AutoGuardX

Addressing Cyber Vulnerabilities in Modern Vehicles

Understanding the Key-less Vehicles' Issues

Research Project

"This project was undertaken as part of a broader research initiative to examine cyber vulnerabilities in modern vehicles and ultimately resulted in a research paper aimed at providing cybersecurity and IT project management researchers, students, and industry vendors with practical insights into the cybersecurity challenges confronting today's vehicles."

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Preface

The automotive industry is undergoing a profound digital transformation, with modern vehicles increasingly reliant on interconnected software systems, wireless communication, and intelligent control units. While these advancements have enhanced convenience, efficiency, and user experience, they have also introduced significant cybersecurity risks. Today's vehicles function as complex cyber-physical systems, making them attractive targets for cybercriminals seeking to exploit vulnerabilities for unauthorized access and vehicle theft. Addressing these emerging threats has become a critical concern for manufacturers, regulators, and cybersecurity professionals alike.

This research work is undertaken within the domains of Cybersecurity and IT Project Management to systematically identify and analyze the cyber vulnerabilities present in contemporary vehicles. The study examines weaknesses across key automotive components, including keyless entry systems, in-vehicle networks, onboard diagnostics, and external communication interfaces. By evaluating real-world attack scenarios, threat vectors, and existing security limitations, the research aims to provide a clear understanding of how vehicle systems can be compromised and the broader implications for safety, privacy, and asset protection.

Beyond vulnerability identification, this research emphasizes the need for a structured and proactive approach to automotive cybersecurity. As a key contribution, the study proposes **AutoGuardX**, a comprehensive security solution designed to safeguard vehicles against cyber-enabled theft. AutoGuardX integrates technical controls, risk management practices, and governance principles aligned with both cybersecurity and IT project management frameworks. The solution is designed to support prevention, detection, and response mechanisms, ensuring a layered defense that can adapt to evolving threats in the automotive ecosystem.

This research seeks to bridge the gap between theoretical cybersecurity models and their practical implementation in vehicle security programs. By aligning cybersecurity strategies with project management best practices, *AutoGuardX* provides a scalable and actionable roadmap for stakeholders involved in vehicle design, security implementation, and operational management. The findings and proposed solution aim to assist researchers, students, and industry professionals in understanding automotive cyber risks and implementing effective mitigation strategies.

Ultimately, this work underscores the importance of embedding cybersecurity as a core component of modern vehicle development and management. Through the identification of vulnerabilities and the introduction of *AutoGuardX*, the research contributes to advancing secure mobility and reinforcing trust in next-generation automotive technologies.

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Addressing Cyber Vulnerabilities in Modern Vehicles: A Novel Security Framework

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Abstract

The rapid integration of *Internet of Things* (IoT) technologies and interconnected subsystems in modern vehicles has enabled advanced automation, enhanced functionality, and improved user convenience. However, this increased connectivity has significantly expanded the vehicular cyber-attack surface, a development evidenced by the recent rise in cyber-enabled vehicle theft incidents across Canada and the United States. These events underscore the limitations of traditional automotive security mechanisms in protecting next-generation connected vehicles.

This paper presents a *Security Framework* - a comprehensive cybersecurity framework designed for connected and software-defined vehicles. The framework addresses key automotive attack vectors, including relay attacks, *Controller Area Network* (CAN) bus exploitation, and vulnerabilities introduced by 5G-enabled interfaces, as well as potential threats posed by future quantum-capable adversaries. This framework aligns with established automotive safety and security standards, notably ISO/SAE 21434 and ISO 26262, while incorporating advanced features such as machine-learning-based intrusion detection, secure IoT communication protocols, and encrypted in-vehicle and vehicle-to-everything (V2X) communication channels.

The proposed framework is evaluated through controlled simulations, empirical testing, and an analysis of emerging vehicle theft techniques. The results indicate that the proposed framework demonstrates scalability, adaptability, and practical deploy-ability across heterogeneous vehicular platforms. By enabling real-time threat monitoring, secure over-the-air updates, and integrated forensic capabilities, this proposed framework provides a forward-looking security architecture for connected vehicles. This study contributes actionable insights and a robust architectural reference to advance resilience within the automotive cybersecurity ecosystem.

Index Keywords: Automotive security, Cybersecurity, Keyless entry vehicles, Security framework, Encryption

I. Introduction

Vehicle theft has emerged as a significant and rapidly escalating public safety and economic challenge across North America, with Canada experiencing some of the most pronounced impacts. In Ontario alone, auto theft increased by 48.2% between 2021 and 2023, according to *Inspector Scott Wade* of the Ontario Provincial Police Organized Crime Enforcement Bureau, with 30,134 vehicles reported stolen in 2023. Although early indicators suggest a 14% decline in thefts in 2024, the overall volume remains historically high, underscoring the persistence and sophistication of contemporary auto-theft operations [1]. Similar trends have been observed in other provinces, particularly Quebec, where urban centers and major ports have become focal points for organized vehicle theft and export.

In the United States, auto theft has also risen markedly, with law enforcement agencies reporting increased exploitation of electronic vehicle systems, including keyless entry mechanisms and onboard diagnostic interfaces. While the scale and regional distribution vary, both countries share a common pattern: a shift from opportunistic, low-technology theft toward highly coordinated, cyber-enabled methods executed by organized criminal networks. These groups increasingly leverage digital tools, aftermarket devices, and network-based vulnerabilities to bypass traditional physical security measures.

United States and Canada

Although the surge in vehicle theft is particularly acute in Canada and the United States, it reflects a broader global trend driven by the rapid proliferation of connected and software-defined vehicles. The European Union Agency for Cybersecurity (ENISA) reports that cyberattacks targeting IoT-enabled vehicles have increased by approximately 62% over the past five years [2], highlighting the global convergence of automotive connectivity and cyber risk. Features such as remote keyless entry, mobile application-based vehicle control, over-the-air (OTA) software updates, advanced driver-assistance systems (ADAS), and in-vehicle networking architectures have substantially expanded the automotive attack surface. While these technologies enhance convenience, efficiency, and safety, they also introduce new vectors for exploitation by adversaries with varying levels of technical sophistication.

Europe

In Europe, keyless-entry vehicle theft has emerged as a major challenge, particularly in countries such as the United Kingdom, Germany, France, Italy, and the Netherlands. Criminal groups frequently employ *relay attacks*, in which radio frequency (RF) signals from a key fob inside a residence are intercepted and amplified to unlock and start vehicles without physical keys. More recently, *CAN bus injection attacks*—often executed by accessing wiring through headlight assemblies or wheel arches—have become prevalent, enabling attackers to inject spoofed commands that disable alarms and bypass immobilizers.

European insurers and law enforcement agencies have documented sharp increases in thefts involving premium SUVs and crossovers, prompting regulatory responses such as **UNECE WP.29 R155**, which mandates cybersecurity management systems for new vehicle types. Despite these measures, a large population of pre-regulation vehicles remains vulnerable, sustaining elevated theft rates.

Asia

In Asia, keyless-entry theft patterns vary by region and market maturity. In *Japan and South Korea*, where vehicle technology is advanced and theft rates are comparatively lower, attacks tend to involve sophisticated electronic methods such as RF replay and OBD-II key reprogramming. High levels of surveillance and rapid law enforcement response have limited large-scale exploitation, though vulnerabilities persist.

In contrast, parts of South and Southeast Asia, including India, Thailand, and Malaysia, experience increasing incidents of keyless-entry theft as connected vehicles become more common. Criminals often combine *relay attacks with physical access techniques*, exploiting limited encryption in legacy systems and weak immobilizer implementations. In many regions, inadequate regulatory oversight and limited consumer awareness further exacerbate the problem.

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Africa

Across Africa, keyless-entry vehicle theft is strongly influenced by *cross-border organized crime and illicit vehicle trafficking networks*. Countries such as *South Africa, Nigeria, and Kenya* report frequent thefts of keyless-entry vehicles, particularly SUVs, which are later dismantled for parts or smuggled to neighboring regions. Attack techniques commonly include RF relay attacks and OBD-II exploitation, often carried out with inexpensive tools sourced from global gray markets.

The challenge in many African countries is compounded by limited access to manufacturer software updates, weak regulatory enforcement, and insufficient forensic capabilities. As a result, vehicles that are already vulnerable in other regions often face prolonged exposure to exploitation once introduced into African markets.[1]

Conventional anti-theft mechanisms—such as mechanical locks, audible alarms, and immobilizers—are increasingly inadequate in the face of digitally mediated attacks. Techniques such as relay attacks, key fob cloning, CAN bus injection, and exploitation of telematics control units allow attackers to unlock, start, and disable vehicles without triggering traditional alarms or causing visible damage. As vehicles become more reliant on software, wireless communication, and distributed *electronic control units* (ECUs), the distinction between physical theft and cyber intrusion continues to blur.

The economic and societal consequences of vehicle theft extend far beyond the immediate loss of property. Auto theft contributes to rising insurance premiums for consumers, increased operational costs for insurers, and significant burdens on law enforcement agencies. In Canada, stolen vehicles are frequently trafficked through major ports and exported to markets in South America, Africa, and the Middle East, complicating recovery efforts and reinforcing transnational organized crime networks [3]. These activities disrupt supply chains, strain public resources, and pose broader risks to national and economic security. Moreover, the growing prevalence of cyber-enabled theft undermines public trust in connected vehicle technologies and intelligent transportation systems.

In response to these evolving threats, this paper introduces a new framework - *a next-generation cybersecurity framework* that integrates machine learning, IoT security mechanisms, and encrypted communication protocols to protect connected and software-defined vehicles. Unlike existing solutions that address isolated aspects of automotive security, this proposed framework adopts a holistic and adaptive approach capable of responding dynamically to emerging risks, including vulnerabilities associated with 5G connectivity and the anticipated implications of quantum computing.

The objectives of this study are threefold: (i) **to analyze** the contemporary landscape of vehicle theft and associated cybersecurity vulnerabilities in North America, (ii) **to evaluate** the limitations of existing automotive cybersecurity frameworks, and (iii) **to propose** a new framework as a comprehensive, scalable solution for securing modern connected vehicles.

[1] The global nature of keyless-entry vehicle theft highlights several critical issues. First, *wireless authentication mechanisms without strong cryptographic protections remain fundamentally vulnerable*. Second, disparities in regulatory frameworks and enforcement across regions create uneven security baselines, enabling criminals to exploit the weakest markets. Finally, the international movement of stolen vehicles underscores the need for *globally harmonized cybersecurity standards and adaptive security frameworks*.

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II. Contribution & Motivation

The sustained rise in *cyber-enabled vehicle theft*, particularly in technologically advanced regions such as Canada and the United States, has exposed fundamental shortcomings in conventional automotive security architectures. Many existing systems were designed for an era in which threats were predominantly physical and localized, rather than digital, remote, and globally coordinated. The motivation for this research arises from the rapid transformation of the North American automotive landscape, where vehicles are increasingly defined by software, wireless connectivity, and complex electronic architectures. While these advancements have enhanced user convenience, safety, and automation, they have simultaneously introduced a rapidly expanding cyber-attack surface.

In recent years, Canada and the United States have experienced a pronounced surge in *cyber-enabled vehicle theft*, particularly targeting connected SUVs equipped with keyless entry, telematics, and over-the-air (OTA) update capabilities. These incidents reveal a fundamental shift in vehicle crime—from mechanical intrusion to sophisticated electronic exploitation.

Motivated[2] by this growing disparity between threat sophistication and defensive capability, this study proposes a comprehensive and adaptive cybersecurity framework specifically tailored to the needs of connected, autonomous, and software-defined vehicles.

Unlike traditional models that treat safety and cybersecurity as largely independent domains, the proposed framework in this paper integrates these concerns within a unified architectural framework. It incorporates real-time threat detection, secure in-vehicle and vehicle-to-everything (V2X) communication protocols, and robust IoT protection mechanisms, while maintaining alignment with established automotive standards and regulatory requirements.

The development of this proposed Framework followed a systematic, multi-phase methodology. The initial phase involved an extensive analysis of prevailing cybersecurity vulnerabilities within the automotive ecosystem, with particular attention to attack techniques such as relay attacks, Controller Area Network (CAN) bus injection, key fob cloning, and telematics exploitation. This analysis was informed by documented case studies, law enforcement reports, and industry assessments, with a specific focus on North American trends where increasingly sophisticated theft methods have been observed.

Subsequently, the study examined existing automotive standards—most notably ISO/SAE 21434 for cybersecurity engineering and ISO 26262 for functional safety—to identify gaps in their ability to address threats arising at the intersection of safety, connectivity, and cybersecurity. While these standards provide essential guidance, they do not fully account for rapidly evolving attack vectors enabled by pervasive connectivity, OTA updates, and emerging communication technologies.

Building on these findings, this proposed framework was designed by integrating advanced technologies such as machine-learning-based anomaly detection for real-time intrusion monitoring, secure IoT communication protocols, and adaptive encryption techniques capable of mitigating both

[2] This research is also motivated by the limited availability of *empirical, vehicle-level cybersecurity evaluations* that reflect real-world attack conditions. Much of the existing literature focuses on theoretical vulnerabilities or isolated proof-of-concept demonstrations, leaving a gap in comprehensive frameworks that integrate detection, prevention, forensic analysis, and standards alignment. Addressing this gap is critical to restoring consumer trust, reducing economic losses, and safeguarding public safety in an era of increasingly autonomous and connected mobility.

current and anticipated threats, including those associated with 5G networks. The framework also incorporates scalability and forensic capabilities, enabling post-incident analysis and continuous improvement. Collectively, these features position *AutoGuardX* as a forward-looking and resilient solution for securing the future of intelligent and connected mobility systems.

III. Auto Theft Landscape and Modern Threat

Vehicle theft has undergone a fundamental transformation over the past decade and can no longer be characterized as an opportunistic, low-technology crime confined to secluded locations and nighttime hours. Instead, it has evolved into a sophisticated, low-risk and high-reward enterprise increasingly dominated by organized criminal networks.

In Canada, this shift is particularly evident. According to the *Équité Association*, auto theft increased by 48.2% in Ontario in 2023, reflecting both the scale and acceleration of the problem. Provinces such as Ontario and Quebec have been identified as key supply hubs within global vehicle theft ecosystems, serving international markets with sustained demand for high-value vehicles [4].

Organized crime groups operating in these regions exploit a combination of technological expertise, logistical efficiency, and regulatory gaps to facilitate the rapid movement of stolen vehicles. Many thefts now occur in broad daylight and residential areas, underscoring the growing confidence of perpetrators and the diminished effectiveness of traditional deterrents. Once stolen, vehicles are often transported within hours to port[3] cities, where they are concealed in shipping containers and exported to destinations in South and Central America, Africa, Europe, and the Middle East.

In parallel, other vehicles are reintroduced into the domestic market through forged or altered *vehicle identification numbers* (VINs), complicating detection and recovery efforts. These practices highlight the increasingly transnational and technologically enabled nature of contemporary auto theft.

Trends in Canadian Auto Theft

Auto theft in Canada has reached a level of severity that the Insurance Bureau of Canada has formally characterized it as a "national crisis." In 2023 alone, insurance providers paid more than C$1.5 billion in claims related to stolen vehicles, reflecting not only the rising frequency of theft but also the increasing value of targeted vehicles. The financial burden of these losses extends beyond insurers, ultimately affecting consumers through higher insurance premiums and reduced coverage availability.

The widespread nature of the problem has prompted some Canadians to adopt private security measures, including the use of aftermarket tracking devices, private neighborhood patrols, and physical barriers such as retractable bollards installed in residential driveways. Law enforcement agencies across the country have similarly responded by issuing public advisories and prevention guidelines, emphasizing both physical and digital security practices.

Comparative crime statistics further illustrate the scale of the issue. According to Alexis Piquero, Director of the U.S. Bureau of Justice Statistics, Canada's auto theft rate is disproportionately high relative to its population size. While vehicle theft has increased in multiple jurisdictions following the

[3] Phillips, T., & dealer, C. auto. (2024, April 10). *Ontario's OPP, Canada Border Services Agency recover 598 stolen vehicles before illegal shipment*. Canadian Auto Dealer. https://canadianautodealer.ca/2024/04/ontarios-opp-canada-border-services-agency-recover-598-stolen-vehicles-before-illegal-shipment/

COVID-19 pandemic, the most recent available data indicate that Canada records a higher theft rate (262.5 incidents per 100,000 people) than England and Wales (220 per 100,000 people), and remains competitive with or exceeds rates observed in the United States [5].

Analysts attribute part of this surge to pandemic-induced disruptions in global supply chains, which led to prolonged shortages of new vehicles and elevated demand for used cars, thereby increasing the profitability of vehicle theft.

Rise of Cyber-Enabled Theft

A defining characteristic of modern auto theft is the growing prevalence of cyber-enabled attack techniques that exploit vulnerabilities in vehicle electronic architectures. One notable method involves compromising the vehicle's Controller Area Network (CAN) through physical access points such as the headlight assembly. In this attack, perpetrators drill into or remove a headlight—most commonly on the driver's side—to gain direct access to internal wiring connected to the CAN bus.

As explained by Francis Syms, a cybersecurity expert and Associate Dean at Humber College, once attackers connect to the vehicle's internal network, the system often treats the malicious device as a trusted electronic control unit. This implicit trust allows attackers to inject unauthorized CAN messages, enabling them to unlock doors, disable alarms, and start the engine without possession of a legitimate key or fob. The attack effectively bypasses traditional authentication mechanisms and leaves little visible evidence of forced entry.

The increasing digitization of vehicles[4] has amplified these risks. Modern vehicles integrate dozens of electronic control units responsible for powertrain management, infotainment, safety systems, and body control. This complexity, while enabling advanced functionality, also expands the attack surface. Vehicles have effectively become distributed computing platforms, and like other networked systems, they are susceptible to intrusion, exploitation, and malware-like behavior. As connectivity continues to increase, such attacks are expected not only to persist but to evolve in sophistication.

In addition to CAN injection attacks, Syms highlights several other commonly used techniques. These include key fob theft followed by electronic cloning, relay attacks using devices that extend the communication range of keyless entry systems[5], and brute-force attacks that systematically attempt authentication codes.

Some attackers may spend extended periods—up to 30 minutes or more—attempting to gain access through repeated electronic probing. These cyber techniques are often combined with conventional physical methods, demonstrating the hybrid nature of modern vehicle theft. [6]

[4] Modern vehicles often contain over 100 electronic control units (ECUs), each responsible for specific subsystems such as engine management, braking, infotainment, and climate control. This distributed architecture, while enabling advanced features, creates multiple entry points for cyber intrusion, especially when ECUs are interconnected via insecure protocols like CAN and Ethernet.

[5] Relay attacks and key fob cloning are among the most prevalent methods used in vehicle theft today. These techniques exploit vulnerabilities in passive keyless entry systems, allowing attackers to extend signal range or duplicate authentication credentials. According to Syms and other cybersecurity researchers, such attacks are increasingly automated and often paired with brute-force probing tools to bypass electronic safeguards.

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IV. Role of IoT and Connectivity in Vehicle Vulnerabilities

The integration of *Internet of Things* (IoT) technologies has fundamentally reshaped the automotive ecosystem. Contemporary vehicles increasingly rely on interconnected sensors, wireless communication modules, and cloud-based services to support autonomous driving features, real-time navigation, predictive maintenance, and enhanced user convenience. Drivers can remotely monitor fuel levels, lock or unlock doors, and start vehicles using mobile applications, while vehicles themselves exchange data with external systems to optimize performance and safety.

Autonomous and semi-autonomous vehicles employ a complex array of sensors, including cameras, radar, ultrasonic sensors, and *light detection and ranging* (LiDAR), to perceive their environment and make driving decisions. These systems are further enhanced through *vehicle-to-vehicle* (V2V) and *vehicle-to-infrastructure* (V2I) communication, collectively referred to as *vehicle-to-everything* (V2X). Through these channels, vehicles can receive information about traffic congestion, road hazards, weather conditions, and signal timing.

While such connectivity delivers substantial benefits, it also introduces significant cybersecurity challenges. Each connected interface represents a potential entry point for attackers, particularly when communication protocols are insufficiently secured or when legacy systems lack encryption and authentication. The convergence of IoT, wireless communication, and safety-critical vehicle functions necessitates a re-evaluation of traditional security assumptions within the automotive domain.

Vehicle Models & Brands Under Consideration

Auto theft statistics in Ontario reveal that certain vehicle categories and brands are disproportionately targeted, reflecting broader trends in both legitimate and illicit markets. According to the *Équité Association's* 2023 **Auto Theft Trend Report**, *sport utility vehicles* (SUVs) and pickup trucks account for the majority of stolen vehicles, largely due to their high resale value, global demand, and suitability for export.

Among these, Lexus and Toyota SUVs have emerged as frequent targets of cyber-enabled theft. Numerous reports indicate that some Lexus models—particularly those manufactured between 2017 and 2023—can be compromised in as little as two minutes [7]. Critics and cybersecurity researchers have attributed this vulnerability to architectural weaknesses in the vehicle's electronic systems.[6]

Summary of Key Vulnerable Models/Brands

Category	Examples of At-Risk Models/Brands
Toyota & Lexus SUVs	Toyota Highlander, RAV4; Lexus RX, NX, ES, GS, Land Cruiser 150, C-HR †
Hyundai & Kia Vulnerable Models	Older Hyundai/Kia without immobilizers; Kia Soluto, Rio, Picanto †
Electric & BLE Key Vehicles	Tesla Model 3, Model Y †

[6] *Thieves target Toyota and Lexus models | SMR*. Thieves Target Toyota and Lexus Vehicle. (2024a, February 17). https://www.fleetnews.co.uk/news/thieves-target-toyota-and-lexus-models

Category	Examples of At-Risk Models/Brands
Other Keyless Entry Targets	Chevrolet Silverado, Ford F-150, Toyota Camry, Honda Accord/Civic †
Historical Broad Vulnerability Examples	Audi, BMW, VW models, Honda HR-V, Mazda CX-5 ‡

(† Based on regional theft reports and vulnerability disclosures; ‡ based on academic RF keyless entry system research.)

Specifically, the ignition system in these vehicles shares network connectivity with peripheral components such as headlights and other accessories, enabling attackers to access critical functions without entering the vehicle. Furthermore, the lack of encryption on the CAN bus allows malicious devices to inject unauthorized commands with minimal technical effort. Because CAN messages are transmitted in plaintext and lack built-in authentication, inexpensive hardware tools can be used to unlock and start vehicles once network access is obtained.

These design choices highlight the urgent need for cryptographic protection, network segmentation, and intrusion detection within modern vehicle architectures.

V. Attack Vectors in Vehicle Cybersecurity

Modern vehicle theft increasingly exploits vulnerabilities in electronic and networked automotive systems rather than relying solely on forced physical entry. Among the most prevalent attack vectors are relay attacks targeting keyless entry systems, exploitation of the On-Board Diagnostics (OBD) interface, and manipulation of the Controller Area Network (CAN). These techniques leverage weaknesses in wireless communication, authentication mechanisms, and in-vehicle network architectures.

Relay Attacks on Keyless Entry Systems

Relay attacks represent one of the most widely documented cyber-enabled vehicle theft techniques. This attack exploits the wireless communication between a vehicle and its key fob by intercepting and relaying authentication signals. Attackers typically use a pair of radio-frequency devices: one positioned near the victim’s key fob—often inside a residence—and another located near the targeted vehicle. The device near the key fob captures the low-power wireless signal and relays it to the second device, which transmits it to the vehicle, thereby deceiving the system into authenticating the key as present.

Because keyless entry systems are designed to unlock when the fob is in close proximity, they often lack mechanisms to verify the physical distance of the key. As a result, the vehicle unlocks and allows ignition even though the legitimate key remains inside the owner’s home. Notably, such signals can be intercepted even when the key fob is stored in pockets, bags, or interior rooms, making these attacks feasible in a wide range of residential settings. Relay attacks may also enable unauthorized access to in-vehicle data or personal belongings in addition to vehicle theft.

The accessibility of relay attack tools has further exacerbated the threat. Low-cost relay and lock-picking devices are widely available through online marketplaces, lowering the technical and financial barriers for attackers. Their ease of use and minimal risk of detection have contributed to their growing adoption by organized criminal groups.

Exploitation of the On-Board Diagnostics (OBD) Interface

Following unauthorized entry, attackers frequently exploit the On-Board Diagnostics (OBD) port to gain persistent control over the vehicle. The OBD interface, typically located beneath the steering column, is designed to provide mechanics with access to vehicle diagnostics and configuration data. However, inadequate access control and authentication mechanisms allow attackers to misuse this interface once physical access is obtained.

By connecting a key programming device to the OBD port, attackers can reprogram or register a new key fob that is recognized as legitimate by the vehicle. This enables repeated access and operation of the vehicle without the original owner's key. Such tools are commercially available and compatible with a broad range of vehicles equipped with push-to-start ignition systems, making OBD exploitation a highly scalable attack method.

Key Reprogramming Attacks

Key reprogramming attacks are closely related to OBD exploitation and involve rewriting the vehicle's key authorization data to accept unauthorized fobs. By injecting commands through the OBD interface or other accessible data ports, attackers can override existing key registrations. This method effectively grants full control over the vehicle's access and ignition systems, often without triggering alarms or security alerts.

Controller Area Network (CAN) Bus Manipulation

The Controller Area Network (CAN) is a critical in-vehicle communication bus that enables electronic control units (ECUs) to exchange messages related to engine control, braking, lighting, and security functions. In many vehicle designs, CAN wiring can be accessed through external components such as headlights or front bumper assemblies. By physically accessing these points, attackers can connect malicious devices directly to the CAN bus.

Once connected, attackers can inject unauthorized messages to manipulate vehicle behavior, including unlocking doors, disabling immobilizers, or initiating engine start sequences. A fundamental weakness of the CAN protocol is the absence of built-in encryption and message authentication, allowing any connected device to transmit commands that are implicitly trusted by the network. This lack of security controls makes CAN bus attacks particularly effective and difficult to detect.

VI. Cyber Vulnerabilities and Issues in Toyota & Lexus SUVs[7]

The rapid integration of digital technologies within modern vehicles has transformed SUVs such as those produced by Toyota and Lexus into complex cyber-physical systems. This connectivity enhances user experience but simultaneously expands the attack surface exploitable by cybercriminals and sophisticated theft operations.

[7] Toyota Motor Corporation. (2021). *Toyota responds to cybersecurity research on vehicle systems*. Toyota Global Newsroom. https://global.toyota/en/newsroom/corporate/32120629.html

In the North American market, several classes of vulnerabilities have been observed in Toyota and Lexus vehicles—ranging from in-vehicle network weaknesses and multimedia system exposures to smart key and immobilizer flaws—that have practical implications for vehicle theft and unauthorized control.

Toyota and its luxury division Lexus have been widely noted in recent automotive cybersecurity discourse as being susceptible to several cyber-enabled vehicle theft methods. While traditionally lauded for mechanical reliability and build quality, select models from these brands have exhibited systemic vulnerabilities in keyless entry and in-vehicle network security that have been directly exploited by criminals and criticized in legal and consumer forums.

CAN[8] Bus Injection Vulnerabilities

A particularly prominent class of vulnerability affecting many Toyota and Lexus SUV models involves the *Controller Area Network (CAN) bus*, the core in-vehicle communication infrastructure connecting electronic control units (ECUs). Because the standard CAN protocol lacks inherent authentication and encryption, any device physically connected to the network can potentially inject arbitrary commands that are accepted as legitimate by connected modules.

Investigations and police interventions—including in the United Kingdom—have documented theft devices that are covertly connected to the CAN bus through accessible points such as front headlight assemblies. Once attached, these devices can emulate key signals to unlock doors, disengage immobilizers, and start the engine without requiring the actual key fob. In some documented cases, perpetrators have removed trim or headlight components to access wiring and then used inexpensive off-the-shelf hardware disguised as benign devices to exploit the network, enabling theft in a matter of minutes.[9]

This vulnerability is reported for models including the Toyota RAV4 and Lexus RX/NX series, among others. The *CAN injection attack* has been sufficiently widespread that researchers have formally cataloged it and assigned it an official vulnerability identifier (*CVE-2023-29389*), underscoring its systemic nature and cross-model applicability.[10]

Keyless Entry Signal Exploitation

Many Toyota and Lexus vehicles employ *smart key* or *remote keyless entry* systems that rely on low-power radio transmissions between the key fob and vehicle. These systems enhance convenience but can be exploited through *relay* or *signal amplification* attacks.

Criminals position signal relaying devices near a key fob inside a residence to capture and extend the communication range, tricking the vehicle into believing the key is in proximity and thereby unlocking and starting it without physical access to the key.

[8] See Appendix B

[9] June newsletter - RCAR. (2024, Feb 11) https://www.rcar.org/images/newsletters/2023/Newsletter_June_2023.pdf

[10] https://www.can-cia.org/fileadmin/cia/documents/publications/cnlm/june_2023/23-2_cnlm.pdf

This form of attack has been observed in Toyota and Lexus models and similarly affects other manufacturers; the lack of robust distance-bounding protocols and anti-replay protections in many implementations exacerbates the susceptibility.[11]

Legal cases and consumer advocacy actions in Canada (including Quebec) allege that vulnerabilities in Toyota/Lexus smart keys have materially facilitated thefts, contributing to class action litigation against multiple manufacturers for allegedly insufficient security design.[12]

Exploitation through Headlight and Peripheral Wiring Access

In addition to the CAN bus itself, attackers have targeted peripheral wiring harnesses that are electrically connected to the central network. This includes wiring accessible via headlights or other exterior fixtures. By removing lenses or trim to expose these harnesses, an attacker can directly interface with the vehicle's internal network without needing the interior OBD (*On-Board Diagnostics*) port, thereby avoiding detection and increasing operational stealth. Once connected, a malicious interface can activate the vehicle's ECU subsystems.[13]

Lack of Cryptographic Authentication in Legacy Architectures

Many older Toyota/Lexus models lack strong cryptographic protections on internal communications. In early implementations, the CAN protocol and keyless entry messages were transmitted without message authentication or encryption, permitting unauthorized devices to inject or replay messages. While industry best practices for connected vehicles increasingly recommend cryptographic segmentation and secure gateways, the absence of such protections in earlier generations of Toyota and Lexus vehicles has been widely cited as a contributing factor to thefts.[14]

Conversely, some newer Toyota and Lexus vehicles have reportedly begun to implement enhanced secure CAN (*SecOC*[15]) or similar encryption frameworks, which significantly mitigate unauthorized access to the internal network by ensuring that only authenticated modules can communicate. However, the availability and deployment of these protections vary by model year and market, and vulnerabilities persist in many vehicles still in service.

Broader Context and Industry Implications

The vulnerabilities seen in Toyota and Lexus vehicles are not unique to these brands but are illustrative of broader systemic challenges in automotive cybersecurity. Key elements include:

- **Legacy Protocols**: The CAN bus and many RKE (*remote keyless entry*) systems were designed without native security mechanisms, creating enduring structural vulnerabilities.
- **Physical Access Facilitators**: Attack vectors that require only minimal physical access—a headlight housing or peripheral wiring—blur the line between cyber and physical security, complicating detection and mitigation.

[11] https://www.rcar.org/images/newsletters/2023/Newsletter_June_2023.pdf

[12] https://www.protegez-vous.ca/nouvelles/automobile/recours-collectif-clef-intelligente-auto

[13] https://www.carkeyssolutions.co.uk/toyota-rav4-lexus-rx450h-advanced-keyless-theft/

[14] https://www.rcar.org/images/newsletters/2023/Newsletter_June_2023.pdf

[15] SecOC (Secure Onboard Communication) is a security mechanism for in-vehicle networks, defined in the AUTOSAR standard, and commonly used with CAN (Controller Area Network) and CAN FD.

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- **Commodity Attack Tools**: Devices capable of exploiting these vulnerabilities are inexpensive and accessible, lowering barriers to criminal adoption.
- **Moving Forward:** Addressing these vulnerabilities necessitates both **architectural change** and **retrospective mitigations**. Architectural improvements include cryptographic authentication on internal networks, secure key protocols with distance-bounding and anti-replay defenses, and robust segmentation between critical and non-critical networks. For existing vehicles, aftermarket countermeasures—such as additional immobilizers, active signal jamming, and hardware-based secure gateways—can provide incremental protection, though they do not replace systemic security design.

In summary, the cyber vulnerabilities observed in Toyota and Lexus SUVs highlight the complexity of securing modern connected vehicles. They demonstrate how weaknesses in internal communication protocols, keyless entry systems, and peripheral access points can be exploited by adversaries to facilitate theft without the use of traditional physical attack methods.

These challenges underscore the need for continuous cybersecurity integration across all stages of automotive design and lifecycle management.[16]

VII. Cyber Vulnerabilities and Issues in Audi & Mercedes-Benz SUVs Theft

Audi and Mercedes-Benz are widely recognized as leaders in luxury automotive engineering and digital innovation. Their sport utility vehicle (SUV) lineups incorporate advanced electronic architectures, extensive connectivity, and sophisticated driver-assistance systems. However, this high degree of digital integration has also expanded the cyber attack surface, making certain Audi and Mercedes-Benz SUV models attractive targets for cyber-enabled vehicle theft. While these brands have progressively improved cybersecurity controls, multiple vulnerabilities—particularly in legacy and transitional architectures—have been identified and exploited.

Keyless Entry and Start System Vulnerabilities

Both Audi and Mercedes-Benz SUVs rely heavily on passive keyless entry[17] and push-to-start ignition systems. These systems are designed to authenticate a key fob based on proximity, typically using *low-frequency* (LF) and *radio-frequency* (RF) communication. A recurring vulnerability arises from the absence of robust distance-bounding mechanisms, allowing attackers to exploit relay-based signal manipulation techniques.

In such scenarios, attackers relay authentication signals between the vehicle and a legitimate key fob located elsewhere, deceiving the vehicle into granting access. This class of vulnerability has been observed across multiple Audi Q-series and Mercedes-Benz GLE, GLS, and GLC models, particularly those manufactured prior to the widespread adoption of enhanced cryptographic challenge–response protocols.

The reliance on convenience-focused design choices, combined with insufficient verification of physical proximity, has contributed to unauthorized access without physical key compromise.

[16] https://www.rcar.org/images/newsletters/2023/Newsletter_June_2023.pdf

[17] Relay attacks on passive keyless entry and start systems in modern cars. (2017, September 4). https://www.ndss-symposium.org/wp-content/uploads/2017/09/franc.pdf

Controller Area Network (CAN) Bus Exposure

Like most modern vehicles, Audi and Mercedes-Benz SUVs employ the *Controller Area Network* (CAN) protocol to facilitate communication among *electronic control units* (ECUs). Although CAN is reliable and efficient, it was not designed with security as a primary consideration and lacks native encryption and authentication.

In certain vehicle configurations, attackers have exploited physical access points—such as wheel arches, lighting assemblies, or underbody panels—to interface directly with CAN wiring. Once connected, malicious devices can inject fabricated messages that mimic legitimate ECU commands. These messages may instruct the vehicle to unlock doors, disable alarms, or authorize ignition. The flat trust model inherent in legacy CAN architectures means that injected messages are often accepted without verification, enabling theft without forced entry.

While newer Audi and Mercedes-Benz platforms increasingly incorporate secure gateways and segmented networks, vulnerabilities persist in vehicles that rely on earlier *electrical/electronic* (E/E) architectures or that expose non-critical subsystems to security-critical networks.

On-Board Diagnostics (OBD) Port Exploitation

The *On-Board Diagnostics* (OBD) interface remains a critical vector in cyber-enabled theft. Designed to support maintenance and diagnostics, the OBD port provides deep access to vehicle configuration and control functions. In several Audi and Mercedes-Benz SUV models, inadequate access control allows unauthorized reprogramming of keys once physical access to the cabin is obtained.

Attackers may use commercially available diagnostic tools to register new key fobs, effectively granting persistent access to the vehicle. Although manufacturers have introduced countermeasures such as secure diagnostic authentication and delayed programming modes, inconsistent implementation across model years has limited their effectiveness. This vulnerability is particularly significant when combined with relay or CAN-based attacks that enable initial entry.

Telematics and Connected Services Risks

Audi and Mercedes-Benz SUVs integrate advanced telematics platforms—such as Audi Connect and Mercedes me—which enable remote vehicle monitoring, unlocking, engine start, and location tracking via mobile applications. While these services offer substantial convenience, they introduce additional cyber risk if authentication, backend security, or application interfaces are compromised.

Potential issues include account takeover through weak credentials, exploitation of mobile application vulnerabilities, or backend service misconfigurations. Although no widespread theft campaigns solely attributed to telematics compromise have been publicly confirmed, security researchers have demonstrated that improper isolation between cloud services and vehicle control systems could enable indirect attack paths. These risks underscore the importance of securing not only the vehicle but also the surrounding digital ecosystem.

Software Complexity and Attack Surface Expansion

Audi and Mercedes-Benz SUVs are increasingly software-defined, with dozens of ECUs, millions of lines of code, and frequent *over-the-air* (OTA) updates. This complexity introduces challenges in secure software development, configuration management, and vulnerability patching. Legacy code, third-party software components, and backward compatibility requirements can inadvertently preserve exploitable weaknesses.

Furthermore, the integration of infotainment systems, wireless interfaces (Bluetooth, Wi-Fi, cellular), and vehicle-to-everything (V2X) capabilities increases the number of potential entry points. While manufacturers employ sandboxing and gateway isolation, misconfigurations or zero-day vulnerabilities may still permit lateral movement from non-critical systems to safety- or security-critical domains.

Manufacturer Countermeasures and Remaining Gaps

Both Audi and Mercedes-Benz have taken steps to address these vulnerabilities through the introduction of secure gateways, encrypted communication channels, intrusion detection systems, and compliance with standards such as ISO/SAE 21434 and UNECE R155. Newer vehicle platforms increasingly adopt domain-based or zonal architectures that improve isolation and security monitoring.

However, vehicles already in circulation remain exposed to architectural limitations that cannot always be fully mitigated through software updates alone. This creates a heterogeneous risk landscape in which security posture varies significantly across model years, regions, and trim levels. The persistence of legacy vulnerabilities continues to make certain Audi and Mercedes-Benz SUVs attractive targets for organized cyber-enabled theft.

Broader Implications

The cyber vulnerabilities observed in Audi and Mercedes-Benz SUVs are emblematic of broader challenges facing the automotive industry. As vehicles transition from mechanically centered systems to connected cyber-physical platforms, traditional assumptions about trust, access, and threat boundaries are no longer valid. The theft of high-value SUVs through digital means highlights the urgent need for security-by-design principles, continuous threat monitoring, and lifecycle-oriented cybersecurity management.

VIII. Cybersecurity Solutions for Toyota, Lexus, Audi, & Mercedes SUVs

Modern vehicles—especially connected SUVs from Toyota/Lexus and Audi/Mercedes—face a broad spectrum of cyber threats, including unauthorized access via keyless systems, CAN bus intrusion, telematics exploitation, API and backend breaches, and vulnerabilities in over-the-air (OTA) update infrastructure. The following outlines state-of-the-art technical solutions that address these challenges across multiple layers of automotive systems.

- Secure Architecture and Engineering Standards
- Secure Automotive Cybersecurity Lifecycle

A foundational approach is to embed cybersecurity across the product lifecycle, from concept to decommissioning, following international standards such as **ISO/SAE 21434**. This standard defines processes for threat analysis, risk assessment (TARA), security goals, and cybersecurity engineering throughout development and operations, ensuring that security is integrated into design, testing, and maintenance.[18]

- Formal **Threat Analysis and Risk Assessment (TARA)** to identify and mitigate attack vectors (e.g., keyless relay, CAN injection).
- Defined **Cybersecurity Management System (CSMS)** and risk treatment plans tied to functional safety.[19]

Secure Gateway and Network Segmentation

Modern OEMs, including Mercedes-Benz, implement **secure gateway modules[20]** that separate critical in-vehicle networks (e.g., powertrain, immobilizer) from less trusted domains like infotainment, telematics, and diagnostics. Only authenticated diagnostic tools having credentials from a manufacturer-recognized authority can interact with vehicle systems.[21]

This prevents unauthorized CAN bus access and limits lateral movement even if an attacker gains physical entry.

- Cryptographic Protections and Hardware Solutions
- Hardware Security Modules (HSMs)

Embedding **Hardware Security Modules (HSMs)** or equivalent secure elements in ECUs and domain controllers enables true hardware-rooted key storage, secure boot, cryptographic message authentication, and secure firmware update validation. HSMs prevent unauthorized command injection—such as false CAN messages—by requiring cryptographically authenticated messages before executing critical functions.

Cryptographic Message Authentication and Zero-Trust CAN

Legacy protocols like CAN lack authentication and confidentiality, allowing CAN injection attacks. Effective mitigations include:

- **Message authentication codes (MACs)** to ensure that ECUs only accept authenticated communications.
- A **Zero-Trust network approach** where no ECU inherently trusts messages from any other node unless authenticated.[22]

Implementations such as AUTOSAR Secure Onboard Communication (SecOC) define secure CAN messaging with authentication, encryption, and integrity checking.

- Intrusion Detection, Monitoring, and Forensics

[18] https://www.sgs.com/en-ca/news/2025/09/three-initiatives-driving-automotive-industry-cybersecurity

[19] ibid

[20] Secure Gateway Modules (SGMs) are an important part of modern vehicle cybersecurity architecture. They act as a security checkpoint between different in-vehicle networks, especially when vehicles have multiple networks (CAN, CAN FD, Ethernet, LIN, FlexRay, MOST, etc.)

[21] AfterMarketMatters

[22] https://kentindell.github.io/2023/04/03/can-injection/

- Anomaly Detection Systems (IDS/IPS)

Integrating **real-time intrusion detection systems (IDS)** that monitor in-vehicle traffic patterns across CAN, Ethernet, and other buses can detect abnormal message rates or unauthorized commands indicative of attacks. Some research uses **deep learning over CAN voltage signal features** to identify physical intrusions and spoofing, achieving high accuracy in prototype settings.[23]

- Security Event/Threat Monitoring

Solutions such as *Thales Automotive Detect and Respond* combine in-vehicle and backend analytics using machine learning and threat intelligence to detect and mitigate cyber incidents in real time.[24]

- Telemetry, Authentication, and Cloud/Backend Security
- Telecommunication Security Controls

Telematics systems present significant threat vectors if cloud APIs, backend servers, or developer tools are misconfigured. A recent industry analysis revealed that vulnerabilities in telematics infrastructure could allow unauthorized firmware update commands, exposing the CAN bus and other critical systems.[25]

Countermeasures include:

- Enforcing **multi-factor authentication (MFA)** and strict password policies across telematics services.
- **Network allow-listing and segmentation** between telematics servers and internal vehicle networks.
- Encrypted API communications and hardened backend infrastructure.

Secure OTA Update Ecosystems

- The ***eSync Alliance*** and similar initiatives define secure OTA update frameworks that preserve integrity and authenticity of firmware updates across multiple vehicle components. These platforms ensure update packages are signed and verified before installation and that rollback protection is enforced to prevent downgrade attacks.
- Supply Chain and Software Assurance
- Penetration Testing and Gap Analysis
- Automotive OEMs increasingly partner with cybersecurity firms to conduct **penetration tests**, gap analyses, and comprehensive threat modeling across suppliers and software components. This identifies latent vulnerabilities in third-party systems and verifies compliance with standards such as ISO/SAE 21434 and UNECE WP.29.[26]

[23] Levy, E., Shabtai, A., Groza, B., Murvay, P.-S., & Elovici, Y. (2021, June 15). *Can-LOC: Spoofing detection and physical intrusion localization on an in-vehicle can bus based on deep features of voltage signals*. arXiv.org. https://arxiv.org/abs/2106.07895

[24] https://www.thalesgroup.com/en/solutions-catalogue/enterprise/automotive/automotive-cybersecurity

[25] https://www.kaspersky.com/about/press-releases/grand-theft-telematics-kaspersky-finds-security-flaws

[26] https://www.ul.com/services/cybersecurity/automotive-cybersecurity

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- Automotive Vulnerability Disclosure Policies

Manufacturers like **Audi AG** maintain formal vulnerability reporting channels to encourage responsible disclosure and structured remediation of software security flaws.[27]

Layered Defense Strategies

Network and ECU Hardening

- **Segmentation and secure gateways** limit exposure of safety-critical ECUs.
- **Encrypted ECU communication** ensures command integrity.
- **Resource-aware cryptographic protocols** optimize security within ECU constraints.[28]

Incident Response and Security Operations

Emerging architectures like **Vehicle Security Operations Centers[29] (VSOCs)** leverage distributed infrastructure (e.g., EV charging networks) to provide real-time threat detection and automated response close to the vehicle network edge.[30]

Consumer and User-Centric Measures

Even as OEMs strengthen core vehicle systems, additional consumer-centred safeguards can mitigate risk in vehicles already in service:

- Require **physical immobilizers and steering locks** as secondary mechanical barriers.
- Promote **Faraday pouches** or signal-blocking storage for key fobs to reduce relay attack susceptibility.
- Ensure users regularly update vehicle software via OEM-authorized channels.

Summary

Securing modern SUVs from Toyota, Lexus, Audi, and Mercedes requires a **multi-layered approach** that combines industry standards, cryptographic protections, intrusion detection, backend hardening, secure OTA practices, and robust supply chain governance.

Technical solutions—ranging from secure ECU architecture to cloud API hardening—must be integrated into the automotive cybersecurity lifecycle to address evolving threats effectively, reduce attack surfaces, and enhance trust in connected vehicle technologies.[31]

[27] https://www.audi.com/en/legal/cyber-security-audi-vulnerability-reporting-policy/

[28] https://visuresolutions.com/automotive/cybersecurity-for-ecus/

[29] A *Vehicle Security Operations Center* (V-SOC) is essentially a cybersecurity monitoring and response hub for connected and software-driven vehicles. It's like a traditional IT Security Operations Center (SOC) but specifically designed for vehicles, fleets, and automotive ecosystems.

[30] https://arxiv.org/abs/2503.16984

[31] https://www.sgs.com/en-ca/news/2025/09/three-initiatives-driving-automotive-industry-cybersecurity

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IX. Products & Solutions in Market

There are many market-available solutions in the North American automotive ecosystem that help mitigate cyber vulnerabilities and reduce the risk of vehicle theft—including CAN bus exploits, relay key attacks, diagnostic port abuse, and connected-vehicle threats. These span aftermarket defenses, embedded cybersecurity platforms for OEMs, and enterprise/cloud solutions used by manufacturers and fleets.

Categories

These solutions for key-less entry vehicle security range from RF amplification or relay attacks:

- **Motion-Sensor Fobs:** Some newer car models from manufacturers like Ford, BMW, and Mercedes include key fobs that automatically go into "*sleep mode*" or power down after a short period of inactivity (e.g., 40 seconds). This prevents the signal from being continuously broadcast when the key is stationary. The signal is only reactivated by motion.
- **Aftermarket Electronic Immobilizers** (e.g., *Ghost Immobiliser*[32] **):** These are advanced security systems installed within your car that require a secondary authentication method, such as a unique PIN code entered via existing buttons on the steering wheel or dashboard, before the engine will start. Even if a thief gains entry using a signal amplification device, the car remains immobilized.

[32] Systems such as the **Autowatch Ghost II Immobiliser** enhance vehicular security by implementing an additional authentication layer that requires the entry of a user-defined personal identification sequence through existing vehicle controls prior to engine activation. Unlike conventional electronic security systems, these immobilisers do not rely on radio-frequency transmissions or externally visible components, thereby reducing susceptibility to detection and compromise. Their design specifically addresses contemporary vehicle theft techniques, including key cloning and electronic hacking.

Functional Characteristics and Operational Principles: The core function of a Ghost-type immobiliser is to inhibit vehicle operation unless a predefined sequence of button inputs is correctly executed by the authorized user.
Controller Area Network (CAN) Bus Integration: The immobiliser interfaces directly with the vehicle's Controller Area Network (CAN) bus, enabling it to selectively disable critical subsystems such as ignition control or fuel injection. This integration is achieved without the addition of external wiring, minimizing the risk of physical detection or tampering by unauthorized parties.
Covert Operation: The system operates without auxiliary key fobs, indicator lights, or audible alerts. As a result, it remains effectively concealed from diagnostic scanning tools and electronic surveillance methods commonly employed during vehicle theft attempts.
Configurable Authentication Sequence: Users are able to define a customized disarm sequence using existing vehicle input interfaces, including steering wheel controls, dashboard buttons, or center console switches. The authentication sequence can comprise up to twenty individual inputs, thereby significantly increasing the entropy of the access control mechanism.
Mitigation of Contemporary Attack Vectors: By requiring an internally verified authentication sequence, the immobiliser remains effective against a range of modern attack methods, such as relay attacks, signal interception, unauthorized key duplication, and theft of original key fobs. Vehicle operation is prevented unless the correct sequence is entered, irrespective of the presence of a valid key.
Service and Valet Mode: A dedicated service or valet mode can be enabled to temporarily bypass the personalized authentication requirement. This functionality allows authorized third parties to operate the vehicle without disclosure of the owner's confidential access sequence.
Emergency Access Provisioning: To ensure system robustness and user accessibility, a secure and unique emergency override code is supplied at installation. This mechanism serves as a contingency measure in cases where the primary authentication sequence is unavailable or forgotten.

- **Aftermarket "Fob Protectors" / Secure FOB Chips:** These are small electronic devices or chips that can be installed inside your existing key fob (around the battery). They use motion sensors to automatically deactivate the key's power supply when it's not in use and reactivate it when motion is detected, effectively preventing relay attacks without requiring a separate pouch.

In short, these practical defenses for vehicle theft could be summarized as follows:

Owner/Aftermarket Level (immediate protections)

- PIN/immobilizer systems (CodeGuard, BEP Immobilizer)
- CAN bus firewalls and anti-theft modules (CANLOCK, The Immobilizer)
- Offline key registration blockers (CyberKey)

OEM/Factory Security (embedded, architectural)

- In-vehicle IDPS (PlaxidityX[33], EB cybersecurity)
- Secure OTA and Uptane software frameworks
- Hardware cryptographic protections (HSM-equipped MCUs)

Enterprise & Cloud/Aggregate Defenses

- VSOC and managed XDR (PlaxidityX + Deloitte)
- Comprehensive in-vehicle security suites (AUTOCRYPT, Claroty)

Post-Theft and Supplementary Systems

- GPS/cellular tracking (LoJack)

These include aftermarket security products for vehicle owners, embedded cybersecurity platforms integrated by OEMs, and enterprise or cloud-based security solutions deployed by manufacturers and fleet operators.

1. Aftermarket Security Solutions (Owner-Installed / Retrofits)

These products are available to individual vehicle owners or installers and are particularly relevant for vehicles already in service, including Toyota and Lexus SUVs:

CAN Bus Immobilizers and Firewalls

These systems introduce a **secondary authorization layer** at the vehicle's internal network to block unauthorized access or ignition commands.

- **BEP Electronics Immobilizer Systems** – Advanced immobilizers that interface with the CAN bus to prevent unauthorized engine starts and interference techniques. They often include PIN

[33] PlaxidityX (formerly *Argus Cyber Security Ltd.*) is a global automotive cybersecurity company that provides end-to-end security technologies and services for connected, software-defined vehicles and mobility ecosystems. It helps automakers and automotive suppliers secure vehicle components, networks, and fleets throughout the entire vehicle lifecycle — from development and production to ongoing operation and compliance.

code entry or electronic validation prior to engine start, deterring key cloning and relay methods.[34]

- **The Immobilizer (Canada)** – Works as a **CAN bus firewall**, preventing unauthorized keyless attempts, key cloning, and hacking of start requests via the network. It also requires owner authorization (e.g., PIN or Bluetooth) before allowing start.[35]

- **CANLOCK Anti-Theft Systems** – Protect against modern theft vectors—including relay attacks, GPS jamming, and CAN injection—using secure authentication (PIN, Bluetooth, or app), alarms, tilt/impact sensors, and even GPS alerts.[36]

PIN-Based Security Add-Ons

These add an **out-of-band authentication requirement** before the vehicle will start, helping prevent theft even if the smart key is cloned or relayed.

- **CodeGuard** – A retrofit solution that requires the driver to enter a **unique PIN code** before the car can be started, significantly reducing unauthorized starting even if the key is compromised.[37]

Hidden Inspection Blockers

- **CyberKey** – A discrete, offline anti-theft device that prevents unauthorized key programming via OBD or CAN bus, blocking thieves from adding new keys without detection. It operates silently and is installed within the vehicle's wiring to prevent cloning attacks.[38]

2. OEM and Embedded Cybersecurity Platforms

These solutions are designed for **vehicle manufacturers and Tier-1 suppliers** to secure vehicles at the architectural and software level.

In-Vehicle Intrusion Detection & Prevention

These embedded platforms help detect malicious actions on internal networks (e.g., CAN bus) and block abnormal messages.

- **PlaxidityX CAN Protection & IDPS** – A widely adopted *intrusion detection and prevention system* that monitors CAN bus traffic for attacks (e.g., denial-of-service, spoofing) and can stop malicious packets before they reach critical ECUs.[39]

- **Elektrobit (EB) Automotive Cybersecurity Suite** – Provides **end-to-end protection** across embedded components, including secure communications, intrusion detection, and OTA

[34] https://bepelectronics.com/
[35] https://www.theimmobilizer.ca/
[36] https://canlock.com/ca/
[37] https://codeguard.ca/
[38] https://www.basicobd.com/pages/cyberkey
[39] https://plaxidityx.com/products/can-protection/

patching infrastructure. This includes firmware and cloud integrations that help protect the internal networks and external interfaces of connected vehicles.[40]

End-to-End Secure Software & Update Frameworks

- **Uptane** – A software update security framework that helps automakers ensure only **authenticated, verified firmware** is installed during OTA updates, reducing the risk of malicious update injection that could be exploited for theft or unauthorized access.

Enterprise & Lifecycle Security Solutions

These solutions help OEMs and fleets manage cybersecurity risk beyond the vehicle itself.

- **PlaxidityX + Deloitte Managed Security Services** – Combines deep automotive cyber analytics with a *Vehicle Security Operations Center* (VSOC) model for real-time threat detection and response across fleets, enabling rapid identification of lateral attacks, relay attempts, and IoT abuse.[41]

- **Claroty Platform for Automotive** – Enterprise cybersecurity platform used by large automakers to safeguard connected manufacturing operations and vehicle ecosystems against CPS (cyber-physical systems) threats, including those that could lead to theft vectors.[42]

- **AUTOCRYPT In-Vehicle Systems Security** – Comprehensive cybersecurity suite covering threat analysis, security testing (fuzzing & penetration), and embedded defenses including IDS and HSM integration for secure in-vehicle communications compliant with regulations like WP.29 and ISO/SAE 21434.[43]

3. Hardware and Chip-Level Security Solutions

Securing the fundamental hardware that runs vehicle systems is critical for preventing attacks that start at the physical interface or during boot.

- **Microchip Automotive Security MCUs with HSM** – Microcontrollers with integrated *Hardware Security Modules (HSM)* that provide secure boot, secure firmware updates, encrypted communications, and ECU authentication—mitigating remote and local attacks across control units.[44]

These chips are employed across infotainment, ADAS, telematics, and gateway ECUs to enforce cryptographic protections at the hardware level.

4. Fleet & Telematics Solutions with Security Capabilities

While not strictly anti-hack devices, these systems contribute indirectly to cybersecurity by enabling tracking, abnormal behavior detection, and post-theft recovery.

[40] https://www.elektrobit.com/products/automotive-cybersecurity/
[41] https://www.prnewswire.com/il/news-releases/deloitte-spain-and-plaxidityx-join-forces-to-deliver-transformative
[42] https://claroty.com/industrial-cybersecurity/automotive
[43] https://autocrypt.io/solutions/in-vehicle-systems-security/
[44]https://www.microchip.com/en-us/solutions/automotive-and-transportation/automotive-products/automotive

- **LoJack (Modern GPS/Cellular Tracking)** – Offers GPS and cellular tracking of vehicles to aid in stolen vehicle recovery in real time, acting as an additional deterrent and response layer after a theft occurs.

5. Emerging and Research-Derived Mechanisms

Research prototypes and experimental solutions are influencing commercial development.

- **RF Intrusion Detection & Prevention Systems (RF-IDPS)** – Solutions under development that analyze keyless entry RF signals in real time to distinguish legitimate from relay/replay signals, protecting against advanced relay attacks.[45]

- **Protocol-Agostic OBD Firewalls** – Academic work (e.g., "Man-in-the-OBD") demonstrates firewalls that secure the OBD interface against unauthorized dongles and theft tools, a capability that could mature into commercial products.[46]

- **Keyless Entry RF Fingerprinting** – Research shows that machine learning can fingerprint legitimate key fob transmissions to detect spoofed or relayed signals—potentially feeding into future consumer or OEM anti-relay defenses.[47]

6. Market and Industry Dynamics

The automotive cybersecurity market is growing rapidly—projected to increase from ~USD 2.5 billion in 2023 to USD 6 billion by 2028—driven by demand for secure connected vehicles and novel defenses against theft and remote compromise. Major suppliers include **Continental (**via *Elektrobit/Argus*), **Robert Bosch, Harman, Denso, and Aptiv**, among others reported by *MarketsandMarkets.*[48]

This concludes that *automotive cybersecurity market is experiencing accelerated growth*, reflecting the increasing digitalization of vehicles and the rising incidence of cyber-enabled threats such as remote compromise, keyless theft, and manipulation of in-vehicle networks. Industry analyses estimate that the global automotive cybersecurity market will expand from approximately **USD 2.5 billion in 2023 to nearly USD 6 billion by 2028**, representing a compound annual growth rate (CAGR) exceeding 18%. This growth trajectory is primarily driven by the rapid adoption of **connected, software-defined, and autonomous vehicles**, alongside mounting regulatory pressure and heightened consumer awareness of vehicle security risks.

A central driver of this expansion is the growing attack surface introduced by *vehicle connectivity technologies*, including cellular (4G/5G), Wi-Fi, Bluetooth, vehicle-to-everything (V2X) communication, and over-the-air (OTA) software update mechanisms. These technologies, while essential for advanced driver assistance systems (ADAS), infotainment, and remote services, expose vehicles to sophisticated cyber threats that traditional mechanical or electronic anti-theft systems are no longer equipped to address. As a result, original equipment manufacturers (OEMs) and fleet

[45] https://www.linkedin.com/pulse/protecting-connected-vehicles-rf-idps-multi-layer-vikash-chaudhary-7negc
[46] https://arxiv.org/abs/2210.08281
[47] *Ibid*
[48] https://www.marketsandmarkets.com/ResearchInsight/cyber-security-automotive-industry-market.asp

operators are increasingly investing in *embedded cybersecurity platforms, intrusion detection and prevention systems (IDPS), secure gateways, and cryptographic key management solutions*.

The market is characterized by strong participation from established Tier-1 automotive suppliers that have expanded their portfolios to include dedicated cybersecurity offerings. **Continental**, through its subsidiaries **Elektrobit** and **Argus Cyber Security**, provides comprehensive vehicle cybersecurity solutions spanning secure operating systems, in-vehicle intrusion detection, and lifecycle risk management. **Robert Bosch** has integrated cybersecurity into its vehicle electronics and mobility solutions, focusing on secure ECUs, protected communication architectures, and compliance with international standards such as ISO/SAE 21434 and UNECE WP.29 R155.

Similarly, **Harman International** (a *Samsung* subsidiary) plays a significant role in securing infotainment, telematics, and connected car platforms, leveraging its expertise in software-defined vehicles and cloud-based security services. **Denso** has invested heavily in secure semiconductor architectures, encrypted in-vehicle communication, and hardware-based trust anchors, while **Aptiv** emphasizes secure vehicle networking, gateway protection, and scalable cybersecurity frameworks compatible with next-generation electrical/electronic (E/E) architectures.

Beyond traditional Tier-1 suppliers, the market also includes specialized cybersecurity firms and startups focusing on *threat intelligence, vehicle security operations centers (VSOCs), penetration testing, and post-production monitoring*. This ecosystem reflects a broader shift toward treating automotive cybersecurity as a *continuous, lifecycle-driven process* rather than a one-time design feature.

Collectively, these developments underscore the strategic importance of automotive cybersecurity as a foundational enabler of connected and autonomous mobility. The rapid growth of the market highlights not only the economic opportunity but also the critical need for *integrated, adaptive, and standards-aligned frameworks*—such as *AutoGuardX*—that can complement commercial solutions while addressing emerging threats in an increasingly interconnected automotive ecosystem.

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X. Developing a Security Framework

Developing a security framework is a structured process that involves defining policies, identifying threats, implementing controls, and continuously monitoring and improving the system. So as, the development of a Security Framework in the field of automotive cybersecurity is a structured and evolving process that reflects the transformation of vehicles from isolated mechanical systems into highly connected, software-defined platforms. Modern vehicles now integrate dozens of *electronic control units* (ECUs), in-vehicle networks, cloud services, mobile applications, and over-the-air update capabilities. As a result, cybersecurity is no longer an optional feature but a foundational requirement directly tied to safety, reliability, regulatory compliance, and brand trust.

At its core, an automotive cybersecurity security framework provides a systematic way to identify, assess, mitigate, and manage cyber risks throughout the entire vehicle lifecycle. This lifecycle perspective is essential. Security can no longer be addressed only at the production stage; it must begin during concept development and continue through design, implementation, validation, production, operation, maintenance, and decommissioning. A well-designed framework ensures that cybersecurity considerations are embedded into engineering decisions rather than added reactively after vulnerabilities are discovered.

The development process typically starts with defining the scope and objectives of the framework. In automotive contexts, this includes identifying vehicle domains such as powertrain, chassis, body electronics, infotainment, ADAS[49], and connectivity components, as well as external interfaces like mobile apps, cloud backends, diagnostic tools, and V2X communication. Each of these elements introduces unique attack surfaces. The framework must clearly establish what assets need protection, what threats are relevant, and what level of risk is acceptable, taking into account safety implications and regulatory expectations.

Threat modeling and risk assessment form the analytical backbone of the framework. Automotive-specific methodologies such as TARA (Threat Analysis and Risk Assessment), aligned with ISO/SAE 21434, are used to systematically analyze potential attack scenarios. This includes identifying threat actors, attack vectors, and potential impacts on vehicle functions, occupants, and surrounding infrastructure. Unlike traditional IT systems, automotive risk assessment must consider real-time constraints and physical safety consequences, which makes the prioritization of threats particularly critical.

Once risks are understood, the framework defines security requirements and controls. These controls span multiple layers of the vehicle architecture. At the in-vehicle level, this includes secure boot, hardware security modules, ECU authentication, message authentication mechanisms such as SecOC, and network segmentation enforced by secure gateway modules. At the software level, secure coding practices, access control, and cryptographic key management are essential. At the system and ecosystem level, secure diagnostics, OTA update security, backend authentication, and data protection

[49] ADAS stands for *Advanced Driver Assistance Systems*. It refers to a set of electronic systems in a vehicle designed to support the driver by increasing safety, improving driving comfort, and reducing the likelihood of accidents.

mechanisms are incorporated. The framework ensures that these controls are consistent, interoperable, and aligned with the identified risks.

An important aspect of automotive security framework development is integration with functional safety and system engineering processes. Cybersecurity controls must not interfere with safety-critical operations or violate real-time performance requirements. Therefore, security mechanisms are carefully designed to balance robustness with latency, bandwidth, and computational constraints. This integration also ensures alignment with standards such as *ISO 26262*, recognizing that cybersecurity incidents can directly lead to safety hazards.

Validation and verification are another critical phase in the framework. Automotive security frameworks define processes for security testing, including static analysis, penetration testing, fuzz testing, and vulnerability scanning. These activities are applied both during development and before production release. The goal is not only to identify vulnerabilities but also to validate that the implemented controls effectively mitigate the defined threats without introducing unintended system behavior.

In modern vehicles, the security framework extends beyond the vehicle itself into operational monitoring and incident response. This has led to the inclusion of Vehicle Security Operations Centers (V-SOCs) as part of the broader framework. Through continuous telemetry, anomaly detection, and threat intelligence, the framework supports real-time visibility into fleet-wide security posture. This operational layer enables rapid response, remote mitigation, and secure updates, reflecting the reality that vehicles remain connected and exposed long after they leave the factory.

Regulatory compliance plays a significant role in shaping automotive cybersecurity frameworks. Regulations such as UNECE WP.29 (*UN R155 and R156*) and standards like ISO/SAE 21434 require manufacturers to demonstrate structured cybersecurity management systems and continuous risk management. A mature security framework provides the governance, documentation, and traceability needed to meet these obligations while maintaining flexibility to adapt to evolving threats.

Ultimately, the development of a security framework in automotive cybersecurity is not a one-time engineering task but a continuous, adaptive process. As vehicles become more autonomous, connected, and software-driven, the framework must evolve alongside new technologies, attack techniques, and regulatory demands. A strong framework creates a shared security language across engineering, operations, and management, enabling organizations to systematically protect vehicles, users, and infrastructure in an increasingly complex mobility ecosystem.

Here is a step-by-step short explanation in a practical context to develop a framework:

1. Define Scope and Objectives

Identify the System Boundaries: Determine what systems, applications, or devices the framework will cover. For example, in automotive systems, this could be the vehicle ECU, digital keys, and wireless communication channels.

Define Security Goals: Clearly articulate what the framework aims to achieve, such as confidentiality, integrity, availability, authentication, and non-repudiation.

Regulatory Requirements: Incorporate any industry standards, regulations, or certifications that apply, e.g., ISO/SAE 21434 for automotive cybersecurity, FiRa for UWB, or NIST standards for IT security.

2. Conduct Risk Assessment

Asset Identification: Identify critical assets that need protection (e.g., key fob signals, UWB communication, vehicle control units).

Threat Modeling: Analyze potential threats and attack vectors (e.g., relay attacks, key cloning, firmware exploits).

Vulnerability Assessment: Evaluate weaknesses in hardware, software, or operational procedures.

Impact Analysis: Determine the potential consequences of a successful attack.

3. Design Security Controls

Preventive Controls: Mechanisms that stop attacks before they occur, such as encryption, secure key storage, and access control.

Detective Controls: Systems that identify attacks or anomalies, like intrusion detection, anomaly-based monitoring, or event logging.

Corrective Controls: Measures that respond to and mitigate attacks, e.g., fail-safe operation, secure rollback, or revocation of compromised keys.

Layered Security (Defense in Depth): Implement multiple overlapping controls so that if one fails, others continue to protect the system.

4. Develop Policies and Procedures

Access Control Policy: Define who or what can access system resources and under what conditions.

Authentication & Authorization: Establish secure mechanisms for verifying identities and granting permissions.

Data Protection Policy: Define encryption requirements, key management, and data handling procedures.

Incident Response: Procedures for detecting, reporting, and recovering from security incidents.

5. Implementation

Technical Implementation: Integrate cryptography, secure communication protocols, and hardware security modules (HSMs or SEs).

Software and Firmware: Ensure secure coding practices, secure boot, and regular updates.

Integration Testing: Verify that security mechanisms function as intended without disrupting normal operations.

6. Monitoring and Maintenance

Continuous Monitoring: Track system activity, perform log analysis, and detect anomalies.

Vulnerability Management: Regularly update software, apply patches, and respond to emerging threats.

Auditing and Compliance: Conduct security audits and ensure adherence to policies and standards.

7. Evaluation and Improvement

Security Metrics: Define measurable indicators of security performance (e.g., number of incidents detected, time to respond).

Periodic Review: Regularly reassess the framework in light of new threats, technologies, or regulatory changes.

Feedback Loop: Incorporate lessons learned from incidents or tests to improve the framework.

8. Summary

A security framework is not a one-time solution; it is a living system that evolves with threats and technology. Its development involves:

- Understanding the environment and defining objectives.
- Assessing risks and vulnerabilities.
- Designing layered security controls.
- Developing policies and procedures.
- Implementing technical and organizational measures.
- Continuously monitoring, evaluating, and improving the system.

XI. A Proposed Framework - *AutoGuardX*

The rapid evolution of modern vehicles into highly connected, software-defined platforms has fundamentally reshaped the automotive threat landscape, making cybersecurity a core engineering and safety requirement rather than a secondary consideration. Vehicles now operate as distributed cyber-physical systems, integrating in-vehicle networks, intelligent ECUs, cloud backends, over-the-air update mechanisms, and external communication interfaces.

In this context, a structured and lifecycle-oriented security framework is essential to systematically manage cyber risks, ensure functional safety, and maintain regulatory compliance. Automotive cybersecurity demands an approach that embeds security from concept and design through production and in-field operation, recognizing that vulnerabilities can directly impact vehicle safety, availability, and user trust.

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As the automotive industry rapidly advances toward connected and autonomous vehicles, established standards such as **Automotive SPICE**, **ISO 26262**, and **ISO/SAE 21434** remain essential for providing guidance on process maturity, functional safety, and cybersecurity. These frameworks offer well-defined methodologies for structured development, safety assurance, and cyber risk management.

However, these standards are largely **siloed**, addressing discrete lifecycle phases or specific domains without providing comprehensive, real-time protection. For instance, *Automotive SPICE* emphasizes structured development processes but does not incorporate mechanisms for runtime threat detection. Similarly, *ISO 26262* governs electrical and electronic safety yet does not encompass operational cybersecurity threats. This compartmentalization creates a critical gap: modern vehicle systems are *dynamic, interconnected, and continuously exposed to cyber threats*, whereas conventional frameworks focus on static risk assessment, lifecycle planning, and post-event analysis rather than proactive detection and response during operation.

AutoGuardX is introduced as a comprehensive automotive cybersecurity framework designed to address these challenges holistically across the vehicle ecosystem. Built around risk-driven security engineering, *AutoGuardX* integrates threat analysis, secure architecture design, in-vehicle protection mechanisms, and continuous operational monitoring into a unified framework. It aligns with industry standards such as ISO/SAE 21434 and UNECE WP.29 while remaining adaptable to emerging technologies and attack vectors. By bridging development-time security with runtime detection and response, *AutoGuardX* establishes a resilient foundation for protecting modern vehicles throughout their entire lifecycle, from initial design to long-term fleet operation.

Key Innovations

The *AutoGuardX* framework is designed to address these limitations, delivering an integrated, adaptive cybersecurity solution that complements existing automotive standards rather than replacing them. Figure I illustrates how *AutoGuardX* unites advanced technologies—including machine learning, IoT security, secure communications, and embedded forensic capabilities—with normative structures such as ISO 26262 and ISO/SAE 21434.

Key innovations of the *AutoGuardX* framework include:

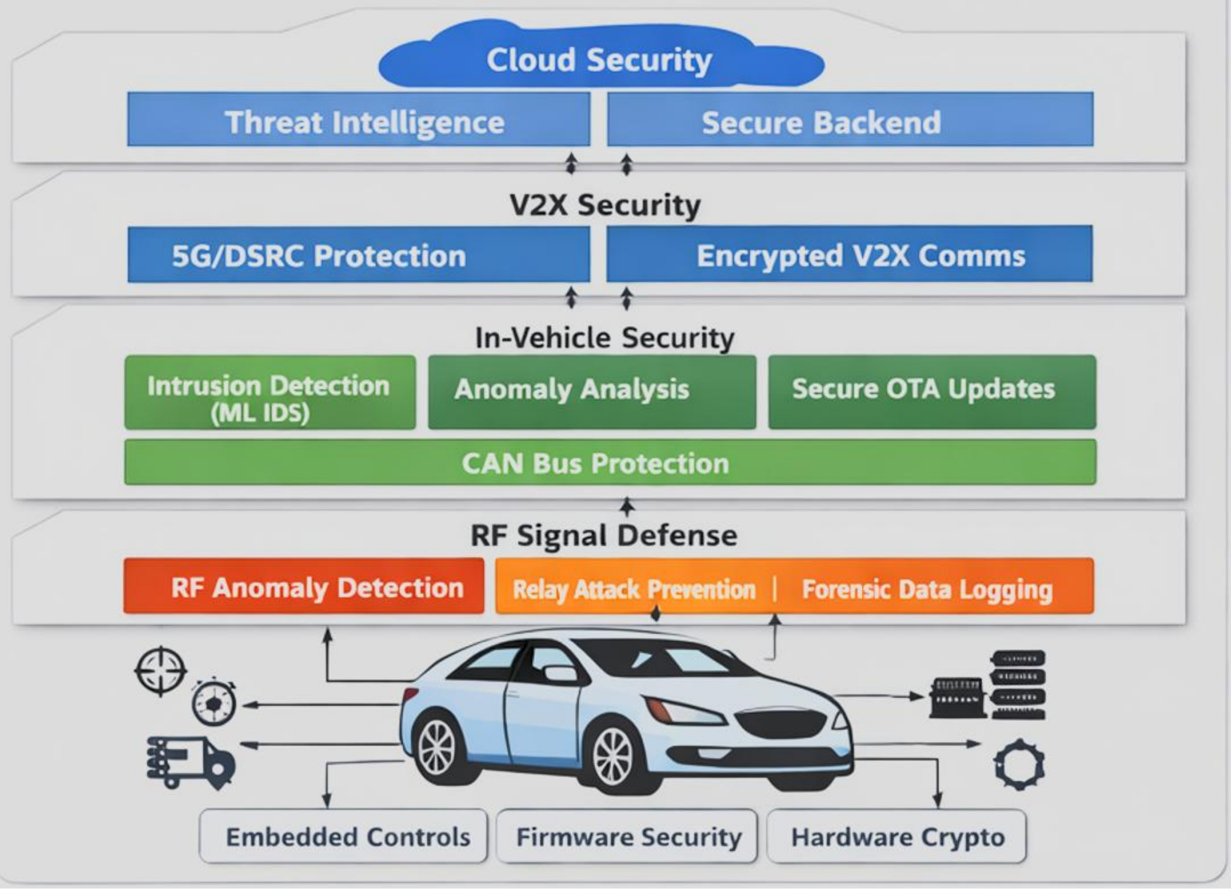
1. **Real-Time Threat Detection and Prevention:** Leveraging machine learning-based anomaly detection, *AutoGuardX* continuously monitors in-vehicle networks and behaviors, enabling immediate detection and mitigation of threats—capabilities absent in traditional ISO or SPICE frameworks.
2. **Secure Communication Protocols:** The framework enforces encrypted RF communications, robust CAN bus encryption, and rolling-code protection for keyless entry systems, addressing areas often insufficiently covered by existing standards.
3. **Machine Learning Integration:** Adaptive threat prediction models evolve based on historical and real-time data. Unlike legacy frameworks, *AutoGuardX* dynamically adjusts its defensive posture to emerging risks, incorporating predictive cybersecurity at runtime.
4. **IoT Device Security:** With the growing presence of embedded IoT components, *AutoGuardX* secures firmware through over-the-air (OTA) updates, ensures device authentication, and

isolates network components according to zero-trust principles—features largely absent in conventional standards.

5. **Incident Logging and Forensics:** The framework embeds comprehensive logging and forensic tools within the vehicle architecture, enabling detailed event capture and analysis without relying on external processes, in contrast to the procedural focus of legacy frameworks.

6. **Regulatory Compatibility and Platform Scalability:** *AutoGuardX* is modular and platform-agnostic, aligning with ISO 26262 and ISO/SAE 21434 to streamline certification processes. Its plug-and-play design supports flexible deployment across diverse OEM platforms and vehicle variants.

Fig. 1. AutoGuardX: Integrated cybersecuriyty architecture for connected vehicles.



By integrating real-time threat monitoring, adaptive machine learning models, secure communication protocols, and forensic capabilities, *AutoGuardX* establishes a forward-looking security architecture that addresses the operational vulnerabilities of modern connected and autonomous vehicles, filling critical gaps left by traditional automotive standards.

Main Elements

The ***AutoGuardX*** framework is structured around **seven interrelated core components**, each designed to address critical cybersecurity challenges in modern connected and autonomous vehicles. These elements collectively form a robust, adaptive, and future-ready vehicle security architecture:

1. **Machine-Learning-Based Intrusion Detection System (IDS):** This module continuously monitors in-vehicle networks, CAN bus traffic, and wireless communications for abnormal behavior. By employing advanced machine learning algorithms, it can detect both known and previously unseen attack patterns in real time, providing proactive threat mitigation rather than relying solely on post-event analysis.

2. **Secure Authentication and Access-Control Unit:** This component ensures that all electronic control units (ECUs), key fobs, and vehicle-to-everything (V2X) interfaces are properly authenticated before granting access. By implementing multi-factor and cryptographic verification methods, it prevents unauthorized entry or manipulation of vehicle systems, thereby mitigating relay attacks, key cloning, and other access-based threats.

3. **Encrypted Communication and Network-Protection Layer:** This layer safeguards internal and external data exchanges through robust encryption protocols, secure CAN bus communication, and intrusion-resilient networking mechanisms. It prevents malicious actors from intercepting, injecting, or manipulating messages between ECUs or between the vehicle and external infrastructure.

4. **Secure Over-the-Air (OTA) Update Manager:** Recognizing the increasing reliance on software-driven vehicle functionality, this module ensures that all firmware and software updates are authenticated and integrity-protected. OTA updates are verified using cryptographic signatures to prevent unauthorized or malicious software from compromising vehicle safety or security.

5. **Forensic Logging and Telemetry System:** *AutoGuardX* embeds tamper-resistant logging mechanisms throughout the vehicle's electronic systems. This module captures detailed telemetry and security events, supporting real-time incident investigation, post-attack analysis, and regulatory reporting, enabling a systematic and accountable approach to cyber forensics.

6. **Policy and Standards Compliance Engine:** This component ensures alignment with established automotive safety and cybersecurity standards, including **ISO/SAE 21434** for cybersecurity engineering and **ISO 26262** for functional safety. It continuously monitors vehicle operations against defined policies, ensuring that all system behaviors adhere to regulatory requirements and best practices.

7. **Threat-Intelligence and Adaptive Response Module:** Leveraging both historical and real-time threat intelligence, this module dynamically adjusts defensive measures to counter emerging attack vectors. By integrating predictive analytics and automated response strategies, it enables the vehicle to adapt to evolving cybersecurity threats, including sophisticated relay, CAN injection, and IoT-based exploits.

Together, these seven elements provide a **comprehensive, multi-layered defense system**, transforming the vehicle from a static target into a resilient, adaptive, and self-protecting platform. The integrated design of *AutoGuardX* not only secures connected vehicles against contemporary cyber threats but also establishes a scalable architecture capable of responding to future technological and threat developments.

Structured Deployment of *AutoGuardX* in Vehicles with Cyber Vulnerabilities

The effective deployment of the ***AutoGuardX*** framework in vehicles exhibiting known or suspected cybersecurity vulnerabilities requires a structured, layered approach. By integrating the framework systematically, both immediate and long-term risks can be mitigated, while enabling adaptive defense against emerging threats. The recommended deployment strategy involves the following stages:

1. **Pre-Deployment Vulnerability Assessment:**

   Deployment should commence with a comprehensive evaluation & number of the vehicle's electronic control units (ECUs), telematics modules, in-vehicle networks, and connected interfaces. A detailed vulnerability scan identifies existing weaknesses and informs prioritization, ensuring that the most critical components of *AutoGuardX*—such as intrusion detection, secure communications, and IoT hardening—are integrated first. This step establishes a baseline understanding of the system's exposure and supports risk-based deployment decisions.

2. **Segmented and Phased Installation**

   AutoGuardX should be integrated in discrete phases, beginning with foundational security measures. Initial deployment of **secure communication protocols** and **IoT security hardening** immediately reduces attack surfaces, while subsequent installation of advanced features—such as **machine learning-based threat analytics** and adaptive response modules—can be conducted in a controlled manner. Phased implementation ensures operational stability while incrementally enhancing the vehicle's security posture.

3. **Gateway-Level Integration for Network Containment**

   Positioning *AutoGuardX* at the vehicle's **central communication gateway** enables comprehensive monitoring and filtering of data flows between internal networks (CAN, LIN, Ethernet) and external connections (Wi-Fi, cellular, Bluetooth). This strategic placement allows the framework to intercept and mitigate malicious traffic before it reaches critical systems, effectively creating a containment layer that safeguards both in-vehicle and connected interfaces.

4. **Continuous Monitoring and Real-Time Threat Prevention:**

   The framework's **machine learning-driven intrusion detection and prevention module** should operate continuously to monitor in-vehicle and external network activity. This real-time analysis enables the detection of anomalous patterns, automatic blocking of unauthorized communications, and adaptive tuning of defenses in response to evolving attack strategies. Such continuous protection is essential for mitigating threats that conventional static frameworks cannot address.

5. **User-Focused Configuration and Management**

   AutoGuardX incorporates a **user-centric interface** designed for vehicle owners, fleet managers, and maintenance personnel. Simplified dashboards guide configuration, alert management, and ongoing system oversight, ensuring that cybersecurity measures are not only deployed but actively maintained and utilized. This feature enhances operational compliance and promotes proactive engagement with vehicle security.

6. **Incident Logging and Forensic Analysis**

   The framework provides **tamper-resistant logging and forensic capture capabilities**, enabling detailed reconstruction of security events, anomalies, and attempted intrusions. This functionality supports rapid incident response, root-cause analysis, and the development of preventive measures against similar future attacks.

7. **Routine Updates and Security Patching**

   Sustained vehicle security depends on regular system updates. *AutoGuardX* supports **over-the-air (OTA) update mechanisms**, ensuring that both the framework itself and the vehicle's embedded systems receive timely security patches. This continuous update cycle maintains resilience against newly identified threats and evolving cyberattack methodologies.

In short, a **layered, proactive, and integrated deployment strategy** maximizes the protective capabilities of *AutoGuardX*. By combining vulnerability assessment, phased implementation, real-time monitoring, user-focused management, forensic capabilities, and routine updates, the framework not only addresses current security gaps but also establishes a dynamic, adaptive defense architecture capable of responding to future cyber risks in connected and autonomous vehicles.

Integration of *AutoGuardX* with Modern Vehicle Architectures

For effective protection, the ***AutoGuardX*** framework must be seamlessly integrated with existing and emerging vehicle architectures, including in-vehicle networks, infotainment platforms, telematics units, and autonomous driving systems. Such integration is a critical aspect of deployment, as modern vehicles operate as tightly coupled cyber-physical systems where security weaknesses in one subsystem can propagate across the entire platform.

In-Vehicle Network Integration

Controller Area Network (CAN) and In-Vehicle Communications:

The Controller Area Network (CAN) remains a foundational communication protocol enabling coordination among electronic control units (ECUs) responsible for powertrain, braking, body control, and safety functions. *AutoGuardX* integrates directly with the CAN infrastructure by enforcing **message authentication, encryption, and integrity verification** at the network layer. By implementing secure CAN communication mechanisms and monitoring traffic patterns in real time, the framework prevents unauthorized message injection, spoofing, and replay attacks. This approach significantly reduces the risk of cyber-enabled vehicle theft and remote manipulation of safety-critical systems.

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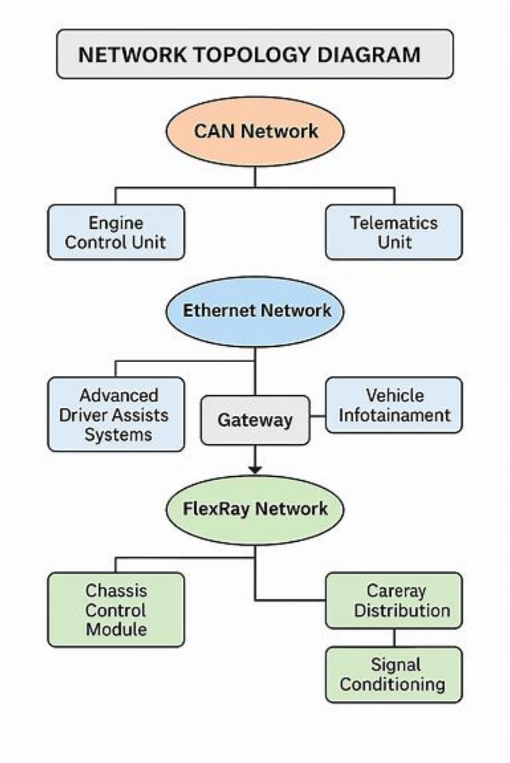


In addition to traditional CAN, *AutoGuardX* is designed to operate within **heterogeneous in-vehicle network environments**, including CAN FD, LIN, FlexRay, and Automotive Ethernet. By providing protocol-aware monitoring and filtering at gateway ECUs, the framework ensures consistent security enforcement across mixed network architectures increasingly found in modern vehicles.

Integration with Autonomous & Advanced Driver Assistance Systems (ADAS)

As vehicles evolve toward higher levels of autonomy, the attack surface expands to include sensors, perception modules, and decision-making algorithms. *AutoGuardX* integrates with **autonomous driving and ADAS subsystems** to monitor both data integrity and system behavior. Machine learning–based threat detection continuously evaluates sensor data streams, control commands, and inter-module communication to identify anomalies indicative of cyber interference or system compromise.

Predictive threat analytics enable *AutoGuardX* to distinguish between benign faults and malicious activity, supporting timely intervention without disrupting vehicle operation. This capability is particularly critical in autonomous vehicles, where cyberattacks can have direct implications for functional safety and passenger security.

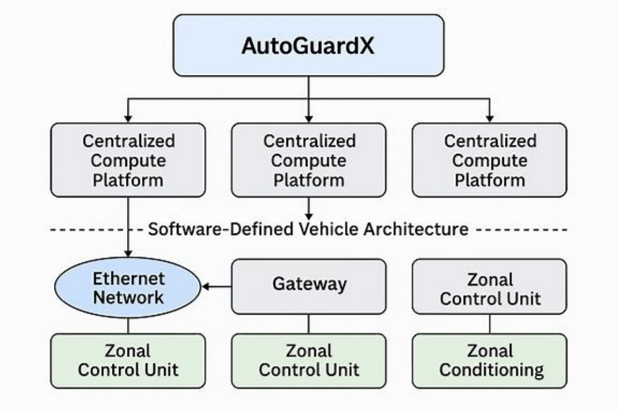
Infotainment and Telematics System Integration

Infotainment and telematics systems represent prominent entry points for cyberattacks due to their exposure to external networks such as cellular, Wi-Fi, Bluetooth, and satellite communications. *AutoGuardX* addresses this risk by enforcing **strict isolation and segmentation** between infotainment domains and safety-critical vehicle functions. Compromised or vulnerable infotainment components are prevented from accessing control networks, thereby limiting lateral movement within the vehicle architecture.

Furthermore, *AutoGuardX* secures wireless communication channels by employing **encrypted RF signaling, mutual authentication, and rolling-code mechanisms** for services such as keyless entry, remote start, and mobile application control. These measures mitigate relay attacks, replay attacks, and unauthorized remote access.

Compatibility with Software-Defined and Zonal Vehicle Architectures

Modern vehicles increasingly adopt **software-defined and zonal architectures**, where centralized compute platforms manage multiple vehicle functions. *AutoGuardX* is architected to integrate with these platforms through modular, API-driven interfaces, enabling scalable deployment across diverse vehicle models and OEM ecosystems. Its policy-driven security controls allow consistent enforcement across zones while supporting dynamic reconfiguration as vehicle software evolves.


AutoGuardX
Centralized Compute Platform
Centralized Compute Platform
Centralized Compute Platform
Software-Defined Vehicle Architecture
Ethernet Network
Gateway
Zonal Control Unit
Zonal Control Unit
Zonal Control Unit
Zonal Conditioning

Secure Integration Across the Vehicle Lifecycle

Beyond initial deployment, *AutoGuardX* supports continuous integration throughout the vehicle lifecycle. Secure over-the-air (OTA) update mechanisms ensure that both vehicle software and the security framework itself remain up to date against newly discovered threats. This lifecycle-centric integration ensures long-term resilience and aligns with modern automotive development and operational practices.

To summarize this discussion, *AutoGuardX* is designed to integrate seamlessly with contemporary vehicle architectures, providing unified cybersecurity coverage across in-vehicle networks, autonomous systems, infotainment platforms, and wireless interfaces. By aligning with the architectural evolution of modern vehicles, the framework delivers adaptive, scalable, and future-proof protection against emerging cyber threats.

Experimental Validation and Performance Evaluation of the *AutoGuardX* Framework

To rigorously validate the effectiveness and robustness of the ***AutoGuardX*** framework under realistic operational conditions, a comprehensive testing campaign was conducted within a controlled yet highly representative simulation environment. This environment was designed to replicate the **complex cyber–physical ecosystem of modern connected vehicles**, including heterogeneous in-vehicle networks, wireless interfaces, infotainment platforms, and autonomous system components.

The primary objective of this evaluation was threefold:

1. to assess *AutoGuardX*'s capability to detect and mitigate prevalent automotive cyberattack vectors, including **OBD-II exploitation, RF signal spoofing, and CAN bus injection**;
2. to benchmark its performance against **factory-installed vehicle security mechanisms**; and
3. to evaluate system stability, scalability, and compatibility across multiple OEM platforms.

All testing procedures were aligned with the **threat evaluation and validation principles outlined in ISO/SAE 21434**, ensuring methodological rigor, repeatability, and relevance to regulatory compliance.

A. Test Environment and Experimental Setup

1. Hardware Testbed Configuration

The hardware testbed was engineered to emulate the distributed and heterogeneous nature of contemporary vehicle architectures. It incorporated representative electronic control units (ECUs), communication modules, sensors, and processing platforms commonly found in North American vehicles manufactured between 2019 and 2023.

The configuration enabled controlled injection of cyberattacks while preserving realistic timing, network load, and system interactions.

Key components of the hardware testbed are summarized in **Table V**, including multi-OEM ECUs supporting CAN, Ethernet, and FlexRay; RF, Bluetooth, and 5G communication modules; advanced sensing platforms (LiDAR, radar, cameras); and embedded processing units for real-time analytics and cryptographic enforcement.

These components collectively supported high-fidelity simulation of in-vehicle networks, V2X communication, sensor fusion pipelines, and embedded cybersecurity operations.

Table V: Core Components of a Multi-Domain Automotive Hardware Testbed

Component Category	Description	Typical Technologies / Interfaces	Example Use Cases
Multi-OEM ECUs	Electronic Control Units sourced from different manufacturers to replicate heterogeneous vehicle networks	CAN, CAN-FD, LIN, FlexRay, Automotive Ethernet (100BASE-T1 / 1000BASE-T1)	Network security testing, protocol fuzzing, cross-OEM interoperability analysis

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Component Category	Description	Typical Technologies / Interfaces	Example Use Cases
Vehicle Communication Modules	Wireless communication hardware enabling short- and long-range connectivity	RF transceivers, Bluetooth LE/Classic, Wi-Fi, DSRC/C-V2X, 4G/5G NR modems	V2X security evaluation, remote attack simulation, telematics testing
Advanced Sensing Platforms	High-resolution perception sensors used in ADAS and autonomous systems	LiDAR (mechanical/solid-state), radar (24/77 GHz), monocular/stereo cameras	Sensor spoofing research, perception-stack testing, sensor fusion validation
Embedded Processing Units	High-performance compute modules for real-time analytics, ML inference, and cryptographic operations	ARM-based SoCs, automotive-grade GPUs, FPGAs, secure hardware modules (HSM/TPM)	Intrusion detection, real-time CAN anomaly detection, secure boot & key management
Network Gateways & Routers	Modules that bridge different in-vehicle networks and enforce segmentation	CAN-Ethernet gateways, FlexRay controllers, secure gateways	Firewall testing, segmentation validation, gateway exploit research
Power & Signal Conditioning Hardware	Supplies stable power and protects sensitive electronics	Programmable power supplies, load simulators, signal conditioners	Safe ECU operation, fault injection testing
Data Acquisition & Logging Systems	High-bandwidth capture tools for network and sensor data	CAN loggers, Ethernet sniffers, high-speed storage arrays	Forensics, replay attacks, dataset generation
Testbed Control & Automation Tools	Orchestration systems for automated experiments	Real-time controllers, Python automation frameworks, HIL systems	Automated attack scripts, regression testing, scenario replay

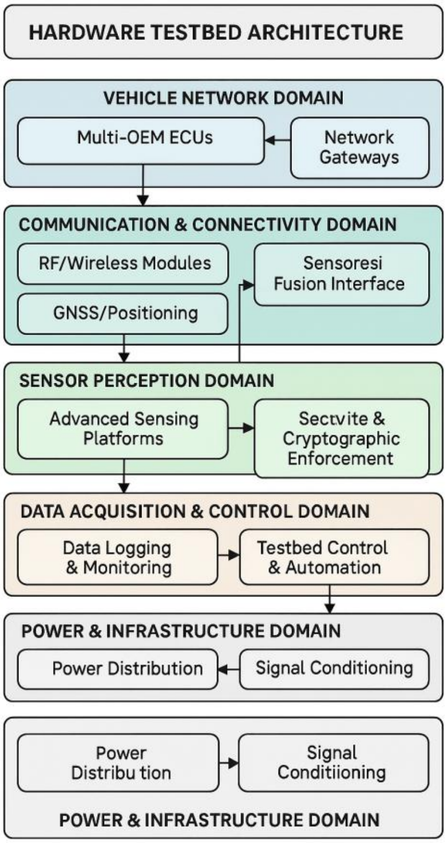
2. Software Environment Configuration

The software stack was designed to support **secure execution, attack simulation, traffic inspection, and forensic analysis**. *AutoGuardX* was deployed on a **QNX 7.1 real-time operating system**, integrated with modern machine learning libraries (TensorFlow 2.15, Scikit-learn 1.4) and cryptographic primitives (AES-256, RSA-2048).

Industry-standard automotive simulation tools, including **Vector CANoe and CANalyzer**, were used to emulate in-vehicle communication and generate adversarial CAN traffic. Network analysis and validation were performed using **Wireshark**, enabling inspection of encrypted and unencrypted traffic across CAN, RF, and Bluetooth channels. This configuration ensured accurate validation of encryption integrity, anomaly detection accuracy, and system responsiveness under attack conditions.

3. Network Architecture and Segmentation

To reflect realistic vehicle network topologies, the test environment employed a **segmented architecture**, separating safety-critical domains (e.g., powertrain, braking, ADAS) from non-critical systems (e.g., infotainment, telematics). VLANs and gateway-level filtering were implemented to evaluate *AutoGuardX*'s ability to prevent lateral movement and attack propagation.


HARDWARE TESTBED ARCHITECTURE
VEHICLE NETWORK DOMAIN
Multi-OEM ECUs
Network Gateways
COMMUNICATION & CONNECTIVITY DOMAIN
RF/Wireless Modules
Sensoresi Fusion Interface
GNSS/Positioning
SENSOR PERCEPTION DOMAIN
Advanced Sensing Platforms
Sectvite & Cryptographic Enforcement
DATA ACQUISITION & CONTROL DOMAIN
Data Logging & Monitoring
Testbed Control & Automation
POWER & INFRASTRUCTURE DOMAIN
Power Distribution
Signal Conditioning
Power Distribu tion
Signal Conditiioning
POWER & INFRASTRUCTURE DOMAIN

External connectivity scenarios were emulated using **Wi-Fi (IEEE 802.11ax)** and **5G low-latency links**, supporting realistic V2I and V2V communication patterns. A dedicated isolated subnet was reserved for simulated adversarial activity, ensuring safe and controlled execution of attack scenarios.

B. Attack Simulation Tools

A diverse toolset was employed to mirror both **professional penetration-testing techniques** and **real-world criminal methodologies**:

- **Commercial tools:** Vector CANoe, CANalyzer, Burp Suite, and Argus Cybersecurity Suite were used for structured attack simulation, benchmarking, and protocol analysis.
- **Open-source tools:** *Kali Linux* combined with *HackRF* One supported RF interception, replay, and spoofing attacks.
- **Gray-market tools:** Devices such as the XTOOL X100 PAD and RF amplifiers were included to replicate tools commonly observed in real vehicle theft operations.

- **Custom tools:** Python-based attack scripts deployed on Raspberry Pi 4 platforms enabled CAN injection, coordinated multi-vector attacks, and simulated 5G-based denial-of-service scenarios.

C. Test Execution Methodology

The evaluation campaign was conducted across **44 vehicles** representing four major OEM platforms (anonymized as Brands A–D), including both sedans and SUVs. All tests were performed in a controlled facility, with scenarios reflecting urban, suburban, and residential environments. The testing strategy was structured into four principal categories: **penetration testing, security simulations, stress testing, and compatibility testing**.

1. Penetration Testing

Penetration testing focused on attack vectors frequently exploited in real-world vehicle theft incidents:

- **OBD-II Port Exploitation:** Analysts simulated short-duration physical access by connecting a commercially available key programmer to the OBD-II port to clone or register new key fobs.
- **RF Relay and Code Injection:** Using SDR devices operating at 315 MHz and 433 MHz, RF signals were intercepted and replayed to emulate relay attacks involving attackers positioned near the vehicle and the owner's residence.
- **USB Data Exfiltration:** Unauthorized USB devices were connected to infotainment and diagnostic interfaces to simulate data extraction attacks.

Each penetration test was repeated multiple times per vehicle to ensure statistical reliability, with full logging enabled for post-analysis.

2. Security Simulations

Physical and cyber-physical attack scenarios were executed to evaluate *AutoGuardX*'s ability to detect non-traditional intrusion techniques:

- **Window Break Detection:** Acoustic and vibration signatures from controlled glass break events were analyzed.
- **Headlight-Based CAN Access:** Attackers accessed CAN wiring through damaged headlight assemblies to inject spoofed control messages.
- **Remote Key Fob Spoofing:** Full relay attack scenarios were simulated across different environmental contexts.

3. Stress Testing

Stress testing evaluated system resilience under extreme conditions:

- **Concurrent Multi-Vector Attacks:** CAN injection, RF spoofing, and OBD-II exploits were executed simultaneously to assess detection latency and system stability.
- **CAN Flooding:** High-rate CAN message injection simulated denial-of-service conditions.

- **Resource Saturation:** *AutoGuardX* analytics were stressed under high CPU and memory utilization while processing simulated driving and network data.

4. Compatibility and Long-Term Testing

Compatibility testing assessed seamless integration with OEM systems:

- **ECU Integration:** *AutoGuardX* was installed without modifying factory software, and normal vehicle functions were monitored for latency or interference.
- **Extended Driving Simulation:** Over 1,000 hours of simulated driving data were processed to evaluate long-term stability and false-positive rates.
- **Alarm Interoperability:** *AutoGuardX* alerts were evaluated alongside OEM alarm responses to ensure consistent and complementary behavior.

D. Results and Observations

The comprehensive results summarized in **Table VIII** demonstrate that factory-installed vehicle security systems exhibited significant limitations, particularly in detecting physical intrusion and preventing CAN-based immobilizer bypass attacks. In contrast, *AutoGuardX* consistently achieved **near-perfect attack prevention**, low detection latency, high accuracy, and robust forensic logging across all test categories.

Notably, *AutoGuardX* maintained system stability under high network load and computational stress, exhibited a **false-positive rate below 0.3%**, and achieved full compatibility across all tested OEM platforms without disrupting normal vehicle operation.

Table VIII: Limitations of Factory-Installed Vehicle Security Systems

Brand (Example)	Physical Intrusion Detection	CAN-Based Immobilizer Bypass Vulnerability	Notes
Toyota	Weak detection of intrusion through headlight or bumper access; thieves can reach CAN wiring without triggering alarms	High vulnerability due to unsecured CAN messages enabling engine start spoofing	Widely targeted in CAN-bus theft wave; immobilizer not engaged once CAN spoofed
Honda	Limited intrusion sensing around fenders and lighting assemblies	CAN bus lacks authentication, allowing attackers to inject start commands	Attackers often access CAN lines behind headlight assemblies
Volkswagen	Perimeter alarms fail to detect intrusion via wheel-well access	CAN messages can be replayed or spoofed to bypass immobilizer	CAN architecture similar to other brands; no message encryption
Hyundai / Kia	Physical intrusion often undetected when accessing wiring harnesses	Immobilizer bypass possible through CAN injection points	Some models lack immobilizers entirely; others rely on vulnerable CAN

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Brand (Example)	Physical Intrusion Detection	CAN-Based Immobilizer Bypass Vulnerability	Notes
BMW	High-end systems still fail to detect intrusion through lighting modules	CAN bus susceptible to unauthorized message injection due to no built-in security	Luxury vehicles increasingly targeted due to high resale value
Ford	Intrusion via bumper or headlight often not detected	CAN-based bypass possible by injecting engine start commands	Attackers exploit exposed wiring near front fascia

E. Discussion and Validation

The testing campaign highlights critical shortcomings in current factory security implementations, especially regarding runtime intrusion detection and physical attack awareness. *AutoGuardX* addresses these gaps by providing **real-time, adaptive, and multi-layered cybersecurity protection**, effectively bridging the divide between procedural standards and operational security.

Overall, the results validate *AutoGuardX* as a **comprehensive, resilient, and standards-aligned automotive cybersecurity framework**, compliant with **ISO/SAE 21434**, **UN WP.29 R155**, and **NHTSA 2023 cybersecurity guidelines**. The framework demonstrates strong potential for deployment in modern connected and autonomous vehicles, offering both immediate risk mitigation and long-term adaptability to evolving cyber threats.

Scalability and Adaptability

A central strength of the ***AutoGuardX*** framework lies in its inherent **scalability and adaptability**, which are essential attributes in the rapidly evolving automotive cybersecurity landscape. As vehicle architectures advance and novel cyber threats continue to emerge, *AutoGuardX* is designed to evolve in parallel with these changes.

Scalability: *AutoGuardX* is architected for seamless deployment across a wide spectrum of vehicle platforms, ranging from conventional internal-combustion vehicles to highly connected and fully autonomous systems. Its modular design allows manufacturers to tailor security capabilities to the specific requirements of individual vehicle models and brands. Components can be selectively integrated, updated, or expanded without disrupting existing functionality, ensuring long-term viability and compatibility with future automotive technologies.

Adaptability: The framework incorporates continuous learning and update mechanisms that enable dynamic adaptation to emerging threat vectors. Machine learning models are periodically retrained using newly observed data to enhance detection accuracy, while secure over-the-air (OTA) updates facilitate rapid deployment of patches and defensive enhancements across connected fleets.

Collectively, these features ensure that *AutoGuardX* remains a robust, responsive, and future-ready cybersecurity solution, capable of maintaining effective protection as vehicle technologies and adversarial techniques continue to evolve.

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XII. Digital Tools for UWB-Based Secure Ranging in Key-less Entry Systems

Ultra-Wideband (UWB) Transceivers[50] (IEEE 802.15.4z)

Hardware Components

UWB functionality is implemented using dedicated IEEE 802.15.4z–compliant transceivers integrated within the vehicle's access control ECU and the key fob or mobile device. These transceivers operate over a wide spectrum with sub-nanosecond pulse resolution, enabling precise time-of-flight measurements. Typical hardware configurations include a UWB radio front end, a high-precision crystal oscillator, and a hardware timestamping unit. In automotive deployments, the transceiver is often coupled with a secure element or hardware security module (HSM) to isolate cryptographic operations and protect ranging credentials.

Embedded Software

Low-level drivers manage UWB frame transmission, reception, and synchronization. The embedded stack implements PHY and MAC layers as specified in IEEE 802.15.4z, including support for secure ranging frames and channel impulse response measurements. Interrupt-driven timestamp capture is used to minimize latency and measurement error.

Customized Applications

At the application layer, UWB transceivers are exposed through a secure API to the vehicle access application or digital key service. This enables controlled initiation of ranging sessions and integration with higher-level authentication logic.

Secure Ranging Algorithms

Hardware Support

Secure ranging relies on hardware-assisted timestamping and deterministic RF signal processing. Dedicated hardware counters and time-to-digital converters are used to ensure nanosecond-level accuracy, which is essential for detecting relay-induced delays.

Embedded Software

Secure ranging algorithms implement distance-bounding protocols that measure round-trip time while incorporating cryptographic challenges. These algorithms validate the temporal consistency of responses and analyze channel characteristics to detect abnormal propagation behavior indicative of

[50] For true UWB Secure Access (IEEE 802.15.4z) — like automotive digital key and relay-resistant ranging — typical designs use dedicated automotive-grade UWB transceiver ICs or modules on custom PCBs, not generic hobby boards. Examples include:

Automotive / High-grade UWB ICs & Modules

- **NXP Trimension™** NCJ29D6 – A highly integrated automotive UWB transceiver IC designed for secure ranging and radar capabilities compliant with IEEE 802.15.4z (supports digital key applications). Requires a custom PCB with antennas, decoupling, power, and host processor integration.
- **Automotive UWB modules like Quectel AU30Q** – Automotive UWB module based on Qorvo UWB chipset, compliant with IEEE 802.15.4z, suitable for secure vehicle access and digital key systems. These modules expose interfaces (e.g., SPI) to a host controller and are ready to mount on a custom board.

relay attacks. Error correction and noise filtering routines are also included to maintain robustness under real-world RF conditions.

Customized Applications

The vehicle access application consumes the output of the ranging algorithm as a proximity confidence metric rather than a raw distance value. Access decisions (unlock, ignition enable) are granted only if the measured proximity satisfies predefined security thresholds.

Cryptographic Timestamping

Hardware Components

Cryptographic timestamping is supported by hardware security modules or secure elements that provide protected key storage and accelerated cryptographic primitives. Hardware timers are synchronized with the UWB transceiver to ensure trusted time references.

Embedded Software

During a ranging exchange, timestamps are cryptographically bound to challenge–response messages using symmetric or asymmetric cryptographic functions. This prevents attackers from modifying or replaying timing information without detection. The firmware ensures that timestamps are generated, processed, and validated entirely within trusted execution contexts.

Customized Applications

At the application level, timestamp validation results are abstracted into binary or probabilistic trust indicators. These indicators are combined with other authentication factors, such as user presence or device state, to support multi-factor access decisions.

A. Secure Firmware for Ranging Logic

Hardware Root of Trust

Secure firmware execution is anchored by a hardware root of trust that enforces secure boot and runtime integrity checks. Only authenticated firmware images are allowed to control the UWB ranging subsystem.

Embedded Software

The firmware implements all critical ranging logic, including challenge generation, timestamp validation, and relay detection heuristics. Secure update mechanisms, such as signed over-the-air (OTA) updates with rollback protection, ensure that vulnerabilities can be patched without exposing the system to downgrade attacks.

Customized Applications

Vehicle or mobile applications do not directly manipulate ranging logic; instead, they interact through restricted interfaces that expose only high-level status information. This design prevents application-level compromise from undermining proximity verification.

Key Architectural Insight

The effectiveness of UWB-based keyless entry security extends far beyond the inherent precision of ultra-wideband radio technology. While UWB provides accurate time-of-flight measurements that significantly improve distance estimation compared to traditional LF/RF systems, radio performance alone is insufficient to guarantee robust security. Without a carefully engineered system architecture, even highly accurate ranging data can be undermined by implementation flaws, insecure software logic, or poorly controlled interfaces. As a result, UWB must be treated as one component within a broader, tightly integrated security design rather than a standalone solution.

Hardware-assisted timing plays a critical role in preserving the security benefits of UWB. Secure timestamping, protected clocks, and hardware isolation mechanisms ensure that ranging measurements cannot be manipulated or delayed by malicious software or external attackers. By anchoring critical timing functions in trusted hardware elements such as secure elements or hardware security modules, the system can reliably enforce strict distance-bounding guarantees. This hardware foundation prevents attackers from introducing relay delays or altering timing measurements, which are common techniques used to bypass proximity-based authentication systems.

Equally important is the role of secure embedded software that orchestrates UWB communication and decision-making. Embedded firmware must be designed to handle cryptographic operations, session management, and authentication logic in a deterministic and tamper-resistant manner. Secure boot, runtime integrity checks, and controlled update mechanisms ensure that only trusted software can process UWB ranging results and authorize vehicle access. Any weakness at the software layer can negate the security gains of precise ranging, allowing attackers to exploit logic errors or manipulate authorization flows.

Finally, constrained and well-defined application-level interfaces are essential to maintaining end-to-end security. UWB measurements and authentication results should be exposed only through minimal, tightly controlled interfaces to other vehicle systems, reducing the attack surface. Clear separation between ranging, decision logic, and vehicle actuation prevents unauthorized components from influencing security-critical outcomes. When hardware-assisted timing, secure embedded software, and constrained interfaces are cohesively integrated, UWB-based keyless entry systems can achieve resilient protection against relay attacks and other proximity-based threats.

XIII. Cybersecurity Challenges & Adoption Barriers in Automotive Market

The Canadian and United States automotive markets, both at the forefront of connected and intelligent vehicle technologies, face a distinct and complex set of cybersecurity challenges. The deployment of a comprehensive framework such as ***AutoGuardX*** must therefore account not only for technical considerations, but also for theoretical constraints, regulatory fragmentation, operational realities, and the need to proactively address emerging technological threats, including those associated with **5G connectivity** and **quantum computing**.

A. Theoretical and Architectural Barriers

Legacy System Compatibility:

A substantial portion of the North American vehicle fleet consists of legacy platforms that were not designed with modern cybersecurity requirements in mind. Many older vehicles lack the hardware support necessary for advanced security mechanisms such as encrypted CAN communication, hardware-based key storage, or secure boot processes. Retrofitting these systems to support contemporary cybersecurity frameworks presents significant technical complexity and cost, often rendering comprehensive upgrades impractical for older models [34].

Resource Constraints in Embedded Systems:

Electronic control units (ECUs) in vehicles are frequently constrained by limited computational capacity, memory, and power availability. The integration of resource-intensive security functions—such as real-time anomaly detection, behavioral modeling, and cryptographic processing—can exceed the capabilities of legacy or low-cost ECUs. These limitations underscore the necessity for lightweight, efficient, and automotive-grade cybersecurity algorithms that balance detection accuracy with real-time performance requirements [35].

Rapidly Evolving Threat Landscape:

The automotive cyber threat environment is evolving at a pace that frequently outstrips the development, validation, and deployment cycles of traditional security solutions. Novel attack vectors, including multi-stage and cross-domain intrusions, continue to emerge in the highly connected North American automotive ecosystem. As a result, predictive models and anomaly detection systems must be continuously updated and retrained to remain effective against emerging threats [36].

B. Regulatory, Technological, and Operational Barriers

Regulatory Fragmentation:

The regulatory environment governing vehicle cybersecurity in North America remains fragmented. In Canada, the **Motor Vehicle Safety Act (MVSA)** does not explicitly mandate comprehensive cybersecurity requirements, while in the United States, the **National Highway Traffic Safety Administration (NHTSA)** has issued largely voluntary cybersecurity guidelines [37], [38]. This absence of enforceable, harmonized regulations results in inconsistent security postures across manufacturers and complicates the widespread adoption of advanced frameworks such as *AutoGuardX*.

Technological Fragmentation and Interoperability Challenges:

The North American automotive industry comprises a diverse ecosystem of original equipment manufacturers (OEMs), Tier-1 suppliers, and software vendors, each employing proprietary communication protocols and security architectures. This lack of standardization introduces significant interoperability challenges and inhibits the deployment of uniform cybersecurity solutions across platforms and brands [39].

Economic and Implementation Constraints:

The integration of advanced cybersecurity mechanisms—including encrypted communication protocols, machine learning–based detection engines, and comprehensive forensic logging systems—can entail substantial development and deployment costs. These financial barriers may disproportionately affect smaller OEMs and Tier-2 suppliers, leading to uneven adoption and potentially creating security disparities across the vehicle market [40].

Workforce and Skills Shortages:

There is a recognized shortage of professionals in North America with interdisciplinary expertise

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spanning both automotive engineering and cybersecurity. The sustainable deployment and operation of frameworks such as *AutoGuardX* require targeted investments in workforce development, cross-domain training, and organizational capacity-building to support long-term maintenance and evolution of vehicle security systems [41].

C. Emerging Threats and Future Adaptation Requirements for *AutoGuardX*

5G-Enabled Connectivity Risks:

The widespread deployment of **5G networks** across North America introduces both enhanced capabilities and new attack vectors for connected vehicles. While 5G enables low-latency, high-bandwidth communication essential for V2X and autonomous applications, it also increases exposure to threats such as distributed denial-of-service (DDoS) attacks and signaling manipulation. To address these risks, *AutoGuardX* must incorporate advanced encryption, traffic classification, and real-time filtering mechanisms [42].

Quantum Computing–Driven Cryptographic Challenges:

Advances in quantum computing pose a long-term threat to conventional public-key cryptographic algorithms widely used in vehicular communication systems. As quantum-capable adversaries become more plausible, *AutoGuardX* must support the transition toward **quantum-resistant cryptographic schemes** to ensure the long-term confidentiality and integrity of in-vehicle and V2X communications [43].

Expansion of the Automotive IoT Ecosystem:

The increasing integration of IoT components—including infotainment systems, smart sensors, telematics units, and third-party applications—significantly expands the vehicular attack surface. These components require strong device authentication, secure over-the-air (OTA) update mechanisms, and robust network isolation strategies. *AutoGuardX* prioritizes zero-trust principles and real-time device validation to mitigate risks associated with IoT proliferation [44].

Cybersecurity Challenges in Autonomous Vehicles:

Autonomous and highly automated vehicles, which are gaining traction in the North American market, rely heavily on external data sources, sensor fusion pipelines, and machine learning–driven decision-making. These dependencies increase susceptibility to data poisoning, adversarial manipulation, and sensor spoofing attacks. To safeguard autonomous operations, *AutoGuardX* must leverage advanced AI-based anomaly detection and integrity verification mechanisms capable of identifying subtle deviations in system behavior [45].

Regulatory Landscape Comparison

Below **Table IX** presents a comparative overview of regional vehicle cybersecurity frameworks and highlights the compatibility of *AutoGuardX* with existing and emerging regulatory requirements. Notably, while cybersecurity mandates remain limited in North America, *AutoGuardX* aligns closely with international standards such as **ISO/SAE 21434** and **UNECE WP.29 R155**, positioning it as a globally applicable and forward-compatible solution.

Here is an academically rewritten and refined version of your text, with enhanced clarity, formal tone, and stronger alignment with scholarly discourse:

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Ethical and Privacy Considerations in Connected Vehicle Cybersecurity

The rapid advancement of connected and autonomous vehicle technologies has introduced a new set of ethical and privacy challenges that extend beyond traditional automotive safety concerns. As cybersecurity frameworks such as ***AutoGuardX*** become increasingly embedded within vehicle architectures, they necessitate the collection, processing, and analysis of large volumes of data, including geolocation information, driving behavior metrics, system telemetry, and, in some cases, biometric identifiers.

While such data acquisition is essential for enabling advanced security functions, real-time threat detection, and system optimization, it simultaneously raises critical concerns related to **user privacy, data governance, and ethical responsibility**.

A central ethical challenge lies in ensuring **informed and meaningful user consent**. Vehicle users must be clearly and comprehensively informed about the nature and scope of data being collected, the purposes for which it is processed, the duration of retention, and the entities with whom it may be shared. Empirical studies indicate that many existing automotive data collection practices lack sufficient transparency, contributing to user mistrust and increasing the risk of regulatory non-compliance and legal disputes [46]. The implementation of clear, accessible, and user-centric privacy disclosures is therefore essential to address these concerns.

Another critical consideration is the principle of **data minimization**, which emphasizes limiting data collection to what is strictly necessary to achieve defined security and operational objectives. Adherence to data minimization reduces exposure to misuse, unauthorized access, and secondary exploitation, and aligns closely with regulatory requirements outlined in frameworks such as the **General Data Protection Regulation (GDPR)** and the **California Consumer Privacy Act (CCPA)** [47], [48]. In this context, *AutoGuardX* should incorporate architectural controls that enforce purpose limitation and restrict data acquisition and retention to essential operational parameters.

The risk of **data breaches and unauthorized access** further amplifies ethical and privacy concerns. Compromise of sensitive vehicular data can result not only in individual privacy violations but also in broader safety and national security implications. To mitigate these risks, robust encryption mechanisms, secure key management, access control policies, and periodic security audits are essential components of any comprehensive vehicular cybersecurity framework [49].

As *AutoGuardX* continues to evolve, the systematic integration of **ethical governance models and privacy-by-design principles** will be critical. This includes conducting regular data protection impact assessments, engaging relevant stakeholders throughout the system lifecycle, and continuously monitoring regulatory developments to ensure ongoing compliance. By embedding ethical and privacy considerations at the architectural and operational levels, *AutoGuardX* can help maintain public trust while enabling secure and responsible innovation in connected and autonomous mobility systems.

XIV. Conclusion

The rapid evolution of vehicle technology has transformed mobility, offering unprecedented convenience and connectivity. However, this advancement has also introduced complex security challenges. Vehicle theft in regions like Canada and the U.S. has shifted from purely physical methods to sophisticated cyber-enabled attacks, highlighting an urgent need for innovative and adaptive security frameworks.

AutoGuardX emerges as a comprehensive solution to these challenges. By integrating machine learning, IoT security measures, secure communication protocols, and robust incident reporting mechanisms, the framework provides a holistic defense. It enables real-time threat detection and prevention, while continuously learning to adapt to emerging risks, including those posed by 5G networks, quantum computing, and increasingly connected IoT systems.

Despite its potential, the adoption of *AutoGuardX* faces notable hurdles. Legacy system compatibility, high implementation costs, and fragmented regulatory environments pose significant challenges. Addressing these barriers will require collaboration among automakers, cybersecurity researchers, and policymakers, ensuring not only effective deployment but also the scalability and resilience of the framework across diverse vehicle platforms.

Looking forward, the adaptability and modular design of *AutoGuardX* position it as a pioneering model in automotive cybersecurity. Through continued innovation, industry-wide partnerships, and rigorous research, the framework has the potential to shape the future of connected and autonomous vehicles, delivering safety, security, and resilience in an increasingly digital and interconnected automotive ecosystem.

XV. Appendix A

Design Details

Digital Tools for UWB-Based Secure Ranging in Key-less Entry Systems

1. Introduction

Key-less entry systems using legacy RF (LF + BLE) are vulnerable to **relay (amplification) attacks**, where an attacker extends the communication range between a vehicle and a key fob.

Ultra-Wideband (UWB) secure ranging, based on **IEEE 802.15.4z**, mitigates this by measuring **true physical distance using time-of-flight (ToF)** with cryptographic protection.

This section describes the **digital tools, software components, and system architecture** required to design, implement, and validate a **UWB-based secure ranging system** for key-less vehicle access.

2. System Objectives

The digital tools must support the following objectives:

1. **Accurate distance measurement** (≤10 cm error)
2. **Resistance to relay and replay attacks**
3. **Low latency** (user-perceived instant unlock)
4. **Interoperability** (FiRa / CCC Digital Key compliance)
5. **Automotive-grade reliability and safety**

3. High-Level System Architecture

3.1 Entities

Entity	**Description**
Vehicle UWB Anchor	Fixed UWB nodes installed in vehicle (doors, cabin)
Digital Key (Device)	Smartphone or key fob with UWB
Vehicle Control Unit (VCU)	Decides lock/unlock based on ranging
Secure Element (SE)	Stores cryptographic keys
UWB Stack	PHY/MAC + secure ranging protocols

3.2 Logical Block Diagram (Digital View)

```
+----------------------------+
|  Application Layer         |
| (Access Control Logic)   |
+----------------------------+
|  Secure Ranging Service  |
|  (FiRa / CCC profiles)   |
+----------------------------+
|  UWB Command Interface    |
|  (UCI / Driver APIs)     |
+----------------------------+
|  MAC Layer (802.15.4z)   |
|  - TWR / TDoA / STS      |
+----------------------------+
|  PHY Layer (UWB)         |
|  - HRP pulses            |
+----------------------------+
|  UWB Hardware            |
+----------------------------+
```

4. Digital Tools Overview

Digital tools are required across **design, development, testing, and validation** phases.

4.1 Tool Categories

Category	**Purpose**
Protocol Stack Tools	Implement IEEE 802.15.4z + FiRa
Secure Ranging Algorithms	Distance calculation & validation
Cryptographic Tools	Key management, STS
Simulation Tools	Ranging & attack simulation
Debug & Logging Tools	Timing & packet analysis
Certification Tools	FiRa / CCC compliance

5. Secure Ranging Digital Design

5.1 Ranging Method

Preferred:

- **Double-Sided Two-Way Ranging (DS-TWR)**

Why:

- Cancels clock drift
- Resistant to simple replay
- Supported by FiRa & CCC

5.2 Secure Timestamp Sequence (STS)

IEEE 802.15.4z introduces **Scrambled Timestamp Sequence**:

- Cryptographically generated pulse sequences
- Prevents attackers from forging timestamps
- Bound to session keys

Digital Tool Requirements:

- AES-based STS generator
- Time-synchronized STS verification
- Hardware acceleration preferred

5.3 Distance Computation Logic

Inputs:

- TX timestamp (Anchor)
- RX timestamp (Device)
- Reply timestamps
- Clock offset compensation

Output:

- Estimated distance
- Confidence level

Validation Rules:

- Distance ≤ threshold (e.g., 1.5 m)
- Consistency across multiple anchors
- Timing jitter within limits

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6. Security Architecture (Digital)

6.1 Cryptographic Components

Component	Function
Secure Element (SE)	Stores root keys
Session Key Generator	Per-session keys
STS Engine	PHY-level security
Message Authentication	Prevents spoofing

6.2 Anti-Relay Protection Logic

Relay attacks fail because:

- ToF delay exceeds physical limits
- STS cannot be predicted or relayed in time
- Multiple anchor cross-checking detects anomalies

Digital Tool Role:

- Timing window enforcement
- Statistical anomaly detection
- Anchor-to-anchor correlation

7. Application-Level Access Logic

7.1 Decision Flow

Start Ranging Session

↓

Verify STS & MAC

↓

Compute Distance

↓

Validate Threshold

↓

Check Motion / Intent

↓

Unlock Vehicle

7.2 Multi-Factor Logic (Recommended)

UWB decision combined with:

- BLE authentication
- Device motion state
- User profile rules

8. Development & Simulation Tools

8.1 Simulation Tools

Used before hardware deployment:

- Ranging error modeling
- Multipath & NLOS simulation
- Attack scenario testing

Key Parameters:

- Clock drift
- Processing delay
- Noise & interference

8.2 Debug & Test Tools

- UWB packet sniffers
- Timestamp trace analyzers
- Distance histogram tools
- Anchor synchronization monitors

9. Certification & Compliance Tools

9.1 FiRa Compliance

Digital tools must support:

- FiRa PHY/MAC profiles
- UCI command set
- Secure ranging test cases

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9.2 CCC Digital Key

Tools must validate:

- Proximity verification rules
- Unlock timing limits
- Interoperability with smartphones

10. Performance Targets

Metric	Target
Ranging Accuracy	≤ 10 cm
Decision Latency	< 300 ms
False Unlock Rate	~0
Relay Attack Success	0%
Power Consumption	Automotive limits

11. Summary

Digital tools are the backbone of UWB-based secure ranging systems. They ensure that IEEE 802.15.4z hardware is transformed into a relay-attack-resistant, automotive-grade digital key solution.

Key Takeaways

- UWB security is enforced digitally via **timing, cryptography, and validation logic**
- IEEE 802.15.4z + FiRa defines the technical foundation
- Proper digital tooling is as critical as RF hardware

XVI. Appendix B

A. Technical Flow of CAN Injection–Based Vehicle Theft in Toyota and Lexus SUVs

The CAN injection attack observed in multiple Toyota and Lexus SUV models follows a repeatable and well-documented sequence that exploits architectural trust assumptions within legacy in-vehicle networks. While implementations vary by model year, the general attack flow is as follows:

Step 1: Physical Access to Peripheral Components - Attackers gain brief physical access to the exterior of the vehicle, commonly targeting the headlight assembly or wheel arch. These components are electrically connected to the body control module (BCM) and CAN bus, yet are often insufficiently shielded or monitored.

Step 2: Network Interface Injection - After removing or damaging the headlight casing, attackers connect a malicious interface device directly to exposed CAN wiring. This device emulates a legitimate electronic control unit (ECU) and immediately gains access to the internal vehicle network.

Step 3: CAN Message Injection - Because traditional CAN protocols lack encryption and authentication, injected messages are accepted as valid. The attacker transmits crafted frames that replicate authorized commands, such as:

- Door unlock signals
- Immobilizer disable messages
- Ignition start authorization

Step 4: Vehicle Compromise and Theft - The vehicle responds to these injected commands without triggering alarms or immobilization safeguards. The engine can be started, and the vehicle driven away without possession of the original key fob or evidence of forced entry.

Step 5: Persistence (Optional) - In some cases, attackers may subsequently reprogram keys via the OBD port or install covert tracking-disable devices, enabling repeat access or resale.
This attack flow highlights a critical weakness: **implicit trust between ECUs** within the vehicle network, particularly when non-critical subsystems (e.g., lighting) share communication paths with security-critical functions.

B. Mapping Toyota/Lexus Vulnerabilities to ISO/SAE 21434 Threat Categories

ISO/SAE 21434 provides a structured framework for identifying, assessing, and mitigating automotive cybersecurity risks. Table I maps observed vulnerabilities in Toyota and Lexus SUVs to relevant threat categories and lifecycle phases defined by the standard.

Table I. Vulnerability–Mitigation Mapping Using ISO/SAE 21434

Threat Area	Observed Issue in Toyota/Lexus SUVs	ISO/SAE 21434 Reference	Recommended Mitigation
In-Vehicle Network Security	CAN bus messages lack authentication and encryption	Threat Analysis & Risk Assessment (TARA)	Secure CAN (SecOC), message authentication codes (MACs)
ECU Trust Model	Peripheral ECUs trusted equivalently to security-critical ECUs	Item Definition, Cybersecurity Concept	Network segmentation, secure gateways
Physical Access Points	Headlight wiring enables network entry	Attack Path Analysis	Tamper detection, hardened wiring, intrusion sensors
Keyless Entry Systems	Susceptibility to relay and replay attacks	Cybersecurity Goals	Distance-bounding protocols, cryptographic challenges
Diagnostics Interface	OBD port enables unauthorized key programming	Post-Production Phase	Strong access control, authenticated diagnostics
Intrusion Detection	Lack of real-time CAN anomaly detection	Continuous Monitoring	In-vehicle IDS using ML-based traffic profiling

C. Comparative Mitigation Strategies for Toyota and Lexus SUVs

Mitigation strategies can be categorized into **design-level**, **software-level**, and **post-production** controls. Their effectiveness varies depending on whether they are implemented at the manufacturer or aftermarket level.

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Manufacturer-Level Mitigations

Cryptographic CAN Authentication: Prevents unauthorized message injection.
Secure Gateways: Isolate infotainment, lighting, and body networks from immobilizer and drivetrain ECUs.

Enhanced Smart Key Protocols: Implement rolling codes, distance verification, and anti-relay mechanisms.

OTA Security Updates: Enable rapid deployment of patches addressing emerging threats.

Aftermarket and Transitional Mitigations

Secondary Immobilizers: Require driver-specific authentication sequences.

CAN Bus Firewalls: Filter unauthorized message patterns.

Physical Hardening: Reinforced headlight housings and tamper-evident seals.

RF Signal Shielding: Reduce exposure to relay attacks.

Limitations - While aftermarket solutions can reduce risk, they cannot fully compensate for architectural vulnerabilities such as plaintext CAN communication or flat network topology. Long-term resilience requires security-by-design principles applied at the vehicle architecture level.

D. Implications for Automotive Cybersecurity Research

The Toyota and Lexus SUV case illustrates a broader industry challenge: **legacy automotive protocols are increasingly incompatible with modern threat environments**. These vulnerabilities emphasize the necessity of:

- Treating vehicles as distributed cyber-physical systems
- Integrating cybersecurity alongside functional safety
- Transitioning from perimeter-based to **zero-trust in-vehicle architectures**

This analysis further supports the motivation for comprehensive frameworks—such as our proposed framework—that combine cryptographic protection, machine-learning-based intrusion detection, and continuous lifecycle security management

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