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Implementing SAE J1939 in commercial, off-highway and heavy-duty vehicle design

Executive summary
The SAE has defined a standard for the interoperability of on-board communication networks, J1939, supporting heavy-duty and off-highway vehicles. The adoption of this standard enables tractors, trailers and accessories to connect together without customization. This paper will discuss how Siemens suite of tools can be used to generatively design the electrical and electronic (E/E) systems of the vehicle from the E/E architecture definition, revolutionizing the vehicle E/E design process. This process can utilize the standard library of signals and messages from the SAE J1939 standard, the defined functions, and E/E architecture to generate the E/E design.

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Figure 1: New agricultural tractor cabins are equipped with electronic controls and displays.

Heavy-duty commercial and off-highway vehicles, such as agricultural and construction equipment, pose multiple electrical and mechanical engineering challenges. These vehicles must be efficient, durable, and reliable as they have long service lives in strenuous environmental conditions that can include extreme temperature, dirt, dust, and altitude.

The challenge of designing commercial and off-highway vehicles is mounting as the electrical systems grow in size and sophistication. Several interconnected networks of electronic control units (ECUs), sensors, and actuators monitor and control the critical systems in modern vehicles. This system of ECUs is constantly measuring parameters such as the temperature, pressure, and position of various components. This system also controls the activation of electrical and hydraulic actuators, engine and driveline ancillaries, and much more. The increasing systems complexity of commercial and off-highway vehicles is similarly evident in the cabin. Agricultural tractors, for example, now feature electronic and digital controls as well as cabin amenities like heated seats and climate control systems (figure 1).

Engineers must determine how to manage the communications and connectivity between the various electrical and electronic components. Therefore, one of the first steps for new vehicle design is defining the electrical and electronic (E/E) architecture. In the definition stage, engineers evaluate various proposals for the layout of the new vehicle and conduct trade studies to determine the quantity, type and location of the necessary ECUs to enable the functionality required for the desired vehicle features. The architectural design data can then feed the downstream electrical, network, software, and hardware implementation.

A key consideration during commercial and off-highway E/E architectural definition is the SAE J1939 standard for communications between ECUs in the vehicle. J1939 is a higher-layer protocol (HLP) for communications across the CAN bus that provides standard messages and conversion rules across commercial, off-highway, and heavy-duty manufacturers. These rules support interoperability between manufacturers and implementations, such as between tractor unit and trailer (figure 2).

J1939 is comprised of a set of parameter group numbers (PGNs) and suspect parameter numbers (SPNs). The PGN identifies the set of related parameters the communication is addressing, and the SPN identifies a specific parameter within the group. For example, there is a PGN identifying data related to engine temperature. Within that parameter group, there are SPNs to identify specific temperature data for the engine coolant, fuel, oil, turbocharger oil, and intercooler.

Since its creation, J1939 has become widely adopted in heavy-duty road vehicles and off-highway applications such as commercial semi-trucks and construction equipment. A number of derivatives of the standard have also been developed for agricultural, forestry, and marine applications, as well as for interfacing with fleet management systems. With the growth of the IoT and connected vehicles, J1939 will only become more important as trucks, busses and other large vehicles began to communicate with each other and into the cloud. To that end, this paper examines a J1939 design flow focused on streamlining the integration of this widely adopted standard into new vehicle architectures.

Figure 2: SAE J1939 ensures interoperability of networks between manufacturers and implementations.

Electrical design challenges

Traditionally, heavy duty commercial and off-highway vehicle manufacturers have taken a separated approach to electrical design that creates silos for hardware, software, networks, and electrical distribution system (EDS) design (figure 3). Teams work separately and exchange data manually using email, marked-up PDF files, or Microsoft Office® tools. These manual data exchanges prevent effective collaboration between teams and present a number of challenges to the design cycle. For one, when integrating between domains, it is important that teams are able to obtain the most up-to-date data from the other design domains. With manual data exchange, engineers must sort through massive file systems to locate the correct data. This increases the likelihood that one of the design teams will proceed with out-of-date data, introducing errors into the design

Furthermore, as commercial and off-highway vehicles grow in complication, current design methods are approaching the limits of their capabilities. When conducting trade studies, teams will discover optimizations for the types and locations of ECUs, signal and message mapping, and the architectural layout. For example, switching to a new supplier of an existing ECU may drive a change in functional partitioning, enabling the combination of functions into fewer ECU's, reducing cost. With existing methods, implementing these changes into a design requires the manual exchange of dozens of files, increasing downtime and the potential for the introduction of errors.

Traditional design methodologies also struggle to quantify the knock-on effects of these design changes. Each change affects the rest of the system, and the unforeseen effects can be very difficult to predict. Migrating an ECU to a new location or network in the architecture may affect performance elsewhere in the system. This change in behavior may cascade, causing any number of sub-systems or functions to fail. Such a change can even completely invalidate the technical implementation of the architecture, driving the re-design of multiple systems. The effects can also be smaller and more subtle, making it difficult to predict and assess the net outcome of a change.

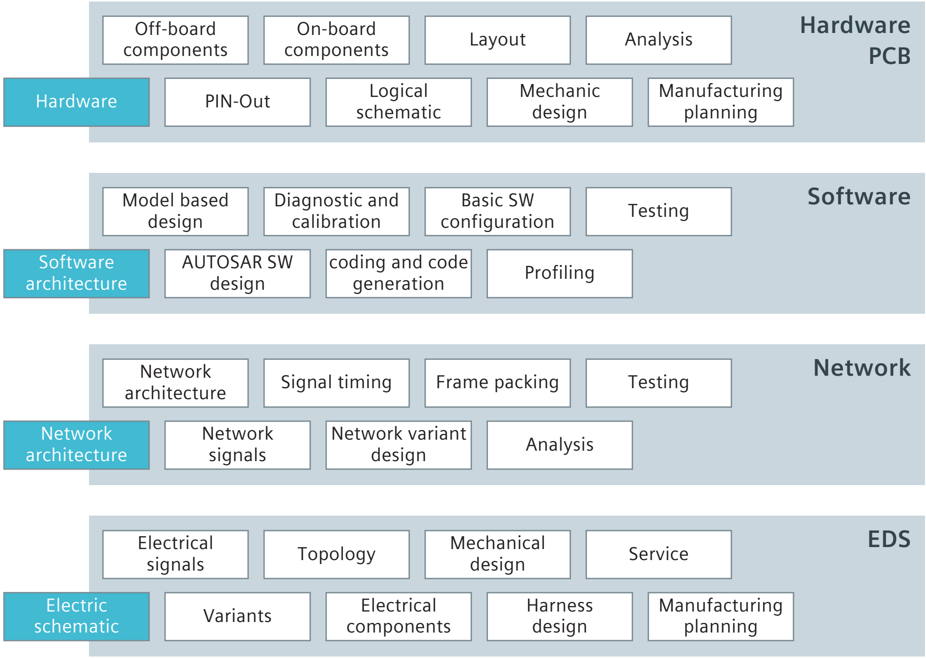


Figure 3: Manufacturers traditionally accomplish hardware, software, network and EDS design separately.

Without a robust, comprehensive design tool, engineering teams run the risk of sinking excessive time, cost, and effort into resolving these issues. Understanding and validating the impact of the required changes is crucial to accurately implementing the design intent. Tight integration between the electrical design domains enables teams to explore multiple potential implementations and consider the best iteration with which to update the E/E architecture, including where to host functions, which networks to connect ECUs to and so forth.

The Capital electrical system design and integration software suite is a data-driven solution that brings all of the electrical design aspects together into an integrated functional E/E architectural design (figure 4). The same data is shared across electrical domains: Capital Systems Capture imports and creates functional designs, and Capital Systems Architect places the functions on to the vehicle E/E architecture. This allows the functional design to feed requirements to downstream flows within Capital and the other E/E domain tools. With Capital, one tool chain and one data flow unifies the entire electrical design from architectural definitions through to the physical implementations.

Integrating the domains of electrical design helps ensure accurate and optimized designs despite the immense complexity of modern commercial and off-highway vehicle systems. For example, commercial and off-highway OEMs frequently use a mixture of in-house, Tier-1 supplier, and hybrid designs for the electronic control units (ECU) inside their vehicles. This results in an electrical system with an array of hardware and software interfaces that must communicate. Then, feature requirements can change when transitioning between model years or designing new derivatives of the vehicle architecture. Consequently, ECUs may need to be relocated, replaced, or merged to support new features or to adapt to new implementations of existing features within the architecture.

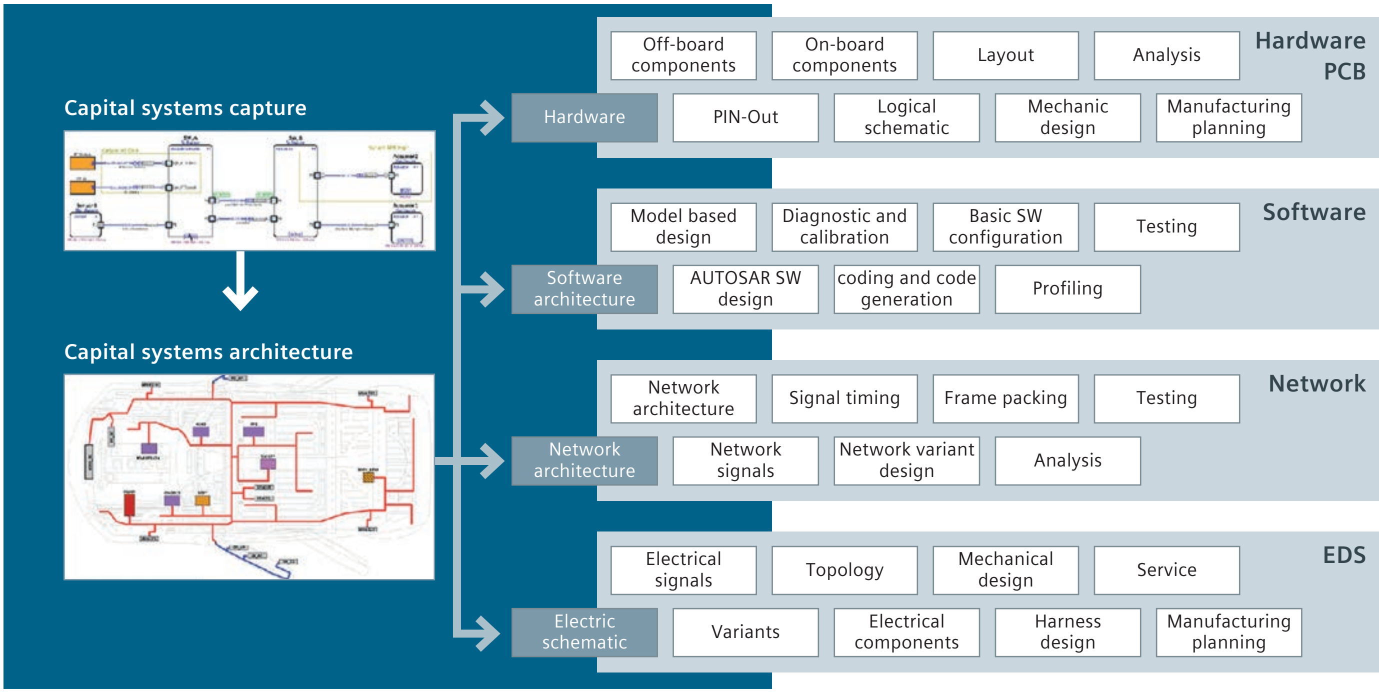
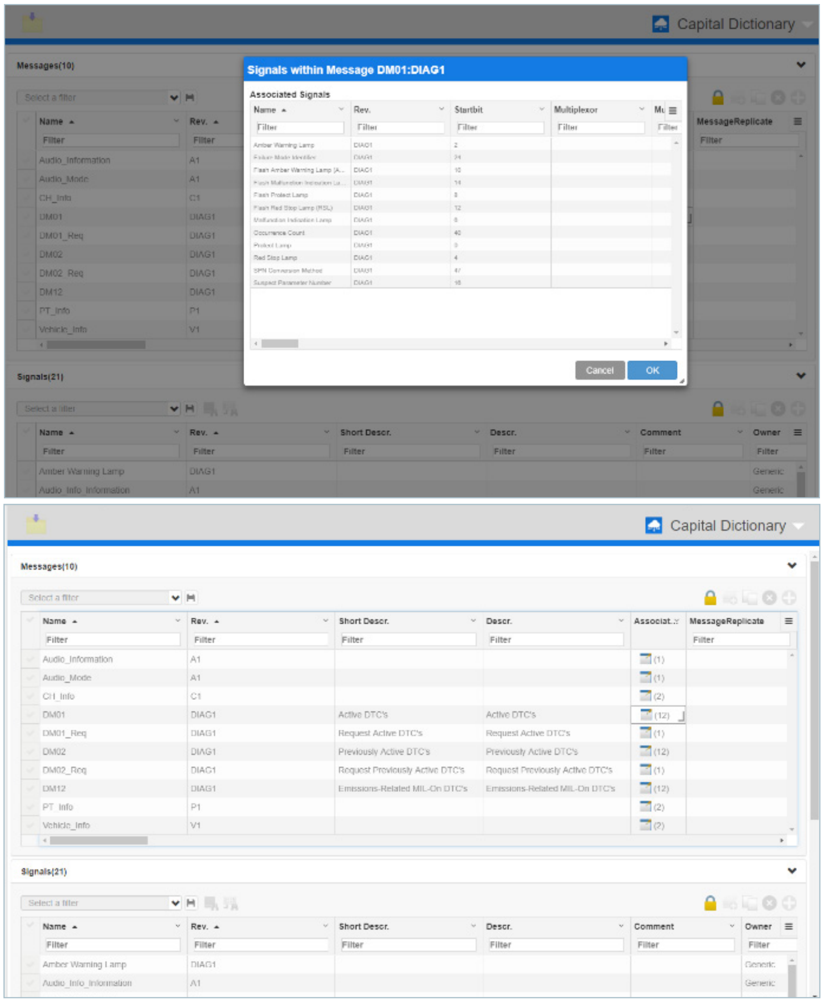


Figure 4: Capital provides an integrated design flow for all aspects of electrical systems design.

J1939 CAN design flow



Signals within Message DM01:DIAG1

Associated Signals

Name	Rev.	Startbit	Multiplexor
Amber Warning Lamp	DIAG1	2	
Failure Mode Identifier	DIAG1	24	
Flash Amber Warning Lamp (A...	DIAG1	10	
Flash Malfunction Indication La...	DIAG1	14	
Flash Protect Lamp	DIAG1	8	
Flash Red Stop Lamp (RSL)	DIAG1	12	
Malfunction Indication Lamp	DIAG1	6	
Occurrence Count	DIAG1	40	
Protect Lamp	DIAG1	0	
Red Stop Lamp	DIAG1	4	
SPN Conversion Method	DIAG1	47	
Suspect Parameter Number	DIAG1	16	

Messages(10)

Name	Rev.	Short Descr.	Descr.	Associat...	MessageReplicate
Audio_Information	A1			(1)	
Audio_Mode	A1			(1)	
CH_Info	C1			(2)	
DM01	DIAG1	Active DTC's	Active DTC's	(12)	
DM01_Req	DIAG1	Request Active DTC's	Request Active DTC's	(1)	
DM02	DIAG1	Previously Active DTC's	Previously Active DTC's	(12)	
DM02_Req	DIAG1	Request Previously Active DTC's	Request Previously Active DTC's	(1)	
DM12	DIAG1	Emissions-Related MIL-On DTC's	Emissions-Related MIL-On DTC's	(12)	
PT_Info	P1			(2)	
Vehicle_Info	V1			(2)	

Signals(21)

Name	Rev.	Short Descr.	Descr.	Comment	Owner
Amber Warning Lamp	DIAG1				Generic
Audio_Info_Information	A1				Generic

Figure 5: Capital can create a dictionary (top) of standard J1939 SPNs, PGNs, the mappings between them (bottom), and other corporate signals and messages.

Modern commercial and off-highway vehicles contain up to six CAN networks to transmit data around the vehicle architecture. The CAN networks connect the dozens of ECUs in the vehicle architecture and carry critical information that ensures the vehicle operates smoothly and safely. Commercial and off-highway OEMs must re-design or update these complex network designs for each new vehicle or derivative they produce. Therefore, an accurate and efficient design flow for J1939 CAN busses is a critical piece of commercial and off-highway vehicle development.

Capital provides a streamlined design flow for J1939 CAN busses, beginning with the creation of a dictionary of the signals and messages that will make up the communications on the CAN. Capital can receive Excel®, XML, or DBC files containing the standardized set of SPN signals and PGN messages as defined in J1939. From this input, Capital forms a dictionary of the J1939 standard SPNs, PGNs, the association of SPNs to PGNs, and any other signals and messages in the corporate dictionary (figure 5).

From the initial import, the signal dictionary will include standard SPN signals. J1939 provides an extensive standard set of signals and messages, but this may still need to be embellished with specific signals and messages that the OEM or project demands. With Capital, engineers can enrich the J1939 standard dictionary with additional signals and messages bespoke to the project or manufacturer. For example, many commercial trucks are equipped with turbocharged engines. For a semi-truck design, the signals and messages dictionary would need to include SPNs related to the turbocharger like boost pressure, mass airflow, intake air temperature and so forth, which may need custom scaling due to implementation requirements.

After importing a standard design, engineers can view the included PGNs and the SPNs within Capital Systems architect as networks and communications reports. In this view, the engineers can analyze the signal and message mapping in terms of its functional and connectivity properties. This enables further assignments or overrides to modify the content of the standard designs to fit the needs of the project at hand. For instance, engineers can modify specific property values depending on the implementation, avoiding the need to create unique signals and messages to account for small differences. This capability facilitates the reuse of existing design data by allowing engineers to adapt existing designs to the specific needs of the target implementation.

Engineering teams can then use this dictionary to streamline future implementations. With a library of reusable design artifacts, engineers are quickly and accurately able to integrate proven architectures, SPN and PGN mappings, and functional designs into a new vehicle's electrical and electronic systems (figure 6). In the above example, any future turbocharged vehicle designs would already have a robust dictionary of signals and messages to implement in the vehicle network. The reuse of these assets significantly improves design efficiency while simultaneously handling the thousands of signals required for modern vehicle networks.

The ability to reuse existing design data is a key advantage of an integrated electrical design flow. By reusing existing design data, engineers can reduce design errors and minimize or eliminate the need for lengthy redesign processes. Capital enables engineers to import black box functional designs and logic models, further leveraging the advantages of design data re-use. It is also possible to import an existing platform plane, complete with properties defined in the 3D CAD environment, or an abstracted networks logical architecture to use in the architectural platform design view, depending on user preference.

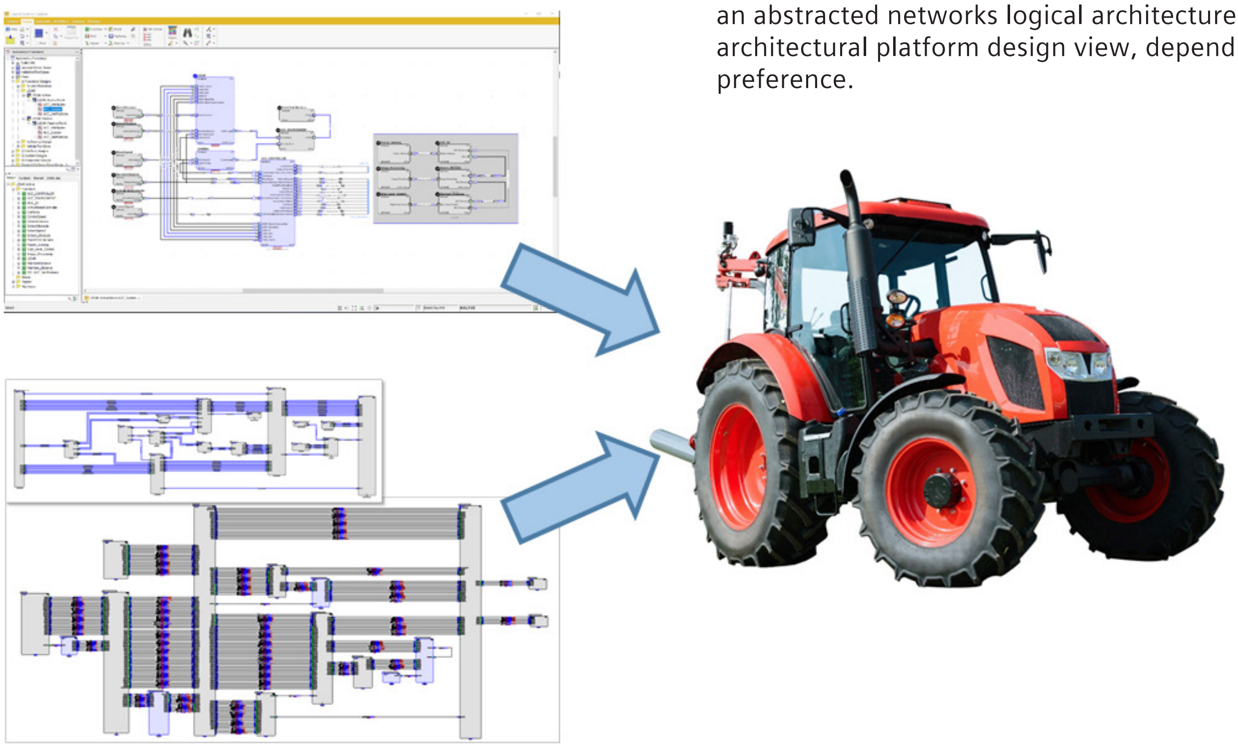


Figure 6: Engineering teams can streamline the design cycle by integrating pre-existing design artifacts.

Design data reuse

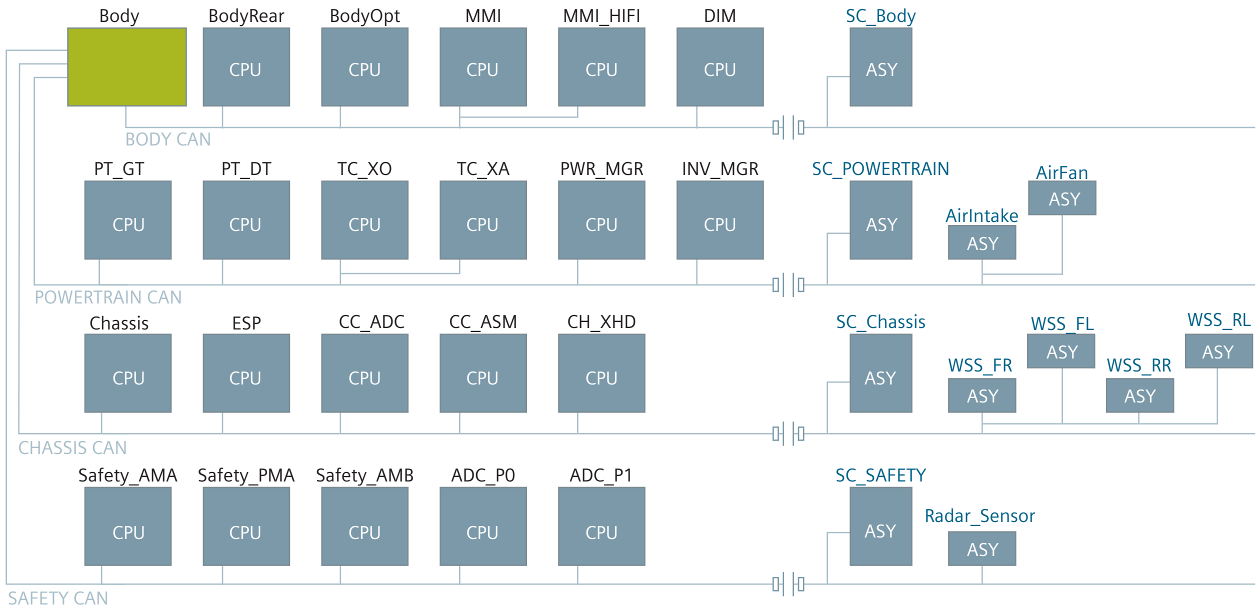
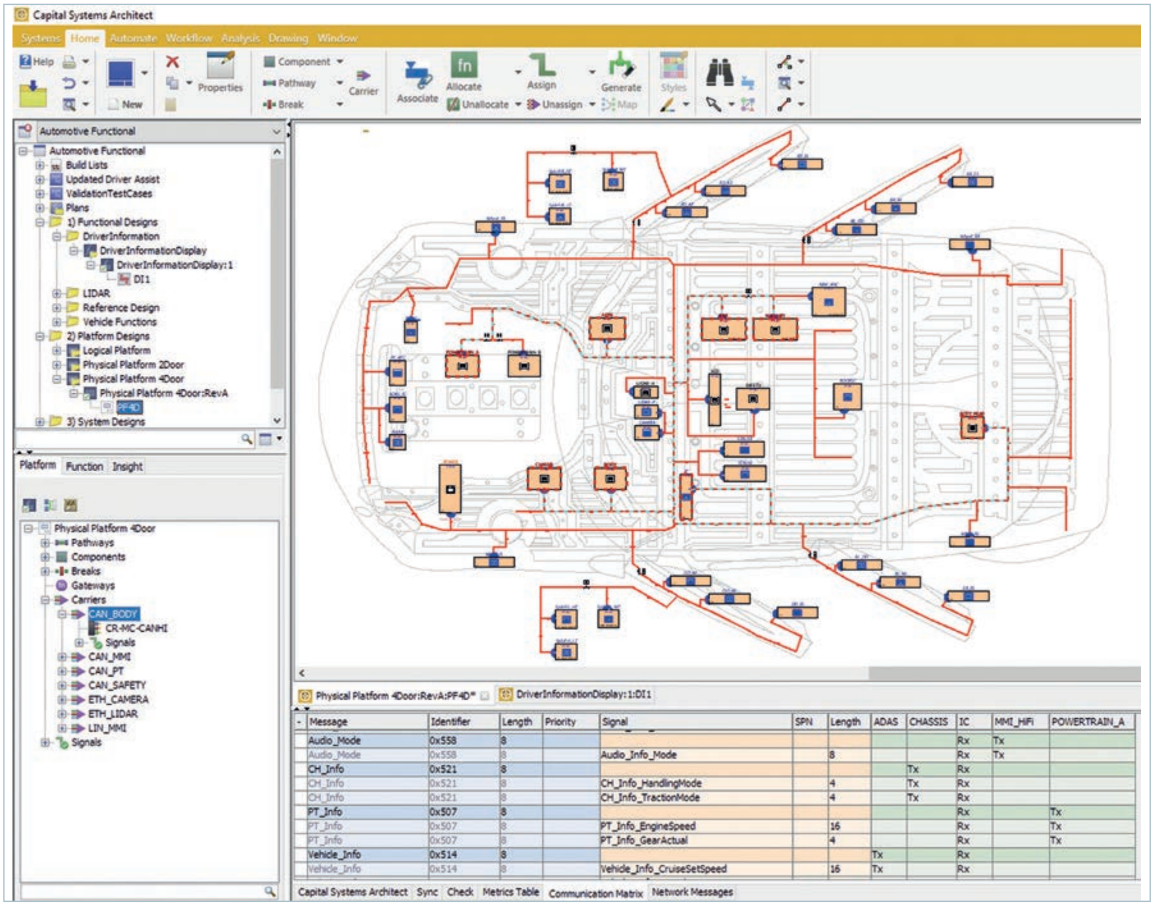


Figure 7: The logical design of the E/E system can be reverse engineered from existing logic models.

Existing design data provides engineers with a wealth of proven and verified assets to employ in new vehicle designs. By reverse engineering existing logic models, engineering teams can generate robust logic designs and component libraries (figure 7). Functional designs can be imported to create the software, hardware, network and electrical functions for the vehicle. Pre-existing vehicle architectures can also be imported to jumpstart device placement, harness routing channel design, connector locations and more. Finally, engineers can incorporate model-based systems engineering data stored in XML to further inform and refine the design.

As with the dictionary of signals and messages from J1939, engineering teams will sometimes need to adapt imported functional designs for the new vehicle architecture. These changes can compromise the efficiency of the default signal to message mapping, resulting in a design in which many messages exist, with only a few signals mapped to each. A common solution is to redesign the allocation of functions to ECUs in the architecture, co-hosting some functions on the same ECU. This increases the number of signals mapped to each message, making the design more efficient. With Capital, engineers can quickly reallocate functions around the vehicle architecture streamlining the evaluation of design permutations and the implementation of an optimal solution (figure 8).

Alternatively, the imported functional design may already describe what is on the CAN bus. In this case, the engineer may wish to add further design details, such as power and ground, or map out the sensor and actuator placement and the resultant flow of data. This provides the opportunity to re-optimize the location of functions for better network bandwidth, shorter power runs, or to reduce the EDS mass. When allocating functions to ECUs in the architecture, the engineer can choose to do so manually or through rules-based automation. Once the functions are allocated to architectural components, Capital can analyze system features such as process loading and network bandwidth utilization to determine if they fall within acceptable ranges.



Message	Identifier	Length	Priority	Signal	SPN	Length	ADAS	CHASSIS	IC	MMI_HIFI	POWERTRAIN_A
Audio_Mode	0x558	8							Rx	Tx	
Audio_Mode	0x558	8		Audio_Info_Mode		8			Rx	Tx	
CH_Info	0x521	8						Tx	Rx		
CH_Info	0x521	8		CH_Info_HandlingMode		4		Tx	Rx		
CH_Info	0x521	8		CH_Info_TractionMode		4		Tx	Rx		
PT_Info	0x507	8							Rx		Tx
PT_Info	0x507	8		PT_Info_EngineSpeed		16			Rx		Tx
PT_Info	0x507	8		PT_Info_GearActual		4			Rx		Tx
Vehicle_Info	0x514	8					Tx		Rx		
Vehicle_Info	0x514	8		Vehicle_Info_CruiseSetSpeed		16	Tx		Rx		

Figure 8: Capital enables engineers to reallocate functions around the vehicle architecture to optimize the employment of ECUs.

Model based analytic capabilities enable further optimization to the architectural and network design. Capital can generate metrics that predict architectural performance and network reporting data that illustrates the system's behavior in terms of signals and messages. With these analytics, engineers can identify optimizations to improve the performance of the architectural design, streamline the PGN and SPN mappings, and increase the network efficiency. Then, Capital can produce reports to communicate with suppliers, to configure test loggers, and to report or document the design for other customers internally or externally.

Software, network, and diagnostics design

The design data can also be sent to the Capital Systems Networks solution to complete detailed AUTOSAR design and network timing analysis. In Capital Systems Networks, engineers can begin designing the software implementation needed to enable the functions that have been assigned to each ECU. Within this environment, the engineers can also zoom in to look at diagnostics systems.

Capital provides the architectural design, functional allocation, and signals to the topology. Each of these features interrelates through the software diagnostics network. Capital is able to extend this visualization and design of signals and messages to other network types, such as Ethernet or CAN FD. The methodology also extends to design in diagnostic messages for diagnostics over internet protocol (DoIP).

Integration overview

Capital Systems Capture can take input from a variety of sources, including SysML and UML descriptions, Rational Doors and Rhapsody, and the Context® System Data Management tool, to create the functional design of a communication network. The generated functional designs can then be automatically enriched with the J1939 standard signals and messages stored in the

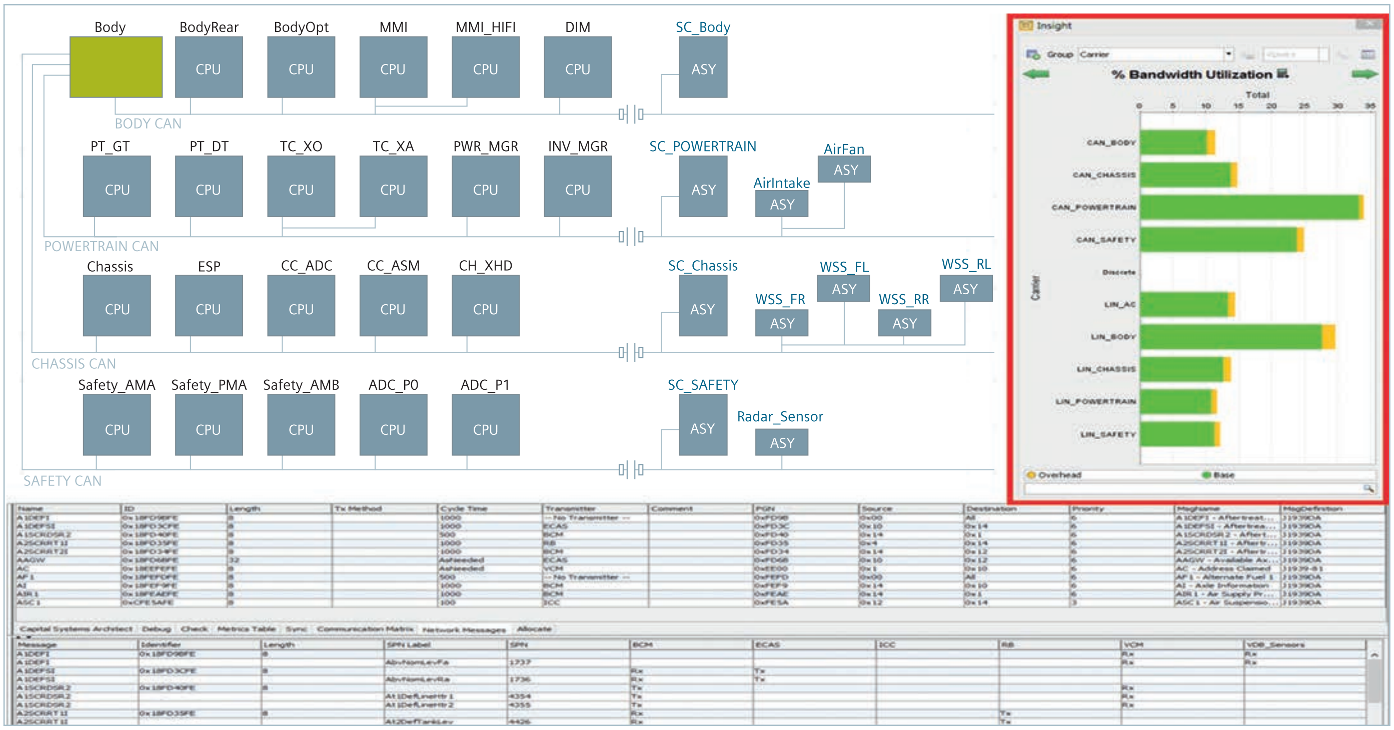


Figure 9: Capital integrates analytics into the design flow so that engineers can evaluate system features such as process loading, network bandwidth utilization, and more.

dictionary. With this enriched functional design, the engineer can then map this onto the architecture design, and begin refining the initial mapping using Capital's built-in metrics. The entire flow to this point can be iterated through to optimize bandwidth utilization, processing, harness weight and length (figure 9). Next, engineers can use the design to generate the electrical systems logic design, network and software architecture, and multi-board PCB designs to prepare for physical implementation. The finished designs can then be stored in Teamcenter.

Alternatively, this flow may begin by importing the SysML, UML, and other models directly into the Teamcenter Architecture Modeller. Using this input, Teamcenter can generate an analysis request that provides the necessary information to build the functional models in Capital System Capture. From here, the process proceeds as before by drawing J1939 signals and messages out of the dictionary, enriching the functional design, mapping onto the architecture, and then iterating. The engineer then pushes the finished design back into the architectural model with all the metrics and data generated.

Conclusion

Integrated architectural and network design

In summary, Capital Systems features built-in data coherency between the electrical design and implementation. This digital continuity fosters multi-domain and multi-disciplinary collaboration to reduce errors and improve design cycle times. Additionally, Capital enables rapid iterations to explore and evaluate different implementation options directly within the design environment with metrics to understand the technical and financial costs of implementing proposed changes.

Capital has now extended to integrate network and electrical system design. Capital Systems Networks expands the synthesis-driven Capital paradigm into network design. This enables engineers to reuse existing network design data to create a network dictionary such as for the SAEJ1939 standard. Network design data can be directly implemented in the functional design. Then, a validated network design output can be synthesized from the electrical system architecture. Finally, teams can generate outputs to enable OEM and supplier collaboration, reporting, testing, simulation, and for further optimization of the design in downstream flows.

The use of Capital Systems tools for SAE J1939 network design removes the manual file exchange and copy and paste tasks from system design for off-highway and commercial vehicles. Data consistency within the design flow assures a correct-by-construction design methodology. Engineers can rapidly assess the impact of proposed changes across the entire platform, reducing the risk of unknown consequences to the system design. Design data is stored in a database for re-use on future platforms, and downstream tools, removing repetitive and error prone tasks throughout the flow. Moreover, an integrated electrical, functional, and network design flow produces more accurate designs while increasing the efficiency of engineers for both near- and far-term projects.

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