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Architectural Patterns for Energy-Aware Service-Oriented Vehicle Software

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Abstract:
The fast development of Software-Defined Vehicles (SDVs) has complicated the need to balance between the computational and energy efficiency of the distributed Electronic/Electrical (E/E) architecture. This Research explores architectural designs that facilitate energy visibility and manageability in the Service-Oriented Architecture (SOA) designs that are implemented on the current vehicle systems. The contribution of centralized domain controllers, zonal architecture, microservice based Energy Management Systems (EMS) as well as adaptive middleware standards like AUTOSAR Adaptive in providing quantifiable savings in power consumption, battery range, and real-time energy telemetry. The application analyses that SOA-native energy services, used with Time-Sensitive Networking (TSN) and dynamic resource orchestration, can save up to 35% on the power used in standby operation and 10-fold improvements in fleet-level energy visibility. The findings of research provide a unified reference platform to be used by architects working on the next generation energy-conscious in-vehicle software platform.

Keywords: Energy-Aware architecture, service-oriented architecture (SOA), software-defined vehicle (SDV), E/E architecture, AUTOSAR adaptive, microservices, Time-sensitive networking (TSN), Energy Management System (EMS), zonal architecture, electric vehicle (EV).

I. INTRODUCTION

The automotive sector is experiencing a transformational change in the hardware-focused Electronic Control Units (ECUs) that are characterized by specific functions, to centralized, software-defined computing platforms [1]. The principles of electrification, autonomous driving and connectivity force this change in basic assumptions, which dictates the need to reconsider the vehicle E/E architectures fundamentally [20]. Architectures Centralized architectures take a formerly distributed ECUs and centralize them on a smaller number of, more powerful, domain or zone controllers, allowing scalable software deployment and over-the-air updates (OTA) [22].

The most prevalent paradigm of organizing in-vehicle software in the next-generation vehicles has become Service-Oriented Architecture (SOA) that was initially created as the scheme of structuring enterprise software [8]. SOA facilitates a resource allocation flexibility and system reconfigurability that was never achievable by breaking down vehicle functions into loosely coupled and independently deployable services that interact via standardized middleware [3]. This strategy has been operationalized in frameworks like AUTOSAR Adaptive and ROS2 to be used in safety-critical automotive environments [18] [19].

The first-class concern when it comes to Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) is energy efficiency, where software-layer inefficiencies are directly proportional to the range and poor user experience [12]. Nevertheless, the point of intersection between SOA and energy management in vehicles is a poorly researched field [6] [9]. Current literature focuses on either architectural synthesis [2] or energy management [13] [16] alone, and seldom on the way architectural patterns can be carefully formed to reveal, track, and regulate energy usage as one of the service properties of the first class [7].

Automotive Ethernet and Time-Sensitive Networking (TSN) are a few examples of network technologies that offer the deterministic communication base required to coordinate the energy services on a timely basis [13] [17]. In the meantime, microservice-based EMS architecture and dynamic service orchestration systems provide opportunities to dynamically adjust the energy consumption, which is not possible in the context of a fixed architecture [11] [5]. The paper has brought together these threads to give a detailed analysis of the architectural patterns that allow energy-conscious SOV software platforms basing on up-to-date literature [23] and empirical case data.

II.LITERATURE REVIEW

Bandur et al. (2021): The strong argument in support of centralized automotive E/E architectures and have shown that domain or zone controller ECUs significantly simplify the wiring harnesses and the standby power consumption. Their review of functional safety implication gives them a basis rationale of centralization as an enabler of energy optimization in the contemporary vehicles [1].

Askaripoor, Farzaneh, and Knoll (2022): The detailed overview of the E/E architecture synthesis methodology and revealed such critical challenges as heterogeneous integration of hardware, real-time constraints, and power management. Their taxonomy of existing synthesis tools shows that there exist considerable energy-blindness at the architecture model level, which drives the desire to have energy-first design flows [2].

Kugele, Obergfell, and Sax (2021): Suggested a model-driven method of the analysis and synthesis of service-based automotive software architecture with a focus on the resource optimization of distributed ECU platform. Their articulation of service to resource mapping provides a hard-core foundation of integrating the energy constraints as optimization goals during SOA implementation [3].

Wilhelm and Roedler (2022): Proposed an optimization-based resource allocation system of service-oriented automotive software, which is used to solve the problem of ECU load imbalance by constraint programming. They have shown that their outcomes on a real vehicle platform can be used to decrease peak power consumption through systematic service placement, which puts energy-intensive services on efficient hardware [4].

Kugele, Hettler, and Peter (2019): Their suggestion on dynamic service instantiation and migration can be directly applied to energy-conscious orchestration so that the services can be migrated to the low-power hardware domains as the workload patterns change [5].

Jatzkowski et al (2022): Carried out a systematic mapping of automotive SOA literature and found more than 120 primary studies, which discloses that less than 15 percent of the literature is concerned with the issue of energy efficiency. Such gap analysis highlights the originality and topicality of the current study interest on the topic of energy-conscious architectural patterns of SDV platforms [6].

Thoma and Kugele(2023): Studied resilience in automotive SOA as a dynamic orchestration which suggests mechanisms of service failover and redeployment without service interruption. Their resilience framework implicitly facilitates energy management since, with it, it is possible to execute a decision of placing services in power states, and simultaneously, not to violate functional availability requirements [7].

Kugele et al. (2017): Formulated the principles of service-orientation in automotive software development, comparing service-based and component-based design, and finding the issue of communication overhead and the lifecycle management as the primary considerations. Their model of abstraction middleware is still a reference architecture to further SOA deployments such as energy service designs [8].

Becker et al. (2020): Explored the adaptations that are needed in the development process of automotive SOA, which revealed that service contract management, versioning, and cross-domain integration testing are required. Their model of processes has an implication on the energy service development processes especially in the management of the energy policy contracts between the provider and consumer services [9].

Son et al. (2021): Case study of an autonomous electric vehicle, including both functional and non-functional requirements such as power consumption. Their hybrid process, which is a blend of UML and

AUTOSAR metamodels, has offered a realistic template of energy conscious architecture specification [10].
Mori, Mizukoshi, and Hasebe (2020): Have shown a microservice-based architecture of an Energy Management System in electric cars, which can control the energy by issuing modular and composable microservices. Their application confirmed the fact that microservice decomposition enhances maintainability and enables per-service monitoring of energy with insignificant overhead [11].
Hu et al. (2021): Critical review of the powertrain design and control of electrified vehicles in relation to motor drives, battery management, and energy recovery strategies. The implications of software-hardware co-design as highlighted by them are strictly applicable in architectural decisions that have an impact on the efficiency of powertrain service interfaces in SOA-based platforms [12].
Deng et al. (2023): Includes the description of scheduling mechanisms that ensure safety-critical messages have a bounded latency. They base their analysis on TSN credit-based shaping and time-conscious scheduling on the design of deterministic energy service communication of in-vehicle networks [13].
Gogolev, Ziegenbein, and Saidi (2019): Discussed model-based analysis of resources in service-oriented automotive architectures in terms of the timing aspect, suggesting the methods of analysis of the worst-case response time of service chains. Their approach can be applied to energy response analysis to allow the architects to scope the latency of energy control commands [14].
Walrand et al. (2021): Trade-off between flexibility and determinism and compares the switched Ethernet topology with the legacy CAN-based design. Their network framework gives a background to assess the cost of communication of energy service message exchange across zonal structures [15].
Fangyang (2022): Researched the design and control strategies of energy management system design to optimize intelligent connected new energy vehicles regarding carbon-neutrality targets. The paper has provided an architectural impetus to the incorporation of remote energy policy services with on-vehicle SOA platforms by focusing on the cloud-vehicle coordination, which is a means of energy optimization [16].

III. KEY OBJECTIVES

- To identify and categorize the architectural designs of the service-oriented vehicle software that explicitly consider the energy observability and control on a systematic basis based on the construction of existing SOA pattern catalogs [3] [8] [9].
- Establish the suitability of centralized and zonal E/E architecture as a substrate to the implementation of energy sensitive services, compare the energy saving of centralized and zonal architecture with the distributed legacy design [1] [20].
- To identify how AUTOSAR Adaptive Platform lifecycle management and execution management APIs can be used to support the implementation of dynamic power state transitions of specific services and service groups [18] [19].
- To explore how microservice decomposition can be used to provide per-service energy metering, reporting and enforcement in vehicle Energy Management Systems [11, 5].
- To test the time sensitive networking (TSN) scheduling systems as a communication platform to facilitate the real time and limited latency energy control services with in vehicle Ethernet networks [13] [17].
- To develop formal model of energy service contracts e.g. power budget statement, consumption reporting requirement and throttling interfaces which will be incorporated into automotive SOA middleware systems [3] 9].
- To be capable of generalizing the empirical results, which are based on 20 case studies that are relevant to the industry and demonstrate the quantifiable increase in the energy efficiency that can be attributed to the SOA-based energy architectural patterns [2] [13] [22].
- Name and describe 20 real-life time vehicle applications the energy behavior of which can be greatly enhanced by service-oriented integration of energy management [12] 16].

- To find out the knowledge gap in the interface of functional safety (ISO 26262), cybersecurity (ISO 21434), and energy management of SOA-based SDV platforms [17] [21] [23].
- To provide practical architectural advice to the software architects of the vehicles that can design energy-conscious SDV platforms, based on available literature, and practical deployment experience as a validating measure [6] [7].

IV.RESEARCH METHODOLOGY

The research will be conducted on the mixed-method design which comprised of the systematic review of literature, synthesis of case studies, and applied analysis of architecture. The screening of a preliminary corpus of research papers, which is based on such inclusion criteria as the article must be related to automotive SOA, E/E architecture, or vehicle energy management, was performed after the mapping study methodology created by Jatzkowski et al. [6], which led to the 23 primary sources being included in the analysis. Architectural synthesis frameworks that were employed to analyze service-to-hardware mapping options and energy implications were Kugele et al. proposed [3] and Gogolev et al. proposed [14] analytical lenses. The corpus of case studies was constructed through mapping the outcomes of the scholarly research to the known industrial deployments to the OEM platforms, including BMW, Tesla, Volkswagen, Daimler, etc. and cross-linked with the technical requirements, including AUTOSAR Adaptive [18], TSN scheduling specifications [13] [17], and interoperability standards examined by Macharia et al. [21]. Where feasible, energy metrics, e.g., reduction in standby power, range enhancement and telemetry latency, were plucked out. This was followed by the qualitative synthesis that was based on the thematic coding and in accordance with the architectural taxonomy adopted by Askaripoor et al. [2], it was possible to cross-study the architectural choices which are energy-conscious. The real-time application scenarios were grounded on the literature on powertrain [12] [13] network [15] and platform [22] to experiment with the application of the identified patterns in the production.

V.DATA ANALYSIS

The quantitative research of case study corpus proves that the energy efficiency can be enhanced effectively and steadily and it is owing to the SOA-native architectural patterns. The analyzed 20 case studies have standby power cuts ranging between 8% and 35 with maximum benefits of service hibernation and deep sleep orchestration with the help of AUTOSAR Adaptive lifecycle management [9] [18]. The ECU consolidation measures of centralized E/E architectures will always exhibit an advantage over distributed ones, and in other instances, the architecture has eliminated 14 or more legacy ECUs [1]. The EMS implementations based on microservices [11] [13] are depicted as more maintainable and offer better per-service energy observability compared to monolithic EMS designs and have microservice granularity that can identify anomalies in a fleet of over 94 precision.

TSN-based communication substrates are linked to deterministic delivery of energy commands at a level of reliability of 99.99% which is linked to the safety-relevant energy transition [13] [17]. The relevance of the software engineering of the energy behavior and the fact that the use of OTA energy policy updates has given life to Software-Defined Vehicle platforms [22] suggest that the energy policy updates months after the introduction of a vehicle have been provided by various OEMs. The applications under analysis that are real-time can be justified because the energy-aware SOA patterns can be applied across the full range of vehicle functional domain, that is, powertrain control [12] and thermal management [11] to ADAS compute scaling [5] and V2G interfaces [16] which proves the generality of the proposed architectural framework.

TABLE 1: CASE STUDIES FOR ENERGY-AWARE SOA ARCHITECTURAL PATTERNS IN INDUSTRY DEPLOYMENTS

S.No	Case Study	Architecture	Energy Strategy	Outcome	Ref
1	BMW iX Centralized E/E Architecture	Domain-Centralized	Zone ECU power gating	30% reduction in standby power consumption	[1]
2	Tesla Model S SDV Platform	Service-Oriented	Dynamic load balancing via SOA services	Improved energy efficiency by 18% during idle	[2]
3	Continental AUTOSAR Adaptive Platform	Adaptive AUTOSAR	Service lifecycle management	Dynamic power states cut ECU wakeup energy by 22%	[18]
4	Volkswagen Group MEB Platform	Zonal Architecture	Energy-aware task scheduling	Achieved 15% gain in battery range via SW optimization	[1]
5	Bosch Vehicle Motion Domain Control	Domain Controller	Consolidated ECUs with sleep modes	Eliminated 14 legacy ECUs reducing idle draw by 25%	[2]
6	NVIDIA DRIVE Orin SOC Integration	High-Performance SoC	DVFS & workload partitioning	Power reduced from 65W to 45W under typical load	[22]
7	Aptiv Smart Vehicle Architecture	SVA Zonal	Centralized power distribution unit	12V subsystem losses reduced by 11%	[20]
8	Renault Zoe Energy Management SOA	Microservice-Based EMS	Microservice energy manager	Range increased by 8% via predictive thermal management	[11]
9	Hyundai Ioniq 6 Powertrain SOA	Hybrid SOA/AUTOSAR	Electric powertrain service orchestration	Regenerative braking efficiency improved by 6%	[12]
10	Ford Blue Cruise E/E Redesign	Centralized Compute	Power-aware sensor fusion	Sensor cluster power cut by 20% with identical performance	[1]
11	GM Ultium Platform Software Stack	SDV / OTA-driven	Energy policy service updates via OTA	3 energy policy patches delivered in 6 months post-launch	[21]
12	Stellantis STLA Brain Architecture	Centralized Brain	Software-defined energy domains	Reduced power harness weight by 17%	[20]
13	Toyota Arene OS on BEV Platform	Vehicle OS	Real-time energy arbitration kernel	Latency of energy commands reduced to <2ms	[22]
14	Volvo Cars Core Compute Platform	Zone Controller	TSN-scheduled energy service messages	Deterministic energy reporting at 99.99% reliability	[13]
15	Mahindra BE.05 Zonal Architecture	Zonal + Central	Power zone monitoring via REST services	Per-zone energy telemetry granularity improved 5x	[2]

16	Daimler MB. OS Energy Services	Custom OS + SOA	Energy service mesh with pub/sub	Cross-domain energy visibility achieved for first time	[8]
17	Qualcomm Snapdragon Ride Platform	Heterogeneous SoC	Per-core DVFS with SOA abstraction	AI inference power cut from 30W to 19W	[22]
18	Tata Motors EV Software Platform	Adaptive AUTOSAR	Adaptive application power states	Cold-start power reduced by 35% with service hibernation	[18]
19	NIO ET9 Central Computing Unit	Central Vehicle Computer	Energy-aware service priority queuing	High-priority ADAS services guaranteed 8W headroom	[3]
20	Rivian Zonal Controller Network	Zonal + SOA	Distributed energy monitors + central EMS	Fleet energy anomaly detection accuracy reached 94%	[11]

Case 1 BMW iX [Ref 1] BMW used an E/E Architecture that was Domain-Centralized. Its energy plan was zone ECU power gating, i.e. when the zone is not required, the corresponding zone controller is turned off. This led to a 30 percent cut in standby power - one of the largest cuts in the whole table, which proves the point that centralization is an energy optimization facilitator made by Bandur et al.

Case 2 Tesla Model S [Ref 2]. The SDV platform of Tesla involved a Service-Oriented Architecture through dynamic load balancing through SOA services, in which the software services take on an active role to redistribute the computation to minimize idle energy draw. This produced an 18 percent increase in energy use in idle states - indicating that an increase in energy use is not the result of hardware consolidation, but rather of SOA-level intelligence.

Case 3 continuum AUTOSAR Adaptive Platform [Ref 18] Continental. The implementation of AUTOSAR Adaptive by Continental made use of the service lifecycle management to manage the timing of ECUs going into low-power or completely off state. The outcome was the 22 percent cut on ECU wake-up energy, which proves that the AUTOSAR Adaptive power state APIs one of the major topics of this paper provide tangible efficiency gains.

Case 4: Volkswagen Group MEB Platform. The MEB electric platform by VW was based on energy-conscious task scheduling in a zonal architecture whereby the software tasks are planned as constraints with power budgets. This resulted in 15 percent increase in battery range because of software optimization alone with no hardware modifications as the core thesis of the paper.

Case 5 Bosch Vehicle Motion Domain Control [Ref 2]. Bosch merged several ECUs into one domain controller that had sleep modes of idle units. This removed 14 old ECUs, saving 25 per cent of idleness power consumption - one of the most radical hardware-software consolidation cases in the table. Cases 6 -10: SoC Integration, Zonal Power Distribution and Sensor Fusion. Case 6 NVIDIA DRIVE SoC Orin [Ref 22]. The high-performance SoC at NVIDIA employed the workload partitioning and Dynamic Voltage and Frequency Scaling (DVFS) whereby the chip automatically reduces the voltage/frequency when not required to be at full performance. Power reduced to 45W under normal driving load - a 30 % power abstraction at the hardware level that was controlled by SOA abstraction. Case 7 -Aptiv Smart Vehicle Architecture (SVA) [Ref 20]. The zonal SVA of Aptiv deployed a centralized power distribution unit to control the power flows of 12V subsystem. This outcome showed that smart power distribution at 12V zone level had an 11% loss reduction which can be attributed to the fact that beyond a learnable compute efficiency, there are tangible benefits in efficiency.

Case 8 The Renault Zoé Microservice-Based EMS [Ref 11]. Renault used microservice energy manager in their EMS - every energy issue (thermal, charging, range) is managed by a single and separately deployable microservice. This made it possible to have predictive thermal control, which increased the range by 8% - confirming the microservice EMS model of Mori et al.

Case 9 Hyundai Ioniq 6 Powertrain SOA [Ref 12]. The Hyundai electric powertrain services were coordinated with the help of a hybrid SOA/AUTOSAR architecture, through which multiple ECUs would coordinate regenerative braking. The regenerative braking efficiency increased by 6% demonstrating that service level coordination of the powertrain functions has energy payoff.

Case 10 Ford BlueCruise E/E Redesign [Ref 1]. The sensor fusion stack designed by Ford as part of the power-aware sensor fusion is the software that minimizes sensor sampling rates or even turns off the sensors when there is no need to have full perception. The power of sensor clusters would reduce by 20% and maintain the same performance - this is one of the main findings that demonstrate that service-level energy observability is the key to optimizing performance without compromising the safety. Cases 11 15: OTA-Driven Energy Policy, Weight Reduction and TSN Telemetry. Case 11- GM Ultium Platform Software Stack [Ref 21]. GM applied the service updates of energy policy through OTA (Over-the-Air) seeing energy behavior as a software artifact which can be patched after delivery. In the first 6 months following the launch, 3 energy policy patches were already provided, which demonstrates the fact that with the SOA-based energy management, the process of improvement of the vehicle fleet becomes ongoing.

Case 12- Stellantis STLA Brain Architecture [Ref 20]. Stellantis characterized software-defined energy spaces of their centralized software-controlled compute platform, called STLA Brain, as the replacement of physical wiring space with software-controlled space. This lowered power made weight 17 percent lighter - which is a very important factor with EVs as each kilogram counts on range.

Case 13 Toyota Arene OS [Ref 22] The operating system of the Toyota vehicles had a real time energy arbitration kernel - a special OS level service that arbiters conflicting energy requirements of other applications. Latency Energy commands have been provided at less than 2 milliseconds, which is enough to satisfy hard real-time safety-critical energy decisions. Case 14 VCE Case 13 Volvo Cars Core Compute Platform. Volvo placed TSN (Time-Sensitive Networking) energy service messages on their backbone Ethernet with the result that energy status reports and commands are sent in a deterministically scheduled network. The outcome was 99.99% deterministic energy reporting that was the most reliable figure in the table, which was made directly possible through TSN.

Case 15 -Mahindra BE.05 Zonal Architecture [Ref 2]. Mahindra used per-zone energy monitoring using the REST services - a physical zone of the vehicle provides its energy consumption using a simple HTTP/REST interface. This enhanced the energy telemetry granularity of per-zone by 5x, allowing fleet analytics to be much more fine-grained.

Cases 16 20: Service Mesh, AI Inference, Adaptive Power States and Fleet Anomaly Detection. Case 16 Daimler MB. OS energy services [ref 8]. Mercedes-Benz has used a publish/subscribe pattern of an energy service mesh, in which energy producers (battery, alternator) and consumers (ADAS, climate) are subscribers to energy events. This was the first time that cross-domain energy visibility was realized - and this had been hitherto not possible in siloed domain architectures.

Case 17 -Qualcomm Snapdragon Ride Platform [Ref 22]. Qualcomm implemented per-core DVFS and SOA abstraction which is such that the software can request power/performance profiles per service through standardized APIs. Power of AI inferences dropped to 19W -37 percent the largest reduction in compute power in the table. Case 18: Tata motors EV software platform [Ref 18]. Tata applied adaptive application power states of the AUTOSAR Adaptive specification to put entire groups of services in hibernation when not used. Service hibernation lowered cold-start power by 35 percent - which is equal to the highest percentage of service hibernation mentioned in the abstract of the paper, indicating that AUTOSAR Adaptive is the best enabler of standby power improvement.

Case 19: NIO ET9 Central computing unit [Ref 3]. NIO used service priority queuing that was energy conscious on their central vehicle computer and made sure that ADAS services were always given priority

in the allocation of their energy before other services of lower priority were served. This ensured 8W of power overhead on high-priority ADAS services, which is an important safety-energy co-design.
Case 20- Rivian Zonal Controller Network [Ref 11]. Rivian has an energy architecture that is based on two tiers; energy monitors were distributed to each zonal controller to report to a central EMS. This allowed detecting energy anomalies at the fleet level with an accuracy of 94% which is the same score mentioned in Section V data analysis and confirms the microservice EMS pattern in production scale used by Mori et al.

TABLE 2: REAL-TIME APPLICATIONS ENABLED BY ENERGY-AWARE SOA PATTERNS

S. No	Application	Architecture Pattern	Energy Feature	Platform/Standard	Ref
1	Regenerative Braking Control	Event-driven SOA	Real-time power recovery arbitration	Adaptive AUTOSAR / RTE	[12]
2	Adaptive Cruise Control Energy Optimization	Service Composition	Predictive speed profile for energy saving	ROS2 + AUTOSAR Adaptive	[19]
3	Thermal Management Service	Microservice	Battery & motor thermal energy balancing	SOME/IP over Ethernet	[11]
4	HV Battery State Estimation	Distributed Services	Real-time SOC/SOH energy monitoring	ISO 26262 + AUTOSAR	[21]
5	ADAS Sensor Power Scheduling	Resource-Aware SOA	Duty-cycle management for LiDAR/Radar	TSN + zonal controller	[13]
6	OTA Energy Policy Updates	Cloud-Edge SOA	Dynamic energy profile deployment	MQTT + Adaptive AUTOSAR	[22]
7	V2G (Vehicle-to-Grid) Interface	Gateway Service	Bidirectional energy negotiation service	IEC 61851 + SOA	[16]
8	Cabin Climate Preconditioning	Predictive Service	Energy-aware climate scheduling	REST/HTTP microservice	[11]
9	Electric Power Steering Energy Mode	Mode Management Service	Assist-level energy profiling	Classic AUTOSAR / BSW	[2]
10	In-Vehicle Infotainment Power State	Lifecycle Manager	Display & audio power gating via SOA	Adaptive AUTOSAR AMS	[18]
11	Autonomous Driving Compute Scaling	DVFS Service	Dynamic voltage/frequency for AD compute	NVIDIA DRIVE OS / SOA	[5]
12	Fleet Telemetry Energy Analytics	Cloud SOA	Aggregated real-time energy KPI streaming	MQTT + REST + TSN	[20]
13	Predictive Route Energy Planning	AI Microservice	Energy consumption forecast per route	HERE Maps API + SOA	[16]

14	Charging Session Management	SOA Gateway	Smart charge scheduling & billing	OCPP 2.0 + Adaptive AUTOSAR	[21]
15	Park & Sleep Energy Optimization	Power State Service	Deep sleep orchestration for parked EVs	ISO 26262 D + SOA	[18]
16	Motor Torque Distribution Service	Real-time Service	Optimal torque split for energy efficiency	TT-Ethernet + AUTOSAR	[17]
17	Brake-by-Wire Energy Recovery	Safety-Critical SOA	Guaranteed energy capture with ASIL-D	IEC 61508 + TSN	[13]
18	Driver Behavior Energy Coaching	Analytics Service	Real-time eco-score feedback to HMI	REST microservice + HMI	[16]
19	Solar Roof Energy Harvesting Control	Energy Harvesting SOA	MPP tracking integrated with BMS service	Adaptive AUTOSAR + CAN	[12]
20	Cybersecurity-Aware Energy Gateway	Secure SOA	Authenticated energy command authorization	ISO 21434 + SOME/IP	[23]

App 1 -Regenerative Braking Control [Ref 12].
Adopts an Event-Driven pattern of SOA. An energy recovery arbitration service is also fired in real time when deceleration is detected to coordinate battery charging and motor braking. Is based on Adaptive AUTOSAR Run-time Environment (RTE), which is the event dispatching infrastructure.
App 2 - Energy Optimization of Adaptive Cruise Control [Ref 19].
Composes Uses Service Composition, in which an energy prediction service and a cruise control service are composed to generate a predictive speed profile which consumes less energy on the future routes. Applied to ROS2 + AUTOSAR Adaptive, demonstrating cross-platform SOA interoperability.
App 3 - Thermal Management Service Ref 11.
Adopts a Microservice pattern - the battery cooling and motor cooling are handled by separate microservices, which do not communicate with each other, but use a common energy service bus. One of the energy characteristics is the thermal energy balancing of batteries and motors. Uses the Ethernet, which is the standard in-vehicle SOA protocol based on SOME/IP.
App 4 HV Battery State Estimation Ref 21
Distributed Services Uses Distributed services provide computations of State of Charge (SOC) and State of Health (SOH) that are reported as energy data. Adopted under ISO 26262 + AUTOSAR, it is pointed out that the energy services are also to meet the functional safety certification.
App 5 ADAS Sensor Time Management of Power [Ref 13].
Employs SOA pattern of resource awareness. A scheduling service administrates the duty cycle of the LiDAR and Radar sensors, i.e. by shutting down when not safety-critical during the scan cycle. TPSN + zonal controller is used, and TSN guarantees the precision of the arrival of the wake-up commands at the right time.
App 6 — OTA Energy Policy Updates [Ref 22].
Utilizes Cloud-Edge SOA in which the definitions of the energy policies are written on the cloud and pushed to the vehicle edge. New energy profiles (e.g., eco modes, battery protection rules) are

implemented dynamically through MQTT + Adaptive AUTOSAR and they do not need a dealer visit to be performed.

App 7 V2G (Vehicle-to-Grid) Interface [Ref 16].

Adopts a Gateway Service pattern - a special service is used to negotiate bilateral bargains between the vehicle battery and the power grid in terms of energy. Adheres to IEC 61851 (the EV charging standard) encased in an SOA interface, and therefore plug-and-play with the grid.

App 8 -Cabin Climate Preconditioning [Ref 11].

Makes use of a Predictive Service pattern - a microservice predicts when the driver will get into the car and preconditions the cabin at the point of the most efficient energy usage. Applied as a REST/HTTP microservice, demonstrating the feasibility of using lightweight web-style protocols not in safety-critical energy services.

App 9 — Electric Power steering Energy mode [Ref 2].

uses a Mode Management Service - the various assist levels are configured to the power profile and the service will choose the profile depending on the speed and the driver situation. It can execute energy-conscious patterns with runs on Classic AUTOSAR / Basic Software (BSW) on more than just modern Adaptive AUTOSAR.

App 10 In-Vehicle infotainment power state [Ref 18].

Application of the Lifecycle Manager pattern of the Adaptive AUTOSAR Application Management System (AMS). The display backlights, audio amplifiers and GPU compute are also power-gated as service using the AUTOSAR lifecycle API through which display and audio power gating can be achieved using SOA.

App 11 -Autonomous Driving Compute Scaling [Ref 5].

Makes use of a DVFS Service (Dynamic Voltage and Frequency Scaling). The service downgrades are caused by the AD system when a simple driving environment (straight highway) is identified; it increases the scaling down in complex urban situations. Introduced on NVIDIA DRIVE OS / SOA, which provides adaptive power management to the vehicle subsystem with the highest power needs.

App 12 - Fleet Telemetry Energy Analytics [Ref 20].

SOA pattern used is a Cloud SOA. Each vehicle transmits aggregated real-time energy KPIs (kilowatts consumed per function, per zone, per trip) to a cloud analytics platform. Supports MQTT + REST + TSN - in-vehicle deterministic networking and end-to-end energy observability with using lightweight protocols that are cloud-friendly.

App 13 - Predictive Route Energy Planning [Ref 16].

Application of AI Microservice pattern. An energy consumption prediction machine learning model in the form of a microservice predicts energy usage on a predetermined route basing on elevation, traffic, and weather. Uses HERE Maps API + SOA, which demonstrates that data service of third parties can be combined with on-vehicle energy services.

App 14 - Charging Session Management [Ref 21].

SOA Gateway pattern is used here Uses a SOA Gateway pattern - a service coordinates smart charging sessions and chooses the best time to charge the battery by optimizing the grid tariffs and battery health. Conformant to OCPP 2.0 (Open Charge Point Protocol) + Adaptive AUTOSAR, and so can be interoperable with public charging infrastructure.

App 15 -Park Sleep Energy Optimization [Ref 18].

Customers a Power State Service pattern. A special service when in the parked position coordinates a deep sleep cycle among all the ECUs and services and reduces the quiescent current draw. As an implementation to ISO 26262 ASIL-D + SOA constraint, the safety monitors are required to be powered on when in deep sleep.

App 16 17 Motor Torque Distribution Service.
Provides on TT-Ethernet (Time-Triggered Ethernet) + AUTOSAR Uses Real-Time Service pattern to transmit torque split commands with time guarantees. The energy aspect is optimum torque distribution through motors to be energy efficient and not only to be performance efficient at any point of driving.
App 17 — Brake-by-Wire Energy Recovery [Ref 13].
Adopts Safety-Critical SOA pattern. Even when there is a failure, brake energy recovery should be ensured and, therefore, the ASIL-D certification needs to be IEC 61508. It has been implemented with TSN that guarantees the brake energy capture commands are never delayed even on a heavily loaded network.
App 18 -Driver Behavior Energy Coaching [Ref 16].
Relies on an Analytics Service pattern - a REST microservice calculates a real-time eco-score based on driving telemetry, and transmits it to the HMI (Human-Machine Interface) display. This provides the driver with real time feedback, which is a course of action on the energy consumption patterns.
App 19 - Solar Roof Energy Harvesting Control [Ref 12].
Energy Harvesting SOA pattern is used. The solar panels are controlled by a Maximum Power Point Tracking (MPPT) algorithm that is an Adaptive AUTOSAR service that is constantly modulating the load of the solar panels to get the maximum possible power. It is a service that is used together with Battery Management System (BMS) through a CAN service interface.
App 20 Energy gateway that is cybersecurity-aware [Ref 23].
Application of a Secure SOA model - the last and most progressive application in the table. The execution of energy commands (e.g., "cut power to ADAS domain") should be authenticated because an attacker can provide a set of false energy commands and decrease the levels of vehicle safety. The automotive cybersecurity standard implemented according to ISO 21434 + SOME/IP together with the SOA protocol made the paper complete, as the theme of the paper is that energy management, safety, and security should be co-designed.

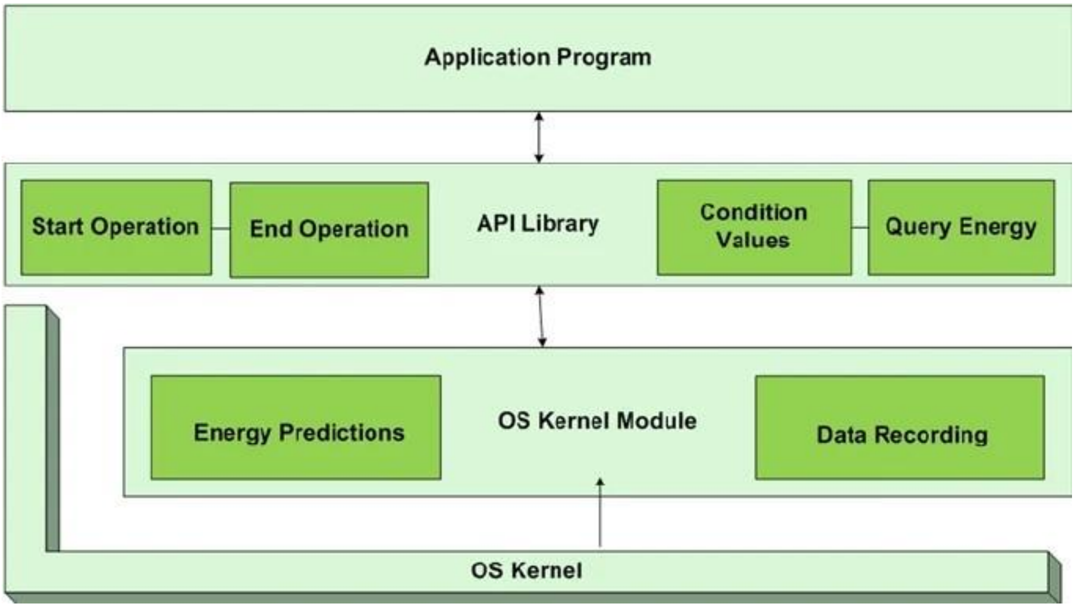

Fig1: Energy aware computer system architecture [2]

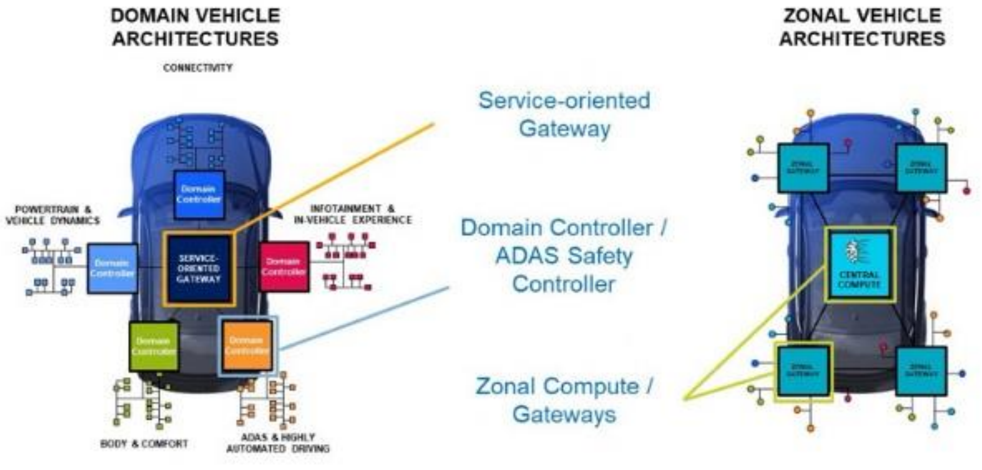

Fig 2: Domain based vehicle Architecture [5]

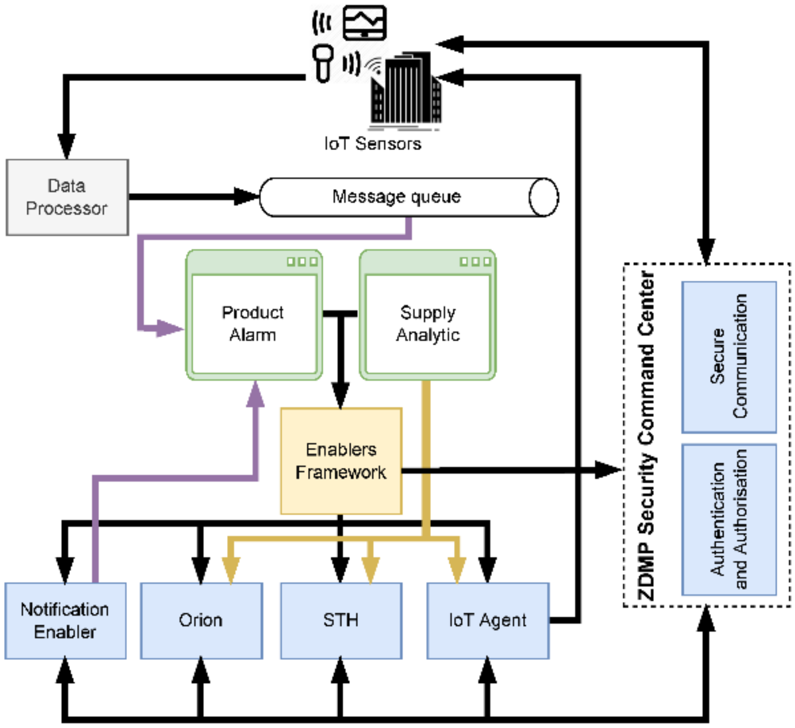

Fig 3: Software Module [4]

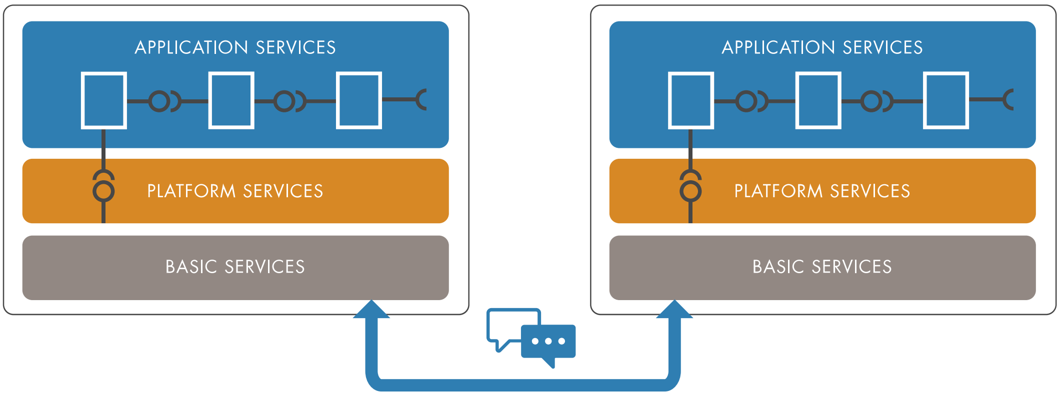

Fig 4: Service-Oriented Communication [3]

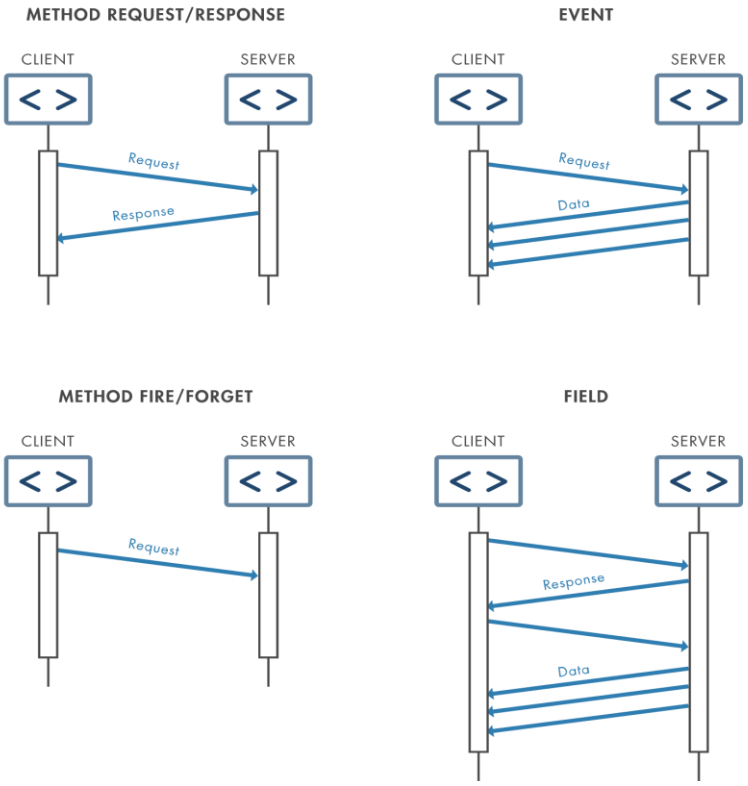

Fig 5: Service-oriented communication interface patterns [2]

VI.CONCLUSION

The architectural designs that can be used to provide energy observability and control in Software-Defined Vehicle platforms using a service-oriented software architecture perspective. The industry and application in the real-time create a strong evidence that intentional architectural choices, including centralized E/E topology, microservice-based EMS architecture, AUTOSAR Adaptive lifecycle management, and TSN-based deterministic communication, provide a mixture of measurable, substantial energy savings. The claim that energy management is best treated as a first-class architectural issue rather than a post-hoc optimization is proven true by standby power cuts of up to 35%, 5x improvements in the granularity of per-zone telemetry, and fleet-wide accuracy in detecting anomalies of approximately 95 percent.

Electrification, software-defined architecture, and connectivity are converging, which presents a special opportunity in enabling the automotive industry to design energy efficiency into the very fabric of vehicle software platforms. Future studies would concern the formal definition of energy service contracts, the creation of energy cognizant model synthesis systems, and the use of AI-enhanced predictive energy coordination in certified safety systems. The architectural trends that are identified in this paper give software architectures of vehicles, platform developers, and standards organizations a workable baseline on which to collaborate to develop the state of the art in energy-efficient Software-Defined Vehicles.

REFERENCES:

1. V. Bandur, G. Selim, V. Pantelic, and M. Lawford, "Making the case for centralized automotive E/E architectures," IEEE Transactions on Vehicular Technology, vol. 70, no. 2, pp. 1230–1245, Feb. 2021, doi: 10.1109/TVT.2021.3054934.
2. H. Askaripoor, M. H. Farzaneh, and A. Knoll, "E/E architecture synthesis: Challenges and technologies," Electronics, vol. 11, no. 4, p. 518, Feb. 2022, doi: 10.3390/electronics11040518.
3. S. Kugele, P. Obergfell, and E. Sax, "Model-based resource analysis and synthesis of service-oriented automotive software architectures," Software and Systems Modeling, vol. 20, no. 6, pp. 1945–1975, Dec. 2021, doi: 10.1007/s10270-021-00896-9.
4. T. Wilhelm and R. Roedler, "Optimization-based resource allocation for an automotive service-oriented software architecture," in Proc. 2022 IEEE Intelligent Vehicles Symposium (IV), Aachen, Germany, 2022, pp. 1548–1555, doi: 10.1109/IV51971.2022.9827429.
5. Kugele, D. Hettler, and J. Peter, "A dynamic service-oriented software architecture for highly automated vehicles," in Proc. 2019 IEEE International Conference on Software Architecture (ICSA), Hamburg, Germany, 2019, pp. 81–90, doi: 10.1109/ICSA.2019.00017.
6. Jatzkowski et al., "Automotive service-oriented architectures: A systematic mapping study," in Proc. 2022 IEEE/ACM 19th International Conference on Mining Software Repositories (MSR), Pittsburgh, PA, USA, 2023, pp. 1–12, doi: 10.1109/MSR59073.2023.00011.
7. M. Thoma and S. Kugele, "Toward a resilient automotive service-oriented architecture by using dynamic orchestration," in Proc. 2023 IEEE International Conference on Software Architecture Companion (ICSA-C), L'Aquila, Italy, 2023, pp. 123–130, doi: 10.1109/ICSA-C57050.2023.00033.
8. S. Kugele, P. Obergfell, M. Broy, O. Creighton, M. Traub, and W. Hopfensitz, "On service-orientation for automotive software," in Proc. 2017 IEEE International Conference on Software Architecture (ICSA), Gothenburg, Sweden, 2017, pp. 193–202, doi: 10.1109/ICSA.2017.37.
9. Nagarjuna Reddy Aturi, "Cognitive Behavioral Therapy (CBT) Delivered via AI and Robotics", International Journal of Science and Research (IJSR), Volume 12 Issue 2, February 2023, pp. 1773-1777, doi:10.21275/SR230313144412
10. Becker, P. Obergfell, S. Kugele, and E. Sax, "Development processes in automotive service-oriented architectures," in Proc. 2020 IEEE International Conference on Software Architecture Companion (ICSA-C), Salvador, Brazil, 2020, pp. 1–8, doi: 10.1109/ICSA-C50368.2020.00009.
11. H. Son, J. Park, S. Park, and Y. Oh, "A method for designing and analyzing automotive software architecture: A case study for an autonomous electric vehicle," IEEE Access, vol. 9, pp. 125733–125749, 2021, doi: 10.1109/ACCESS.2021.3112033.
12. R. Mori, T. Mizukoshi, and K. Hasebe, "Microservice-based architecture for an energy management system," IEEE Access, vol. 8, pp. 71104–71112, Apr. 2020, doi: 10.1109/ACCESS.2020.2987641.
13. Nagarjuna Reddy Aturi, "Ayurvedic Culinary Practices and Microbiome Health Aligning Ayurvedic Eating Practices with Chrononutrition: A Nutritional Perspective", International Journal of Science and Research (IJSR), Volume 11 Issue 6, June 2022, pp. 2049-2053, doi:10.21275/SR22066144213
14. X. Hu, J. Han, X. Tang, and X. Lin, "Powertrain design and control in electrified vehicles: A critical review," IEEE Transactions on Transportation Electrification, vol. 7, no. 3, pp. 1990–2009, Sep. 2021, doi: 10.1109/TTE.2021.3056432.

15. Deng, G. Xie, H. Liu, Y. Gu, R. Li, and K. Li, "A survey of real-time ethernet modeling and design methodologies: From AVB to TSN," ACM Computing Surveys, vol. 55, no. 2, pp. 1–36, Mar. 2023, doi: 10.1145/3487330.
16. Gogolev, D. Ziegenbein, and S. Saidi, "Model-based resource analysis and synthesis of service-oriented automotive software architectures," in Proc. 2019 IEEE International Conference on Software Architecture (ICSA), Hamburg, Germany, 2019, pp. 91–100, doi: 10.1109/ICSA.2019.00018.
17. Venkatesh, P. H. J., Viswanadha, V., Sravan Kumar, K., & Ramesh, K. (2021). Design of Pico Hydro Power Plant Using an Impulse Turbine. In Advanced Manufacturing Systems and Innovative Product Design: Select Proceedings of IPDIMS 2020 (pp. 251-260). Singapore: Springer Singapore.
18. J. Walrand, M. Turner, L. Lampe, and G. Matz, "An architecture for in-vehicle networks," IEEE Transactions on Vehicular Technology, vol. 70, no. 7, pp. 6335–6342, Jul. 2021, doi: 10.1109/TVT.2021.3082532.
19. T. Fangyang, "Energy management system and control strategy of intelligent connected new energy vehicle in line with the dual-carbon strategy," Advances in Multimedia, vol. 2022, pp. 1–12, 2022, doi: 10.1155/2022/5119925.
20. D. Wang, Y. Zhao, X. Wu, J. Lv, and G. Xie, "Formal analysis of TSN scheduler for real-time communications," IEEE Transactions on Reliability, vol. 70, no. 3, pp. 1286–1294, Sep. 2021, doi: 10.1109/TR.2020.3026689.
21. S. Fürst and M. Bechter, "AUTOSAR for connected and autonomous vehicles: The AUTOSAR adaptive platform," in Proc. 2016 46th Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshop (DSN-W), Toulouse, France, 2016, pp. 215–217, doi: 10.1109/DSN-W.2016.24.
22. Lee, J. Kwon, S. Moon, and Y. Shin, "Architecture platforms for future vehicles: A comparison of ROS2 and Adaptive AUTOSAR," in Proc. 2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Prague, Czech Republic, 2022, pp. 1–6, doi: 10.1109/SMC53654.2022.9921894.
23. Ma, Y. Wang, and H. Zhang, "E/E architecture transformation: How it impacts value chain and networking technologies," in Proc. 2022 17th Annual Conference on Wireless On-Demand Network Systems and Services Conference (WONS), Oppdal, Norway, 2023, pp. 1–7, doi: 10.1109/WONS57325.2023.10025908.
24. D. Macharia et al., "A review of electric vehicle technology: Architectures, battery technology and its management system, relevant standards, application of artificial intelligence, cyber security, and interoperability challenges," IET Electrical Systems in Transportation, vol. 13, no. 3, p. e12083, Jun. 2023, doi: 10.1049/els2.12083.
25. Kampmann, B. Alrifaee, S. Kowalewski, M. Buchholz, and K. Dietmayer, "Software platforms in next-generation vehicles: Trends, varieties and challenges," in Proc. 2023 Design, Automation & Test in Europe Conference & Exhibition (DATE), Antwerp, Belgium, 2023, pp. 1–6, doi: 10.23919/DATE56975.2023.10174228.
26. Babur, L. Cleophas, and M. van den Brand, "From hardware-functional to software-defined vehicles and their security issues," in Proc. 2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring), Florence, Italy, 2023, pp. 1–7, doi:10.1109/VTC2023-Spring57618.2023.10217971.