# System Engineering guided Approach to Manage In-Vehicle Network System

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*Abstract*— **With modern electric vehicles becoming increasingly software-driven, they now support a wide range of functionalities. This evolution has led to the integration of multiple electronic control systems, each responsible for specific functions, working together to create a responsive, reliable, and robust automotive platform. As a result, real-time data exchange among these controllers has become increasingly complex, driving exponential growth in in-vehicle network (IVN) data. This poses significant challenges in terms of bandwidth efficiency, configuration management, and cross-functional coordination.**

**This paper presents a system-level overview of the challenges faced by OEMs in associating, integrating, and managing IVNs in alignment with the needs of cross-functional teams (CFTs). To address these challenges, a holistic Systems Engineering framework has been proposed, considering the details of trace-driven analysis and message-construction methodology that reduces peak network utilization while satisfying stringent latency requirements.**

**The paper then describes the design of a scalable, secure relational database—built from a rigorously vetted entity-relationship model—that tracks signal definitions, version histories, and user permissions. Additionally, a closed-loop process for on boarding CFTs and other stakeholders through Role Based Access Control (RBAC), ensuring the inclusion of relevant and accurate data in communication networks for every vehicle project is introduced. Finally, a suite of interconnected solutions that enhance network analysis, impact assessment, and overall IVN management is presented.**

Keywords— Systems Engineering, Bandwidth optimization, Automotive Communication, In Vehicle Network, Collaboration of CFTs.

## I. INTRODUCTION

Today's electric vehicles are becoming increasingly defined by their software capabilities, enabling a wide range of functionalities across the control systems involved. While architecting such vehicles, functions are bundled together and assigned to the different control systems. These control systems are responsible for those assigned functions as well as the exchange of information among themselves. As a result of this, communication in the vehicle becomes complex and time critical which leads to significant growth in the in-vehicle network (IVN) data volume, posing challenges like bandwidth utilization, data management and organizational level coordination. To address this, the network design requires appropriate topology and bandwidth management.

In large Original Equipment Manufacturers (OEMs), multiple vertical and diverse cross-functional teams (CFTs) work together simultaneously, thus managing IVN data at system level becomes challenging [1]. The decentralized nature of communication data, irregular ingestion practices, and lack of impact analysis mechanisms often lead to data duplication, corruption, and inefficient bandwidth utilization.

To address these challenges, this paper presents a holistic Systems Engineering framework that standardizes, manages, and validates IVN data across the vehicle platforms. A System of Interest (SoI) has been defined with clear boundaries, and system requirements were elicited [2]. The V-Model has been followed throughout development, verification and validation of the system. The framework ensures traceability from stakeholder needs to validation activities, aligning all CFTs through a single source of truth.

Key components of the solution include: Role-Based Access Control (RBAC) [3], a closed loop process for change management and system level impact analysis, bandwidth optimization strategy based on the bus traffic and data priority, visual representation such as communication matrix and network architecture, and standardized file formats to capture the data laying the foundation for scalable and future ready IVN strategy. The research also underscores the importance of transdisciplinary collaboration and systems thinking in modern automotive development, offering a blueprint for robust network configuration and lifecycle management.

This paper is outlined as follows: Section 2 elaborates the challenges consolidated before implementation of this system. The system Approach taken into consideration has been explained in Section 3. Section 4 explains the implementation and solution for the defined constraints and conditions. Lastly the paper concludes with the future scope.

## II. CHALLENGES

In large OEM environments, where multiple program verticals and diverse CFTs operate simultaneously, the volume and variability of data pose substantial challenges. These challenges span data governance, system integration, and network performance, and must be addressed to ensure scalable and reliable vehicle development.

If the strategy of individual controllers is defined around their respective requirements and functionalities, integrating into a system becomes difficult, as the synchronization of transmitting and receiving end cannot be guaranteed while focusing on individual design strategies.

Following are the key challenges identified:

*A. Decentralised communication data management*

In absence of centralized data management system, it becomes difficult to consolidate data from various sources. Each team may maintain its own version of data, making it difficult to draw a unified baseline for future references. This fragmentation hinders traceability, complicates future references, and makes it challenging to track which parameters have been utilized across vehicle platforms.

*B. Lack of Impact Analysis Mechanism*

IVN data change requests for – addition, mapping and removal, are often received late in product development phase. With improper management of non-standard data, it becomes difficult to analyse impacts of change requests on the complete system. This leads to unforeseen issues during validation and deployment.

*C. Data Ingestion Irregularity*

Different CFTs would ingest data as per their individual convenience of controller design. As most of the times, individual CFTs can only fathom their control systems, their methodology cannot foresee the impacts of their design decisions on system at large which leads to data duplication and non-standardisation. The mentioned scenarios lead to data corruption in the long run at the system level.

*D. Improper Bandwidth Utilization*

Suboptimal utilization of bandwidth in network communication causes delay between sending and receiving of data thereby restricting scalable design approach for the network. Data congestion would not allow timely reception of critical data by control systems. This induces latency which can cause the system to work as disrupted system all together.

Improper distribution of data on bus with respect to periodicity leads to peak bandwidth utilization for shorter interval though the average busload looks optimized. Due to this data staling can be observed as expected data is not able to win the arbitration queue. Hence an in-appropriate bandwidth utilization causes one of the bigger network design challenges.

## III. Analysis and Systems Approach

A deep analysis was run through the extensive IVN data in existence to figure out identifiable patterns across vehicle platforms to derive an organisation wide standard for data. This standard made sure to accommodate existing as well as any future communication data.

As a solution to the aforementioned challenges, a System of Interest (SoI) was identified with clear system boundaries. For this SoI, System Requirements were elicited, and Test Cases were drafted in strict coherence with System Requirements [4].

System architecture ensured:

a. IVN data is stored digitally in securely accessible database.

b. Verified and access-privileged users were created according to their roles at the organisational level.

The architecture ensures integrity of data so that it is not subject to corruption owing to irrelevant data inputs.

*A. Lifecycle Devlopment Models Utilization*

For many years, the V-Model has served as the industry standard for automotive development, directing system design, validation, and verification. It highlights a methodical but linked process in which every stage of design is supported by an associated testing and validation stage.

In alignment with the V-Model development methodology, all processes commenced with the elicitation and definition of comprehensive system requirements. Following this, individual modules were developed in accordance with the specified requirements. A systematic design phase was then undertaken, encompassing both high-level architectural design and detailed component-level design. Once development was complete, the modules were integrated and subjected to thorough verification procedures to ensure consistency with the design specifications. The integrated system then underwent rigorous testing, culminating in validation efforts to confirm that the final system met all expectations and functional requirements.

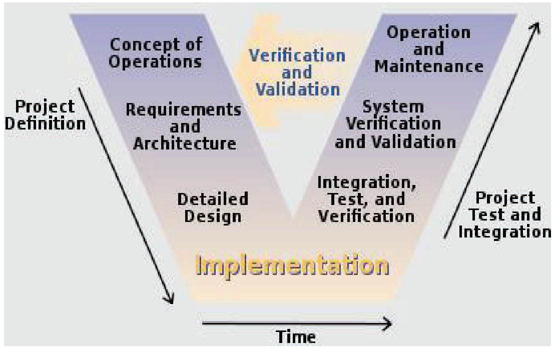


Fig. 1. System Development Lifecycle: V - Model

*B. Closed loop Process Establishment*

To address the mentioned challenges, this approach has been designed taking all the entities which are part of this system in the consideration. It gives an outline about how the process should be structured on both system and team interaction level.A request response scenario has been considered to abide by the standards and validation for correct data ingestion in the database. Multiple flows and sequences have been derived from this to add, remove or map the data in the network.

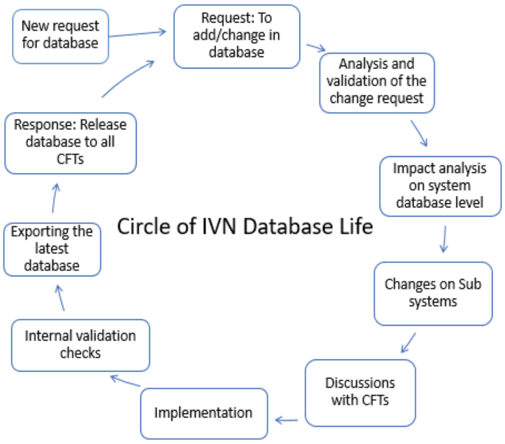


Fig. 2. Closed loop system approach: request and response

## C. Role Based Access Control (RBAC)

Cross-Functional Teams (CFTs) spanning software, hardware and integration frequently submit requests to add, remove or edit IVN data items. To manage this, applying Systems Engineering's stakeholder management practices, Role Based Access Control (RBAC) workflow is defined. RBAC permits system access based on a person's role within an organization. Access can be based on several factors, such as authority, responsibility, and competence.

Each CFT user logs a structured request specifying attributes, and justification. Requests are automatically routed to designated approvers, and each decision is recorded in the database alongside rationale and test requirements. This process ensures traceability from initial stakeholder needs through verification activities, reduces ad hoc changes, and aligns all CFTs via a single source of truth. In addition, access inside the system can be limited to specific tasks as mentioned in Fig. 3.

RBAC [2] (designed in such a way that) comprises two logical sections:

a. The 'authority' is responsible for analysing and validating data ingestion. They maintain data integrity, handle approvals request and, decide on assigning access privileges.

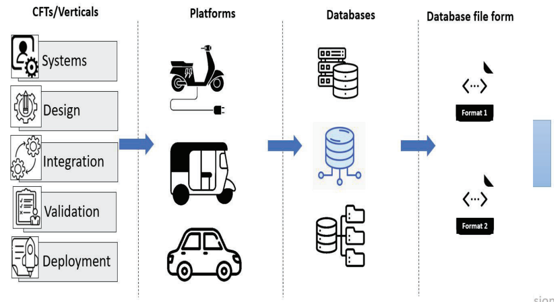


Fig. 3. Systems Approach at Org. Deployment

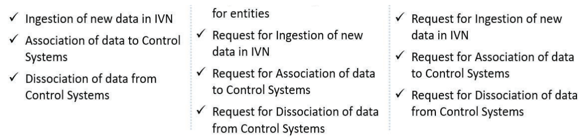


Fig. 4. Role Based Access Control

b. Based on other 'user' roles and access-privileges, each user can request to ingest, read, and modify the data.

## D. Organizational Level Deployment

A standard aids in bringing diverse CFTs on the same page. Any future ingestion or modification of data is governed centrally and accommodated in a stream-lined manner.

Along with this, it is also ensured that every stakeholder has the latest and consistent data. The discrepancies are avoided because of governed process establishment across the organization. The model for Organizational level deployment is as shown in Fig 4.

# IV. Towards Implementation and Solution

Efficient network design relies on optimizing bandwidth through intelligent use of network topology. By allocating periodic data transmission windows based on priority, the system minimizes bus loading and ensures timely delivery of critical data. This approach maintains low latency across the network. Visual tools such as communication matrices and detailed representations of the network architecture provide clarity on control unit interactions and data flow, especially within complex or layered topologies. Furthermore, tailored file formats—designed for both development and testing—enable seamless integration with control software, supporting consistent data interpretation across varied sub-networks.

## A. Bandwidth Optimization

By first characterizing the traffic exchanged between controllers—identifying periodic, event-driven, and sporadic message patterns—we applied a trace-driven analysis to quantify peak loads and idle intervals. Bandwidth optimization in the focused network design was effectively achieved through the proper allocation of data periodicity, resulting in a more scalable and efficient network. By strategically scheduling data transmissions based on their importance and timing requirements, bus congestion was significantly reduced, allowing for smoother data flow.

This approach ensures that critical information is delivered within its required time phase, thereby minimizing latency and enhancing overall network performance. Consequently, the system becomes better equipped to handle increasing data loads without compromising on timing or reliability. This coordination of timing, data size, and priority reflects the Systems Engineering stages of requirements definition (capturing performance targets), architecture design (mapping controllers to network segments), and verification (demonstrating bandwidth savings through simulation) [5].

### B. *Tracking of Data*

When multiple projects or networks are maintained within a single system, a vast amount of data is involved. Mapping of these data for each project requires a broader perspective of implementation considering characteristics like:

- Uniqueness in the content and linkages in an individual project.
- There should not be any duplication of data in the whole system.
- Data should be transmitted according to their priorities.

Thus, tracking of data helps in assuring proper bandwidth utilization, estimating volume growth of data over time and standardize authentic data.

### C. *Methodical Database Design for IVN Data Management*

Managing thousands of signal definitions and configuration parameters across multiple vehicle platforms necessitated rigorous data architecture. Guided by Systems Engineering principles, clear requirements for scalability, access control, and traceability were established. The problem has been decomposed into data entities (signals, messages, nodes, networks and subnetworks) and defined their relationships in an entity-relationship model.

Iterative refinement cycles—mirroring the V-model—ensured alignment between stakeholder needs (engineering, integration and validation teams) and the logical data model. This model has been implemented in a relational database, incorporating referential integrity constraints and audit trails.

### D. *Network Visuals*

Visual representations are easy to perceive and analyze in the case of huge and complex data. This helps knowing and predicting system evolution, thereby reducing the efforts and time consumption required for the analysis.

#### 1) *Communication Matrix*

It's a point-to-point mapping of data exchange among control systems. It helps in conceiving the impact of addition or removal of data. It represents the number of control units present on the network and their contribution in terms of data which benefits in estimation of bandwidth utilization.

#### 2) *Network Architecture*

Network architecture refers to the structural design of the system network. It encompasses the physical and logical layout of the network, including the arrangement of nodes, communication protocols, transmission methods, and the control mechanisms used to manage data flow. A well-designed network architecture ensures efficient communication and scalability. When multiple networks are involved, it eases the analysis of each subnetwork, gateways and network as a whole, shown in Fig. 5.

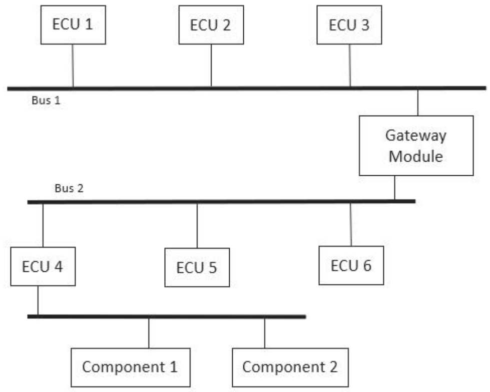


Fig. 5. Example: network architecture in star topology

### E. *File Fromats*

#### 1) *Development oriented format*

A JSON format suitable for use with auto-generation scripts was arrived at to ease software developments for control systems of networks. The structure of the schema is such that it can accommodate type-diverse data for networks and sub-networks with different bandwidth requirements which makes this format scalable and universal organization wide. Thereby this format allows the developers to optimally read, and fetch data.

Leveraging Systems Engineering's emphasis on standard interfaces, core elements were identified — signal aggregation identifiers, signal handling and timing attributes—and captured in a hierarchical schema with strong typing and required/optional field annotations. This schema underwent model-based validation against sample data sets. By designing the schema in industry-standard JSON Schema notation, it facilitated seamless integration with downstream tools—ranging from diagnostic utilities to software-in-the-loop simulators—thus demonstrating robust interface control and configuration management.

#### 2) *Visual and Testing oriented format*

A preexisting file format was considered and generated from the system using the data. The generated file is compatible with the existing software system which helps in visualization of the data. It fits with the surrounding software systems which helps in better analyzing of the data during testing of a network, subnetwork or individual control systems.

## V. SUMMARY AND CONCLUSION

This paper offers a broad summary of organizational implementations and issues encountered during database management system development and deployment. It has demonstrated the approach and ideas that were employed in the system's conception and creation. The Lifecycle Management technique was used throughout this journey for this work.

This research presents a structured approach to implementing In-Vehicle Networks (IVN) through Systems Engineering (SE) principles, emphasizing the standardization of data identifiers—namely signals and messages. By establishing a unified schema and incorporating Role-Based Access Control (RBAC), the workflow ensures centralized authorization and traceable transaction management via a request-approval mechanism. The integration of inputs from Cross-Functional Teams (CFTs) was methodically streamlined, enhancing data integrity and governance. The standardization of data not only optimized bandwidth usage but also enabled robust validation mechanisms for filtered data inputs. Furthermore, the development of a JSON schema tailored for multi-network compatibility ensures that the data files are readily machine parse-able, facilitating seamless integration and scalability across diverse vehicular platforms. These advancements collectively contribute to a more efficient, secure, and interoperable IVN architecture.

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