 2008, 363)
	Cyber-physical systems (CPS) are physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core. (Rajkumar et al. 2010)
IBM	“Sophisticated computer devices that work together to perform functions, control physical elements, and respond to human control.”
Intel	“These types of systems blend human and compute power and integrating mechanical systems with human physical interaction giving both a form of "superpowers".”

Following the definitions shown in Table 1, it can be deduced that, CPS are complex systems that integrate physical and logical components and consider the human interaction as part of the overall system. These systems rely on networking strategies, high performance computers, algorithmic models, to enhance the control, operation, and management of the system.

To provide a graphical description of CPS structure, Ali, Gupta and Nabulsi, suggest a six-layer approach where the lower layer is the physical layer, and the higher layer corresponds to the domain to which CPS are applied to. Figure 3 adapts the six-layer approach to the smart transportation domain using electric vehicles.

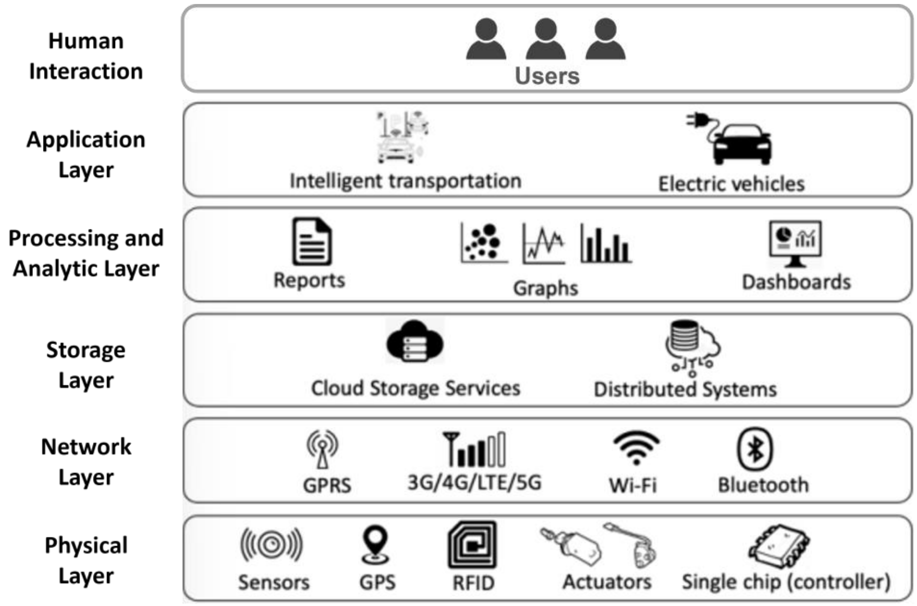


Figure 3. Six layers of cyber-physical systems

A more detailed description for each layer is as it follows:

- **Physical layer –** This layer relates to the components that occupy area in the space domain. Examples of equipment include sensors, controllers, actuators, and the human as interacting agent Network layer – In this layer, communication and data transfer standards are defined to facilitate the transmission of collected data to other systems or cloud data bases. Examples of network protocols include Bluetooth, Wi-Fi, 3G/4G/LTE/5G, Ethernet, Universal asynchronous receiver-transmitter (UART), among others.
- **Storage Layer –** Data collected from the physical layer can be stored locally or in cloud-based systems. Also, Database systems are used to manage the dedicated data formats required to manipulate the data.
- **Processing and Analytics Layer –** This layer relies on analyzing the collected data to enhance the strategic decision-making process. The use of data analytics models such as machine learning is generated insights, create simulations, and data visualizations. The

outcomes for this layer can go back to the physical layer to inform the actuator or controller and to provide the end user system with relevant system information.

- **Applications layer –** This layer relates to the Human System Interaction portion of the CPS. In this layer, users engage with the system based on displayed performance parameters developed in the processing and analytics layers. In this layer, context is important to define effective methods for user interactions.
- **Human interaction–** This final layer refers to the system in which humans and cyber technologies are interconnected to achieve a goal. In CPS, humans are considered integral parts of complex cyber-physical systems that integrate communication, computing, control, and networking technologies into the physical system. This is in contrast to conventional wisdom, where humans are viewed as independent entities that are passive and consume, use, or operate these systems.

Following the previous examples of components, layers, and characteristics of CPS, the transportation system has proposed approaching transportation systems as CPS. For example, Henshaw and Deka introduced the concept of Transportation Cyber-Physical Systems (TCPS), which can be further classified according to their scope: infrastructure-based, vehicle infrastructure and vehicle-based. In TCPS, the authors suggest five components that include users, TCPS sensors. TCPS actuators, smart controller, and Decision Based Layer. The following section discusses the vision for electric vehicles in the US and their characteristics as CPS systems.

2.1.2. Electric Vehicles as Cyber-Physical Systems.

On April 22, 2021, the U.S. Secretary of Transportation, Pete Buttigieg, announced that the federal government will be investing over $170 billion in the EV industry for the next years. The investment is a viable alternative to close the gap with the Chinese EV market, which is currently two thirds the size of U.S. The funds plan to support U.S. manufacturers on securing materials and modernize manufacturing environments (U.S. Department of Transportation). More recently, with the signing of a presidential executive order, which states that 50% of new vehicles sold by 2030 shall be zero-emissions, President Biden has set the path to a digital transformation in the automotive industry, which aims to understand, analyze, and develop efforts for manufacturing readiness through cyber-physical systems (The White House, 2021).

Following the aforementioned and characteristics of CPS, it can be understood that (EV can be approach through CPS principles. For example, EV include sensors, and cameras that alert proximity, temperature, energy consumption, GPS, humidity, speed, among others. The data from these sensors can be accessed through various mechanisms including in-vehicle display or through mobile applications via owner's smart phone. Data is stored for owners' discretion and in some instances updates and software bugs are shared with the manufacturer. The analytics portion can be conducted by monitoring battery performance, conducting prognostics, and informing other systems and the users of malfunctioning's. Lastly, the application layer consists of the driver (user) receiving a warning alert, informing of root causes, and providing recommendations to the end user.

On the other hand, in the transition that vehicles have had from federated electromechanical systems to complex cyber-physical systems, the increase in complexity at the system level translates into an increase in the number of interfaces, capacities, lines of code and implementation of behaviors of learning and adaptation to the environment.

In addition, CPS rely on monitoring, and control mechanisms to efficiently adapt their behavior to improve system's performance. Similarly, EV explore the use of monitoring methods to enhance system behavior. E.g. Sankavaram, Jodali and Pattipati, introduced a health management system that considers diagnostic and prognostic methods for braking systems (Sankavaram, Pattipati, & Kodali, 2013). In addition, Lv et al., (Lv, et al., 2018) proposed an EV energy consumption optimization method that recognizes and adapts to multiple driving styles. Besides, CPS bring new requirements to the development of automotive vehicles. The use of new components such as battery, electric powertrain, inverters, converters, mechanisms to understand the interaction between the vehicle and the grid, electrical/electronic architectures, and vehicle-to-grid infrastructure is needed and new methods need to be explored. (Lukasiewycz, et al., 2012) (Sortomme & El-Sharkawi, 2011) Given its diverse applications CPS in EV, and the need to consider humans in the loop. Socio-technical systems engineering (STSE) would seem to be a strong candidate to improve the flexibility of CPS.

2.1.3. Cyber-Physical Systems Challenges

Socio-technical systems.

According to the Systems Engineering Book of Knowledge (SEBoK), socio-technical systems (STS) provide an approach to understand how humans and machine engage in a relationship that influences both parties. In a similar note, Schöttl and Lindemann, state that STS are characterized by complexity, and it must consider the role individuals play in the overall system performance and vice versa (Schöttl & Lindemann, 2015). In the INCOSE Vision 2035, the professional organization for systems engineering, suggest a transformational perspective on the development of complex systems. The rational states that systems are expected to increase in complexity due to an increase in number of capabilities, the integration of interdependent systems, rapid-changing scenarios, the adoption of autonomous behaviors, and the addition of more stakeholders into the system, lifecycle, and emerging technologies such as Artificial Intelligence (AI) (INCOSE, n.d.). Therefore, the organization calls for methods that understands socio-technical complex systems with human systems integration models.

Recent studies that approach complex systems through the lens of a socio-technical perspective include the analysis of including the human into the national infrastructure resilience processes (Thomas, Eisenberg, Seager, & Fisher, 2019), the merging concept of Industry 5.0 that explore role of humans with Industry 4.0 technologies (Akundi, et al., 2022), the use of blockchain technology in healthcare systems (Wong, Yee, & Nøhr, 2018), and policy analysis to understand the barriers of electric vehicles (Steinhilber, Wells, & Thankappan,, 2013). The integration of electric vehicles with wireless transportation networks offers many potential benefits. Therefore, approaching their development through the lens of CPS and socio-technical perspectives seem to be automatic. However, it turns out there are challenges in CPS that must be addressed together (socio-technical) and separately (social and technical). The integration of electric vehicles with wireless transportation networks offers many potential benefits. Therefore, it is important to approach its development through the lens of a Cyber Physical Systems perspective. However, it turns out there are challenges in CPS that need to be addressed.

CPS Challenges Analysis - The case for Electrified Transportation Systems

Information was collected from around 150 different articles in the literature, in order to find the biggest challenges that different authors and organizations have faced during the development and research on development issues of Electrified Transportation Systems and their infrastructure. The Table 2 below presents the concentrated information of the consulted literature, describing in the different articles the challenges identified and subsequently classified.

Table 2. CPS Challenges in Electrified Transportation Systems

Source	Author Name	Domain	Article Title	Challenge Type	Challenge Description
IEEE Xplore	Liu, Yang. Peng, Yu. Wang, Bailing	Technology	Review on Cyber-physical Systems	Technical	Implementation, Understanding
IEEE Computer Society	Zanero, Stefano	Technology	Cyber Physical Systems	Technical	Integration, Interoperability
IEEE Xplore	Jazdi, Nasser	Technology	Cyber Physical Systems in the Context of Industry 4.0	Technical / Social	Applicability, Adaptation, Integration
Wiley Online Library	Uday, Payuna. Marais, Karen.	Technology	Designing Resilient Systems-of-Systems: A Survey of Metrics, Methods, and Challenges	Technical	Safety, Reliability
IEEE Xplore	Tao, Fei. Qi, Qinglin. Wang Lihui.	Manufacturing	Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0	Technical	Clear definition. Ambiguity
IEEE Xplore	Bianchi, Thiago. Soares, Daniel. Felizardo, Katia.	Systems Engineering	Quality Attributes of Systems-of-Systems: A Systematic Literature Review	Technical	Clear definition. Ambiguity

Reserach Gate	Dahmann, Judith.	Military	Systems of Systems Test and Evaluation Challenges	Techical	Ambiguity. Interoperability
Elsevier	Yaacouba, Jean-Paul	Cyber-security	Cyber-physical systems security: Limitations, issues, and future trends	Social	Physical security
ACM Computing Surveys	Nielsen, Claus. Larsen, Peter. Fitzgerald, Jhon	Transportation, Defense	Systems of Systems Engineering: Basic Concepts, Model-Based Techniques, and Research Directions	Technical	Integration
Wiley Online Library	Axelsson, Jakob	Technology	Achieving System-of-Systems Interoperability Levels Using Linked Data and Ontologies	Technical	Integration, Interoperability
IEEE Xplore	Axelsson, Jakob Nylander, Stina	Transportation and Mobility	An Analysis of Systems-of-Systems Opportunities and Challenges Related to Mobility in Smart Cities	Social	Integration
IEEE Xplore	Anher, Darryl	Defense	Workshop Report: Test and Evaluation of Autonomous Systems	technical	Interoperability
Elsevier	Stjepandic, Josip	Technology	Agile digital transformation of System-of-Systems architecture models	Technical	Ambiguity, Adaptability
IEEE Xplore	Svenson, Pontus	Transportation	A design method for collaborative systems of systems applied to Metropolitan	Social	Interoperability
IEEE Xplore	Axelsson, Jakob. Fröberg, Joakim. Eriksson, Peter.	Roads	Towards a System-of-Systems for Improved Road Construction Efficiency	Social	Sustainability, Adaptability
IEEE Xplore	Traganos, Konstantinos. Grefen, Paul. Vanderfeesten, Irene.	Manufacturing	The HORSE framework: A reference architecture for cyber-physical systems in hybrid smart manufacturing	Technical	Integration, Interoperability
Elsevier	Pivoto, Diego. Da Rosa, Rodrigo. Rodriguez, Joel.	Cloud Computing	Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0	Technical	Integration, Adaptability
Elsevier	Aheleroff, Shohin. Xu, Xun. Y.Zhong , Ray. Lu, Yuqian	Technology	Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model	Technical	Adaptability, Interoperability
Int. J. Agile Systems and Management, Vol. 12	Wognum, Nel. Bil, Cees. Elgh, Fredrik.	Systems Engineering/Engineering Education	Transdisciplinary systems engineering: implications, challenges, and research agenda	Social	Work Culture, Integration
IEEE Xplore	Fleischmann, Hans. Kohl, Johannes. Franke, Jörg.	Manufacturing	A reference architecture for the development of socio-cyber-physical condition monitoring systems	Social/Technical	Integration, Interoperability
Elsevier	FuiTie, Siang. WeiTan, Chee.	Transportation	A review of energy sources and energy management system in electric vehicles	Technical/Social	Accessibility
Wiley	Nordal, Helge. El-Thalji, Idriss.	Manufacturing	Modeling a predictive maintenance management	Technical	Reliability, Adaptability

			architecture to meet industry 4.0 requirements		
IEEE Xplore	Rawat, Danda. Bajracharya, Chandra. Yan, Gongjun	Transportation	Towards intelligent transportation Cyber-Physical Systems	Technical	Reliability, Security, Privacy , Interoperability
ABCM	Cardoso, raul. Mastelari, Nedierauer. Bassora, Murilo.	Transportation	Internet of things architecture in the context of intelligent transportation systems	Technical	Reliability, Adaptability
IEEE Sensors Council	Epiphaniou, Hammoudeh. Belguith, S.	Transportation	A Service-Oriented Approach for Sensing in the Internet of Things	Technical	Implementation, Scalability, Interoperability
Springer-Verlag Berlin Heidelberg	Liebel, Grischa. Marko, Nadja. Tichy, Matthias	Systems	Model-based engineering in the embedded systems domain	Technical	Training, Tool support
University of Southern California	Deshmukh, Jyotirmoy. Sankaranarayanan, Sriram.	Systems	Formal Techniques for Verification and Testing of Cyber-Physical Systems	Technical/ Social	Social Understanding, Security
University of Oslo	Arcuri, Andrea. Zohaib Iqbal, Muhammad.	Informatics	Black-Box System Testing of Real-Time Embedded Systems Using Random	Social	Understanding, Integration
Technische Universit¨at Berlin	Marrero, Abel. Kaiser, Stefan.	Systems/Automotive	Integrating Test Levels for Embedded Systems	Technical	Holism, Interoperability
IEEE Xplore	Neves, Vânia de Oliveira. Bertolino, Antonia	Systems	Do We Need New Strategies for Testing Systems-of-Systems?	Technical	Operational Independence. Interoperability
MDPI	Raulf Christian. Proff, Moritz. Huth, Tobias.	Automotive	An Approach to Complement Model-Based Vehicle Development by Implementing Future Scenarios	Technical	Integration, Understanding
IEEE Xplore	El Hadraoui, Hicham. Ahmed, Chebak. Mourad, Zegrari	Automotive	Model-based system engineering design of a versatile control test bench of an electric vehicle's powertrain for educational purpose	Technical	Integration, Interoperability
IEEE Software	Weyrich, Michael. Ebert, Christof.	Automotive	Reference Architectures for the Internet of Things	Technical	Standardization, Integration
Elsevier	MiaoTan, Kang. Ramachandaramurthy, Vigna K. YingYong, Jia.	Automotive	Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques	Social	Understanding
Elsiever	N.Shaukat. B.Khan. C.A.Mehmood.	Transportation	A survey on electric vehicle transportation within smart grid system	Technical / Social	Integration, Holism, Understanding, Interoperability
IEEE Xplore	Mouli, G. R. Chandra. P. Bauer. M. Zeman.	Automotive	Comparison of system architecture and converter topology for a solar powered electric vehicle charging station	Technical	Understanding, Interoperability

Wiley Systems Engineering 2019	Axelsson, Jakob. Fröberg, Joakim. Eriksson, Peter.	Construction	Architecting systems-of-systems and their constituents: A case study applying Industry 4.0 in the construction	Technical	Flexibility, Application
Wiley Online Library. MIT	Selva, Daniel. Cameron, Bruce.	Systems	Patterns in System Architecture Decisions	Social	Knowledge, Ambiguity Experience
United States Department of Transportation	United States Department of Transportation	Transportation	ITS 2015-2019 Strategic Plan	Technical / Social	Design and Integration, Social adoption of new technologies, integration
IEEE Xplore	Garces, Lina.	Healthcare	A Reference Architecture for Healthcare Supportive Home Systems	Technical	High Abstraction in architecture
IEEE Xplore	Wouters, Laurent. Creff, Stephen. Effa, Emma.	Aerospace	Collaborative systems engineering: Issues & challenges	Social	Work Culture, Integration, Interoperability
IEEE Xplore	Torngren, Martin.	Engineering Education	Towards Integration of CPS and Systems Engineering in Education	Technical	Implementation, Integration
Elsevier / Science Direct	Bagheri, Behrad. Yang, Shanhu.	Industry	Cyber-physical Systems Architecture for Self-Aware Machines in Industry 4.0 Environment	Technical	Integration, Adaptability, Interoperability
Elsevier/ Science Direct	Lee, Jay. Bagheri, Behrad	Manufacturing	A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems	Technical	Understanding, Adaptability
Elsevier / Science Direct	P.Hehenberger. B.Vogel-Heuser. D.Bradley	Informatics	Design, modelling, simulation, and integration of cyber physical systems: Methods and applications	Technical	Uncertainty to Design
Elsevier	Gürdür, Didem. Asplund, Fredrik	Academia	A systematic review to merge discourses: Interoperability, integration, and cyber-physical systems	Technical	Understanding, Interoperability, Integration
IEEE Wireless Communications	Guerrero, Juan Antonio. Zeadally, Sherali.	Transportation	Integration challenges of intelligent transportation systems with	Social/Technical	Understanding, Culture, Adaptability, Interoperability
IEEE Xplore	Sztipanovits, Janos.	Informatics	Toward a Science of Cyber–Physical System Integration	Technical	Heterogeneity, Integration, Interoperability, Uncertainty
Wiley	Henderson, Kaitlin. Salado, Alejandro	Academia	Value and benefits of model-based systems engineering (MBSE): Evidence from the literature	Social / Technical	Empirical applications, Reliability
INCOSE (Special Feature)	Freeman, Laura.	Industry	Test and Evaluation for Artificial Intelligence	Technical	Interoperability, Implementation, Security
IEEE Xplore	Behere, Sagar. Torngren, Martin.	Automotive	A Functional Architecture for Autonomous Driving	Technical	Design, Distribution
Lancaster University	Sommerville, Ian	Artificial Intelligence	Artificial Intelligence and Systems Engineering	Social	Misunderstanding, Culture
North Carolina A&T State University	Gebreyohannes, Solomon. Karimoddini, Ali. Homaifar, Abdollah.	Automotive	Applying Model-Based Systems Engineering to the Development of a Test and Evaluation Tool for Unmanned Autonomous Systems	Technical	Predictability, Uncertainty, Reliability

Research Gate	Chami, Mohammad. Michel Bruel, Jean. Zognib, Christophe	Artificial Intelligence	A First Step towards AI for MBSE: Generating a Part of SysML Models fromText Using AI	Social / Technical	Empirical applications, Interoperability, Reliability
Elsevier	Gürdür, Didem. Asplund, Fredrik.	Academia	A systematic review to merge discourses: Interoperability, integration and cyber-physical systems	Technical	Interoperability
Elsevier	Hehenbergera, P. Vogel-Heuserb, B. Bradleyc, D. Eynardd, B. Tomiyamae, T.	Academia	Design, modelling, simulation and integration of cyber physical systems: Methods and applications	Technical	Operational Independence, Interoperability
IEEE Xplore	Neuman, Clifford.	Security	Challenges in Security for Cyber-Physical Systems	Technical	Security, Interoperability
IEEE Xplore	Ji Eun Ji Eun, Kim. Daniel, Mosse.	Technology, Software Development	Generic Framework for Design, Modeling and Simulation of Cyber Physical Systems	Technical	Abstraction, Flexibility, Interoperability
Old Dominion University	Keating, Charles. Adams, Kevin	Academia	System of Systems Engineering Requirements: Challenges and Guidelines	Technical / Social	Resistance, Culture, Understanding
Science Direct	Albrekht, Yosyp.	Space	Multi modular Cyber physical Systems: Challenges and Existing Solutions	Technical / Social	Security, Reliability
IEEE Xplore	Gunes, Volkan.	Technology	A Survey on Concepts, Applications, and Challenges in Cyber-Physical Systems	Technical	Reliability, Scalability, Distribution, Interoperability
IEEE Xplore	Bakirtzis, Georgios. Ward, Garrett L.	Software Development	Fundamental Challenges of Cyber-Physical Systems Security Modeling	Technical	Cybersecurity, Security
IEEE Xplore	Hofer, Florian.	Industry	Architecture, technologies and challenges for cyber-physical systems in Industry 4.0	Technical	Reliability, Security
IEEE Xplore	Wang, Eric Ke.	Computing and Communications	Security Issues and Challenges for Cyber Physical System	Technical	Security, Interoperability
IEEE Xplore	Lee, Edward.	Telecomm	The Past, Present and Future of Cyber-Physical Systems: A Focus on Models	Technical	Integration, Interoperability

The challenges to harnessing CPS were organized into three main groups: social challenges, technical challenges and socio-technical challenges. Social challenges are defined as issues caused by the set of interactions: (1) among individuals, (2) between individuals and organizations, and (3) among organizations. These are specifically characterized by the participation of humans. For investigation purposes, technical challenges are defined as current limitations that involve physical and logistical resources required to functionally support the development and maintenance of EV. Socio-technical classification is understood as the set of 'social' and 'technical' aspects that come together and are treated as interdependent parts of a complex system for its proper functioning.

Figure 4 shows us that in the consulted literature, 67% of the challenges found for the development of electric vehicles are technical challenges, followed by 19% socio-technical challenges, and finally 14% are social challenges.

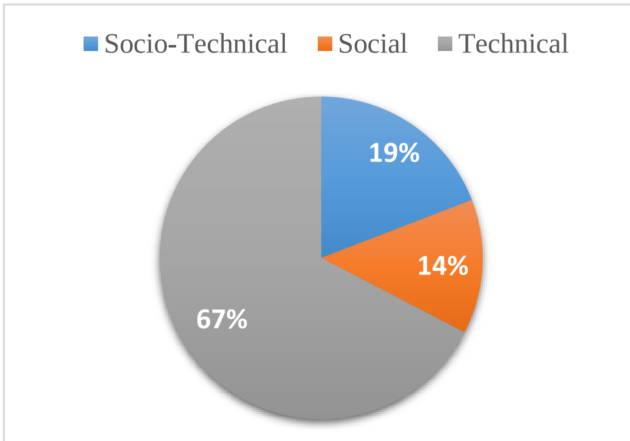


Figure 4. EV Challenges classification

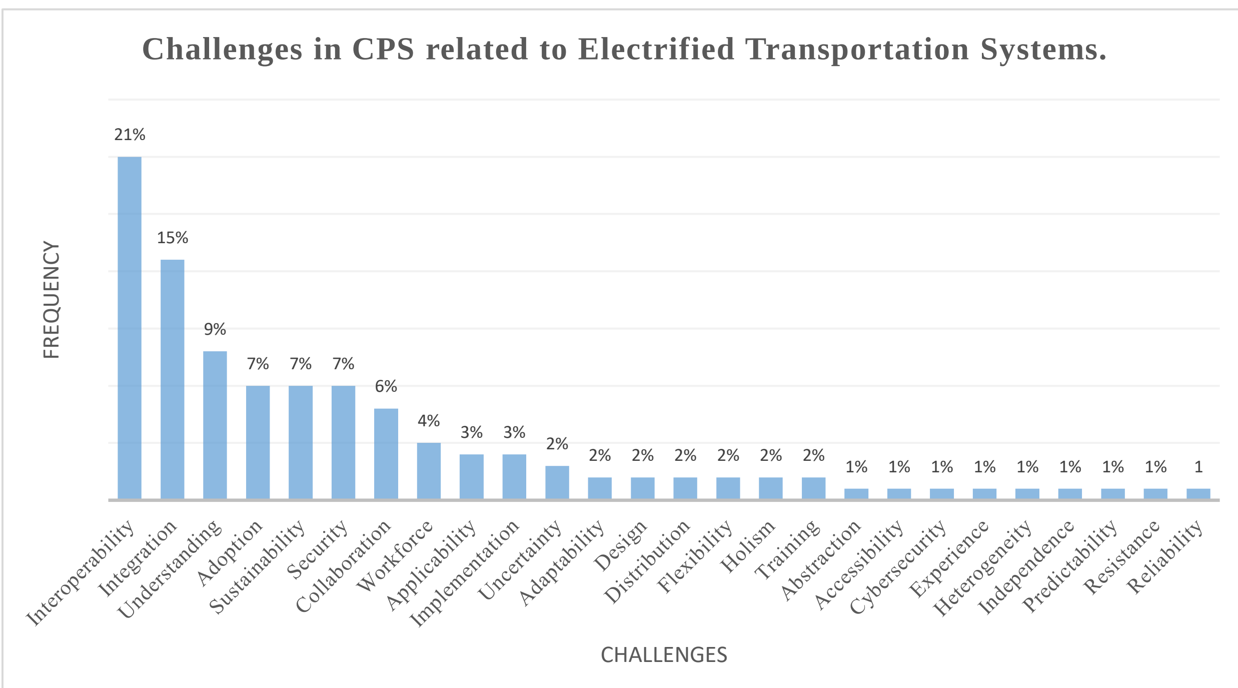


Figure 5. Challenge Type in issues related to ETS and their infrastructure

Figure 5, shows us the different types of challenges found by the different authors in the concentration of the 150 papers consulted in the literature on issues related to electrified transportation systems and their infrastructure.

For this investigation, Interoperability and Integration were the most recurrent challenges faced by the authors with 21% and 15% recurrence respectively. According to the definitions in SEBoK, Interoperability is the degree to which two or more systems, products or components can exchange information and use the information that has been exchanged, and Integration is a process that combines system elements to form complete or partial system configurations in order to create a product specified in the system requirements (SEBoK, 2022).

Other relevant challenges are explained according to the literature consulted below, in addition to raising some important questions for future research work.

Social Challenges

A. *Collaboration among stakeholders*

In an organization due to the exponential rise of CPS, computer scientists and engineers continue to understand how to transform the system's physical requirements, such as stability, calculation performance, and power consumption (Liu, Peng, et al., 2017). Specifically, tools are needed for proper coordination among engineers, researchers, practitioners, and educators. The objective is to facilitate instruction and communication between systems architects and researchers in other fields, such as combinatorics, computer science, and operations research (Deshmukh & Sankaranarayanan, 2019).

In addition, effective team collaboration strategies must be explored in order to address issues such as difficulties with shared vocabulary, project orchestration, controlled exposure, and consistency (Oliveira Neves, et al., 2018). Also, efforts that define activities needed to achieve a successful transdisciplinary collaboration in engineering, withing companies, and among organizations are needed. It is suggested that a successful collaboration requires transdisciplinary education that includes problem-orientation based on problems relevant to the company, multidisciplinary collaborators, formation of transdisciplinary teams, well- defined goals, a dynamic environment, a professional team of teachers and orientation support, and finally an evaluation of results obtained and feedback (Oliveira Neves, et al., 2018).

In summary, is required a better understanding of:

- What resources are needed to carry out an effective collaboration?
- Who will be responsible for organizing work teams from different disciplines to collaborate together?
- Who will be the specialized experts to guide these teams?

B. Adoption

A recurrent challenge of CPS research is the adoption of its methods and tools during its implementation (Sortomme & El-Sharkawi, 2011). There is a need for established plans that contain the priorities and strategic issues to carry out research, development, and adoption activities for the transportation system.

The results of these plans are expected to be safer vehicles and roads, improved mobility, reduced environmental impacts through better management of traffic flow, speeds, and congestion, support for transport connectivity through the development of standards and system architectures, and the application of advanced wireless technologies (Gunes, et al., 2014). Where society can see these results to thereby facilitate adaptability and adoption as new transportation technologies.

In summary, is required a better understanding of:

- What are the criteria and standards for establishing an adoption plan?
- Who formulates the adoption plan and its standards?
- How and when is this adoption plan applied?

C. Workforce Development

According to the National Academy of Sciences (NAS), as systems evolve and complexity increases, a new breed of engineers is required. A workforce able to design, develop, manufacture, and maintain CPS requires a systemic thinking since systems are being integrated forming the so-called system-of-systems. It is also identified by NAS that universities could benefit from adapting a CPS curriculum that includes hands-on projects, systems engineering including requirements management and integration, verification testing, and evaluation, modeling, and simulation of deterministic and non- deterministic systems. Also, it is important that new curriculums include continuous and discrete math, sensing, and control theory (National Academies of Sciences, 2016). For this challenge, it is important to ask questions such as:

- What will be the new capabilities required for future generations?
- What will be the bases and sources of knowledge to establish these study plans?
- Who will be responsible for establishing the new study plans?
- Apart from universities, what other institutions could transmit this knowledge?

Technical Challenges

A. Security

CPS systems are prone to cyber and/or physical security threats, attacks, and challenges because they operate in multiple domains of the internet of things (IoT) simultaneously and communicate using different technologies and protocols (Yaacoub, et al., 2020).

Threats to CPS can be classified by cyber threats and physical threats. If combined, they can be considered as cyber- physical threats. Though both threats can cause critical impacts on the system, cyber threats require more attention since they are easier to launch since they do not require physical presence or physical tools, unlike physical threats, which are prone to physical damage, loss, and repair (Eason, et al., 1995). It is important to highlight the fact that CPS needs more detailed attention to privacy, dependability, resiliency, interaction, and coordination to improve confidentiality, integrity, authentication, and privacy-preserving (Gürdür & Asplund, 2018).

As more and more autonomous driving features are integrated into vehicles, and vehicle-to-everything communications become more prevalent, system complexity is likely to continue to accelerate given the vast amount of data that will need to be captured, so basic functions that ensure the robustness and stability of problems such as uncertain environments, error detection, and control and transmit them safely so that the vehicle can be operated safely and efficiently must be established and provided immediately (Wognum, et al., 2019).

For this challenge, the following questions are then presented:

- How complex is the system security?
- What are the security measures that are currently being taken in the system?
- Are these security measures evaluated? and how effective are they?

B. Interoperability

CPSs operate in dynamic environments, the idea is to establish a prototype CPS model and a set of effective and consistent measurement standards, build highly reliable dynamically configured CPSs, and organize interoperable aggregation systems to capture uncertainty, errors, failures, and security attacks and to collaboratively detect and manage system interfaces to prevent failures (D'Ambrosio et al., 2017). IoT and CPS involve a lot of data and information from heterogeneous systems, but they need to be properly managed to improve human-machine interaction and properly control the adaptive behaviors of machines and their interfaces (Wognum, et al., 2019).

The interoperability of the CPS in transportation focuses on the complexity of the interactions between the information systems in terms of procedures, applications, infrastructure, and data (Gürdür & Asplund, 2018). Conceptual models do not go beyond project scope, hence, to not include socio-economical aspects. The current methos use of complex metrics, a focus on selective aspects of interoperability, and the limited support for decision-making.

Given this situation, it is proposed to present the following series of interesting questions:

- How is the channel for data and information exchange between the different entities of the system handled?
- What are the communication channels between the subsystems of the system?

- Are these communication channels effective?
- Does the system operate internally as it should?

C. Sustainability

A sustainable cyber-physical system is a system capable of running efficiently without compromising its main goal and requirements while, at the same time, using and renewing its resources in an effective manner (Gürdür & Asplund, 2018). If a system is highly sustainable, it will have the capabilities to tune itself dynamically under evolving circumstances, use energy efficiently, minimize environmental impact, and have a long- lasting life cycle. Sustainability can be referred to, in terms of energy, as the balance between the power required to run a physical component and the power available from resources (Eason, et al,. April 1995). Green energy extracted from the resources of the physical environment is used as an energy source to sustain CPSs. However, the use associated with this source of energy comes with challenges that need to be kept into consideration such as intermittent energy and unknown load characteristics. Additionally, the energy available from the environment is, sometimes, not sufficient to operate the CPSs.

For this challenge, it would be important to question:

- What sustainable measures are currently being taken?
- What are the current energy sources?
- Are the measures currently taken sustainable?

CHAPTER 3. A MODEL-BASED SYSTEMS ENGINEERING SOLUTION

3.1. SYSTEMS ENGINEERING

In many important fields, including infrastructure, health care, transportation, emergency response, and defense, information is based on a system made up of largely independent systems, often already in existence. The International Council on Systems Engineering defines a "System", as an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. It is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not. The system's properties (as a whole) result, or emerge from the parts or elements and their individual properties, and from the relationships and interactions between the parts, the system and its environment. (INCOSE, 2019).

Systems engineering, on the other hand, is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and managerial methods. "Engineering systems" can be composed of one or all of the people, products, services, information, processes, and natural elements. (INCOSE, International Council on Systems Engineering, 2019).

To better understand the focus of this research, it is important to mention the term "System of systems". The term "System of Systems" (SoS) has been used since the 1950s to describe systems that are made up of independent constituent systems, acting together towards a common goal through synergy between them. Examples of SoS arise in areas such as power grid technology, transportation, manufacturing, and military enterprises. SoS engineering is challenged by the properties of independence, heterogeneity, evolution, and emergence found in SoS. (Ballegaard N, et al, 2015) System-of-Systems integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future field scenarios. (Jamshidi, 2008) The SoS engineer faces several significant challenges, including the need to identify the boundaries, interactions, and relationships between the overall SoS and the independent constituent systems within it.

In general, the goal of all Systems Engineering activities is to manage risk, including the risk of not delivering what the customer wants and needs, the risk of late delivery, the risk of excess cost, and the risk of negative unintended consequences. One measure of utility of Systems Engineering activities is the degree to which such risk is reduced. (INCOSE, International Council on Systems Engineering, 2019).

3.2. MODEL BASED SYSTEMS ENGINEERING (MBSE)

For several years, systems engineering within organizations has moved from relying on document-based approaches to employing model-based approaches. Model-Based Systems Engineering is considered an engineering approach that uses models as an integral part of the technical baseline that includes the requirements, analysis, design, implementation and verification of a capability, system and/or product throughout the acquisition life cycle. (Hart, 2015)
INCOSE defines MBSE as the formalized application of modeling to support system requirements, design, analysis, verification activities beginning in the conceptual phase and continuing throughout development and later life cycle phases. (INCOSE, Systems Engineering Handbook. A Guide for System Life Cycle Processes and Activities, 2015)

In summary, this methodology focuses on the creation and exploitation of models as the main way of exchanging information, instead of sharing information as we traditionally do, based on documents, what model-based systems engineering intends is to base the information of a system into a model that understands how the whole process fits together, so that specific decisions are always made with an overview of the system in mind.

Some researchers and engineering design professionals have adopted and/or explored MBSE practices. In fact, there is a close relationship between the work done by/in the areas of design engineering and systems engineering. (For example, the National Science Foundation

(NSF) has assigned research in the areas of systems engineering and engineering design under a common umbrella, the Systems Engineering and Design Engineering (EDSE) program. (Henderson & Salado, 2020).

3.2.3. MBSE Benefits

According to the opinions of different authors, MBSE has multiple benefits, among them is the reduction of costs due to the elimination of rework and the strange design iterations that generally occur when not all the interested parties have been able to contribute to the initial engineering. (Madni & Purohit, 2019) The reasons for using MBSE and its potential have already been identified in several publications where benefits such as improved communication between stakeholders, improved understanding of the system, traceability and transparency of design decisions, and overall consistency were found. (Wilking,et al, 2020)

Here it is important to mention an important contribution made by one of the main authors of the MBSE research (Henderson & Salado, 2020). Where according to 847 identified papers, they compiled and classified the main benefits claimed from MBSE, which are presented in Figure 6 below.

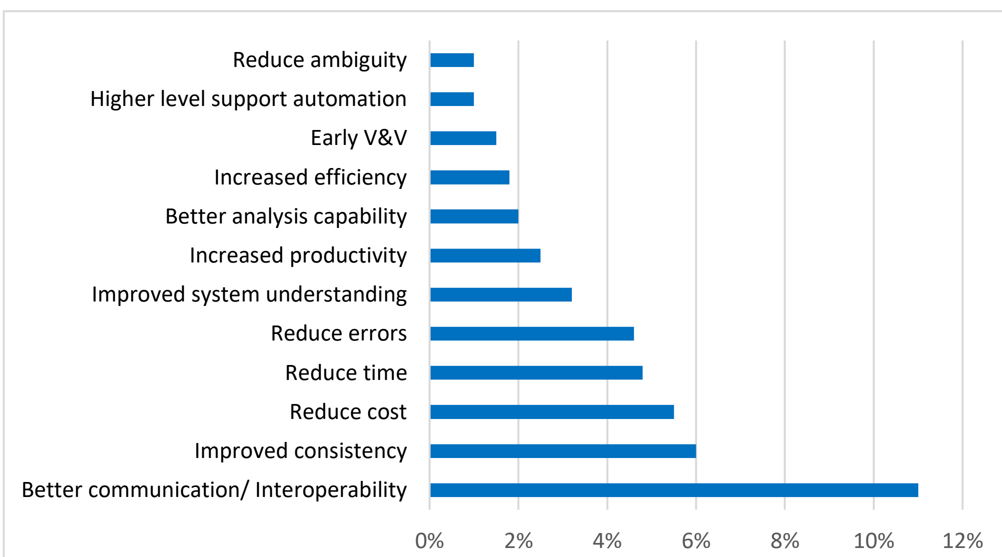


Figure 6. Total benefit types found in 847 papers
(Henderson & Salado, 2020). (Adapted from the original graph)

The graph shows us that the greatest number of MBSE benefits, are focused on improving communication and shared information (interoperability), improving consistency, as well as reducing costs, time, and errors. Despite the multiple benefits found, currently, the industry is complaining about the difficulties to apply MBSE within their companies, where they have encountered challenges such as lack of experience and lack of adequate methods that allow the introduction and execution of the approach of MBSE, this due to the intense conjunction of the elements of the system, the focus, and the lack of use of a consistent and interconnected method (Wilking, et al,. 2020).

3.3. INFRASTRUCTURE AND IMPLICATIONS FOR ELECTRIFIED TRANSPORTATION SYSTEMS.

Developing an Electric Vehicles infrastructure presents opportunities. Energy storage technology is the fundamental element needed for Electric Vehicles market evolution. While high battery costs limit market penetration, identifying multi-value stream pathways for EV energy storage is important. (Markel, 2010)

Designing and developing a correctly interconnected charging infrastructure without having so much operational experience and for the time being lacking standards becomes complex due to the early development of these technologies.

There is a demand for electric transportation in the market, which is incalculable in the future, in addition to the uncertainty about the necessary load capacities for each particular case. Burkert and Schmuelling, in their article "Challenges of Conceiving a Charging Infrastructure for Electric Vehicles", mention that among the factors that influence charging infrastructure are geographical characteristics, target group, charging stations capacities, access and payment, tariffing and legal and authorization processes (Burkert & Schmuelling, 2019).

Proper site planning, population, traffic density, and security must be considered before deploying large-scale charging infrastructure. However, it seems that the most important issue in building an electric vehicle market and EV charging system is the integration of activities in the fields of energy and transportation. Only the systematic development of both systems will provide a stable and reliable electric power system. (Kumar & Dash, 2013)

3.3.1. Interoperability in Infrastructure Systems.

The main challenge is the interoperability of the components within the system. The interoperability of the components of the Electric Vehicle infrastructure is essential for their widespread deployment. By visualizing an electric vehicle as a system, and its external components as its subsystems, we can then understand it as a set of systems, which share information to achieve a common goal. If we talk about the dynamic wireless charging system specifically, we can say that it is made up of different sub systems: The pavement, the power transmitting coil and the power receiving coil. By working these three parts together we can say that we have an interoperable system that is working by exchanging joint information between its subsystems.

Fitting the electrical values of the electric vehicle wireless charging system to the standard range is important since it is directly related to the interoperability of the charging system. Nevertheless, adjusting the inductance of a coil is difficult, especially the dimensions have already been fixed (Dongwook, et al., 2020). When these parts that make up the main system are made up of specific requirements, it is important to consider that they are carried out under established standards that allow them to have compatibility when working together.

3.4. MBSE AND INTEROPERABILITY

To face the challenge of Interoperability, a methodology based on models will be applied. INCOSE defines MBSE as the formalized application of modeling to support system requirements, design, analysis, validation and verification activities, beginning in the conceptual phase and continuing throughout development and later life cycle phases (INCOSE, 2015). When we base our entire system on models, we can have better interoperability, improve communication, and see the system as a whole in a more visual and dynamic way.

To apply this methodology, we choose a case study and we take as an example the part of the electrified pavement structure system, which is a part that is being investigated currently at UTEP, then, the questions to better understand the application of the case study to the model are:

a) How can we solve the interoperability challenge within the pavement subsystem?
b) How can we represent the pavement subsystem in a digital model that allows us to visualize its architecture more clearly?

In general, the main idea of this thesis is proposing a digital engineering model to create a pavement subsystem that supports interoperability between components and stakeholders.

3.4.1. Digital Tool Solution: Magic System of Systems Architect.

Engineers use model-based systems engineering (MBSE) to manage the complexity of systems, improve communication, and produce optimized systems. The effectiveness of the MBSE depends on synthesizing stakeholder requirements in the form of architecture models to create intuitive system descriptions. There are various software tools that can help us develop a complex model.

To develop this model, a digital engineering tool called Magic SoS Architect was chosen, where in addition to digitally visualizing the system, we can interact and visualize the characteristics of the pavement such as requirements, values and interfaces with other parts of the system. Magic Systems of Systems Architect is a software for modeling System of Systems architectures and the concept of Operations. This solution software has diagramming, collaboration, persistence, requirements, and documentation capabilities while offering more customized capabilities tailored to the needs of the organization's architecture. With digital engineering tools such as Magic SoS Architect, it is possible to propose solutions that allow us to visualize the system as a whole instead as independent and individual subsystems, having an updated system and visualized by all interested parties, and with this we can achieve better interoperability and communication inside and outside the system.

3.4.2. Case Study and model application.

To apply this methodology, we choose a case study and we take as an example the part of the electrified pavement structure system, which is a part that is being investigated currently at UTEP, then, the questions to better understand the application of the case study to the model are:

c) How can we solve the interoperability challenge within the part of the pavement?

d) How can we represent the pavement system in a digital model that allows us to more clearly visualize its architecture?

The purpose of this research is to develop a digital model that can help solve the interoperability problem within a system. To develop the model, the case study of the UTEP Electrified Pavement System was taken from a CPS (Cyber-Physical Systems) and MBSE (Model-Based Systems Engineering) approach.

Case Study Questions

As part of the research in the UTEP Electrified Pavement System case study, we began asking the UTEP Civil Department these questions in order to understand and obtain the information needed for the model.

Introduction questions

1. What part of the UTEP Electrified Pavement project are you working on?

2. Who are your stakeholders?
3. What are you currently working on?

Pavement Structure questions

4. What are the main parts that make up the pavement structure?

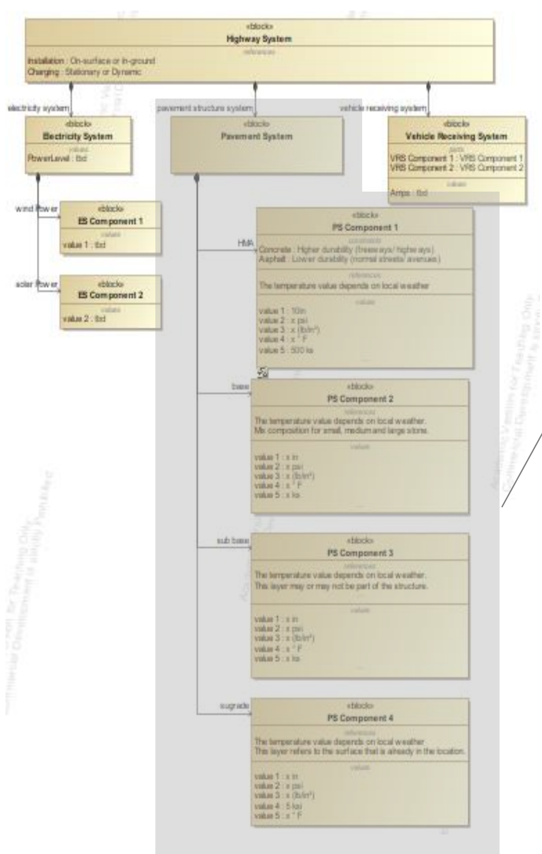
Requirements questions

5. What are your requirements, limitations and constraints that you have within that pavement structure?
6. What are the requirements for the modeling team? What do you expect to receive from this model?
7. With what other departments are you connected with, exchange information (resources, inputs & outputs: physical/logical)?
   7.1. What is your information exchange channel between you and those departments?
8. What challenges have you identified during that exchange of information?
9. What information do you need that you don't have?
10. How often have do you face changing requirements?
    10.1. How do you handle a change in a requirement?
11. Do you have a reference model? (for example: Magment)
12. What units are you using? (English units/ int sist SI units).

Model Development to a Sample Electrified Pavement System Case Study

If we apply the model to the Electrified Pavement part of the Infrastructure of the Electrified Transportation System, we would have a model with certain modules and characteristics such as the following figures of the model. It is important to mention that the model was designed with the requirements and specifications provided during the information gathering process. For modeling purposes, some values were changed to preserve the confidentiality of the UTEP Department of Civil Engineering research.

For a better understanding, figure 8 below shows us an approximation of how the structure system of the Electrified Pavement would be represented graphically for the case study, and figure 7 on the left side, It shows us how this structure would be represented in a digital model in a highways system for electric vehicles. The shaded portion in figure 7 belongs to the part of the pavement, which will be the scope for the development of the model as a case study



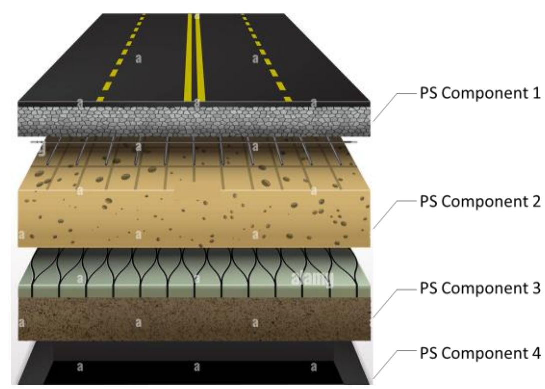


Figure 8. Physical Structure of the Electrified Pavement

Figure 7. Electrified Pavement Structure in a Model

Figure 9 show us the general architecture of the Pavement System with its certain modules. The system architecture allows us to visualize the relationship and interaction with certain modules. If we need to visualize details of its parts, there are diagrams that allow us to assign and specify references, restrictions and specific values to these modules. In Figure 10, we can visualize a specific module (Block) of that architecture, where relevant information to that part of the system is shown, such as: constraints properties, value properties and reference properties.

For this purpose, in Magic SoS Architect Software:

- *Value property*: Is a property that specifies the quantitative property of its containing Block.
- *Constraint property*: Is a property that specifies the constraints of other properties in its containing Block.
- *Reference property*: Is a property that specifies a reference of its containing Block to another Block.

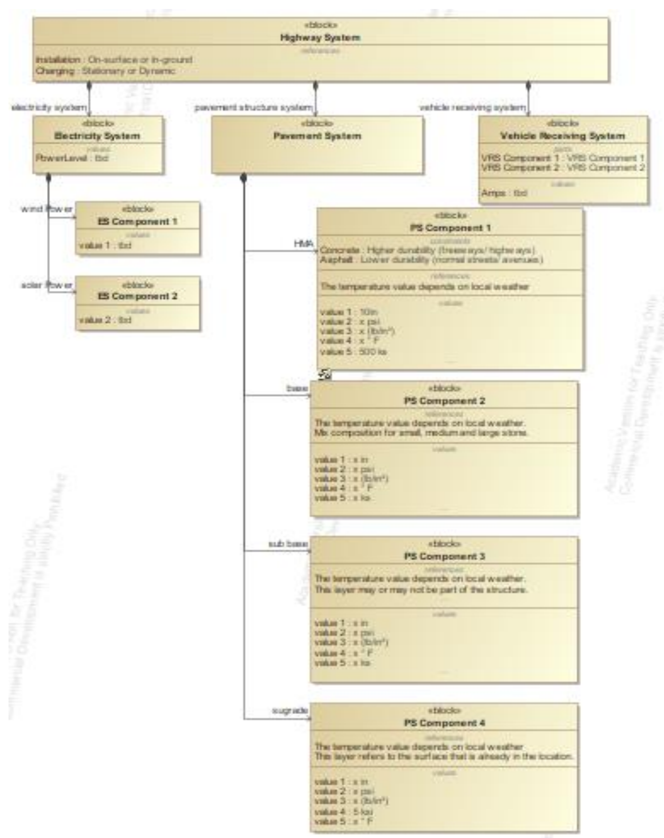


Figure 9. Pavement general system structure

Figure 10. Block as a system component module

The software also allows us to create specific diagrams within any block module of the system, so that a block can be made up of a subsystem that makes up the overall architecture of the system. For example, in Figure 11, the model allows us to visualize (based on the general structure) a specific module and its content and characteristics. To this new structure, values, references and constraints properties can also be assigned.

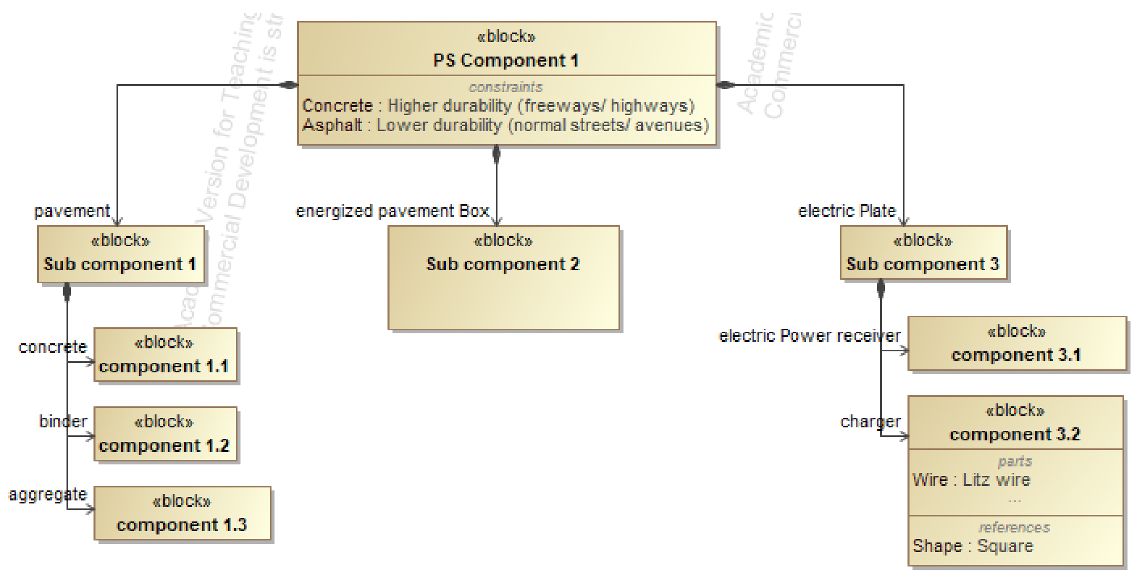


Figure 11. Internal module from the general System

Another important part that we can visualize in a more dynamic way and that should be highlighted in the model is the requirement's part. The model will allow us to visualize lists of requirements and matrices of requirements where we can see how they are linked to the values of the system. The matrices allow us to analyze, create, and modify relationships between requirements and other design elements. For Magic SoS Architect Software purposes, these requirements matrices allow the user to analyze, create, and modify relationships between requirements and other design elements. It is especially valuable that we can show relationships that cannot be represented in diagrams, such as representations of behavior in other diagrams, representations of operation by behavioral actions, among others. All requirement matrices allow for requirement gap and coverage analysis.

Figure 12 shows a matrix of requirements, where it is possible to satisfy relationships between Requirements and other design elements. The rows represent the elements that are the customers of the Satisfy relationship. The columns represent the Requirements that are the providers of the Satisfy relationship. The blue arrows indicate to which value each system requirement is linked.

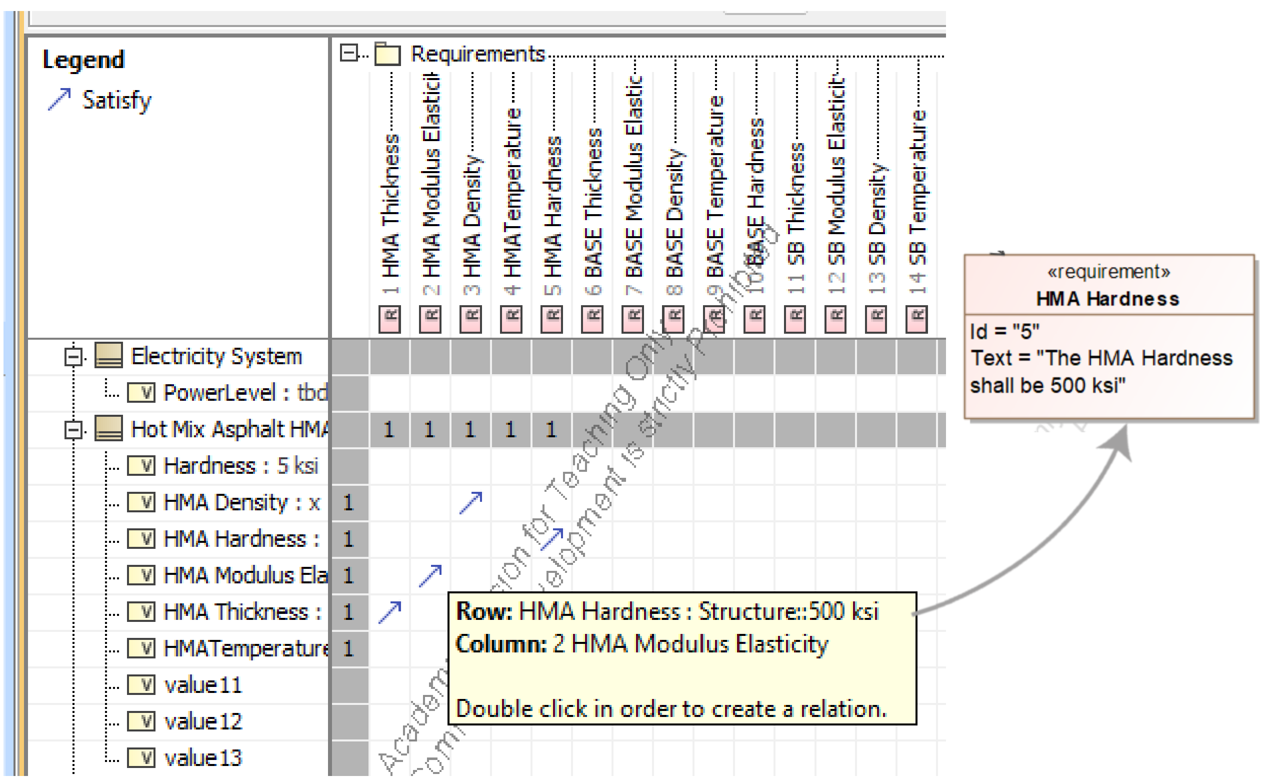


Figure 12. Matrix of requirements and linked values

Matrix like these allow us to identify when we are not meeting the requirements of our stakeholders, when a requirement changed, when we are missing information in our model, or when there are requirements that aren´t satisfied. If a modification is made to a value of a model requirement, it is changed throughout the system, so it is always updated in real time.

Figure 13 shows us another type of requirement's analysis that allows us, for example, for a specific block module, to visualize what requirements are linked to the values of that component, as well as specifically review the description and references of the stakeholders.

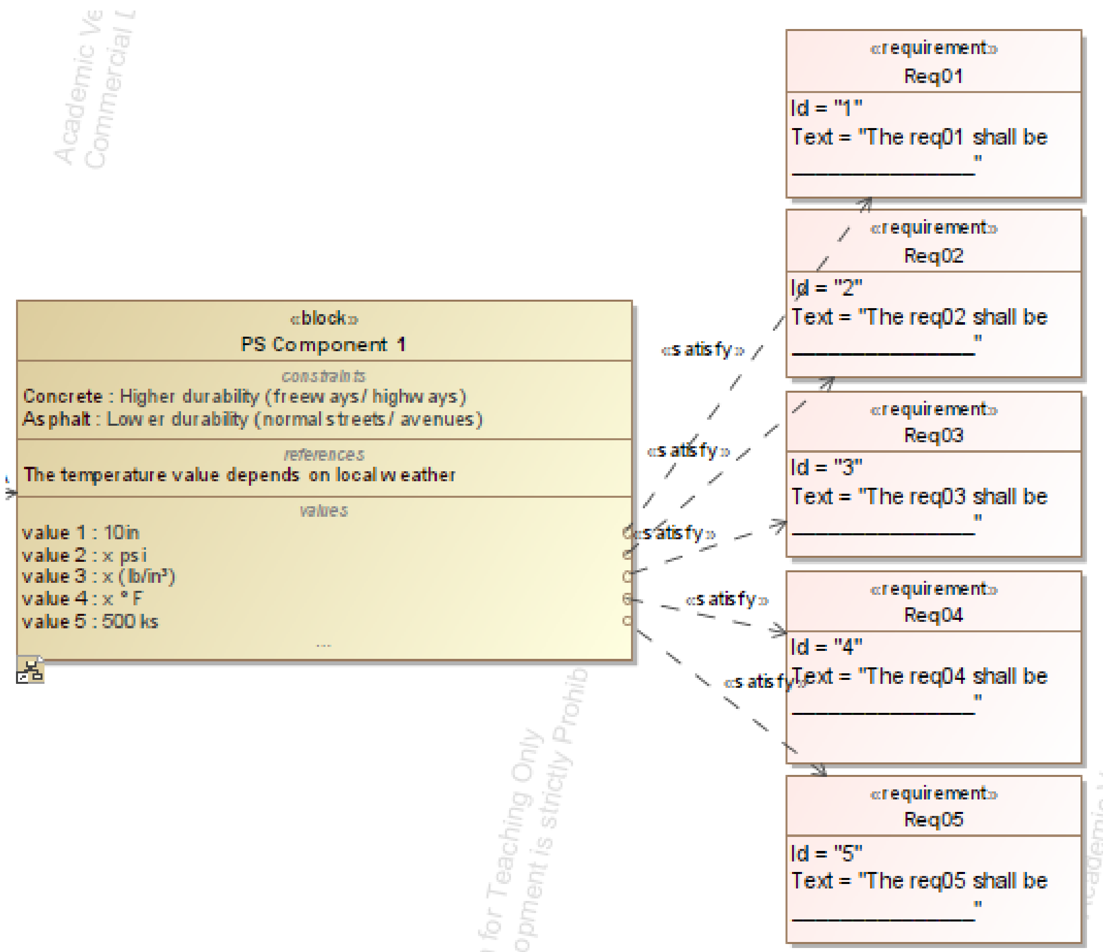


Figure 13. Specific requirements analysis

CHAPTER 4: FINDINGS AND RESULTS.

4.1. Study context

The fields of study applied to this research are Systems Engineering (mostly) and Industrial Engineering. Systems engineering in terms of the methodology used MBSE (Model Based Systems Engineering) and approaches achieved such as Systems Architecture and Systems of Systems. For its part, Industrial Engineering deals with the optimization of processes within the system achieved through the development, improvement and implementation of integrated systems of people, resources and information.

For this research, the initiative was taken to propose a digital model to create a electrified pavement system that supports interoperability between components and stakeholders (Taking the Electrified Pavement System as a case study). This initiative is important because a model will allow us to visualize the system as a whole in real time, in addition to facilitating the joint and orderly management of all the information. Plus having a digital copy of how the system is connected will reduce labor costs, increase throughput and support delivery schedule. In addition, the information obtained within the model can be of support to help make better decisions.

In summary, within the context of this research, the purpose is to develop a model of the pavement structure, a model that is intended to serve as a support for better interoperability between the different parts that make up the system.

4.2. Data collection and analysis

In order to be able to address the problem of Interoperability within a system, for this thesis taking the UTEP Electrified Pavement System Case Study, it is important to understand the way in which the information was emerging and the direction that the investigation was taking. The chronology of events within this data collection and analysis for this thesis occurred as follows in Figure 14.

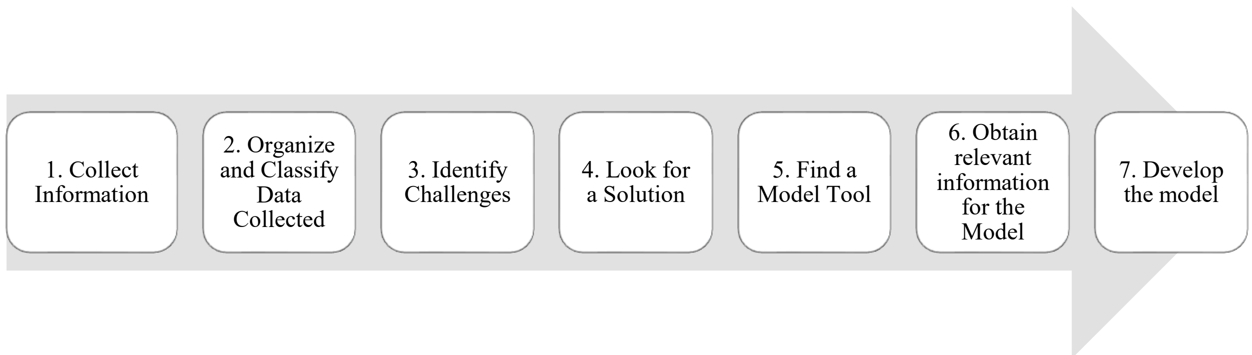


Figure 14. Data Collect and Analysis

1. Collect Information.

The initial question was raised to begin collecting information within around 150 articles in the literature review: What are the challenges within the development and research of Electrified Transportation Systems? (With a CPS perspective).

2. Organize and Classify Data Collected

Due to the diversity of articles consulted, all of them focused on research topics, it was possible to identify a diversity of particular and specific topics and challenges, where those challenges found were classified by "Type of Challenge" in an Excel database.

3. Identify Challenges.

After being classified, the challenges that had the greatest recurrence within these articles of the consulted literature were identified, where the most recurrent challenges by keywords found were Interoperability and Integration of Systems.

4. Look for a Solution.

After identifying interoperability as one of the biggest challenges within the development and implementation of Electric Vehicle Systems, the most used methods were sought to solve interoperability problems within the systems, and it was decided to use a Case Study to apply the solution found (UTEP Electrified Pavement System for this research). Among the solutions found, it was discovered that one of the most used methodologies to deal with interoperability problems within systems is MBSE (Model Based Systems Engineering).

5. Find a Tool.

Since MBSE is an engineering systems methodology that focuses on creating and exploring system model domains as sources of information exchange, we then proceeded to find a tool to develop and simulate the model: Magic Systems Of Systems Architect, a software for simulating models that will focus on realizing system design and architecture through modeling.

6. Obtain relevant information for the Model.

Once the methodology that we will use and the software tool that will help us apply the MBSE methodology have been found, the relevant information that is necessary to develop the model in Magic Systems Of Systems Architect Software was defined, based on the questions raised in the point 3.4.2. ¨Case Study and model application¨.

7. Develop the Model.

After having taken the training ¨Applying SysML with Magic Systems Of Systems Architect Modeler Software¨ offered by the University of Texas at El Paso, we proceeded to develop the model with the information obtained.

4.3. RESULTS AND DISCUSSION.

This thesis was carried out to discover the challenges that authors and organizations face in the development and research of electrified transportation systems, from the perspective that electric vehicles are Cyber-Physical Systems. Many applications and benefits for these systems were found in the literature review, but on the other hand it is important to emphasize that the challenges faced by organizations must always be considered when applying and developing Cyber-Physical Systems, for the purposes of this research specifically for the field of electric transportation systems.

To support the development of Cyber-Physical Systems, in this document, a review of the recent literature on the challenges in this type of systems is presented, in order to provide a comprehensive guide to help both academics and professionals to identify underdeveloped areas that should be considered for further investigation. To establish a final context, CPS as an EV, through the lens of a system engineering perspective, possess the following characteristics:

- Nonlinear – there is no fixed equilibrium point
- Independent agents
- Self-organization
- Agents are intelligent and learn from previous experiences
- There is no single point of control

The integration of electric vehicles with wireless transport networks offers many potential benefits, therefore, approaching their development through the lens of CPS and socio-technical perspectives seems to be automatic. However, it turns out that challenges were found in CPS, which were classified as social and technical. For specific cases they must be addressed as sociotechnical and for other cases they must be addressed separately (social and technical).

For this research, different technical and social challenges found in the literature were identified and compiled, to later be classified and counted. In the review of the literature, those with the highest recurrence were presented, among them those shown in Figure 15.

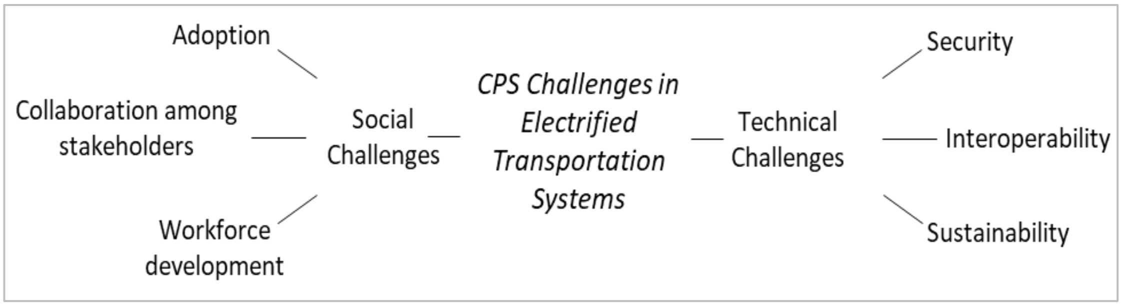


Figure 15- Most recurrent CPS Challenges in Electrified Transportation Systems

In addition, these challenges were explained from different perspectives of the authors in the literature review and possible questions were raised that can help the reader to question these challenges for specific purposes.

Showing evidence of the challenges and areas of opportunity within this area, one of the challenges that had the highest recurrence was specifically taken into account to make a solution proposal: Interoperability with 21% of the total challenges identified (Figure 16).

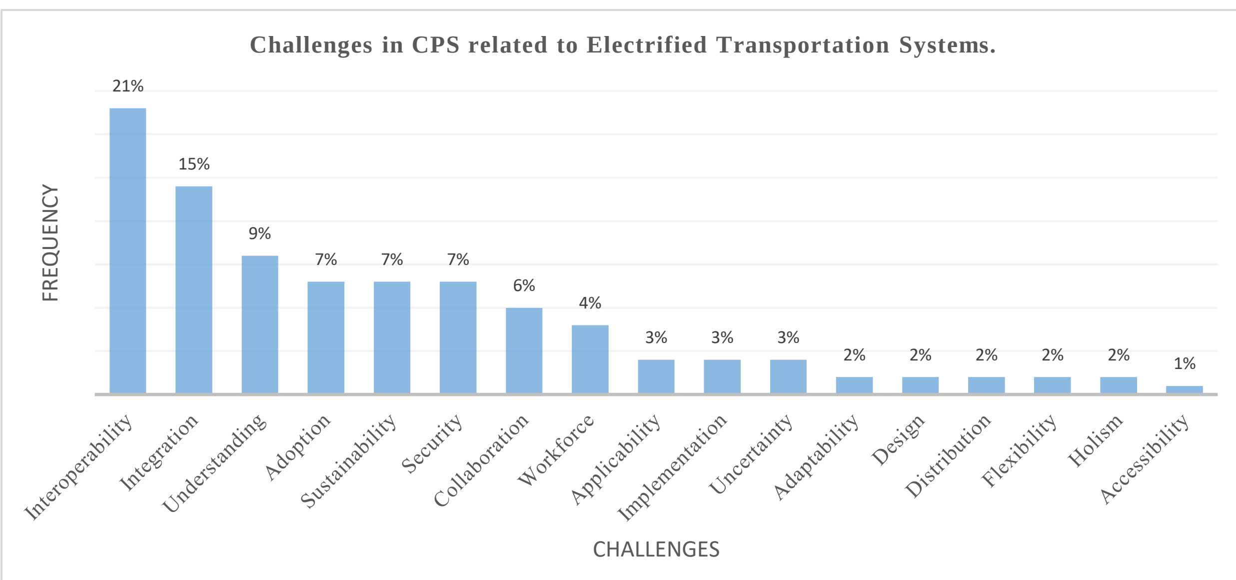


Figure 16. Recurrence rate on CPS challenges for Electrified Transportation Systems

As mentioned in this research, Interoperability is the ability of systems to provide services to, and accept services from, other systems, and to use those exchanged services to enable them to operate together effectively. Basically, it is the capacity for effective communication and information exchange between one system and another.

The authors showed their Interoperability challenges for specific and particular cases as it was shown in the literature review. Due to the diversity of application of possible solutions to the particular cases of interoperability of the authors, to propose the solution of this thesis, a research case study was taken that is currently being developed at UTEP: A pavement system for electrified highways. Figure 17, shows us a simulation example of what represents a general electrified pavement system for electrified highways, and which is hypothetically composed of: electricity generator, the vehicle receiving coil, the pavement structure and the receiver of electricity.

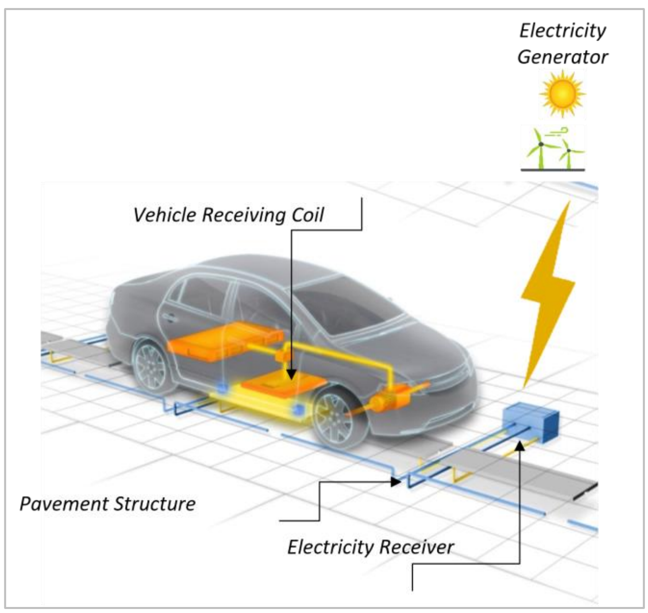


Figure 17. Case Study: Pavement System for electrified highways

Before proceeding to the solution applied to the case study (electrified pavement system), an alternative methodology was sought to propose a solution that would help solve the interoperability problem. For this research, MBSE was applied as an alternative solution to solve this challenge due to its multiple benefits according to the literature consulted. The literature tells us that when you base your entire system on models, you can:

- Improve interoperability
- Improve communication
- Better Testing, Verification, and Validation
- Reduce costs, time and errors.

Among other benefits mentioned in the literature review of this thesis.

There are multiple tools such as MATLAB, Cameo and Simulink for Model-Based Systems Engineering (MBSE), which help design, analyze and test system and software architectures. For this case it was decided to use Magic Systems of Systems Architect, a Cameo Systems Modeler, which provides smart, robust, and intuitive tools to define, track, and visualize all aspects of systems in the most standard-compliant SysML models and diagrams. For reference, if we wanted to represent our pavement system for electrified highways in a model, we would have a transition as shown in Figure 18.

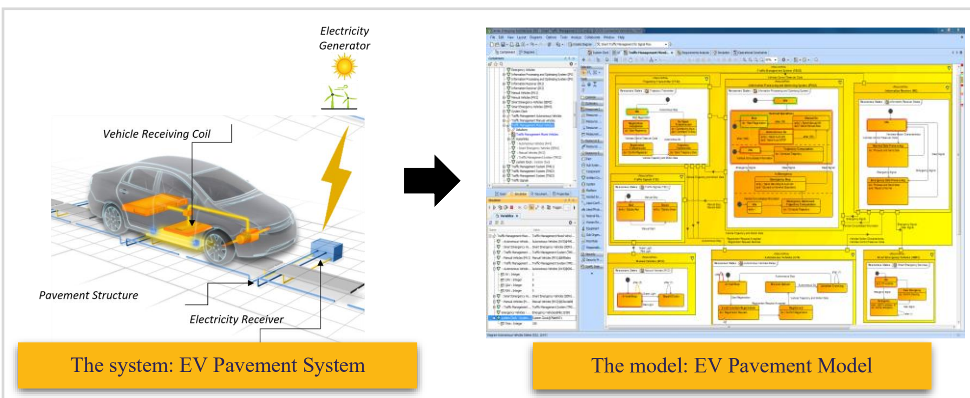


Figure 18. Transition from the "System" to the pavement "Model" for EV.

As a final result, we obtained a model applied to the aforementioned case study (Electrified Pavement System, only to the Pavement part) with information, characteristics and requirements provided by the Department of Civil Engineering of UTEP. Figure 19, represents the complete solution context for the Interoperability challenge within cyber-physical systems applied to electric transportation systems.

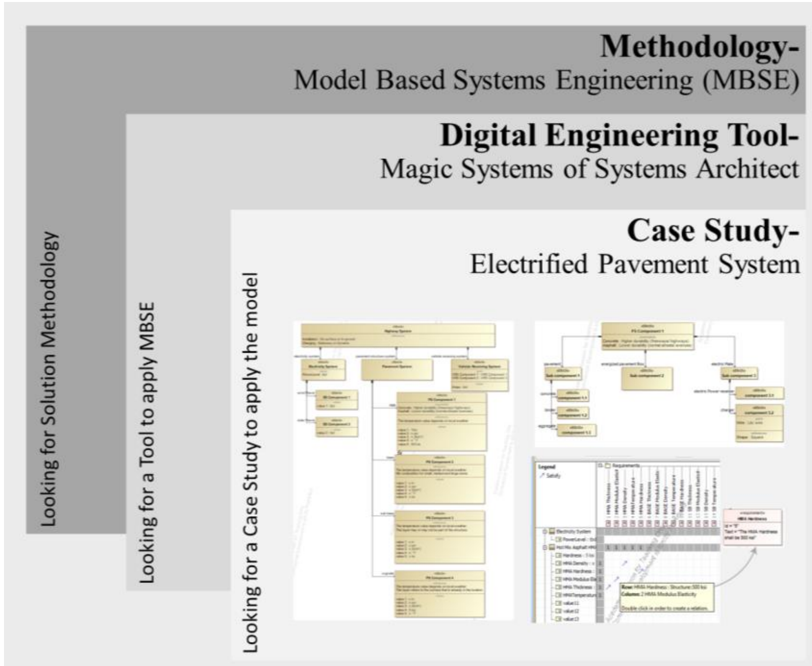


Figure 19. Solution context to address the Interoperability challenge

The presented model, is intended to be a digital model to create a pavement system that supports interoperability among components and stakeholders. Furthermore, this modeling tool aims to propose an environment for creating descriptive architecture models that connect directly to detailed implementation models. It is a connected environment that guarantees that the elements of the architecture and design fields remain synchronized and with this the users who manipulate the model can establish a digital thread to navigate between the system requirements, the architecture models, the implementation models and the software used (if applicable).

4.3.1. Study limitations.

The greatest limitations were faced during the development of the model applied to the case study, due to the fact that:

- There is information on the Electrified Pavement system that is restricted, this is due to the fact that there is information still under development and that has not yet been published.

- Initially the idea was to develop the model on a larger scale (complete infrastructure of the charging system from the pavement to the electric vehicle), but due to time constraints and the current development of the project, it was decided to apply it only to the pavement system.

Therefore, the study was applied only to the pavement system portion of a total electrified highway system. The electrified highway system is composed of different subsystems such as: The vehicle receiving coil, the electricity generator, the electricity receiver and the pavement structure, which is the one that was taken as a case study.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1. CONCLUSIONS

The integration of sensors and actuators with mathematical models and network principles plus the addition of control mechanisms has led to the emergence of multidisciplinary systems also called cyber-physical systems. Due to their characteristics, flexibility, and adaptability, these systems have gained sufficient recognition that they are being explored in across multiple domains. Efforts to leverage CPS in government, industry, and academy are developed with significant successes. However, there are still considerable challenged so that organizations fully embrace the benefits of CPS. This thesis reviews the literature on CPS challenges and provides the scenario for electric vehicles as cyber-physical systems.

It was found that the challenges can be classified as social and technical, in addition to raising possible questions that open the way to discuss and solve problems within the CPS.
For societal challenges, stakeholder collaboration, adoption, and workforce development are the areas of opportunity, and for technical challenges include interoperability, security, reliability, and sustainability.

After this literature review, it was identified that one of the most recurrent problems in cyber-physical systems and the development of electric vehicles and their infrastructure system is the Interoperability.

With methodologies such as Model-Based System Engineering (MBSE), we can propose solutions to Interoperability challenges, formally applying models that allow us to support system requirements, design, analysis, and verification activities that begin in the conceptual phase and continue throughout development and later phases of the life cycle.

In addition, with digital engineering tools such as Magic SoS Architect, it is possible to propose model-based solutions that allow us to visualize a system as a whole, having an updated system and visualized by all interested parties, in addition to achieving better interoperability and communication inside and outside the system.

5.2. RECOMMENDATIONS AND FUTURE WORK.

For the infrastructure pavement case study, it is important to mention that the model was developed on a small scale, taking only the pavement part as a case study, but the idea is to propose it for its applicability on a larger and more complete scale. In the future, a complete model integrated by all the parts that make up the electrical infrastructure for electrified transportation systems promises to be a tool that will allow all interested parties to interact, visualize and share important and relevant information for the common project, serving this model as a basis for future applications.

For the purposes of this model specifically, it can continue to be developed beyond the pavement system, that is, to parts that make up the entire electric highways infrastructure for electric vehicles such as: the electrical system, the external electricity generating system and the electricity receiving system in the vehicle. Propose tools or methodologies that are useful and that allow all interested parties to interact, visualize and share important and relevant information through a digital model for systems of this magnitude, in order to have better interoperability between the different parts that make up this system and its stakeholders.

Also, as another possible future work, it would be interesting to look for other methods and alternative solutions for the other challenges identified in the literature, in addition to Interoperability.

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