27th INTERNATIONAL DEPENDENCY AND STRUCTURE MODELING CONFERENCE, DSM 2025
HOBOKEN, NJ, USA, 24 – 26 September, 2025

Vehicle Software Configuration Strategies for SDVs: A Comparative Analysis of On-Board and Off-Board Methods

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Abstract: The increasing complexity and variability of modern vehicles require advanced methods for software configuration through parameter management. With the ongoing transition toward Software-Defined Vehicles (SDVs), new challenges and requirements arise, necessitating a reassessment of current vehicle configuration strategies. Against this backdrop, this paper investigates the comparative advantages and disadvantages of performing vehicle software configuration via parameters either on-board (directly on the vehicle) or off-board (via backend systems) at the example of an automotive OEM. We define two distinct configuration processes - one conducted on-board, the other off-board - and evaluate them through criteria assessed by industry experts. Additionally, we determine the optimal scope of configuration data for the case of on-board configuration. Our analysis reveals that for an OEM characterized by high production volumes, substantial variant diversity, and the traditional way of parameter handling, the benefits associated with an off-board configuration process significantly outweigh those of an on-board approach.

Keywords: Configuration Management, Embedded Software, Software-Defined Vehicle, Automotive

1 Introduction

The automotive industry is currently undergoing a significant transformation, shifting from traditional, mechanically-oriented vehicles towards Software-Defined Vehicles (SDVs). Consumers increasingly expect not only mechanical reliability but also digitally intelligent vehicles capable of continuous updates and integrating new functionalities throughout their lifecycle (Aust, 2022). With innovation increasingly driven by software rather than hardware, vehicle components must adapt accordingly. This transformation, however, is neither trivial nor straightforward - it represents a substantial paradigm shift, especially concerning electric/electronic (E/E) architectures (Sieben et al., 2024). These new architectures must support new requirements of SDVs e.g. Over-the-Air (OTA) updates. Consequently, established automotive manufacturers face considerable challenges, necessitating a thorough reassessment of their conventional practices and the adoption of entirely new strategies. A central challenge in this context is vehicle software configuration. Given the extensive variety of vehicle variants and increasing customization demands, OEMs employ software solutions that can be adapted via parameters to meet individual customer specifications. Parameters enable manufacturers to activate or deactivate functionalities, adjust control behaviors, and define distinct performance characteristics (Wozniak and Clements, 2015). Historically, this configuration process has been executed off-board, at the production line, where parameters and configuration elements are preprocessed in the backend, tailored to specific vehicle variants, and subsequently installed during manufacturing. As a result, vehicles inherently lack awareness of their configurations, receiving only predefined parameters. However, the customer-driven requirement for OTA updates significantly alters this traditional approach, demanding software updates and consequently parameter adjustments even long after a vehicle leaves the production line (Stoll et al., 2021). This evolution raises critical questions: Is the traditional off-board software configuration method still suitable for SDVs and OTA updates? If not, what constitutes a more sustainable, future-proof alternative? This paper directly addresses these questions by analyzing the potential advantages and disadvantages of adopting an on-board software configuration approach compared to the traditional off-board method. Unlike external preprocessing, which results in vehicle identification number (VIN) specific configuration files containing predefined parameters, the on-board method involves vehicles directly receiving a "150 % data package" that includes parameters for multiple variants, subsequently interpreting this data independently. Configuration tasks would thus shift from the backend into the vehicle itself, enhancing the intrinsic awareness of the vehicle regarding its configuration status.

In this paper, we present two concepts for software configuration using parameters. The first concept is based on an off-board approach, in which parameterization is performed in the backend. This method is currently used in practice, including at Volkswagen. The second concept adopts an on-board approach, where parameterization is executed directly on the vehicle using a powerful computing unit. The key difference between the two approaches lies in the location of parameter calculation and application. As part of our investigation, we first determine the optimal scope of parameter data that needs to be transferred to the vehicle within the on-board approach. Building on this, we systematically compare both concepts using a set of defined evaluation criteria. The results of this comparison provide a sound basis for deciding between configuration strategies and highlight the contextual conditions under which alternative approaches should be considered. Furthermore, we derive potential research directions and opportunities for future work based on the insights gained.

The structure of this paper is as follows: Chapter 2 introduces the identified research problem, derives the central research questions, and describes the methodology chosen to address them. Chapter 3 presents the results of our investigation and maps them to the respective research questions. Chapter 4 discusses these findings in terms of their implications for both practice and academia. Chapter 5 reviews related scientific work and outlines how our contribution differentiates from existing approaches. Finally, Chapter 6 summarizes the key insights and offers an outlook on future research directions.

2 Research Problem, Research Questions and Methodology

Modern generations of automobiles are mechatronic systems with a high degree of system complexity and a wide range of variants. In general, the automotive industry is characterized by highly varied products and high volumes like no other industrial sector. In the Volkswagen Group, the variance in model configuration is represented in PR-numbers (Primäre-Eigenschaften, German for "Primary Characteristics") and PR-families (Primäre-Ausstattungsfamilien, German for "Primary Characteristics Families"). This model configuration ensures the legal, sales and customer-specific requirements in the vehicle project and configures technically buildable and approvable vehicles. Customers experience this variance when using the vehicle configurator to assemble their individual vehicle of the respective corporate brand. There, they can select specific features in addition to equipment packages. Over time, these features have shifted from hardware-intensive options to increasingly software-based equipment options. However, quality requirements have remained, especially in the premium segment. After successfully configuring the desired vehicle in the configurator, a production order containing a PR-number string is created. This string is used to resolve the production bill of materials into a 100% buildable vehicle. During this process, all the necessary parts and ECUs, along with their associated parameterization, are pulled and supplied to production for processing. The build order indirectly performs the corresponding software configurations. Due to customer requirements for updated software throughout the product lifecycle, including post-series support, the updateability of vehicles is subject to changed demands. In addition to requiring current software and usability, customers also want additional functional features provided via OTA-updates. These features can also contribute to a positive business case for the company by offering additional features to customers for a fee throughout the vehicle's lifecycle.

One of the central topics of this research paper is software configuration management (SCM). Therefore, the fundamentals are first introduced and key terms are clarified to provide a basis for further study. Configuration management (CM) is a systems engineering (SE) process and product data management (PDM) supports configuration management by storing and managing data that defines and represents a product as a result of its development. This data is made available in subsequent phases of the product lifecycle, expanding to the product lifecycle management (PLM). The purpose of CM is to manage and control system elements and configurations over the life cycle. As part of overall system configuration management, SCM is a formal engineering discipline that provides the methods and tools to identify and control the software throughout its development and use. The scope of SCM activities encompasses the identification and establishment of baselines, the review, approval, and control of changes (American National Standards Institute et al., 2005). For consistent, traceable, and controlled development of complex systems across the lifecycle, model based systems engineering (MBSE) and configuration management complement each other. MBSE provides structured, model-based system descriptions, while CM/SCM ensures the control and traceability of these models and related artifacts. To manage system complexity and represent structured development in a model-based way, RFLP is an established method at Volkswagen. By clearly separating the requirements, functional, logical, and physical views across different abstraction levels, the RFLP approach enables a structured and systematic approach to system architecture. At all levels of the RFLP approach CM is required and applied. Our research builds on this approach and focuses primarily on the physical realization level, with an emphasis on software configuration, in particular the parameterization of software configurations. Based on the current car configuration process and the fundamentals of SCM, this research paper compares on-board and off-board configuration methods for software parameterization in SDVs. The goal is to efficiently meet customer requirements and OEM corporate interests through OTA updates. Within the Volkswagen Group, the established approach of off-board configuration is primarily applied under the current framework conditions. However, in the industry, there is a growing emphasis on methods that prioritize on-board configuration, with the goal of ensuring optimal support for the development of SDV.

Today, there is a significant deficit of research and analysis in science and industry comparing the on-board and off-board methods. This research paper addresses the overarching question: Is off-board configuration still suitable for the changed conditions of SDVs, or does on-board configuration better meet the requirements? As part of a scientific approach, this question was divided into three research questions, as shown in Figure 1. To address the three research questions, the methodology illustrated in Figure 1 was employed, and the assigned procedural steps were systematically carried out. Case studies, data analyses, interviews, and additional investigations were conducted within the context of the Volkswagen AG.

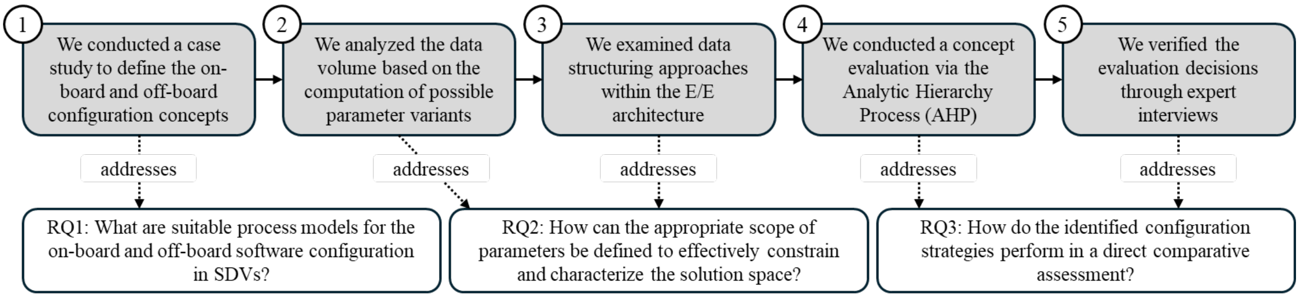

Figure 1. Methodology and Procedure for Answering the Research Questions

3 Results

The following chapters present the results of our study in alignment with the previously formulated research questions. The investigation was conducted using the case of Volkswagen AG as a representative example. Accordingly, the examples, processes, and procedures described refer to the conditions and practices at Volkswagen AG.

3.1 Research Question 1

To effectively compare the two configuration concepts - on-board and off-board - they first need to be clearly defined. It is crucial to ensure comparability regarding relevant characteristics. In our use case, configuration is understood purely as software configuration achieved through parameters and datasets. Therefore, to facilitate a valid comparison, the handling of software configuration must remain consistent across both concepts. The fundamental distinction between the two concepts thus lies in the location where vehicle-specific parameters and datasets are calculated and generated, as well as the associated implications. Both concepts share a common fundamental principle of software parameterization: parameters and datasets are assigned to specific vehicle features through a set of predefined rules. The difference between parameters and datasets lies in the level of aggregation: datasets consist of pre-grouped parameters that apply to multiple predefined, more general variants, often in the form of characteristic curves or maps, whereas parameters represent individual values that can vary between variants. These configuration rules are systematically stored and maintained within data containers (DC). Based on these rule sets, the appropriate parameters are selected for each specific vehicle. The selected parameters are subsequently written into the memory of the corresponding ECU. Within the software code, references exist that point to these memory locations and thus to the corresponding parameter values. Consequently, the management, referencing, and handling of the parameters within the software code remain unchanged in both concepts. The significant difference lies solely in whether the calculation of vehicle-specific data containers is executed directly within the vehicle itself (on-board) or in an external backend system (off-board). Despite those conceptual differences, there are fundamental requirements and process steps that must be fulfilled in both approaches. These include, first and foremost, the creation of a data container that encompasses all variant descriptions along with the associated parameters. Based on this container, a data package is created, which must then be transferred to the vehicle. Another essential step is the computation of the data container, which can take place either in the backend or directly on the vehicle. To comply with safety and security requirements, it is necessary to generate specific SFD (Schutz Fahrzeugdiagnose, German for "protected vehicle diagnostics") tokens, a secure digital key required for authorization, for each individual control unit. Additionally, the integrity of the data transmission must be verified by comparing a predefined target hash value with the actual hash value calculated in the ECU. Regardless of the data volume, it is crucial that the data is fully transferred to the vehicle and that the corresponding parameters are written into the appropriate control units. For the assignment of parameters to ECUs, a so-called Configuration Task is created. This task defines which control unit receives which parameters, along with the corresponding hash values.

Below, the two concepts are illustrated using the previously described steps, although presented in a different order and with slight modifications. Figure 2 depicts the process flow for backend-based calculation, representing the off-board concept. The subsequent Figure 3 illustrates the process flow when data containers and thus parameters are calculated directly on the vehicle.

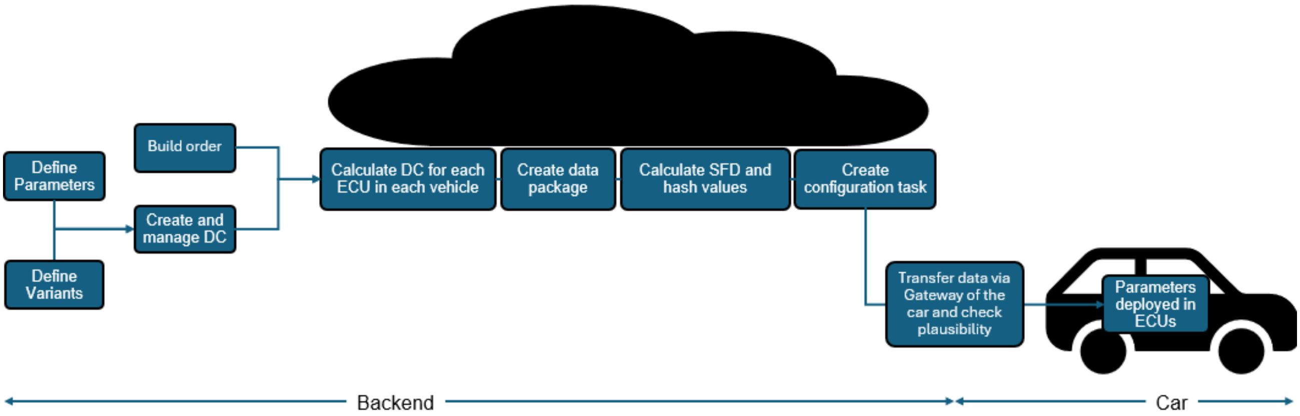

Figure 2. Off-Board Approach

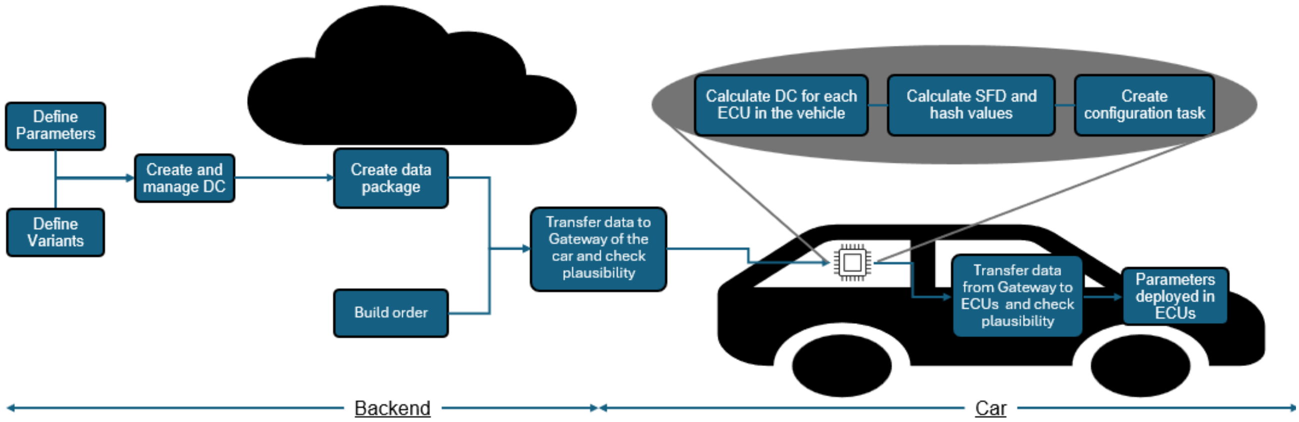

Figure 3. On-Board Approach

3.2 Research Question 2

The amount of data to be transferred is an important factor in the evaluation and comparison of on-board configurations. In order to assess the data package to be transmitted via OTA meaningfully, the data transmission solution space must first be defined. At this stage, the topology of the vehicle's E/E architecture must be considered. A vehicle can be divided into a "hat scope" and a "platform scope". The goal of a platform is to enable a high proportion of identical scopes to be used in different vehicles within a vehicle segment (synergy effects) and thus define a common technical basis for similar vehicles. In product documentation within the Volkswagen Group, a product is documented at various levels. The product level represents the highest level within the bill of materials and is depicted in a three-tier product class hierarchy: platform class, vehicle group class, and vehicle class. In the product development process, vehicles are represented and described in a derivative structure. The Volkswagen Group uses the group project description (KPB) to describe derivatives in a defined syntax. Electronic architectures are related to the "mechanical" platforms. An E/E architecture describes the structure and interconnection of all electrical and electronic components in a vehicle. It includes control units, sensors, actuators, and the communication networks between these components. The goal is to create a functioning overall system that reliably and efficiently supports vehicle functions. Electronic architectures differ in the number of functions they can represent, as well as in the various strategies for networking control units with each other.

The topology of the E/E architecture is structured into the E/E architecture base and associated E/E architecture variants. E/E architecture variants evolve over time with new features, creating new branches with extended functional scope. These E/E architecture variants are linked with functional models to establish traceability between the architecture and the offered functions. The E/E architecture base E^3V1.2 Premium currently includes several E/E architecture variants represented as clusters (e.g., CL 1-3, CL 6, etc.). In the current data model, vehicle derivatives/KPBs are assigned to an E/E architecture variant depending on the configuration time and model maintenance time. Together with the validity periods of the E/E architecture variant and the project information of the vehicle project, KPB-specific vehicle architecture variants and versions can be configured (e.g., AU416/xxx_x | SOP KW41/YY - KW47/YY "A"), corresponding to a 150 % topology. Documenting the E/E architecture variants offers the advantage of control across assigned vehicle derivatives/KPBs (170 % topology), instead of at the vehicle product level (150 %).

To meet the customer requirements for OTA updates, a suitable solution space for the data volume must be identified, aiming to transmit the data package (number of parameter variants) as efficiently as possible. For future vehicle generations, configuration parameters must be identified that limit the data volume of parameter variants to a solution space that meets the requirements for on-board configuration. For this purpose, an evaluation of the data volume (number of unique parameter variants) is conducted by analyzing current vehicle classes / TMAs of the E/E architecture base E^3V1.2 Premium. The analysis of the number of software parameter variants relative to the respective technical vehicle class shows significant differences within the E/E architecture base E^3V1.2 Premium. This result is unsurprising due to the differentiated model and segment selection within the E/E architecture base E^3V1.2 Premium. Transmitting the E/E architecture base E^3V1.2 Premium as a solution space is not considered because, at configuration time, each vehicle derivative is assigned to an E/E architecture variant. The number of parameter variants also varies among the E/E architecture variants within the E/E architecture base. Notably, the analysis reveals differences between model families/vehicle group classes (even within a single E/E architecture variant). From this internal company evaluation, it can be concluded that the model family is most suitable as a configuration scope for the on-board criterion "OTA Update - Size and duration of an update." In the current data model, there is no configuration option at model family level, as shown in Figure 4, which is why the data model is being further developed and the vehicle architecture variant adapted accordingly as part of this research work. It is recommended to document the vehicle architecture variant based on the model family in the data model, which means clustering several KPBs into one family. A corresponding vehicle architecture version can be derived from this architecture variant for each KPB at the time of configuration.

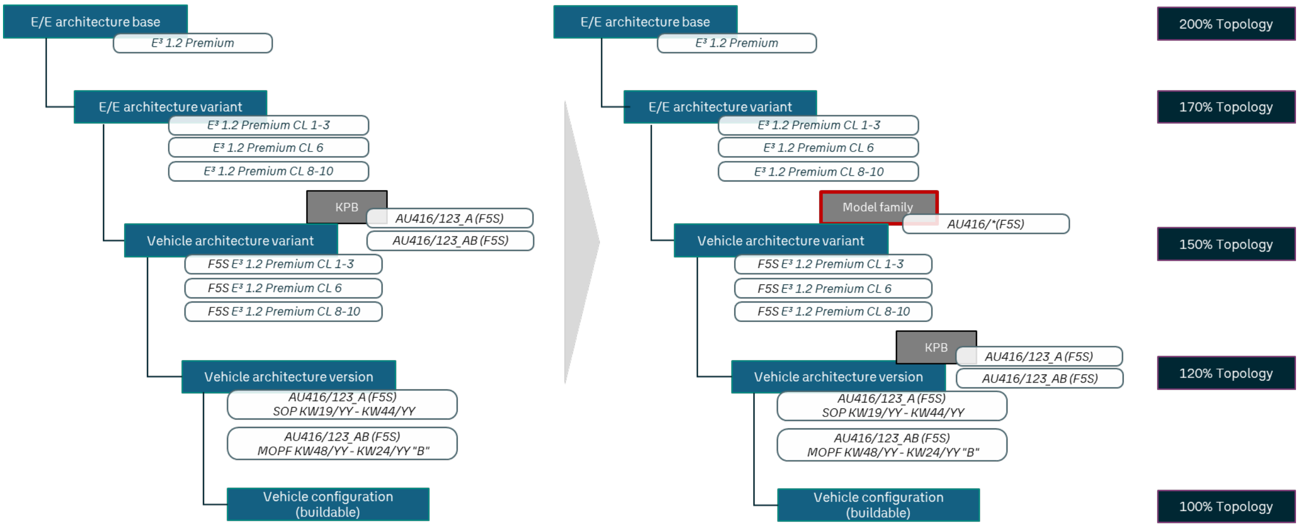

Figure 4. E/E Topology

The E/E architecture variant as configuration scope also constrains the solution space, meaning that the local optimum for data transmission depends on the technical implementation of the on-board configuration method. The finer the granularity of the configuration, the more efficient the data transmission. At the same time, transmitting the E/E architecture variant allows for less variance and potentially synergies in the development and after-sales processes. The subsequent step is to determine if adapting the data model and controlling the vehicle architecture variant based on the model family is suitable for the onboard configuration processes.

3.3 Research Question 3

Research question 3 aims to determine which of the two configuration strategies - off-board or on-board - is more advantageous within the given application context. The required concept evaluation is conducted using the case of Volkswagen AG, a representative automotive OEM characterized by both a high production volume and significant product variability. To enable a systematic comparison and evaluation of the two approaches, we defined four primary evaluation categories: Hardware and Production Impacts, OTA Updates, Safety & Security, and Data Management and Preparation. For each category, specific assessment criteria were derived at a subordinate hierarchical level to capture the relevant dimensions of evaluation. A structured overview of the defined categories, the associated criteria, and the abbreviations used in this context is provided in the top left-hand section of Figure 5.

Category	Abbreviation	Criterion	Abbreviation
Hardware and Production Impacts	HPI	Hardware Costs (Memory and Processing Capacity)	HC
		Preprocessing of Data	PD
		Duration to Transfer Raw Data to the Vehicle	DTRDV
OTA-Updates	OTA	Size and Duration of an Update	SDU
		Required Update Frequency	RUF
		Implementation Complexity in the Vehicle	ICV
Safety & Security	S&S	Compliance with SFD Requirements	CSFDR
		Validation of Correct Data Transmission	VCDT
		Data Privacy and Cybersecurity	DPC
Data Management and Preparation	DMP	Control over the Target State of the Vehicle	CTSV
		Flexibility in Modifying the Vehicle Configuration	FMVC
		Efficiency of Fault Diagnosis and Resolution	EFDR

	Numeric Rating		Reciprocal
Equal Importance	1	Equal Importance	1
Moderate Importance	3	Moderate Unimportance	1/3
Strong Importance	5	Strong Unimportance	1/5
Very Strong Importance	7	Very Strong Unimportance	1/7
Extremely Important	9	Extremely Unimportant	1/9

Final Evaluation

	HPI	OTA	S&S	DMP	Priority
On-Board	0,203	0,255	0,283	0,728	0,398
Off-Board	0,797	0,745	0,717	0,272	0,602

Factor	HPI	OTA	S&S	DMP
HPI	1	1/3	1/3	1/3
OTA	3	1	1/3	1
S&S	3	3	1	1
DMP	3	1	1	1
Total	10,000	5,333	2,667	3,333

	HPI	OTA	S&S	DMP	Priority
HPI	0,100	0,063	0,125	0,100	0,097
OTA	0,300	0,188	0,125	0,300	0,228
S&S	0,300	0,563	0,375	0,300	0,384
DMP	0,300	0,188	0,375	0,300	0,291

HPI	HC	PD	DTRDV	Priority
On-Board	0,167	0,125	0,250	0,203
Off-Board	0,833	0,875	0,750	0,797

HPI	HC	PD	DTRDV	Priority
HC	1	7	1	0,467
PD	1/7	1	1/7	0,067
DTRDV	1	7	1	0,467
Total	2,143	15,000	2,143	

HC	On-Board	Off-Board	Priority
On-Board	1	1/5	0,167
Off-Board	5	1	0,833
Total	6,000	1,200	

PD	On-Board	Off-Board	Priority
On-Board	1	1/7	0,125
Off-Board	7	1	0,875
Total	8,000	1,143	

DTRDV	On-Board	Off-Board	Priority
On-Board	1	1/3	0,250
Off-Board	3	1	0,750
Total	4,000	1,333	

OTA	SDU	RUF	ICV	Priority
On-Board	0,250	0,500	0,167	0,255
Off-Board	0,750	0,500	0,833	0,745

OTA	SDU	RUF	ICV	Priority
SDU	1	1/3	1/7	0,088
RUF	3	1	1/3	0,243
ICV	7	3	1	0,669
Total	11,000	4,333	1,476	

SDU	On-Board	Off-Board	Priority
On-Board	1	1/3	0,250
Off-Board	3	1	0,750
Total	4,000	1,333	

RUF	On-Board	Off-Board	Priority
On-Board	1	1	0,500
Off-Board	1	1	0,500
Total	2,000	2,000	

ICV	On-Board	Off-Board	Priority
On-Board	1	1/5	0,167
Off-Board	5	1	0,833
Total	6,000	1,200	

S&S	CSFDR	VCDT	DPC	Priority
On-Board	0,100	0,500	0,250	0,283
Off-Board	0,900	0,500	0,750	0,717

S&S	CSFDR	VCDT	DPC	Priority
CSFDR	1	1	1	0,333
VCDT	1	1	1	0,333
DPC	1	1	1	0,333
Total	3,000	3,000	3,000	

CSFDR	On-Board	Off-Board	Priority
On-Board	1	1/9	0,100
Off-Board	9	1	0,900
Total	10,000	1,111	

VCDT	On-Board	Off-Board	Priority
On-Board	1	1	0,500
Off-Board	1	1	0,500
Total	2,000	2,000	

DPC	On-Board	Off-Board	Priority
On-Board	1	1/3	0,250
Off-Board	3	1	0,750
Total	4,000	1,333	

DMP	CTSV	FMVC	EFDR	Priority
On-Board	0,833	0,833	0,167	0,728
Off-Board	0,167	0,167	0,833	0,272

DMP	CTSV	FMVC	EFDR	Priority
CTSV	1	1/3	1	0,187
FMVC	3	1	5	0,655
EFDR	1	1/5	1	0,158
Total	5,000	1,533	7,000	

CTSV	On-Board	Off-Board	Priority
On-Board	1	5	0,833
Off-Board	1/5	1	0,167
Total	1,200	6,000	

FMVC	On-Board	Off-Board	Priority
On-Board	1	5	0,833
Off-Board	1/5	1	0,167
Total	1,200	6,000	

EFDR	On-Board	Off-Board	Priority
On-Board	1	1/5	0,167
Off-Board	5	1	0,833
Total	6,000	1,200	

Figure 5. AHP for On-Board and Off-Board Configuration Strategies

3.3.1 Evaluation Criteria and their Implications for On-Board and Off-Board Configuration Strategies

The following section consolidates and analyzes the evaluation criteria with regard to their specific implications for the on-board and off-board configuration concepts.

A first central aspect concerns hardware costs, particularly with respect to memory and processing capacity. The two configuration concepts differ in the volume of data transferred to the vehicle and in the location where data containers are computed. These differences have direct implications on the hardware requirements of gateways, influencing both design complexity and cost. In the on-board configuration concept, the gateway requires increased memory and processing capacity to store and compute the configuration data containers locally. Although the additional hardware demands are moderate, they are economically significant and cannot be neglected in cost-sensitive environments. Closely related is the preprocessing of data. Before transmission to the vehicle, data must be packaged appropriately. The timing and location of this packaging process are critical, as errors introduced during packaging may propagate through the system. Off-board configuration allows for early preprocessing and validation of data, reducing the risk of transmission errors. In contrast, the on-board approach requires data to be packaged twice: first for transfer to the vehicle and second for distribution from the gateway to individual ECUs, thereby increasing complexity and error potential. The duration of the transfer of raw data to the vehicle during vehicle production represents another important aspect, as prolonged durations can negatively affect production efficiency. Minimizing these times is therefore essential in manufacturing contexts. The on-board configuration necessitates the transfer of a larger data volume into the vehicle, resulting in longer transfer times. To mitigate production delays, the gateway might need to be prepared separately prior to vehicle integration - an approach that adds either time or cost, making off-board configuration more favorable in this aspect.

With regard to update size and duration, user perception is primarily shaped by the time required for the update, although technically both size and duration affect the risk of failure and system stability. On-board updates tend to be slightly larger, as more configuration data and encoded datasets must be delivered to the vehicle. This leads to marginally longer update durations and a potentially increased likelihood of transmission or processing errors. The required update frequency is also of strategic relevance. While frequent updates may be desirable in principle, they should deliver functional benefits to users rather than serve purely for data maintenance. Depending on the selected data scope, the on-board configuration concept may require a higher update frequency, as a greater volume of data must be maintained. In order to maintain the internal consistency of the vehicle fleet, data changes may need to be propagated across all vehicles, even if a given vehicle does not benefit functionally from the change. Thus, a higher frequency of updates does not automatically translate into added value for the customer. Another critical factor is the implementation complexity within the vehicle, particularly with regard to the handling of OTA updates. Even within the off-board approach, OTA updates pose considerable technical challenges. When extended by the on-board concept, where additional data containers are introduced and must be processed locally on the vehicle, the overall system complexity increases substantially. This leads to a more intricate update process and necessitates a higher volume of internal data transfer within the vehicle.

Compliance with SFD requirements is essential to prevent unauthorized access to ECUs. Therefore, SFD mechanisms encrypt each ECU and require unique SFD tokens for each vehicle variant. In the on-board scenario, each vehicle must request VIN-specific tokens from an SFD server in the backend in order to configure itself, increasing communication overhead and enlarging the system's attack surface. In contrast, the off-board concept restricts access to the SFD servers to a few designated backend systems that are specifically configured for this purpose and thus avoids direct interaction between the vehicle and server. The current architecture of SFD calculators poses a legacy constraint for on-board approaches and should be reworked. Equipping vehicles with local SFD calculation capabilities could eliminate the need for backend interaction. The validation of correct data transmission is another crucial aspect. Each data transfer within the context of software updates must be verified to ensure that the data has been received completely and without errors. For this purpose, expected (target) hash values are generated and compared with actual hash values calculated at the receiving system. In this context, the term Integrity Validation Data (IVD) is used, which, as previously described, serves to verify the integrity of the update process. Validation is already performed on-board the vehicle today and therefore shows little difference between the two configuration concepts. In light of the increasing prevalence of digital threats, data privacy and cybersecurity have become critical concerns in the context of vehicle software systems. As SDVs rely heavily on interconnected ECUs and external communication interfaces, ensuring the protection of sensitive data and safeguarding system integrity are essential prerequisites for the reliable operation of modern automotive platforms. The on-board approach stores all relevant configuration data within the vehicle, which - while enabling autonomy - increases the attack surface. A successful intrusion could compromise a broad dataset. The off-board concept, by minimizing the volume of stored on-vehicle data, inherently reduces this risk.

Maintaining control over the vehicle's target configuration state is essential for both functional reliability and quality assurance. The vehicle must be brought into a defined target state through a dedicated configuration process. A key aspect in this context is the question of who initiates, controls, and monitors the achievement of this state. In contrast to the off-board concept, where external systems are responsible for managing these tasks, the on-board approach assigns full control to the vehicle itself. Here, the vehicle acts as the single source of truth and autonomously and automatically ensures that the intended configuration state is achieved and maintained. Flexibility in modifying the vehicle configuration is another important factor that users expect - quick and seamless activation of additional hardware or features post-purchase, such as when installing a trailer hitch. With on-board configuration, relevant data already resides on the vehicle, enabling rapid local reconfiguration with minimal backend communication. In contrast, off-board configuration requires extensive remote communication with backend systems, delaying reconfiguration processes. Finally, the efficiency of fault diagnosis and resolution is a key operational concern. Development errors must be detected and resolved quickly to limit costs and system downtime. In the on-board approach, faults may go unnoticed for longer periods and require more effort to resolve. In the event of an error in the interpreter or configurator, it must be replaced for each individual vehicle, as the configurator is an integral part of the vehicle software and the gateway. This leads to a significantly higher implementation and maintenance effort compared to off-board configuration approaches, where the interpreter or configurator can be more easily exchanged or adapted within the backend infrastructure.

3.3.2 The Analytic Hierarchy Process

To evaluate the two configuration concepts, we apply the AHP which is structured into hierarchically distinct levels and is used to weight and evaluate criteria. As a multi-criteria decision-making method, AHP typically consists of an overarching goal at the top level, followed by the criteria contributing to that goal, and finally the alternatives to be assessed against these criteria. By employing pairwise comparisons, AHP facilitates both the prioritization of decision criteria and the evaluation of competing alternatives. Furthermore, it enables the identification of inconsistencies and supports the systematic handling of complex decision-making processes (Saaty, 1990). The AHP is particularly well suited for decision-making problems involving multiple hierarchical levels. The selection of AHP was motivated by the difficulty of assigning absolute numerical scores to the on-board and off-board configuration strategies for each criterion. Instead, it is more feasible to assess which concept performs better or worse in direct comparison under a given criterion and to what extent. This principle of pairwise comparison is a core characteristic of the AHP methodology. An additional advantage of the AHP lies in its ability to identify inconsistencies in the decision-making process through the calculation of the Consistency Ratio (CR). The CR quantifies the degree of inconsistency in a judgment matrix. However, it does not indicate which specific pairwise comparison is responsible for the inconsistency. A CR value below 0.1 is generally considered acceptable (Saaty, 1990). The usefulness of AHP for identifying the most suitable solution or concept has been demonstrated in numerous studies. One recent example can be found in Sirin et al. (2024).

3.3.3 Application of the AHP

For this evaluation, the authors developed a dedicated AHP assessment template. Within this framework, three dimensions were evaluated: (1) the relative importance of the main categories to each other, (2) the relative importance of the criteria within each category, and (3) the comparative performance of the two concepts for each individual criterion. After the creation of the template, the evaluation was conducted by the authors. In a second step, the evaluation process was repeated in collaboration with domain experts from Volkswagen AG. Together with the experts, the previously developed AHP assessment template was completed once again. The insights gained from these expert interviews were used to validate the initial evaluation results and, if necessary, to adjust the input data accordingly. The scale used for the pairwise comparison during the evaluation is shown in the center left of Figure 5. A condensed excerpt of the completed AHP calculation template, developed by us, is also presented in Figure 5 and highlighted by a gray background. It depicts the hierarchically structured evaluations within the categories, complemented by the final overall assessment of the two concepts at the highest hierarchical level. This final evaluation can be found in the upper right section of Figure 5. The white cells shown in the AHP represent the input fields where the numeric ratings were entered during the AHP process according to the pairwise comparison scale. The off-board configuration concept achieved an overall utility score of 60,2 %, outperforming the on-board configuration concept, which scored 39,8 %. Under the given evaluation framework, the off-board strategy was therefore identified as the more suitable concept. In scenarios where operational flexibility is a key requirement, the on-board configuration approach demonstrates its strengths. However, with respect to system complexity and required effort - particularly in the event of malfunctions or unexpected conditions - the disadvantages of the on-board approach outweigh its benefits. This trade-off is reflected in the outcomes of the previously discussed AHP evaluation. The consistency of the decision-making process was confirmed throughout the entire AHP procedure, as the CR remained below the threshold of 0.1 at all hierarchical levels.

4 Discussion

As part of our investigation, we were able to derive several key insights. First, we analyzed the current backend-based configuration process. Building upon this, we developed a concept outlining how an on-board configuration of ECUs could be implemented. To enable a meaningful comparison between the two approaches, it was assumed that the handling of parameters within the ECU software remains unchanged. This means that the process steps, as well as the structure and development of parameters, are consistent across both scenarios. Based on this assumption, the two concepts were systematically evaluated. The analysis, supported by expert interviews, revealed that under current conditions and with the existing handling of parameters, the off-board configuration concept is more advantageous. This allows for a high level of certainty in concluding that, within the current parameter management process, the on-board configuration approach is not viable. To fully exploit the potential of on-board configuration in the future, fundamental adjustments to parameter management and related processes are required. One possible approach for redesign could involve integrating parameters directly into the software, while continuing to manage datasets separately. The advantage of such a model would be that individual parameters would no longer need to be maintained as standalone artifacts. Instead, the parameters would already be written into the ECU software code. Only data sets and the software itself would be transferred to the vehicle instead of the whole data container with parameters as separate entities. This would not only simplify data preparation but also increase the efficiency of software distribution. A deeper analysis of this alternative approach could reveal how the evaluation criteria, particularly with regard to data handling and system complexity, would change compared to the existing concept. One important factor hereby is the origin of the ECU software. If the software is developed internally by the OEM, this described new parameterization process can typically be adjusted more flexibly and with higher update frequency. However, if the software is developed externally by suppliers, any change would require a significantly more complex coordination and validation process, contradicting the goal of agile software maintenance, especially in the context of OTA updates. Against this backdrop, a potential trend becomes apparent: central control units such as domain or central computers with extensive functionalities are increasingly being developed in-house by OEMs. For these, on-board configuration approaches may be particularly well suited. In contrast, so-called secondary ECUs, such as brake or airbag systems, will likely remain the responsibility of specialized suppliers in the future. For these ECUs, off-board configuration may continue to be the more appropriate option. Overall, this could point toward a potential dual approach: on the one hand, an on-board configuration concept for internally developed ECUs with high change frequency and short update cycles; on the other, an off-board concept for externally developed components that require extensive validation. Future work should investigate, if an on-board concept with a revised parameterization method is viable, how such a hybrid configuration concept can be practically implemented and to what extent synergies between both approaches can be realized. Another key aspect that must be considered in the evaluation is the number of possible variants. The current analysis is based on the assumption that the diversity of variants remains high, which means that customers will continue to have access to a wide range of configuration options. This diversity particularly pertains to the number of parameter variants within vehicle configurations. However, if an automotive manufacturer were to decide to significantly reduce the variety of options and instead offer only predefined equipment packages, this could have far-reaching implications for the concept of software configuration. In such a scenario, only standardized datasets might be required, as the parameters would already be assigned to specific equipment lines. Individual settings would no longer be necessary. Such standardization would also have a significant impact on the evaluation of an on-board concept. Some of the challenges identified in the current analysis could thereby be eliminated. The previously discussed issue related to secondary control units would also likely become less relevant in this context. It is therefore necessary to conduct further investigations that incorporate alternative assumptions into the evaluation. However, we are confident that these follow-up analyses can be carried out swiftly, as we provided a methodological framework with clearly defined evaluation criteria. This framework only needs to be applied and, if necessary, adapted in future studies.

5 Related Work

Configuration management has been widely studied, both in general and within the specific context of the automotive industry (Heinisch et al., 2004; Xu and Russello, 2022). However, the focus of existing research varies significantly. Our work investigates the parameterization as part of configuration management in SDVs, especially the question of whether configuration tasks should be performed on-board or off-board. This includes how configuration processes are organized and where they are executed. A key area of related research explores the connection between configuration and release management for software updates in vehicles (Guissouma et al., 2022; Guissouma et al., 2019; Halder et al., 2020; Ji et al., 2024). Guissouma et al. (2018) for example, highlight the strong dependencies between both areas and argue that traditional methods are no longer suitable for today's development workflows and OTA updates. They call for new solutions that integrate configuration and update logic from the start of the development process. Other researchers, such as (Aust, 2022), focus more on architecture: how ECUs should be built to support OTA, and how the update process works on a technical level. While these studies are valuable for understanding system design, they do not address what kind of data should actually be sent during OTA updates. In particular, the scope and structure of the configuration data itself are rarely examined in detail. This missing perspective becomes even more relevant in the context of Features on Demand (FoD) or Feature as a Service (FaaS). (Slama and Lachenmaier, 2024) for instance, analyze how FaaS can be implemented in SDVs and describe the challenges that come with the wide variety of physical vehicle configurations, a challenge that we also explore in our work. They argue that service-oriented architectures (SOA) offer more flexibility, but their model is based on a uniform vehicle setup with maximum features, which we consider to not depict the use case for most automotive companies. Our work assumes that vehicle configurations will remain diverse and must be supported accordingly. Another related topic is diagnostics in SDVs. Recent studies (Bickelhaupt et al., 2024; Bickelhaupt et al., 2023; Boehlen et al., 2024) explore advanced diagnostic systems that work on-board and enable more accurate error detection. However, they largely ignore how the initial configuration affects these systems. The role of parameterization in diagnostic accuracy is still unclear. In summary, although many papers highlight that SDVs bring new challenges for configuration management, there is no in-depth analysis of whether moving configuration tasks on-board would be helpful - or under what conditions. While various methods exist for OTA updates and variant handling, they do not clarify when in the development process parameterization should happen, or where these tasks should be executed. Our research addresses this gap by comparing today's off-board configuration approach with a possible on-board alternative.

6 Conclusion and Outlook

In this paper, we examined and compared two concepts for the configuration of ECU software. The first concept involves parameterization carried out in the backend, reflecting the current approach used at Volkswagen. In contrast, the second concept calculates parameters directly on-board the vehicle using a powerful computing unit. Thus, the primary distinction between the two concepts is the location of parameterization. Additionally, we investigated the optimal scope of parameter data that should reasonably be transferred to the vehicle within the on-board concept. Both concepts were evaluated based on clearly defined criteria. Our analysis demonstrates that, under current conditions and established working methods, the off-board concept offers more advantages. However, we note that changes in parameter management and handling of parameters in software could potentially lead to a different outcome of the evaluation. Particularly important in this context is the origin of the ECU software - whether it is developed by the OEM or a supplier. Future research could look deeper into the evaluation of traditional and new methods of handling parameters in software code. Such research should systematically examine specific conditions, prerequisites, and the advantages and disadvantages of each approach. Additionally, another promising research direction could more closely explore the structuring and terminology used in the configuration management of E/E architecture. In our study we found out that Volkswagen currently has varied semantics across different E/E architectures. Therefore, unifying these differing semantics and establishing clear, standardized definitions should be an important goal.

Another potential research direction lies in the analysis of parameter variants using Design Structure Matrices (DSM). Based on this, clusters could be identified in which specific parameters frequently occur together. This would enable the detection of parameter groups that are particularly closely linked, functionally or contextually, which is a crucial step for efficiently transferring these parameters to the vehicle. However, such an approach requires the development of a suitable DSM structure capable of adequately representing the specific relationships between parameter variants. The goal should be to design a DSM that accounts for both technical and functional couplings between parameters, while incorporating domain-specific requirements, particularly those relevant to the automotive context. Future work could also include a comparative analysis of DSMs representing two paradigms: one diagram capturing the centralized, sequential flow of information typical for off-board configurations, and another illustrating the decentralized logic of on-board configurations. Such models could provide valuable insights into the structural implications of each approach and guide the selection of appropriate strategies based on system complexity, domain requirements, or update scenarios.

References

American National Standards Institute, IEEE Computer Society, Institute of Electrical and Electronics Engineers, IEEE-SA Standards Board, 2005. IEEE standard for software configuration management plans. Institute of Electrical and Electronics Engineers, New York, N.Y.

Aust, S., 2022. Vehicle Update Management in Software Defined Vehicles, in: 2022 IEEE 47th Conference on Local Computer Networks (LCN). 2022 IEEE 47th Conference on Local Computer Networks (LCN), Edmonton, AB, Canada. 26.09.2022 - 29.09.2022. IEEE, pp. 261–263.

Bickelhaupt, S., Hahn, M., Morozov, A., Weyrich, M., 2024. Towards Future Vehicle Diagnostics in Software-Defined Vehicles, in: SAE Technical Paper Series. 2024 Stuttgart International Symposium, Stuttgart, Germany. SAE International400 Commonwealth Drive, Warrendale, PA, United States.

Bickelhaupt, S., Hahn, M., Nuding, N., Morozov, A., Weyrich, M., 2023. Challenges and Opportunities of Future Vehicle Diagnostics in Software-Defined Vehicles, in: SAE Technical Paper Series. WCX SAE World Congress Experience, Detroit, Michigan, United States. SAE International400 Commonwealth Drive, Warrendale, PA, United States.

Boehlen, B., Fischer, D., Wang, J., 2024. Diagnostics of Automotive Service-Oriented Architectures with SOVD, in: SAE Technical Paper Series. SAE 2024 Intelligent and Connected Vehicles Symposium, Shanghai, China. SAE International400 Commonwealth Drive, Warrendale, PA, United States.

Guissouma, H., Diewald, A., Sax, E., 2019. A Generic System for Automotive Software Over the Air (SOTA) Updates Allowing Efficient Variant and Release Management, in: Borzemski, L., Świątek, J., Wilimowska, Z. (Eds.), Information Systems Architecture and Technology: Proceedings of 39th International Conference on Information Systems Architecture and Technology – ISAT 2018, vol. 852. Springer International Publishing, Cham, pp. 78–89.

Guissouma, H., Hohl, C.P., Lesniak, F., Schindewolf, M., Becker, J., Sax, E., 2022. Lifecycle Management of Automotive Safety-Critical Over the Air Updates: A Systems Approach. IEEE Access 10, 57696–57717. https://doi.org/10.1109/ACCESS.2022.3176879.

Guissouma, H., Klare, H., Sax, E., Burger, E., 2018. An Empirical Study on the Current and Future Challenges of Automotive Software Release and Configuration Management, in: 2018 44th Euromicro Conference on Software Engineering and Advanced Applications (SEAA). 2018 44th Euromicro Conference on Software Engineering and Advanced Applications (SEAA), Prague. 29.08.2018 - 31.08.2018. IEEE, pp. 298–305.

Halder, S., Ghosal, A., Conti, M., 2020. Secure over-the-air software updates in connected vehicles: A survey. Computer Networks 178, 107343. https://doi.org/10.1016/j.comnet.2020.107343.

Heinisch, C., Feil, V., Simons, M., 2004. Efficient configuration management of automotive software 2nd Embedded Real Time Software Congress (ERTS'04), 2004, Toulouse, France. hal-02271215.

Ji, W., Wang, H., Su, Y., 2024. New Software Upgrade Configuration Management Mode Based on UNECE R156, in: Ramayah, T., Lee, P.M., Ng, E.H.K. (Eds.), Proceedings of the 2024 International Conference on Applied Economics, Management Science and Social Development (AEMSS 2024), vol. 284. Atlantis Press SARL, Paris, pp. 259–265.

Saaty, T.L., 1990. How to make a decision: The analytic hierarchy process. European Journal of Operational Research 48, 9–26. https://doi.org/10.1016/0377-2217(90)90057-I.

Sieben, D., Macke, D., Hake, J.-P., Kriebel, S., Heinen, K., Uthayakumar, K., Kirchhof, J.C., 2024. The Anatomy of Software-Defined Vehicles Realized for Series with Systems Engineering, in: Kulzer, A.C., Reuss, H.-C., Wagner, A. (Eds.), 2024 Stuttgart International Symposium on Automotive and Engine Technology. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 218–229.

Sirin, H., Bitsch, G., Leipzig, K. von, 2024. Decision Support Tool for the selection of the most suitable Indoor Localization Technology (ILT) using the Analytical Hierarchy Process (AHP). Procedia CIRP 130, 1435–1440. https://doi.org/10.1016/j.procir.2024.10.263.

Slama, D., Lachenmaier, J., 2024. Enabling applications for variable vehicle configurations with Software-defined Vehicle and Service-oriented Architecture. Procedia CIRP 126, 289–294. https://doi.org/10.1016/j.procir.2024.08.341.

Stoll, H., Grimm, D., Schindewolf, M., Brodatzki, M., Sax, E., 2021. Dynamic Reconfiguration of Automotive Architectures Using a Novel Plug-and-Play Approach, in: 2021 IEEE Intelligent Vehicles Symposium Workshops (IV Workshops). 2021 IEEE Intelligent Vehicles Symposium Workshops (IV Workshops), Nagoya, Japan. 11.07.2021 - 17.07.2021. IEEE, pp. 70–75.

Wozniak, L., Clements, P., 2015. How automotive engineering is taking product line engineering to the extreme, in: Proceedings of the 19th International Conference on Software Product Line. SPLC '15: 2015 International Conference on Software Product Lines, Nashville Tennessee. 20 07 2015 24 07 2015. ACM, New York, NY, USA, pp. 327–336.

Xu, J., Russello, G., 2022. Automated Security-focused Network Configuration Management: State of the Art, Challenges, and Future Directions, in: 2022 9th International Conference on Dependable Systems and Their Applications (DSA). 2022 9th International Conference on Dependable Systems and Their Applications (DSA), Wulumuqi, China. 04.08.2022 - 05.08.2022. IEEE, pp. 409–420.

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