Comparing Different Vehicle Architectures Based On Attack Path Analysis

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Ulm, May 9, 2023

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ABSTRACT

The increased use of technology in modern vehicles has made cybersecurity a crucial part of the development process of modern vehicles, making it more and more critical for the safety and security of the vehicle and the privacy and personal data of drivers and passengers.

The internal vehicular network of such E/E systems plays a vital role in the overall cybersecurity of a modern vehicle. For example, attackers might exploit potential attack paths in the network to gain unauthorized access to a vehicle's systems or networks.

However, most security testing is done at later stages of development, when it is more complex and costly to address vulnerabilities. Additionally, due to the nature of security testing, it is carried out manually by experts with a high level of expertise and experience with other cybersecurity tools and techniques. These factors result in a stagnant security testing process that cannot maintain pace with the increasing complexity of modern vehicles.

This thesis focuses on comparing various vehicular network architectures in terms of which offers more security based on their attack path feasibility. A comprehensive evaluation of multiple architectures is conducted by discussing different criteria to evaluate the security of vehicular networks in an automated manner. The results offer a guiding beacon for future development and evaluation of vehicular network designs.

CONTENTS

1 INTRODUCTION

1.1 RESEARCH FIELD: CYBERSECURITY OF VEHICULAR NETWORKS

Modern vehicles are becoming increasingly reliant on technology, with a wide range of systems and components being connected to the internet and each other. This includes everything from infotainment systems and navigation to advanced driver assistance systems and autonomous driving features. ISO 26262 describes these so-called "Electronic/Electrical (E/E) systems" as systems that consist of electrical and electronic elements and components. Examples include Electronic Control Unit (ECU)s, sensors, actuators, connections, and communication systems like Controller Area Network (CAN), Ethernet, and Bluetooth [5]. As these technologies become more and more important, strong cybersecurity measures are also becoming increasingly important. Cybercriminals are constantly finding new ways to exploit vulnerabilities in these systems which can have serious consequences for users, which includes their safety, privacy, finances, and operational viability [4]. Ensuring the safety and security of connected vehicles is crucial to the success of the emerging world of connected and autonomous transportation.

The internal vehicular network architecture plays a crucial role in the overall cybersecurity of a modern vehicle as it determines how different vehicle systems and components are connected and communicate. Attack paths play an important role in vehicle networks and security because they define the specific routes that a malicious actor might use to attack a vehicle's systems or networks. A well-designed internal vehicular network architecture can help minimize cyberattack risk. With the increasing number of systems and components that are connected to the internet and each other, the complexity of the internal vehicular network architecture is also increased. This can make it more challenging to design and implement effective cybersecurity measures as more potential points of vulnerability arise that need to be addressed. Therefore, companies developing connected and autonomous vehicles need to prioritize cybersecurity in designing their internal vehicular network architecture, which can help to ensure the safety and security of the vehicle, as well as protect the privacy and personal data of drivers and passengers.

Security testing is, therefore, a crucial part of the development process. A Threat Analysis and Risk Assessment (TARA), for example, is performed early during the development process to identify and prioritize potential risks. This information can be used to guide the design and implementation of controls or countermeasures to reduce or mitigate these risks. Once the system is developed, e.g. a penetration test is carried out to validate the effectiveness of these controls and to identify any remaining vulnerabilities. The results of the pentest can then be incorporated back into the TARA process to update the risk assessment and prioritize future risk mitigation efforts. For example, companies can implement appropriate security measures by understanding the attack paths that might be used to gain unauthorized access to a vehicle's systems. These include encryp-

tion, authentication protocols, and firewall systems, etc. to protect against cyber threats.
In this way, the combination of a pentest and TARA provides a complete and iterative approach to security assessment.
However, security testing is often carried out in the late stages of development, which can lead to the discovery of vulnerabilities at a time when it is more difficult and costly to address. Additionally, they are considered to be a skill-based activity that is still carried out manually. It requires a high level of expertise and experience with other cybersecurity tools and techniques. The increased complexity of modern vehicles and the arduous nature of state-of-the-art security testing methods make it more unfeasible for companies to conduct them as is done now.
Thus, the need for a more efficient approach to improve overall security testing is evident. By automizing the process of evaluating automotive network architectures and their attack paths, potential vulnerabilities can be assessed early on in the development process resulting in overall more efficient security testing, improving the flexibility, costs and accelerateing it.

In this thesis we will explore Criteria for Evaluation that can be used to evaluate the security of vehicular network architectures and how they can be used to automate the process of security testing.
These criteria are based on the experience of security experts and the results of a Survey conducted by the author of this thesis. This survey will feature a training set of architectures which the security experts will evaluate and give feedback on the architectures' security. Their ratings and feedback will be used as calibration for the criteria.

In order to automize the evaluation of vehicular network architectures, we will use a graph-based approach to model the network architecture and its attack paths and develop a Tool that can be used to evaluate the security of vehicular network architectures based on the criteria in an automated manner. The Proof Of Concept contains another set of architectures that will be used to test the criteria and the tool. In the end, we will evaluate the results of the tool and the criteria and discuss the limitations and potential improvements.

1.2 THESIS QUESTIONS

The questions this thesis will answer include:

- How can different E/E architectures be rated based on attack paths?
- How secure is the given vehicular network architecture?
- What architectural approach makes a network safer than others?
  - How do small changes in network positioning affect the network security overall?
  - How do simple and more branched out networks compare in terms of security?

2 STATE OF THE ART

There are various approaches to assessing the security of vehicular networks. Cybersecurity standards and frameworks give guidance and best practices for designing, implementing, and testing the cybersecurity of automotive systems and networks. The following standards are mentioned in virtually every piece of literature; thus, they are the most important ones to consider. Moreover, they offer a basis for the thesis itself as well as the development of a tool to assess the security of vehicular networks, as their further use is intended to be used in conjunction with these standards and frameworks to ensure compliance with them:

ISO 26262 is an international standard for ensuring the functional safety of E/E systems in vehicles. It provides a framework for the development and management of safety-related systems throughout the lifecycle of a vehicle, from design to operation. The standard is divided into several parts, each addressing a specific aspect of functional safety. It aims to help organizations manage the functional safety of their systems, ensure they meet a defined level of safety, and demonstrate that the systems are safe for the intended use. ISO 26262 helps organizations identify and mitigate potential hazards, reducing risks to an acceptable level. It provides a systematic approach to functional safety, ensuring the safety of vehicles and their passengers.

ISO 21434 is an international standard for the execution of functional testing and specifies engineering requirements for cybersecurity risk management regarding the lifecycle of E/E architecture systems in road vehicles, including their components and interfaces [4]. ISO 21434 outlines the security requirements, goals, and measures to consider throughout the entire lifecycle of a vehicle, including design, development, production, and operation. It aims to assist organizations in managing the security of their vehicles and ensuring they meet a defined level of security by providing a systematic approach to identifying and evaluating security-related risks and implementing measures to reduce them to an acceptable level. The standard is intended to be used in conjunction with ISO 26262, which focuses on functional safety, to provide a comprehensive approach to ensuring the safety and security of vehicles. It also explains how to integrate security into the functional safety process, helping organizations manage security risks similarly to how they manage functional safety risks.

SAE J3061 is a guide for cybersecurity best practices for the automotive industry and was created based on existing methods. The guide provides a comprehensive set of best practices for securing automotive systems and vehicles from cyber threats and covers various aspects of cybersecurity, including threat modeling, risk management, security testing, incident response, and security management. They are intended to be flexible, pragmatic, and adaptable in their further application to the vehicle industry and other cyber-physical vehicle systems. It provides a framework for organizations to incorporate cybersecurity into the lifecycle of vehicle systems, information on standard tools and methods

used in designing and verifying systems, basic principles for cybersecurity, and a foundation for further standards development. SAE J3061 is intended to be used in conjunction with other standards and guidelines, such as those mentioned above [8].

AUTOSAR is a standard for the development of software for ECUs in the automotive industry [1]. The goal of AUTOSAR is to create and establish an open and standardized software architecture for automotive ECUs that is scalable to different vehicle and platform variants, transferable of software, considering availability and safety requirements, collaboration between various partners, sustainable use of natural resources, and maintainable during the product lifecycle. This improves the efficiency of development, enables the integration, exchange, reuse, and transfer of functions within a vehicle network, and helps manage the growing complexity of technology and economics in automotive software development.

TARA is an essential process for ensuring the cybersecurity of systems and networks, especially in the automotive industry. In the context of automotive systems, a TARA can be used to identify and evaluate potential threats and vulnerabilities to the electronic and electrical (E/E) architecture of vehicles. This includes identifying assets such as connected systems and networks and evaluating the likelihood and potential impact of threats such as cyberattacks, hacking, and software vulnerabilities as well as determine appropriate countermeasures to mitigate these risks. In addition, it can help prioritize these threats and vulnerabilities based on their potential impact on safety, financial, operational, and privacy aspects.
An attack path analysis can be an important component of TARA, helping to identify and evaluate the potential pathways that an attacker might use to gain unauthorized access to the vehicle's system. Based on such analysis, appropriate changes can be made to the vehicle's network architecture as a countermeasure. The TARA process can be used to ensure compliance with industry standards, such as ISO 26262 or ISO 21434, and can be integrated with other frameworks, like HEAVENS or EVITA. Regularly reviewing and updating the TARA process is crucial to keep up with the evolving threats and vulnerabilities in the automotive industry, which is constantly evolving with the integration of new technologies such as connected cars, autonomous driving, and V2X communication [7].

Important frameworks include HEAVENS, and EVITA. HEAVENS performs risk assessments of general IT systems and models explicitly built for automotive systems and uses threat and impact levels to calculate risks [3]. The primary objective of the framework is to identify security requirements and vulnerabilities in automotive systems and to provide countermeasures to minimize the risks associated with these vulnerabilities. It uses the Microsoft STRIDE model for threat modeling and aligns its impact level estimation parameters with established industry standards such as ISO 26262. It is a great candidate as a framework for automotive risk assessments over traditional IT risk assessment models.
The EVITA framework, which essentially performs the same things as HEAVENS, but also considers the potential of attacks to impact the privacy of vehicle passengers, financial losses, and the operational capabilities of the vehicles sys-

tems and functions [6].

Many of these approaches aim to standardize the process of assessing the security of vehicular networks. However, most of them are based on manual penetration testing and manual vulnerability assessment today. This is because penetration testing is an experienced-based and explorative skill that is difficult to automate. Further research aims to improve or couple existing approaches like performing a TARA, as well as automate and accelerate the process of security testing.

F. Sommer et al. introduce the concept of Model-Based Security Testing using an EFSM model [10]. The Automotive Security Model section describes an E/E architecture, security measures, and further development artifacts to protect vehicles against attacks. The model is based on the EFSM, with nodes representing attacker privileges and transitions representing a vulnerability. The Proof of Concept section of the paper demonstrates how the model can be used to identify different attack paths, analyze the model for attack paths, and execute the attack paths on a real vehicle. The incremental approach allows for the redefinition of attack paths, making it useful at different stages during development. The paper concludes that this approach can be helpful in identifying attack paths and potential vulnerabilities in automotive systems, thus helping to improve the security of vehicles.

F. Sommer et al. further expand on the same model-based approach by using a database of successful vehicular penetration tests [9]. The attack path generation process involves using an attack database, which describes vulnerabilities and exploits that can be used, including attack taxonomy and classification, attack steps, requirements, restrictions, components, and interfaces. The database can also be used to find new attack paths by permuting existing attack steps. Additionally, the process of creating the database can be done iteratively over several penetration tests and can be transferred to test scripts. However, there is a risk that the attack path generated may not be transferable, which can be circumvented by permuting previous attacks. The authors also suggest that further testing activities, such as black-box testing, should be carried out. Despite its limitations, this approach can be used as a useful tool to automate the process of penetration testing and improve the efficiency of security testing in the automotive industry.

J. Dürrwang et al. further describe the concept of attacker privileges mentioned in the papers above [2]. Several types of privileges that an attacker may seek to gain access to a vehicle's communication system and components are defined, such as "Read/Write," "Execute," "Read," "Write," and "Full Control.". They note that channels that are not protected by security measures can be immediately accessed by an attacker, but interpretation is needed in other cases. It also mentioned that the attacker needs to reach one of these privileges to access further attached communication systems and components. The authors applied their privilege model to real-world automotive security attacks to demonstrate its practical use, in which an attacker is connecting to the vehicle via the OBD port, which is connected to the central gateway via CAN, and then uses the central gateway to gain access to the internal vehicle network. They also showed the automatic generation of attack trees using a model checker in a custom software

tool and an application of their privileges in security testing by describing attack paths. In future work, the authors plan to formalize the security testing approach to allow for early testing during development and to evaluate the TARA and security testing approach in a case study.

In contrast, D. Zelle et al. introduce a concrete approach, "ThreatSurf" [11], which presents an algorithm for automated generation and rating of attack paths in the automotive industry, using various attack building blocks and assessing attack feasibility. The attack feasibility assessment can be used in a TARA to assess an entire attack path of a threat scenario. It also discusses different methods for weighing attack paths, such as Sum, Average, Maximum, and Hybrid-weighted Sum. The paper describes four different types of threat agents - Thief and Owner, Terrorist, Organized Crime and Mechanic, Hacktivist, and Foreign Government - and their motivations, capabilities, and window of opportunity for performing an attack. The paper provides an example of how the proposed attack feasibility rating concept can be applied to threat scenarios derived from the use cases and also compares it with other rating approaches such as attack-potential-based approaches, CVSS based approaches, and attack vector-based approaches. The proposed attack feasibility rating concept is based on the attack-potential approach due to the complex nature of attacks against electric vehicles.
Other approaches include the CVSS and attack vectors. They conclude that attack-potential-based approaches have high flexibility but high complexity, CVSS-based approaches are easier to handle but have lower flexibility, and attack vector-based approaches are simpler but less suited for automotive applications. The tool and algorthmic approach fits the needs of the thesis much better than the model-based approach, as the feasibility rating is represented as a single variable and it is easier to compare multiple architectures.

While those papers mentioned above are a great foundation for this thesis, they do not provide a complete solution for the problem of automating the process of security testing in the automotive industry. The most important missing piece is the automatic evaluation of the possible attack paths and thus the automatic evaluation of the vehicle's architecture in general. While all of the approaches include a tool and an automaitc attack path search, they do not further consider the evaluation of the attack paths and architecture. This thesis aims to provide further steps to fill this gap by providing a tool as well as discuss different criteria to evaluate and even compare multiple architectures.

3 ARCHITECTURES

Similarly to a common network, a vehicle network is a system of electronic components and devices within a vehicle that communicate with each other to perform different functions, such as engine performance, safety, entertainment, and navigation.

What started as a simple network of a few electronic control units (ECUs) has evolved into a complex network of ECUs, and while the evolution of these systems has resulted in improved vehicle efficiency and features, it has also created new cybersecurity concerns.

There are several types of components in a vehicle network, and in order to understand these and their security features, we will first elaborate on those and define certain terms in this chapter that will be used throughout this thesis. Throughout this thesis, we will use the term *architecture* to describe a vehicular network architecture of ECUs and their connections.

3.1 FEASIBILITY

First, we want to explain and define the term *feasibility* in the context of this thesis. Typically, the term feasibility describes the possibility of something to be done or achieved or the likelihood of something to happen. This also applies to the term in this thesis, as we will use it to describe the likelihood of an attack's success. This means a higher *attack feasibility* means that an attack is more likely to be successful, while a lower *attack feasibility* means that an attack is less likely to be successful.

However, due to further factors used in this thesis, this thesis will also refer to the term of *feasibility rating* which refers to the security feasibility of a component, i.e., the likelihood of an attack being unsuccessful. Architectures and their components will receive security feasibility; a higher rating means the component is more secure. In comparison, a lower rating means that the component is less secure. The rating or score an architecture receives is similar to a benchmark used to compare the security of different architectures. The higher the score, the better the rating and the more secure the architecture is.

3.2 COMPONENTS

While architectures in the automotive industry are complex, often featuring up to 150 ECUs in a single model, this thesis will focus on more manageable examples, each consisting of 20 ECUs Each architecture was represented as a graph and was modeled using these components:

- **ECUs**: The different ECUs in the architecture. They are the nodes of the graph.
- **Entry points**: The entry points to the architecture. The only possible entries are the external interfaces that an ECU might have.

- **Targets**: ECUs that are considered targets for an attacker. They are targets because they contain sensitive data or because they are critical for the vehicle's functionality.
- **Bus systems**: ECUs are connected to each other using bus systems. The bus systems are the edges in the graph. The possible bus systems are *CAN, CAN FD, LIN, FlexRay, MOST* and *Ethernet*.
- **Interfaces**: The interfaces are the connections between the ECUs and the external world. They are the connections between the ECUs and the bus systems. The possible interfaces are *Bluetooth*, *WiFi*, and *GNSS*.
- **Attack Feasibility**

Using the scale mentioned in 4.1 for each component, a higher rating means that the component is more secure, i.e. might have more security mechanisms in place, while a lower rating means that the component lacks such mechanisms. This also indicated that the higher the overall rating one architecture receives, the more secure it is. This subsection will further explain some the aforementioned components as well as their attack feasibility based on their attributes.

- **ECU**: An ECU is an embedded system in an automotive system that cotrnols various systems in the vehicle. ECUs are typically connected to each other using a bus system, enabling communication between the each other. Over the years, vehicles have become more and more complex, and thus the number of ECUs has increased. Since each ECU has an individual task, whose criticality varies, the attack feasibility of an ECU is based on the criticality of the task it performs. For example, the Engine Control Unit is responsible for the engine, and thus is a critical ECU, whereas the SEAT ECU, that are responsible for the seats in a vehicle, are not as critical. For simplicity, the ECUs and their feasbility rating in this thesis are divided into three as seen in 3.2.
- **CGW**: In the context of automotive network architectures, the CGW acts as a key communication node. It's a device that interconnects various ECUs or different networks within the vehicle. This can include networks operating on different protocols such as those mentioned below. The CGW is responsible for routing and sometimes filtering messages between these different networks. It also plays a crucial role in managing security, as it can help to prevent unauthorized access to the vehicle's internal networks. With the rise of connected and autonomous vehicles, the CGW has become more complex and sophisticated, capable of handling higher data throughput and managing more advanced security measures. It's an important component for the operation and security of modern vehicles.
- **CAN**: CAN a communication protocol utilized in modern vehicles and industrial applications to enable devices and microcontrollers to communicate with one another. It was developed by Bosch in the 1980s and has since become a widespread standard for in-vehicle communication. It is a dependable, durable, and cost-effective communication protocol that has become an indispensable component of modern vehicle electronics. Since the CAN bus is the most common bus system used in a vehicle, it will be set as a baseline for security in this thesis.

- **CAN FD**: It is an extension of CAN bus. It provides higher data transfer rates, more efficient data communication, and increased bandwidth compared to the original CAN bus. It is backward compatible with the original CAN bus, which means it can function on the same network as older CAN devices. In terms of security it will be rated a bit higher than CAN. Modern implementations of both protocols incorporate security features, such as message authentication and encryption.

- **FlexRay**: It is a bus system that is used in the automotive industry used to facilitate high-speed real-time communication. It was developed by a group of automotive companies and aims to meet the growing need for real-time communication in complex automotive systems. FlexRay is utilized to link ECUs requiring high bandwidth, such as advanced driver-assistance systems and safety-critical systems. It ensures deterministic data transfer, delivering data at predetermined intervals with a guaranteed maximum latency. This is crucial for safety-critical systems that rely on fast and dependable data transfer. FlexRay is designed for use in safety-critical systems and provides deterministic data transfer, making it highly reliable and resistant to interference. It also supports encryption and authentication, providing additional security features.

- **LIN**: LIN is a communication protocol used to connect and communicate with low-speed peripherals in modern vehicles and other industrial applications. It is a lower-cost alternative to the CAN bus communication protocol, developed by a group of automotive companies and generally considered to be less secure than other protocols, as it doesn't support encryption or authentication LIN is weaker bus system than CAN and CAN FD, in terms of technology but also use, which will contribute to the rating.

- **MOST**: It is a communication protocol that enables high-bandwidth multimedia data transfer between devices in modern vehicles. It was developed by a consortium of automotive and multimedia compaGNSnies and offers high-speed, dependable, and cost-effective data transfer. It is a highly dependable communication protocol that has gained increase popularity in the automotive industry and provides secure communication between devices through encryption and authentication

- **Ethernet**: Ethernet is a wired networking technology that enables the transfer of data between computers and devices within a local area network (LAN) It delivers fast, secure, and reliable data transfer, which makes it ideal for a variety of applications such as internet connectivity, file sharing, and multimedia streaming. Ethernet is commonly used in modern vehicles for connecting various devices, including infotainment systems, sensors, and advanced driver-assistance systems. It is a crucial part of modern automotive systems, providing dependable and swift data transfer for various applications, however, it is also expensive and complex to implement. While it is vulnerable to physical attacks, such as cable tapping, it is generally considered to be more secure than wireless technologies.

- **Bluetooth**: Bluetooth is a wireless technology used to exchange data between electronic devices over short distances. In modern vehicles, Blue-

tooth is used for hands-free phone calls, music streaming, and other features that require wireless connectivity. It has become an essential component in modern automotive systems, providing a convenient and safe way for drivers to interact with their vehicles. Though Bluetooth uses encryption to secure the communication between devices, vulnerabilities have been discovered in the past that allow attackers to intercept and decrypt Bluetooth traffic.

- **WiFi**: WiFi is a wireless communication technology that enables electronic devices to connect to the internet and exchange data wirelessly over a local area network (LAN) It uses radio waves to transmit data between devices, typically using the 2.4GHz or 5GHz frequency bands. In modern vehicles, WiFi is used for a variety of applications, such as infotainment systems, navigation, and telematics. It enables passengers to access the internet, stream video content, and browse the web, enhancing the in-car entertainment experience. WiFi also provides a means for vehicles to communicate with other devices, such as smartphones or smart home devices, to access remote services or home automation features. Though WiFi has improved in terms of security over the years, it is still vulnerable to various attacks, including weak encryption, insecure network configurations, and attacks on the wireless network itself.

- **GNSS**: GNSS is a satellite-based navigation technology that can determine precise positioning and timing information anywhere on Earth. It comprises various satellite navigation systems, such as GPS, GLONASS, Galileo, BeiDou, and other regional systems. GNSS uses a constellation of satellites orbiting the Earth to provide accurate location and timing data to receivers on the ground. These receivers analyze signals from the satellites to determine their position and velocity, making it possible to navigate precisely over long distances. GNSS is used in vehicles primarily for navigation purposes. It is generally considered to be the most secure technology since it is difficult to intercept and manipulate signals from GNSS satellites, and modern receivers incorporate security features to mitigate the risk of attacks.

Ranking these technologies in terms of security is a complex task, as each technology works differently, has different use cases and different security characteristics and vulnerabilities. However, based on experts' experience, these values were given each component:

Technology	Feasibility Rating
CAN	0.5
CAN FD	0.6
FlexRay	0.9
LIN	0.1
MOST	0.3
Ethernet	0.8
Bluetooth	0.4
WiFi	0.4
GNSS	0.8

Table 3.1: Ranking of automotive communication technologies based on security

ECU	Feasibility Rating
Target	0.9
LIN connected ECUs	0.1
Other	0.5

Table 3.2: Ranking of ECUs based on security

4 TOOL

Evaluation of multiple architectures by hand is a tedious and time-consuming task, so finding a way to automate this process is essential. A tool was developed to accelerate the evaluation of a vehicle network architecture based on their attack path feasibility by automatically generating the most feasible attack paths for the different complex architectures, as well as evalaute them based on the criteria.

The following sections will describe the tool's implementation.

4.1 CONFIGURATION FILES STRUCTURE

First, the architecture, ECUs and buses need to be defined in a configuration file. The configuration files for the simulation are stored in JSON format, which is a lightweight data interchange format that is easy to read and write, and easy for machines to parse and generate.

There are three main configuration files used in the simulation: buses.json, ecus.json, and graph.json. Each file has a specific structure and contains different attributes.

BUSES.JSON

The tool takes as input three sets of configuration files, each of them represented in the JSON format: the system architecture, the ECUs in the system, and the buses connecting the ECUs.

This file defines the different communication buses that are used in the simulation. It contains an array of objects, where each object represents a bus and has the following attributes:

- **type**: The type of the bus: *CAN, CAN FD, FlexRay, Ethernet, MOST, LIN*.
- **feasibility rating**: A value between 0 and 1 indicating the bus' attack feasibility (*see 3.1*).

ECUS.JSON

This file defines the electronic control units (ECUs) that are used in the simulation.

It contains an array of objects, where each object represents an ECU and has the following attributes:

- **name**: The name of the ECU.
- **type**: The type of the ECU (e.g., entry, target, interface).
- **feasibility rating**: A value between 0 and 1 indicating the ECU's attack feasibility (*see 3.2*).

GRAPH.JSON

This file defines the topology of the system being simulated, i.e. the architecture. It contains an array of objects, where each object represents a communication link which contains the ECUs and interfaces and has the following attributes:

- **name**: The name of the link.
- **type**: The type of the link (*CAN, CAN FD, FlexRay, Ethernet, MOST, LIN Bluetooth, WiFi, Ethernet, GNSS*).
- **ECUs**: An array of the names of the ECUs that are connected by this link.

Note that external interfaces (e.g., Bluetooth, WiFi, GNSS) are also considered as ECUs as well as buses in the simulation. Treating them as such simplifies the implementation of the tool using the following libraries. The feasibility of the interface can be set in either the buses.json or ecus.json file, however it is recommended to set it in the buses.json file. Whichever file is used, note that the feasibility must be set to 0 in the other file, to avoid double counting.

4.2 TOOL IMPLEMENTATION

The tool is implemented in Python 3.10 and newer. Python was chosen as the implementation language because it is a script-based language, allowing for quick prototyping and development, and is popular in the security domain. Additionally, the language offers a vast variety of libraries that can be used to implement the tool. The most important and useful library in the tool is *networkx* for graph manipulation and generation.

`main()` calls the following functions, which are integral to the tool's functionality:

`parse_files(architecture, ecu, bus)`: it takes in three parameters: `architecture, ecu, bus`. They are the above described configuration files and loads the contents of these files. Specifically, the function loads the contents of the architecture file, ECU file and bus file, and extracts the architecture name, architecture, ECUs configuration, and buses configuration, respectively. The function returns these four objects as a tuple.

`generate_graph(architecture, ecus_config, buses_config)`: This function takes three arguments as input: `architecture`, `ecus_config`, and `buses_config`. The function processes this input to create a directed graph `(nx.DiGraph())` that represents the system's architecture and computes the feasibility between various nodes (ECUs). It returns the generated graph, a list of entry points, and a list of target ECUs.

Note: This is why it was easier to treat external interfaces as ECUs as well as buses. Since we are looking for the shortest path for an interface type, not the ECU using it, treating all interfaces as a bus and ECU conntected to the internal ECUs using such interface facilitates the shortest path generation.
The function returns the generated graph, along with the entry ECUs and target

Algorithm 4.1: Generate Graph

```
1: procedure GENERATE_GRAPH(architecture, ecus_config, buses_config)
2:     entry_points ← EMPTYLIST
3:     target_ecus ← EMPTYLIST
4:     G ← NX.DIGRAPH
5:     for all bus ∈ architecture do
6:         bus_type, bus_feasibility, bus_ecus ← EXTRACT-
   INFO(bus)
7:         for all ecu ∈ bus_ecus do
8:             ecu_type, ecu_feasibility ← EXTRACT-
   INFO(ecu, ecus_config)
9:             if ecu_type is entry or both then
10:                APPEND(entry_points, ecu)
11:            end if
12:            if ecu_type is target or both then
13:                APPEND(target_ecus, ecu)
14:            end if
15:            for all target_ecu ∈ bus_ecus do
16:                if target_ecu is interface then
17:                    G.ADDEDGE(ecu, target_ecu, weight =
   bus_feasibility)
18:                else
19:                    target_ecu_feasibility ← EXTRACT-
   INFO(target_ecu, ecus_config)
20:                    G.ADDEDGE(ecu, target_ecu, weight =
   bus_feasibility + target_ecu_feasibility)
21:                end if
22:            end for
23:        end for
24:    end for
25:    entry_points ← MAKEUNIQUE(entry_points)
26:    target_ecus ← SET(target_ecus)
27:    return G, entry_points, target_ecus
28: end procedure
```

ECUs lists.

`find_attack_path`: This function is designed to find the feasibility and the shortest path from each entry ECU to each target ECU in a given directed graph (`nx.DiGraph`).

The resulting table can be used to analyze the most feasible attack paths between various entry points and target ECUs in the system's architecture.

Finally, `apply_criteria` applies the Criteria for Evaluation to the table. Each architecture receives a feasibility score and the result can be interpreted as a benchmark for the architecture's security.
Since the evaluation of the feasibility of the architecture is represented by a single number, it is easy to rank and compare the results of different architectures,

Algorithm 4.2: Find Attack Path

```
1: procedure FindAttackPath(G, entry_points, target_ecus_names)
2:     table ← EmptyDict
3:     table["feasibility"] ← EmptyDict
4:     table["shortest_path"] ← EmptyDict
5:     table["hops"] ← EmptyDict
6:     for all entry ∈ entry_points do
7:         table["feasibility"][entry] ← EmptyDict
8:         table["shortest_path"][entry] ← EmptyDict
9:         table["hops"][entry] ← EmptyDict
10:        for all target ∈ target_ecus_names do
11:            table["feasibility"][entry][target] ← BellmanFord(G, entry, target)
12:            table["shortest_path"][entry][target] ← nx.shortest_path(G, entry, target)
13:            if length(table["shortest_path"][entry][target]) ≥ 2 then
14:                table["hops"][entry][target] ← length(table["shortest_path"][entry][target]) − 2
15:            else
16:                table["hops"][entry][target] ← 0
17:            end if
18:        end for
19:    end for
20:    return table
21: end procedure
```

which the function is also designed to do.

It is easy to extend the tool to support other criteria.

Various *I/O functions* are responsible for printing the results, saving them to an external file, or quickly saving the graph as an image file and other *helper functions* are used to simplify the code.

Below is the implementation of the Bellman-Ford algorithm used in `Find Attack Path`.

The Bellman-Ford algorithm is a graph search algorithm that computes the shortest paths from a single source vertex to all other vertices in a weighted graph. It is very similar to the Dijkstra algorithm, but it can work with negative edge weights.

T Both algorithms are possible solutions to the our proble, but we chose the Bellman-Ford algorithm because it was mentioned in [11].

Algorithm 4.3: Bellman-Ford Algorithm

```
1: procedure BellmanFord(Graph, source)
2:     for all vertex ∈ Graph.vertices do
3:         distance[vertex] ← ∞
4:         predecessor[vertex] ← null
5:     end for
6:     distance[source] ← 0
7:     for i ← 1 to |Graph.vertices| − 1 do
8:         for all edge ∈ Graph.edges do
9:             if distance[edge.source] + edge.weight < distance[edge.target] then
10:                distance[edge.target] ← distance[edge.source] + edge.weight
11:                predecessor[edge.target] ← edge.source
12:            end if
13:        end for
14:    end for
15:    for all edge ∈ Graph.edges do
16:        if distance[edge.source] + edge.weight < distance[edge.target] then
17:            return "Graph contains a negative-weight cycle"
18:        end if
19:    end for
20:    return distance, predecessor
21: end procedure
```

5 CRITERIA PREPARATION

One of the most critical aspects of this thesis is the criteria used to evaluate the different architectures.

In order to find and calibrate criteria, a survey was conducted in which security experts in the field of automotive security evaluated ten architectures. The criteria were calibrated based on their ratings and feedback on this "training set". Surveying with such a set rather than the architectures was done to avoid biased results and have well-evaluated criteria.

5.1 TRAINING SET ARCHITECTURES

The training set comprised ten distinct architectures, which served to define and calibrate the evaluation criteria. The following section will delve into the test architectures, providing a description and hypothesizing the impact of architectural choices on system security.

5.2 ARCHITECTURE 1

Architecture 1 is a simplified rendition of an architecture applied in a real vehicle. It presents six entry points and eight targets, including three that involve the CGW. The multitude of entry points amplifies the attack surface and diversifies the attack paths. We anticipate this architecture may underperform in terms of security compared to the others in this set due to its extended attack surface.

5.3 ARCHITECTURE 2

Architecture 2 is essentially the same as Architecture 1, but without a CGW.his setup allows us to analyze how the architecture would function without it. We predict that this architecture's performance will align closely with or perhaps fall slightly short of Architecture 1 and 5.

5.4 ARCHITECTURE 3

Architecture 3 was designed to group all the entry interfaces to see how a centralized entry would affect the architecture. By confining potential entry locations, the attack surface is reduced, the attack path to each target is elongated, and more ECUs are utilized in the path, making an attack more challenging as the intruder would need to compromise more ECUs. This architecture, similar to Architecture 10, also centralizes entry points but does not confine them to a single ECU. We anticipate this architecture to be among the most secure in this set due to its confined entry points.

5.5 ARCHITECTURE 4

Architecture 4 offers entry points from all domain controllers.allows entry points from all domain controllers, each of which has only one type of interface. The inclusion of an entry point from each domain controller expands the attack surface. To gain quick access to the whole domain, an attacker would only need to compromise one ECU within each domain controller. This architecture, however, is essentially equivalent to Architecture 9, including the CGW. We anticipate that due to its numerous and dispersed entry points, this architecture might be one of the least secure within this set.

5.6 ARCHITECTURE 5

Architecture 5 uses only Ethernet as the bus system. The purpose here is to examine how the architecture would perform without incorporating any other bus system. Ethernet was selected due to its highest security feasibility rating among bus systems. Moreover, its rising popularity in the automotive domain makes it a valuable insight. We expect this architecture to perform similarly to Architecture 1 and Architecture 2.

5.7 ARCHITECTURE 6

Architecture 6 maps each ECU onto its unique bus system. While this layout amplifies communication complexity between the ECUs, it provides robust isolation between them. However, it also reduces the hops per attack path and the number of ECUs used for the path. This design may not be feasible in a real-world scenario due to its complexity but is intriguing to examine its performance. It is not expected to appeal to security experts, given its inherent challenges.

5.8 ARCHITECTURE 7

Architecture 7 carries a concept similar to Architecture 6. Instead of placing all ECUs on their own bus system, it groups ECUs that use the same bus system. This configuration amplifies the significance of the bus rating to the overall architecture rating, indicating whether the employed bus systems are sufficiently secure. Comparing this architecture's performance to Architecture 6's will yield interesting insights.

5.9 ARCHITECTURE 8

Figure Architecture 8 designates the CGW as the sole entry point. This setup eliminates other entry points, meaning all attack paths originate from the same point, thereby reducing the attack surface. Also, the feasibility rating of the interfaces becomes more significant, and the attack paths might become much more linear, underscoring the importance of component feasibility ratings. This architecture is expected to perform well in terms of security due to the singular

entry point. However, the entry point's central location may slightly undermine the architecture's security.

5.10 ARCHITECTURE 9

Architecture 9 is the same as Architecture 4 but excludes a central gateway. Again, the dispersed entry points lead to a larger attack surface, and the significance of the CGW can be more accurately deduced from this comparison. This architecture is not expected to perform well in security, possibly scoring worse than Architecture 4.

5.11 ARCHITECTURE 10

Architecture 10, the final architecture of the test set, includes only one of each interface, but they are more dispersed than in Architecture 8. However, the entry points are still grouped together, aligning with the concept of Architecture 3. This architecture is expected to be one of the most secure due to its few, isolated entry points.

5.12 SURVEY

Security experts at Mercedes-Benz Tech Innovation were given ten architectures, as shown in Architectures. The experts were asked to rank the architectures, give the reasoning behind their ranking, and add any comments they had. Since there are ten architectures, the ranking went from 1 to 10, where 1 is the most secure and 10 is the least secure. Each rank was given a score: the first place got 1 point, the second place got 2 points, and so on. In the end, each architecture ranking/score got was summed up, and the architecture with the lowest score was the most secure.

Of course, there are many ways how a security architect approaches an evaluation. Each architect comes from a different background with different experience and thus will see some factors as more or less important than others. Even though architects generally agree about what makes an architecture secure and what does not, opinions differ in the details. This result thus represents the architects' mean opinion on the security of the architecture.

The experts agreed that the number of hops between the entry and target is a criterion in evaluating the security of attack paths. The more hops there are, the more challenging it becomes for attackers to navigate from the entry point to the target. However not every hop is the same.

Separation and isolation, both of domains and ECUs, is a crucial consideration, as it enables compartmentalization and application of security measures to each domain or ECU individually. The Powertrain domain, which controls the engine, transmission, and other critical systems, is of particular concern, and its position in the network must be carefully considered. It was thus somewhat

expected that Architecture 3 received the highest score, as all of the external interfaces were placed in the same domain. Architecture 10 was also expected to receive a high score, as it is similar to Architecture 3 regarding the placement of the external interfaces. However, the Telematic domain controller being a target was a concern, and we expected it to rank better than the survey results did in the end.
Architecture 6 was also not expected to receive a good score, as the maximum number of hops between the entry and target is two on average. However, the experts agreed that isolation played a huge role in the evaluation.

However, excessive isolation would make the system too complex. Architectures Architecture 6 and Architecture 7 also provide high levels of isolation, but at the cost of increased overall complexity. Communication between ECUs must also be considered, as it is an essential part of the vehicle. Too many isolated ECUs communicating with each other can result in significant overhead. Media change, such as from CAN to CAN FD, FlexRay, or Ethernet, also introduces additional hurdles. That is why it is astonishing to see that Architecture 6 received such a good score in the survey and in addition for it to be in such stark contrast to Architecture 7, which received one of the worst ratings.

Other criteria that need to be evaluated include the presence of a CGW and the number of external interfaces. More interfaces mean more attack vectors and the need for more security mechanisms. Architecture 4 and Architecture 9 have the most spread out interfaces. Thus they were expected to receive a low score, whereas Architectures Architecture 8 was expected to receive a high score, as the CGW is the only entry vector into the network. However, a CGW with no external interfaces is overall likely more secure than an architecture with no CGW at all, and that is why Architecture 2 received a higher score than Architecture 1. Of course, the type and the security of the external interface also play a role because every interface has different security properties.

While the attack feasibility of each component accounts for the security mechanisms implemented in the vehicle, such as firewalls or IDCs, these mechanisms and the component's feasibility have not been explicitly stated in the architectures under consideration since every component can vary in their implementation. However, these assessments are represented through the feasibility of each ECU, bus, and interface as explained in Section Configuration Files Structure. The experts agreed that the presence of security mechanisms is a critical factor in evaluating the security of the architectures. Such security measures impede attackers from progressing quickly through the attack path. For example, intelligent domain controllers that differentiate between domains are more effective than those that only forward messages. As a result, the final results varied between experts, as expected.

To summarize, architectures Architecture 3, and Architecture 8 received the best feedback, closely followed by architectures Architecture 6 and Architecture 10 and Architecture 2, whereas architectures Architecture 4, Architecture 7, and Architecture 9 received the worst feedback, as they have been ranked last place at least once.

5.13 RESULTS - TRAINING SET ARCHITECTURES

The result is as follows:

Table 5.1: Rank and Architecture

Rank	Architecture	Score
1	Architecture 3	10
2	Architecture 8	11
3	Architecture 6	15
4	Architecture 10	16
5	Architecture 2	17
6	Architecture 1	25
7	Architecture 5	27
8	Architecture 7	28
9	Architecture 9	29
10	Architecture 4	30

6 CRITERIA FOR EVALUATION

Just as there are many ways to evaluate an architecture, there are many ways to come to criteria for this thesis. Similar to [11], we approached the criteria as a mathematical equation that can be applied equally to every architecture. This equation considers the architecture feasibility, attack path feasibility, presence and influence of a CGW, amount of hops, isolation of ECUs, and amount of interfaces/entry points.

Finding the most fitting equation was done in a manual, brute-force-like attempt. The following chapter will describe the equation, the factors considered, and the reasoning behind them.

6.1 EQUATION FACTORS

We define a set of architectures A, where each architecture a has a set of attack paths P:

$$A := Architectures \qquad a \in A \tag{6.1}$$

$$P := AttackPaths_a \qquad p \in P \tag{6.2}$$

Next, we define the factors that are considered for the equation.

Since the Bellman-Ford algorithm finds and takes the lowest weighted attack path, i.e., the least secure one, a high score for this path means the most feasible path receives a high security rating. Multiplying the feasibility of each attack path with the number of hops it has, we also consider the number of hops in each attack path. The more hops there are, the better. This is because the more hops there are, the more ECUs there are to compromise, and the more ECUs there are to compromise, the more likely the attacker will be hindered from reaching the target ECU.
We calculate the architecture feasibility $feasibility_a$ by multiplying the feasibility of each attack path $feasibility_p$ with the amount of hops $hops_p$ in each attack path:

$$feasibility_a := \sum_p feasibility_p cdot hops_p cdot cgw_a \tag{6.3}$$

The CGW also plays a role in the security of an architecture. As mentioned before, the benefit of a CGW depends on whether it is present, an entry point, or a target. A CGW is beneficial if it is present but not an entry point or a target. The CGW factor is 1 by default and is then decreased by 0.15 if the CGW is not present, by 0.1 if the CGW is an entry point, and by 0.05 if the CGW is a target.

This reflects the opinion of the security experts.
To include the influence of a CGW, we define the CGW factor cgw_a as follows:

$$cgw_a := \begin{cases} 1, & \text{base case} \\ cgw_a - 0.15, & \text{if } \notin a \\ cgw_a - 0.1, & \text{if external interface} \in a \\ cgw_a - 0.05, & \text{if target} \in a \end{cases} \tag{6.4}$$

In this thesis, we define *hops* in an attack path as the amount of $ECUs - 1$ in the path from an entry point to a target. The interface itself does not count as a hop, only the entry point, i.e., if the entry point is also the target, the amount of hops is 0. To later norm the number of hops, we set $hops_a$ as follows:

$$hops_a := \sum_p hops_p \tag{6.5}$$

Isolation of an architecture is defined as the amount of ECUs per bus, which we call the separation factor $separation_a$:

$$isolation_a := \text{average amount of ECUs per bus in } a \tag{6.6}$$

And lastly, we define the number of entry points as the interfaces factor $entrypointsa$:

$$entrypoints_a := \text{total amount of entry points in } a \tag{6.7}$$

6.2 EQUATION

Iterating over each of the ten architectures, their factors were given a weight and were then arranged in different mathematical operations. These weights were iterated from factors between 0 and 100, resulting in millions of combinations for every attempted equation. Each combination of the ten architectures using the same weights was then represented as a ranked table. In the end, the weights of the tables with the smallest Euclidean distance to the survey table 7.1 were considered. There were hundreds of feasible weight combinations, and ultimately, the smallest possible weights were chosen.

Finding an equation that fit the criteria was a step-by-step progress. In general, we asked ourselves the questions:
Which of the factors is it favorable to have more of? and *Which of the factors is it unfavorable to have more of?*

Let us consider any one architecture:
The most desirable is a high architecture feasibility score and many hops in each attack path. To get the architecture feasibility, each attack path feasibility is multiplied by the number of hops it has 6.3. We know that the more difficult the

path, the more secure the architecture, and the more hops there are in a path, the more difficult it is to reach the target ECU.
This is then multiplied by the CGW factor 6.4.
To get a reasonable rating score, the product of the feasibility and CGW factor are multiplied by 100.

Next, we consider the factors that are unfavorable to have more of.
The isolation of an architecture, i.e., the amount of ECUs per bus, is unfavorable to have more of. This is because the more ECUs there are per bus, the more ECUs there are to compromise on one bus. Looking back at Architecture 6, which received a good rating, we can deduce that the more isolated the ECUs are, the better.
The amount of interfaces is also unfavorable to have more of. In this case, we only consider the number of entry points and not the number of total interfaces. Doing so, we can differentiate between one ECU with many interfaces and many ECUs with one interface since more entry points are also likely more spread out. Combining entry points and the number of hops, we can deduce whether the entry points are secluded or spread out. High hops most likely mean that the entry points are all grouped, and low hops mean that the entry points are spread out.

In the end, we receive the following equation:

$$rating_a := \frac{100cdotfeasibility_acdotcgw_a}{hops_acdotw_1 + isolation_a^{w_2} + entrypoints_acdotw_3} \tag{6.8}$$

In order to determine the optimal weights w_1, w_2, and w_3, we carried out iterations over the factors ranging from 0 to 100 for each architectural model. Every permutation was subsequently ranked, and the weights of the permutations that were closest to the survey table 7.1 in terms of Euclidean distance were taken into account. Eventually, we selected the permutation with the smallest weights. However, other options were also plausible since their scores were relatively close in terms of how the architecture was ranked. We assigned 1 to w_1, 4 to w_2, and 32 to w_3.

We multiplied the CGW factor with the architectural feasibility score because it impacts the overall architecture, rather than just a specific attack path or factor. It is already weighted, and the weights are calibrated in a way that it influences the feasibility of the architecture without overshadowing it. Trials involving subtraction and modifications of the CGW led to impractical results, as it would either become too dominant over the other factors or not considered sufficiently. Architectures without a CGW factor ranked significantly lower or not low enough. This holds true for architectures with no CGW but other compensatory advantages, when compared to architectures with an entry point CGW, such as Architecture 2.

Looking first at the nominator only and not regarding the denominator, results vary drastically, from the desired outcome. Architecture 4 would be ranked fourth, and in contrast Architecture 6 would be among the last, with Architecture 8 even scoring last place. Architecture 3 however, scores second place, long beind Architecture 10 in first place. Even though this is not ideal it is a good start, bt the denominator is definitely needed to get a better result.

We considered the possibility of entirely excluding w_1 since its weight is only 1. However, the inclusion of w_1 produced better results. For instance, without w_1, the score gap between Architecture 10 and other architectures was much wider, leading to Architecture 8 ranking higher than Architecture 3 and Architecture 6, which didn't align with the survey results. There is a limit to how large this factor can be; testing with a higher weight for w_1 is illogical, as it would imply that an increase in hops leads to a poorer architecture, which is contrary to our understanding. Initially, we introduced the factor to normalize the hops for each architecture. We concluded that the inclusion of total hops with a low weight of 1 was necessary to yield the desired results.

Initially, w_2 was intended to serve as a standard multiplication factor like others in our model. However, during the course of our tests, we found that the most optimal results were achieved when the weight was set at 99. This suggested that the isolation factor had a more significant influence on the outcomes than initially anticipated. Therefore, we decided to transform it into an exponent to better represent its significance. Architecture 6 displayed the highest isolation factor and, interestingly, also ranked top in our survey results. Its strength lay in the effective isolation of the ECUs. We came to the conclusion that the isolation factor should be accorded a higher weight in our ranking to reflect its importance. Otherwise, its effectiveness wouldn't be sufficiently recognized in the ranking. However, the challenge was that increasing the weight for the isolation factor would lead to a larger denominator in our calculations. This, in turn, could overpower the numerator, resulting in undesirable outcomes. For instance, some architectures might end up with a score of zero due to this imbalance.

The entry point factor holds a significant sway on the overall assessment and comparison of the architectures. If this factor is not considered, Architecture 4 lands in the middle of the ranking, which contradicts the survey results. Furthermore, without it, Architecture 8 would be deemed extremely unsecure, placing second from the bottom. If we were to assign a higher weight to this factor, it would result in a lower score for Architecture 6, but it would not change the other architectures significantly.

The resulting table had a Euclidian distance of 6 to the survey table 7.1, which was the best result out of all the permutations, and looked as follows:

Table 6.1: Rank and Architecture

Rank	Architecture	Rating
1	10	151.48
2	3	60.58
3	8	59.85
4	6	59.8
5	2	56.52
6	5	44.69
7	1	43.46
8	4	42.21
9	9	31.38
10	7	13.02

As we can see, the table is very similar to the survey table 7.1, with the Euclidean distance being 6. The architectures that received the best rating, which

were Architecture 10, Architecture 3, Architecture 8, and Architecture 6 also being the ones that were ranked the highest, and the architectures that received the worst rating also being the ones that were ranked the lowest. Differences are that Architecture 10 jumped from rank 4 to rank 1, Architecture 1 and Architecture 5 switched places, and so did Architecture 9 and Architecture 7.

We were able to replicate the order of architectures 3, 8, 6. Looking at their feasibility score, it is evident that their rating was very close to each other, just like the security experts' opinions. Concentrated entry points were an advantage of Architecture 3 and 8, however the CGW being the entry point in Architecture 8 is what made it rank below Architecture 3. In contrast, Architecture 6's strong isolation is what made it rank high. We consider this distribution of this rating a success.

Architecture 10 ranked first in our table, which was not the case in the survey table 7.1. This is due to the isolated entry points, the CGW only being a target and not an entry point, and the number of hops being high, as no interface shares an ECU with another interface. The priorities of the security experts are reflected in this architecture, and strictly sticking to the criteria, Architecture 10 is the best. The opinion was not shared by the security experts, ranking it fourth, but it was also surprising.

Architecture 2 is correctly ranked above Architecture 1 and Architecture 5.. Though it is missing the CGW, the CGW in 1 is an entry point, which is more unfavorable, as it reduces the number of total hops. 5 uses Ethernet only, which has a higher security rating than CAN, thus placing above 1.
The result is interesting because the architectures are the same with one key difference each. Thus we can see the priorities of the security experts as reflected in the criteria. 5 and 1 ranked close to each other. Thus we consider this result a success.

Unfortunately, we could not replicate the low ranking of 4. As our criteria weighs isolation the most out of all the factors, it is understandable that 7 is placed last, even though it is placed third in the survey. Isolation in this architecture was intentionally removed, with every ECUs having to share the bus with every ECU using the same bus technology. It is surprising to see that Architecture 4 ranked much better than 9 and even 7. 9 and 4 are the same, except for the presence of the CGW in 4. However, this reflects some security experts' opinion that having a CGW is better than having none if it is not an entry point.

To summarize, we were able to choose criteria and according weights in such a way that the resulting table was very similar to the survey table 7.1. The criteria were constructed so that the priorities of the security experts were reflected, and the weights were chosen so that the resulting table was as close to the survey table as possible. Though Architecture 10 and 4 were the only major exceptions, we find that the results, and thus our criteria equation, is nevertheless valid.

7 PROOF OF CONCEPT

To prove that the criteria are properly calibrated and gives desired results, another set of architectures is evaluated.
These architectures were designed with the survey feedback in mind. In the following, they are referred to as *Proof Of Concept* architectures.
The training set architectures sometimes differ immensely from each other to be able to better crystallize the criteria, whereas these now are kept relatively similar to each other to ensure the criteria are not biased towards a specific architecture.
Similarly to the test set, this chapter will describe the architectures, estimate the desired results, and evaluate the architectures using the tool. The following architectures all use the same building blocks with the same values as described in 3.

7.1 ARCHITECTURE A

Architecture A features four entry points and six interfaces - the highest amount of all the architectures. However, the strong point here is that they are relatively separated from the rest of the components. In addition, it features a CGW that is not an entry point.
These factors indicate a high amount of hops for some targets. In terms of isolation of ECUs, most ECUs share their bus with at least two or more other ECUs, resulting in low isolation compared to the other architectures.
Based on the criteria, this architecture is expected to do the best out of the three architectures.

7.2 ARCHITECTURE B

Architecture B features three entry points and five interfaces. Though the number is lower than that of Architecture A, the entry points are more spread out, meaning that the maximum amount of hops is lower. The CGW, however, is not an entry point, and the isolation of ECUs is better compared to 11.
This architecture, though offering better isolation, is expected to perform worse than 11 due to the lower amount of hops.

7.3 ARCHITECTURE C

Architecture C has only three entry points and three interfaces - however, one of them being the CGW and in addition, the entry points are distributed across the architecture. This results in a lower amount of hops for the targets, putting this architecture at a disadvantage compared to the other two. Isolation of ECUs here is similar or somewhat better to Architecture B.

Due to the low amount of hops and the CGW being an entry point, this architecture is expected to perform similar to Architecture B, but still the worst out of the three.

7.4 RESULTS - PROOF OF CONCEPT ARCHITECTURES

The results are as follows:

Table 7.1: Rank and Architecture

Rank	Architecture	Rating
1	Architecture A	152.97
2	Architecture B	129.2
3	Architecture C	124.66

Taking the criteria into account, the results reflect the expectations. Architecture A, with the highest amount of hops, due to the secluded entry points, is ranked first. Architecture B, with a lower amount of hops but better isolation, is ranked second. Architecture C, with the lowest amount of hops and the CGW being an entry point, is ranked third.

Architecture A was expected to perform the best due to the high amount of hops and the secluded entry points. It was predicted that Architecture B and Architecture C would perform similarly and score lower than Architecture A, but the difference between Architecture B and Architecture C is smaller than initially thought. However, we expected Architecture B to perform better than Architecture C, because the CGW being an entry point in Architecture C is the deciding factor for the lower score.

Overall, we are satisfied with the results, as our predictions matched the actual results. In conclusion, this Proof of Concept confirms that the criteria are properly calibrated and give the desired results.

8

CONCLUSION

In this thesis, we have embarked on an in-depth investigation into the safety measures of automotive network designs.

Our first step was to explore the present state of automotive network security, where we identified a significant shortfall in the evaluation of security measures. To address this issue, we devised an innovative method to gauge the security of automotive network designs.

We conducted a comprehensive survey to discern what security architects consider crucial when evaluating a network's architecture. These factors were then used to create a set of criteria for assessing the security of a network's architecture. To streamline this process, we designed a tool that would automate the evaluation process by generating model-based architectures, identifying their most plausible attack path, and calculating their security feasibility based on the established criteria.

The survey's findings indicated that the most critical aspects for security architects were the attack path's feasibility, the number of hops between entry points and targets, the isolation of ECUs on a bus, the presence and impact of a CGW, and the quantity and distribution of entry points across a network's architecture.

This thesis has introduced an approach to evaluating the security of various automotive architectures. By establishing a set of factors deemed essential to the overall security of the architecture, we formulated a mathematical equation that provides a measurable security score.

This equation takes into account aspects such as the architecture's feasibility, the attack path's feasibility, the CGW's presence and impact, the number of hops, isolation of ECUs, and the quantity of interfaces or entry points. Each of these factors was thoughtfully selected based on an understanding of vehicle architecture and the potential threats it could face.

Balancing these various factors posed one of the most significant challenges in this endeavor. We addressed this by i an iterative processes and expert opinion comparisons and we managed to find an optimal weight assignment for each factor in the equation.

The resulting model is a robust and adaptable tool for evaluating the security of automotive architectures. Its accuracy was confirmed through comparisons with expert rankings, showing a strong correlation. Despite some discrepancies in the rankings, the model's results were consistent with the experts' opinions.

The model's versatility is a critical component of our work. It can accommodate different vehicle architectures, attack strategies, and technological advancements by adjusting the weights of the factors in the equation. This makes the model applicable in various contexts and future scenarios.

Furthermore, the model's quantitative nature provides a clear and objective measure of security, which is a valuable tool for engineers and designers in the field. It allows for quick evaluation of different design proposals and identifica-

tion of the most secure ones.

Despite providing valuable insights into automotive network architectures' security, the thesis has its limitations. While we believe this model significantly contributes to vehicle architecture security, we acknowledge its imperfections. As demonstrated in our evaluation, there are instances where the model's results deviate from expert opinion, pointing to areas where the model could be refined.

Furthermore, the criteria are based on a small pool of security experts' opinions, indicating a need for further validation by consulting more security experts. Additionally, a larger training set would have provided more data, allowing for more accurate criteria. It would also have been beneficial to use more accurate architectures used in the automotive industry, even though our architectures were kept simple for the sake of concept and survey simplicity. Observing how the criteria would perform on more complex architectures could provide interesting insights.

Another limitation lay in the development and calibration of the criteria. Employing machine learning to construct a neural network that would learn the criteria might have yielded more accurate results and allowed for the creation of more precise criteria.

Regarding future work, improvements could include the suggestions mentioned above. The role of a security architect could be further automated in this process by accepting various data formats for input files, such as XML, PDF, or image files, and generating a report on the architecture's security.

In spite of these limitations, our research has proven successful as the criteria, represented as a mathematical formula, closely replicated the security experts' evaluations.

This thesis has provided valuable insights into the evaluation of different E/E architectures based on their attack path feasibility, determining which architectural approach makes a network safer, and quantifying a vehicular network architecture's security using expert-calibrated criteria. Overall, the research serves as a significant contribution to the understanding of vehicular network architecture security.

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ACRONYMS

AUTOSAR AUTomotive Open System ARchitecture. 4

CAN Controller Area Network. 1, 5, 8, 9, 11–13, 20

CAN FD Controller Area Network Flexible Data Rate. 8, 9, 11–13, 20

CGW Central Gateway. 8, 17–20, 22–24, 26–28

CVSS Common Vulnerability Scoring System. 6

E/E Electronic/Electrical. 1, 3, 5

ECU Electronic Control Unit. 1, 4, 7–9, 11–14, 17–20, 22–27

EFSM Extended Finite State Machine. 5

EVITA E-safety vehicle intrusion protected applications. 4

FlexRay FlexRay bus. 8, 9, 11–13, 20

GNSS Global Navigation Satellite System. 8, 10, 11, 13

HEAVENS HEAling Vulnerabilities to Enhance Software, Security, and Safety. 4

LIN Local Interconnect Network. 8, 9, 11, 13

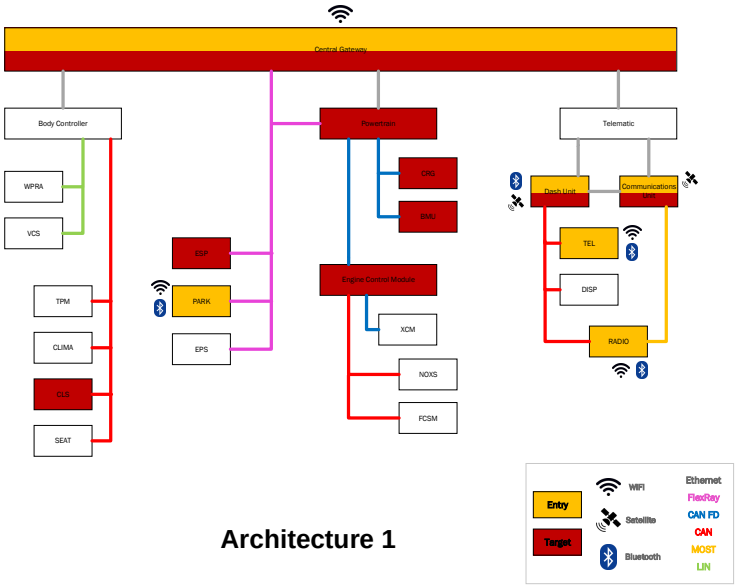
MOST Media Oriented Systems Transport. 8, 9, 11, 13

OBD On-board diagnostics. 5

STRIDE Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, Elevation of Privilege. 4

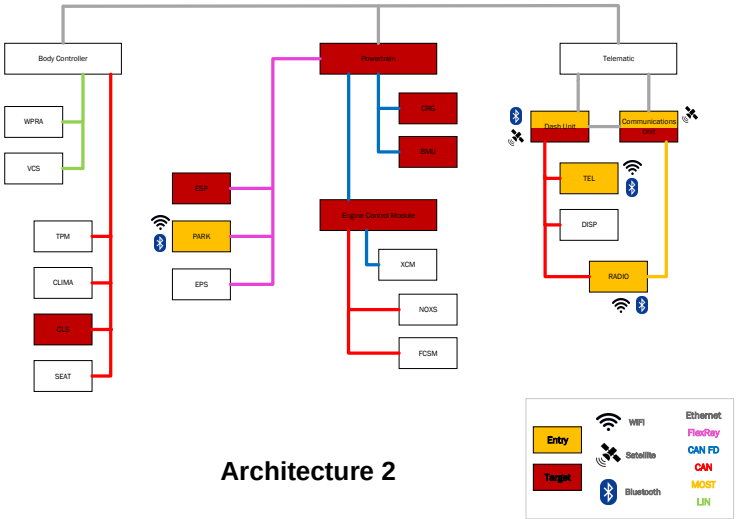
TARA Threat Analysis and Risk Assessment. 1, 2, 4–6

Figure 1: Architecture 1



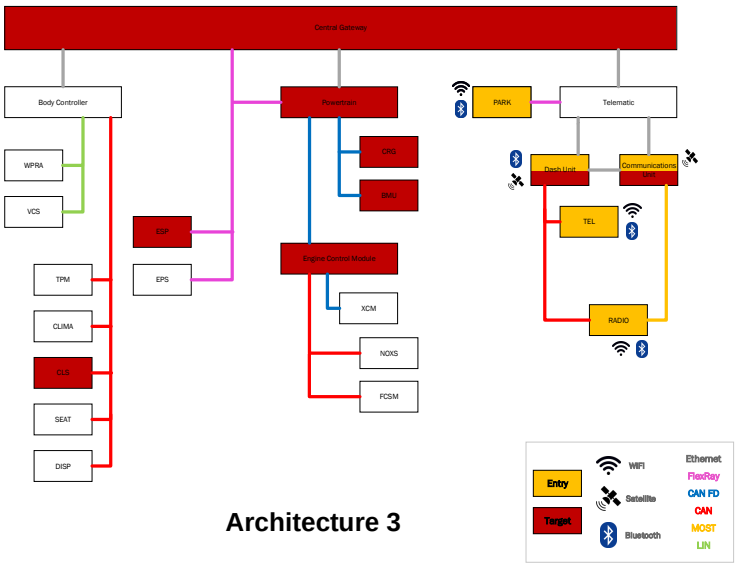
Architecture 1

Figure 2: Architecture 2



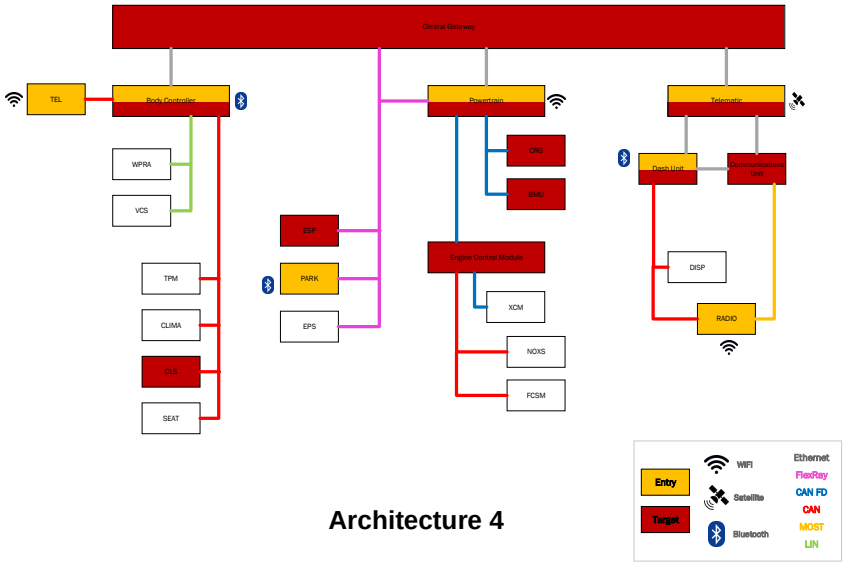
Architecture 2

Figure 3: Architecture 3



Architecture 3

Figure 4: Architecture 4



Architecture 4

Figure 5: Architecture 5

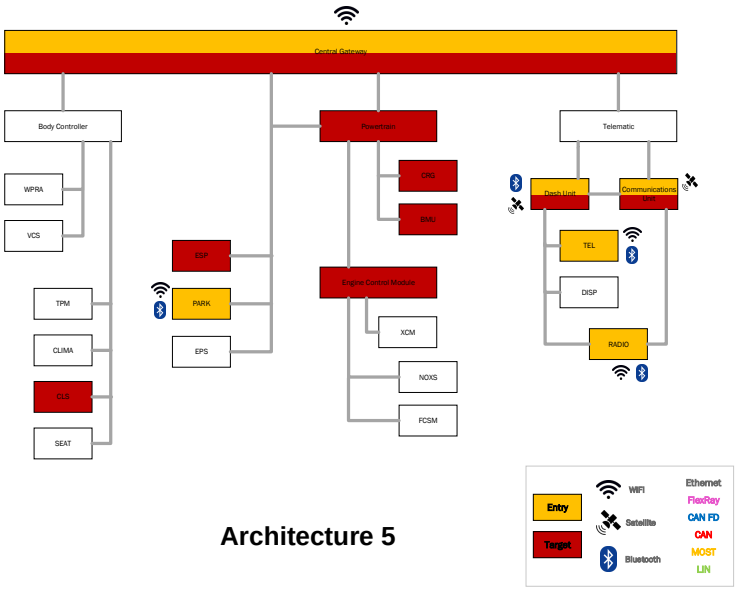
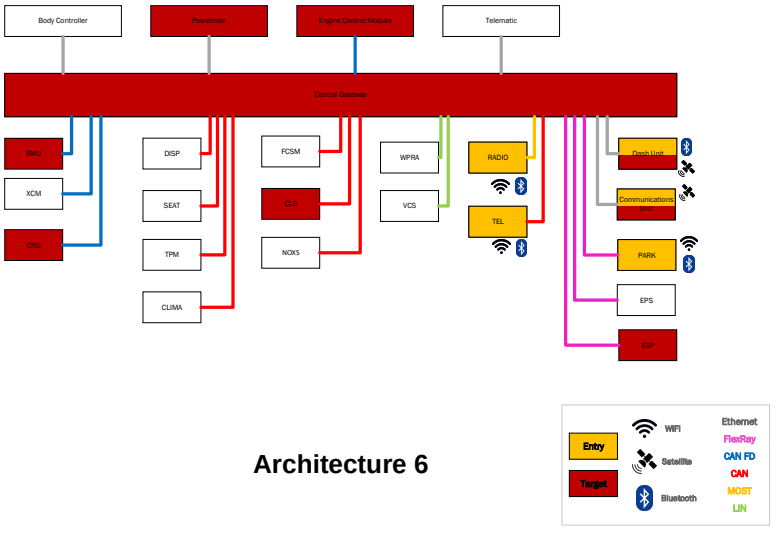


Figure 6: Architecture 6



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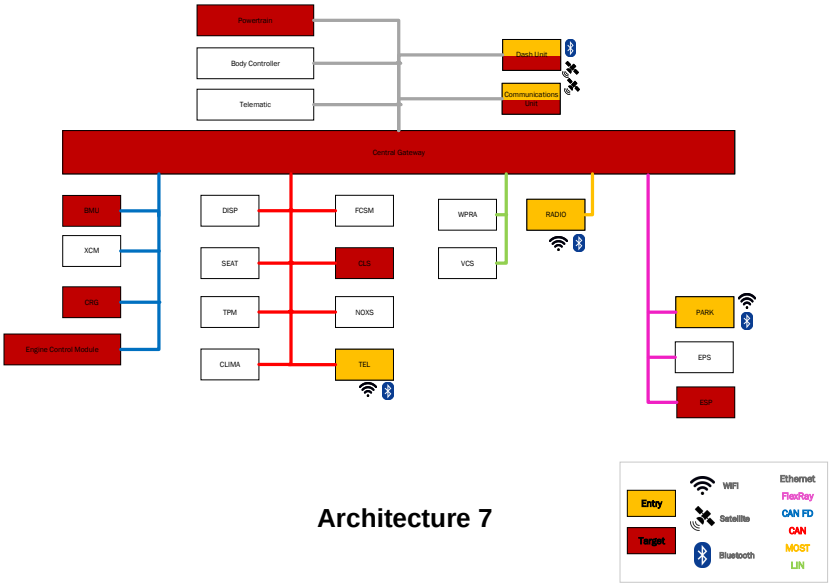
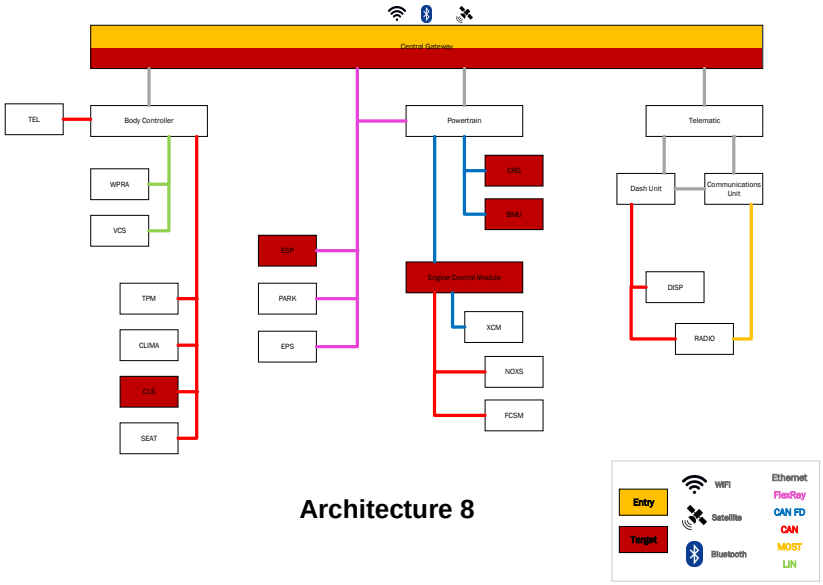


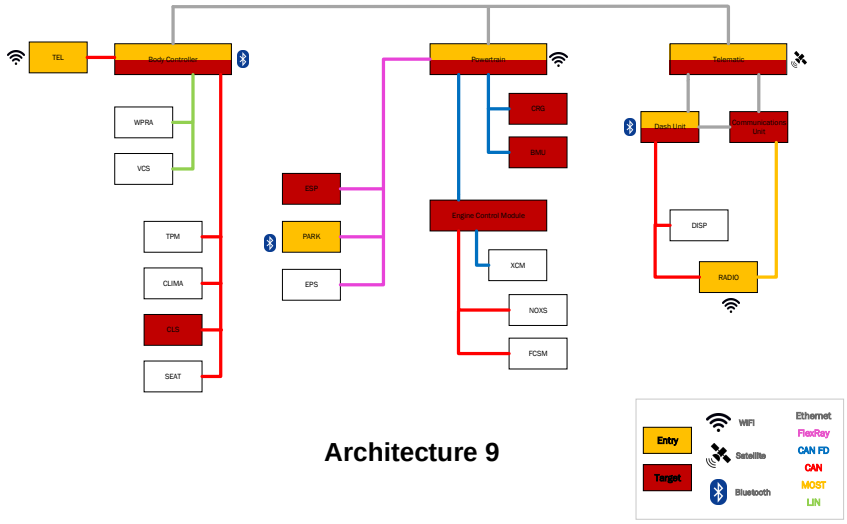
Architecture 7

Figure 8: Architecture 8



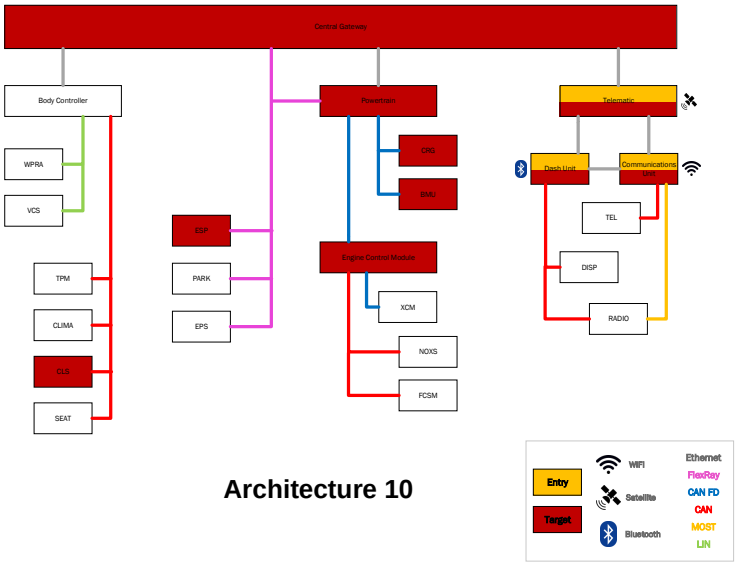
Architecture 8

Figure 9: Architecture 9



Architecture 9

Figure 10: Architecture 10



Architecture 10

Figure 11: Architecture A

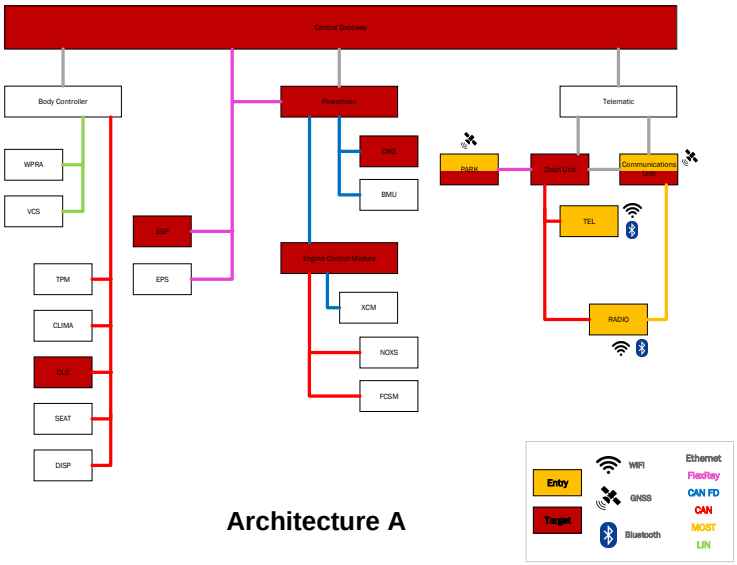


Figure 12: Architecture B

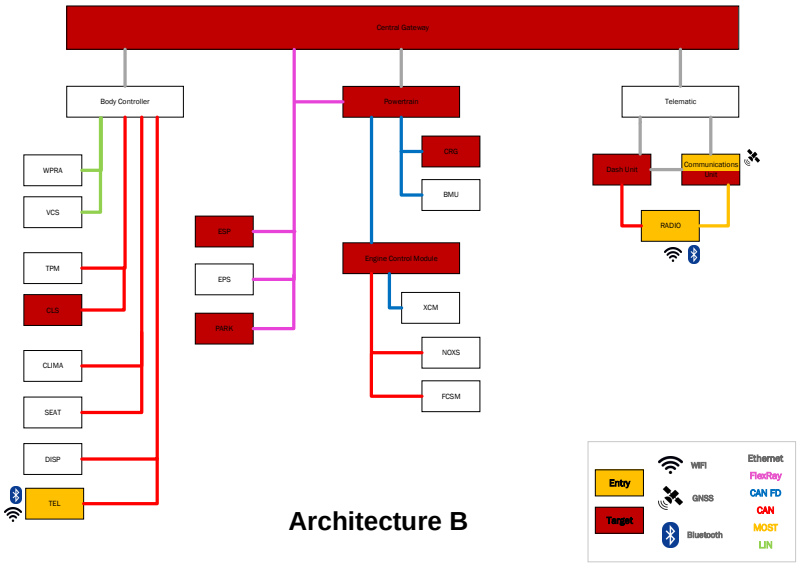
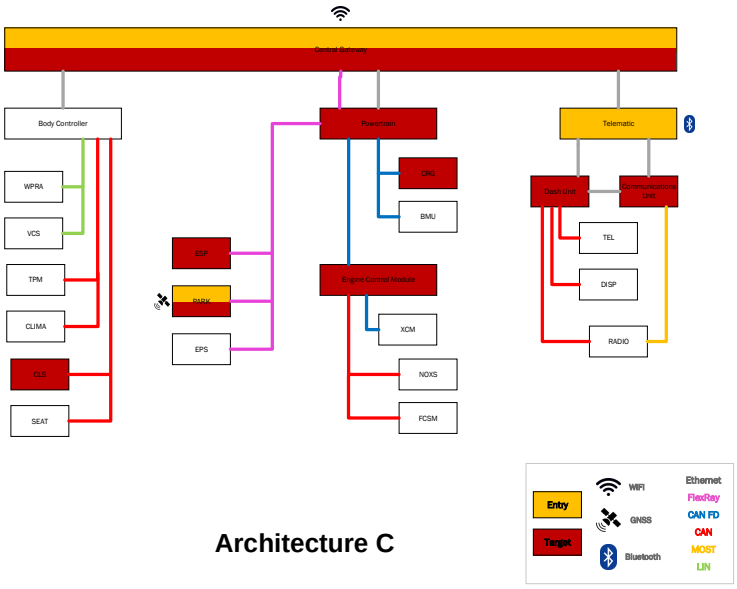


Figure 13: Architecture C



Architecture C