EAST-ADL –

An Architecture Description Language for Automotive Software-Intensive Systems

White Paper

Version 2.1.12

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Abstract

This White Paper gives an overview to EAST-ADL. The document is intended for engineers that need a short introduction to the language, through descriptions and examples.

EAST-ADL is an Architecture Description Language (ADL) initially defined in the ITEA project EAST-EEA around 2000. Subsequently, several national and international funded projects have refined the language, and it is now aligned with the more recent AUTOSAR automotive standard. It provides a comprehensive approach for describing automotive electronic systems through an information model that captures engineering information in a standardized form. Aspects covered include Vehicle Features, Requirements, Analysis Functions, software and hardware components and communication. The representation of the system's implementation is not defined in EAST-ADL itself but by AUTOSAR. However, traceability is supported from EAST-ADL's lower abstraction levels to the implementation level elements in AUTOSAR. In this document we describe EAST-ADL, including a case study to show how it relates to AUTOSAR as well as other significant automotive standards and present current research work on using EAST-ADL in the context of fully-electric vehicles, the functional safety standard ISO 26262 and for multi-objective optimization.

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1 Introduction

EAST-ADL represents an Architecture Description Language (ADL) initially defined in the European ITEA EAST-EEA project. It was subsequently refined and aligned with the modeling approach of the AUTOSAR automotive standard [2] in national and international funded projects including the ATESST and MAENAD projects [1], [5]. It is maintained by the EAST-ADL Association [3].

EAST-ADL is an approach for describing automotive systems through an information model that captures engineering information in a standardized form. Aspects covered include vehicle features, functions, requirements, variability, software components, hardware components and communication.

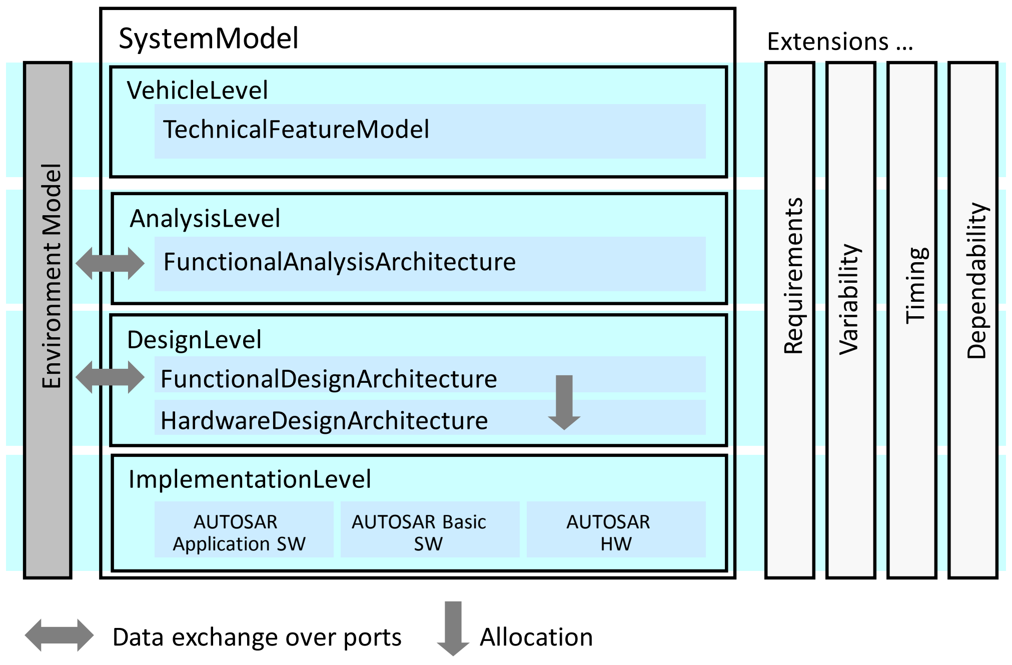


Figure 1: The EAST-ADL's breakdown in abstraction levels (vertically) and in core system model, environment and extensions (horizontally).

The functionality of the vehicle is described at different levels of abstraction and in different parts.

The four abstraction levels covered by the EAST-ADL are (see Figure 1):

- **Vehicle Level**
  Feature trees characterizing the vehicle content as it is perceived externally.
- **Analysis Level**
  An abstract functional architecture defining systems from a functional point of view.
- **Design Level**
  The detailed functional architecture allocated to a hardware architecture.
- **Implementation Level**
  The implementation of the embedded system represented using AUTOSAR elements

Each of the abstraction levels has a specific role. From the Vehicle Level stating *what* the vehicle should do through Analysis, Design and Implementation levels that define, at various level of abstraction, *how* this is done. Features on the Vehicle Level allow the organization of vehicle content in a solution-independent way. Requirements can be linked to features such as markets and brands as well as to technical features such as wipers or brakes.

The proposed abstraction levels and the contained elements provide a separation of concerns and an implicit style for using the modeling elements. The system description is complete on each abstraction level with respect to the concerns of that level.

The EAST-ADL extensions include requirements, variability, safety, behavior, timing, and generic constraints. Such elements reference the core elements at all abstraction levels. The behavior extension support modes, which allows different requirements, behaviors and constraints to be active at different time instants.

The core model at the Vehicle Level is organized around *Features* in the *TechnicalFeatureModel.* These represent the vehicle from a top-level perspective without exposing the realization. It is possible to manage the content of each vehicle and entire product lines in a systematic manner using sets of Feature Models with internal relations like needs and exclude, and configuration decisions across Feature Models.

A complete representation of the electronic functionality in an abstract form is modeled in the *Functional Analysis Architecture* (FAA). One or more entities (Analysis Functions) of the FAA can be combined to realize Features in the *TechnicalFeatureModel*. The FAA captures the principal interfaces and behavior of the vehicle's subsystems. It allows validation and verification of the integrated system or its subsystems on a high level of abstraction. Critical issues for understanding or analysis can thus be considered, with less risk of obscuring by implementation details.

The implementation-oriented aspects are introduced while defining the *Functional Design-Architecture* (FDA). The Features are realized here in a function architecture that takes into account efficiency, safety, legacy and reuse, purchasing strategy, hardware allocation, etc. The function structure is such that one or more functions can be subsequently realized by one or more AUTOSAR software components (SW-C). The external interfaces of such components correspond to the interfaces of the realized functions.

The *Hardware Design Architecture* (HDA) should be considered parallel to function development. On the design level and down, the HDA forms a natural constraint for development and the hardware and application software development needs to be iterated and performed together. There is also an indirect effect of hardware on the higher abstraction levels. Control strategies or the entire functionality may have to be revised to be implemented on a real hardware architecture. This reflection of implementation constraints needs to be managed in an iterative fashion.

The representation of the system implementation, the *software architecture* and its allocation details to the embedded system, is not defined by EAST-ADL but by AUTOSAR. Traceability is supported from implementation level elements (AUTOSAR) to Vehicle Level elements. Further, the EAST-ADL extensions for ISO26262, requirements, variability, etc. can be applied to the AUTOSAR elements. Traceability through the extension elements is applicable through the abstraction levels all the way down to implementation level.

As a complement to the above, an *environment model* is required for verifying and validating Features across all abstraction levels. Verification could for example be carried out using simulation or formal analysis techniques.

The Environment Model, sometimes referred to as plant model, captures the behavior of the vehicle dynamics, driver, etc. It represents all relevant elements interacting with the vehicle systems defined in the previously described architectures. Examples include a) the mechanical and hydraulic systems in the vehicle, b) the near environment including road surface and adjacent vehicles, and c) the far environment such as road traffic informatics.

Different tasks will typically require different detail and scope of the Environment Model. For example, there may be a detailed vehicle and powertrain dynamics model to assess gear change performance and a low-detail dynamic model for fuel consumption assessment. The alternatives are selected using the variant management extension or using alternative Environment Models for each task. The same Environment Model can typically be used across several abstraction levels.

After this short introduction to the EAST-ADL concepts, we go on to discuss the motivation and modeling concepts in more detail.

2 Challenges for Modeling Automotive Embedded Systems

Automotive embedded systems have evolved enormously over the past decades. The use of electronics and software in automotive products has grown exponentially. A majority of automotive innovations are related to electrical and electronic systems. Virtually all vehicle systems rely fully or partly on electronics and software. It is obvious, that the vehicle's electrical and electronic architecture will continue to grow in complexity, criticality and authority.

To manage some of the challenges of automotive software, the AUTOSAR consortium has developed a standardized automotive software architecture. One of its main features is the support for componentization of the application software architecture, to favor reuse and assist collaboration and integration aspects. The software development effort is no longer bound to a specific hardware platform or a particular provider. A standardized software architecture and methodology is a first step towards meeting the challenges connected with the development of automotive systems, often distributed over several suppliers with different responsibilities.

However, there still remains the critical issue of managing the overall engineering information to assist the system definition from the early phases. The early phases of system definition involve the most decisive steps in meeting safety challenges, controlling complexity and avoiding development errors and delays. Many stakeholders are involved here, and development is distributed over several departments and locations across several suppliers.

While system modeling and model-based development is the trend in the automotive industry to solve this issue, current practice is typically to use a federation of different modeling approaches. Without a clear integration concept for heterogeneous set of models, its full value cannot be achieved. The modeling notations involved must be integrated in a way that correctly composes to a meaningful overall model, in terms of structure and behavior and additional aspects such as safety or variability annotations.

To support complexity and facilitate component development, an adequate organization of the system model is important. Representing the system in several "models" at different abstraction levels is a way to ensure separation of concerns and allow smooth interaction between disciplines. Supporting a functional decomposition of the system is also important to hide implementation aspects while the functional aspects are addressed.

Another aspect of system model organization concerns external annotations of the core stucture, for example timing and variability. By managing such information in external packages, the meta-model as well as the user models are modular.

Another challenge is the capability to use product line engineering. Today, component reuse is the state of the art in the automotive industry. The organization and structuring of a product line approach, from Feature selection up to decomposition into components, requires innovative and efficient techniques.

Finally, an important challenge is assessing the dependability of the application. What is needed is a means to the early evaluation of system architectures, in terms not only of functional properties, but also non-functional ones (such as timing, resource and safety level). In this context, the application of the standard for functional safety (ISO DIS 26262) must be supported by appropriate techniques and a structured development approach. An architecture description language provides a means to represent the safety life-cycle information according to the requirements of the standard.

Last but not least, tool support for engineering development is organized today as a patchwork of heterogeneous tools and formalisms. The meaning and organization of modeling elements must be agreed to ensure consistent syntax and semantics across tools, and thus drive the tool market to improve the available engineering support.

3 EAST-ADL Meta-Modeling Approach

The EAST-ADL language is formally specified as a meta-model that captures domain specific (i.e. automotive) concepts. The meta-model follows guidelines originating from AUTOSAR for definition of templates. Modeling concepts are represented by the basic notions of MOF (www.omg.org/mof/) supplemented by the AUTOSAR template rules [2]. The meta-model thus fits as a specification of a domain specific tool environment, and also defines an XML exchange format. This *domain model* represents the actual definition of the EAST-ADL language and constitutes the heart of the EAST-ADL language specification.

The meta-model is organized in abstraction levels. On the lowest abstraction level, i.e. the implementation level, AUTOSAR elements are used to represent the software architecture. The abstraction levels can be seen as a vertical layering of information. A horizontal structure is based on core vs. environment vs. extensions.

Depending on company needs, different strategies to apply the EAST-ADL are foreseen:

(1) As a reference model, where a company will adapt the EAST-ADL information model and implement what they find useful, e.g. through a domain specific language or a custom tooling environment.
(2) A partial deployment of the meta-model where the core parts at one or several abstraction levels are used according to their definition. One or several extensions may be attached to these, according to which information is needed.
(3) EAST-ADL and its corresponding exchange format is fully deployed.

In addition to the domain model, the EAST-ADL language is also implemented as a *UML2 profile*. UML profiles are standard extension mechanisms in the UML2 language, in which domain-specific concepts are provided as tags applicable to a selected subset of UML2 elements (such as classes, properties, ports, etc.) giving them different meaning and extra properties. The profile allows users to do system modeling according to the EAST-ADL semantics by using off-the-shelf UML2 tools. Constraints are also part of the profile definition; this makes it possible to constrain the rich set of modeling constructs allowed by UML2 and to validate the conformance of the model. The EAST-ADL profile is delivered as an XMI file ready for use in UML2 tools.

In the definition of the EAST-ADL profile, the general strategy has been to provide stereotype properties even for properties already populated within the UML2 superstructure. In other words, the property values that appear when defining a UML2 user model are duplicated with semantic names in the stereotypes. This yields a user model that is quite complete even without a profile.

This approach is in line with the intention of UML2 that the views and features of existing UML2 tools can be used readily, including for example, UML2 activity diagrams and related profiles such as SysML (www.omgsysml.org) and MARTE (www.omgmarte.org). The applied profile adds automotive semantics to this self-contained UML2 user model.

4 EAST-ADL Modeling Concepts

The modeling concepts of EAST-ADL fall into various areas, for example functional abstraction, timing modeling, requirements modeling, functional safety modeling, variability modeling and cooperative active safety systems. Below these will be elaborated with descriptions and conceptual figures. Some examples can be found in Section 8.

4.1 Vehicle Feature Modelling

Vehicle Features are used to characterize the vehicle content as it is perceived externally. For this purpose, a Technical Feature Model represents the Features that are realized by various systems. To characterize Vehicle Features, requirements and use cases and other annotations can be used. The Features are organized in a tree, where the basic semantic is that the child nodes of a tree together make up the parent. This is reflected by Realization semantics, where a function realizing a Feature is also responsible for Realizing its complete subtree. Similarly, Requirements on a Feature may be amortized over all its children, and the set of all Requirements on those children should be consistent with the Parent’s overall requirements.

A set of Product Feature Models can be used to configure a Technical Feature Model. Product Feature Models organize non-product aspects, such as brands, markets and ranges, and can be used to make systematic decisions on product content for a specific brand or market.

4.2 Functional Abstraction

EAST-ADL provides a means to capture the functional decomposition and behavior of the embedded system and the environment.

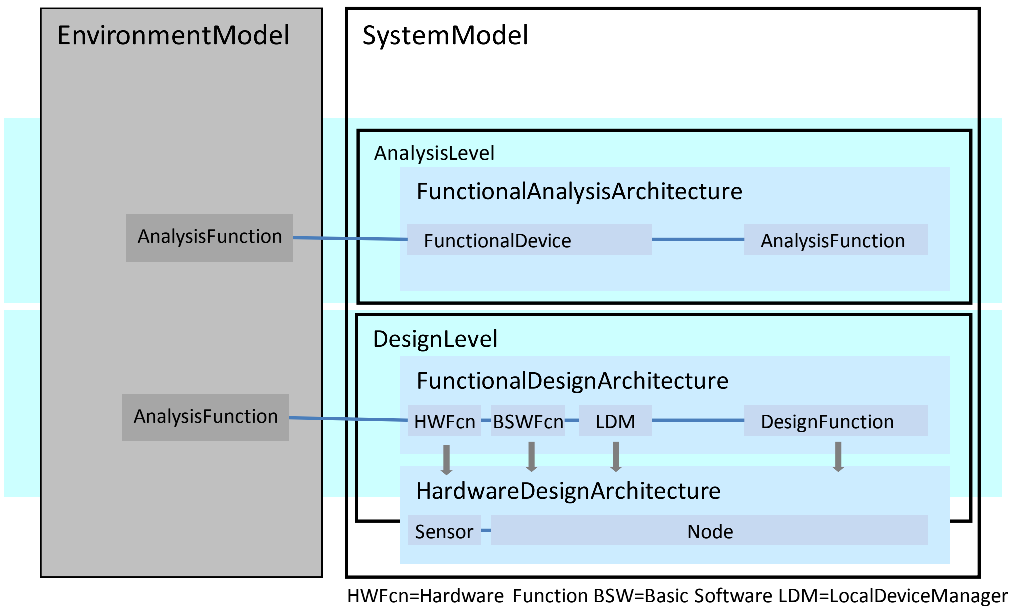


Figure 2. Functional decomposition in EAST-ADL on analysis and design levels.

At the Analysis Level, the *Functional Analysis Architecture* contains *Functions* that can be hierarchically composed and connected to each other. Functional devices represent sensors and actuators with their interface software and electronics, and these are connected to the environment. Figure 2 illustrates the entities involved and shows how they are connected.

The “Functions” can have two types of ports, *FlowPorts* and *ClientServer* ports to represent data exchange and client-server interaction respectively. FlowPorts provide or receive data according to its (single) datatype. ClientServer ports declare multiple operations, each with argument and return value with datatypes. The argument value is provided to the server function on the client call. A return value is received from the called function on its completion. The data exchange semantics is single buffer overwrite, i.e. the last written value is always used.

The functions can be hierarchical, but the leaves have synchronous execution semantics, which means that they read inputs, calculate and provide outputs. They are triggered based on time or data arrival on ports. For FunctionFlow ports, input and output are provided asynchronously from sender to receiver. Calls to ClientServer ports on event-triggered functions are blocking until the execution time has expired. At this point, the return value is provided. If the server function is time triggered, the delay until triggering has to be added.

In addition to the triggering and execution semantics, the data transformation inside the function needs to be defined. Such transfer function is typically defined by external tools using their respective notation for behavioral descriptions. A native behavioural notation has also been developed for EAST-ADL allowing direct definition of behavior, which is independent of which tool is used. These are denoted Behavioural Constraints, because they can be used to define behavior for several purposes including requirements, test results, Features and of course function behavior in Environment Models and Functional Analysis and Design Architectures.

The behavior of the environment is captured in the *EnvironmentModel*. The Environment Model also contains *Functions*, but they represent vehicle dynamics, other vehicles, road-side IT systems, etc.

The design level (see Figure 2) contains a more detailed functional definition of the system. *Functions* and *LocalDeviceManagers* represent application software in the Functional Design Architecture. “*BasicSoftwareFunctions*” are used to capture middleware behavior affecting application functionality. *HardwareFunctions* represents the logical behavior of hardware components and complete the logical path to the Environment Model with the controlled “plant” and surrounding elements. The *HardwareDesignArchitecture* represents the resources of the embedded computing platform, i.e. ECUs, communication networks, sensors, actuators and I/O to which the functions are allocated. The Hardware Design Architecture also reflects the physical topology of electrical elements and connectors.

4.3 Traceability within the Model

Because the EAST-ADL model integrates several aspects, different kinds of traceability is possible by investigating the relations of the model. Some examples include:

- Requirements allocation: For elements like Hardware Component, Design Function or Analysis Function it is possible to see which Requirements it shall fulfill by following the *Satisfy* relations.
- Requirements decomposition: The requirement set into which a parent requirement is decomposed is identified by the *Derive* relation.
- Functional interaction: Connectors define which functions interact with a given function through input, output or client-server ports.
- Hardware interaction: Hardware connectors define which hardware components that are physically connected to a given hardware component.
- Functional allocation: For Hardware Components, it is possible to see which functionality it hosts by investigating the *FunctionAllocation* relations. On the same basis, the functional interface represented by a Hardware Component can be established by identifying the set of interfaces of its allocated functions.
- Realizations: The elements at a lower abstraction level responsible for realizing a particular element can be found by inspecting the *Realize* relations.

When referencing functional or hardware elements, there is a distinction between its definition, then called type versus its occurrence as an element in a product hierarchy, then called prototype. For example, a requirement regarding an ABS braking function in general is linked to its type definition, while a requirement regarding ABS braking on the rear axle, right side is linked to the specific prototype in the product hierarchy. Similarly, allocation of a function to a node must refer to a specific prototype, e.g. the front left ABS is allocated to the front left wheel ECU.

4.4 Timing Modeling

EAST-ADL provides support for model-specific engineering information, including non-functional properties that are relevant for the timing of automotive functions. Conceptually, timing information can be divided into timing requirements and timing properties, where the actual timing properties of a solution must satisfy the specified timing requirements.

Modeling of timing requirements and properties at the functional abstraction levels of the architecture description language is done by means of the *Timing Augmented Description Language*, TADL developed by the TIMMO project [6]. At the implementation level, i.e. AUTOSAR, this is addressed by the *Timing Extensions* which were introduced in AUTOSAR release 4.0 [2].

Timing constraints are defined separately from the structural modeling and reference the structural elements of the EAST-ADL. The requirements modeling support in EAST-ADL allows for tracing from solutions as modeled in the structural model to requirements, and from verification cases to requirements. The TADL constraints fit in the requirement support as refinements of the requirements.

The fundamental concepts for describing timing constraints are that of *Events* and *Event Chains*. On every level of abstraction, observable events can be identified, e.g. events that cause a reaction, i.e. a stimulus, and resulting observable event, i.e. a response.

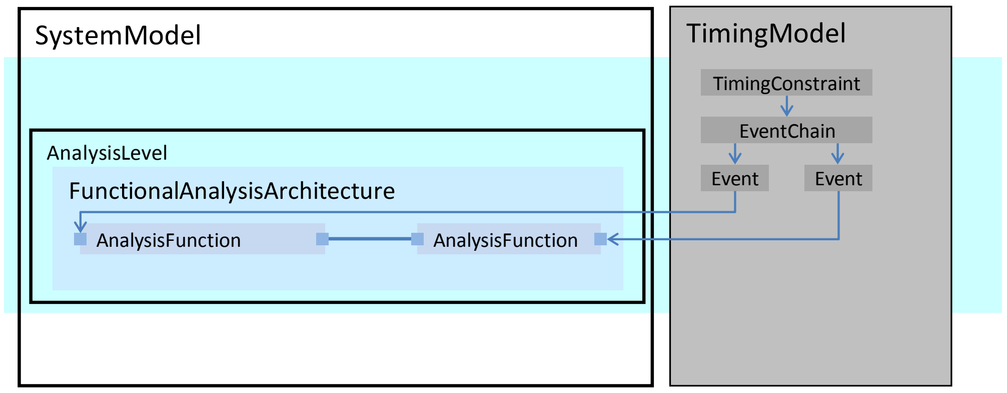


Figure 3. Event Chain with associated timing constraint.

Timing requirements can be imposed on Event Chains, for example, specifying that the time between the occurrence of a stimulus event and the occurrence of the expected response event shall not exceed a specific amount of time, e.g. an end-to-end delay from a sensor to an actuator. In addition, requirements regarding the synchrony of events can be expressed, stating that a number of events shall occur “simultaneously“ in order to cause a reaction, or be considered as a valid response of a system function. For example, in case of a passenger vehicle, its brake system shall apply the brakes simultaneously, or the exterior light system shall simultaneously turn on and off the rear and front turn signal indicators.

Figure 3 shows a simple example of an event chain with a reaction constraint. The timing elements extend a basic Functional Analysis Architecture. The “in event” refers to the reading of data on the in port and the “out event” to the delivery of data on the out port.

4.5 Requirements Modeling

In order to support the development of complex automotive systems, EAST-ADL provides a means to requirements specification, i.e. for specifying the required properties of the system (at varying degrees of abstraction). The Requirements concepts are aligned with the SysML and Requirements Interchange Format (ReqIF) standards, but are adjusted to follow the meta-model structure of EAST-ADL.

4.5.1 System Model Structure vs. Requirements

The *Requirement* element is linked to any other EAST-ADL element using a *Satisfy* relation. This makes it possible to define solution independent requirements, organized according to Vehicle Features on the Vehicle Level. Solution requirements concerning pure functionality, independent of physical system topology can be defined on the Analysis Level and allocated to elements of the AnalysisFunction hierarchy. Requirements concerning detailed design are allocated to elements of the Functional and Hardware Design Architectures on Design Level. This provides a means to organizing requirements according to the functional decomposition of the vehicle; requirements concerning the physical infrastructure are organized according to the system/subsystem/component hierarchy of the hardware architecture. Detailed requirements on software and hardware implementation are allocated to elements of the implementation level.

The requirement decomposition is formalized using a *Derive* relation, typically between requirements on different abstraction levels.

4.5.2 Hierarchical Organization of Requirements

Except for the implicit organization of requirements that follows from the structure of the satisfying elements discussed above, Requirements are organized in a flat list in one or several *Requirements Models*. Within one Requirements model, it is possible to define hierarchy as an “add-on” to the flat list. Using the RequirementsHierarchy construct, one or several (orthogonal) hierarchies can be defined. Each requirement may thus occur simultaneously in hierarchies for emission-related aspects, brand and range, environment aspects, etc.

4.5.3 Requirement Representation

Methodically, EAST-ADL allows a differentiation between functional requirements prescribing how and what to deliver, such as “ABS shall control brake force via wheel slip control”, and quality requirements prescribing how well or according to what characteristic to deliver, such as “ABS shall reduce the stopping distance on snow by 40%”. There are several categories among the quality attributes like availability, configurability, ergonomy, etc. if a more specific marking is needed.

Because requirement engineering is a complex process, highly integrated with company specific needs, it is necessary to be able to add company specific information to requirement elements. The User Defined Attribute concept of EAST-ADL provides a means to attaching attributes varying from simple booleans to complex data structures to each Requirement. This way it is possible to keep track of status, author, responsible, etc. of each requirement, according to predefined data templates given for the user element type.

Requirements can be formalized by using the constraints of EAST-ADL, including timing, safety and behavior. The *Refine* relation links the requirement and the formalized constraint. It is also possible to link any EAST-ADL construct including functional or hardware hierarchies to a requirement, to indicate a mandatory aspect which requires explicit verification.

4.5.4 Verification and Validation

EAST-ADL offers detailed means to model artifacts of verification and validation activities and to relate these artifacts to requirements. This facilitates planning and tracking V&V activities and their impact on the system parallel to the system's development.

A *VVCase*, decomposed into *VVProcedures* specifies how one or several requirements are verified or validated. The requirements are identified with The *Verify* relation links cases or procedures to one or several requirements, identifying how these are verified.

The VVCase identifies which aspects of the system model is subject to verification using the *VVSubject* association. The particular test environment or experimental setup used for verification is identified by the *VVTarget* concept.

VVCase can appear both as a specification of a test activity (abstract VVCase), and as a concrete test activity (concrete VVCase). In the latter case, test results are logged as *VVActualOutcome* and can be compared with *VVIntendedOutcome* for a given *VVStimuli..*

4.6 Functional Safety Modeling

The overall objective of the support for functional safety modeling is to enforce explicit considerations of safety concerns throughout an architecture design process, including all safety related information that is necessary for developing a safety-critical system, in compliance with the Standard ISO 26262 (an international standard dedicated to functional safety for road vehicles, [4]).

As an overall system property, safety is concerned with anomalies (e.g. faults, errors and failures) and their consequences under certain environmental conditions with the goal to mitigate risks. Safety is one particular aspect of system dependability that normally also encompasses reliability, availability, integrity, maintainability and security. Functional safety represents the part of system safety that depends on the correctness of a system in performing its intended functionality. In other words, it addresses the hazardous events of a system during its operation (e.g. component errors and their propagations).

EAST-ADL facilitates safety engineering in terms of safety analysis, specification of safety requirements, and safety design. While promoting safety in general through its intrinsic architecture modeling and traceability support, EAST-ADL provides explicit support for efficient integration of functional safety activities along with the nominal architecture design and evolution.

As illustrated in Figure 4, EAST-ADL provides language-level support for the concepts defined in ISO 26262, including vehicle-level hazard analysis and risk assessment, the definition of safety goals and safety requirements, the ASIL (Automotive Safety Integrity Level) decomposition and the error propagation. The information is included in the Dependability package, as an extension of the nominal architecture model.

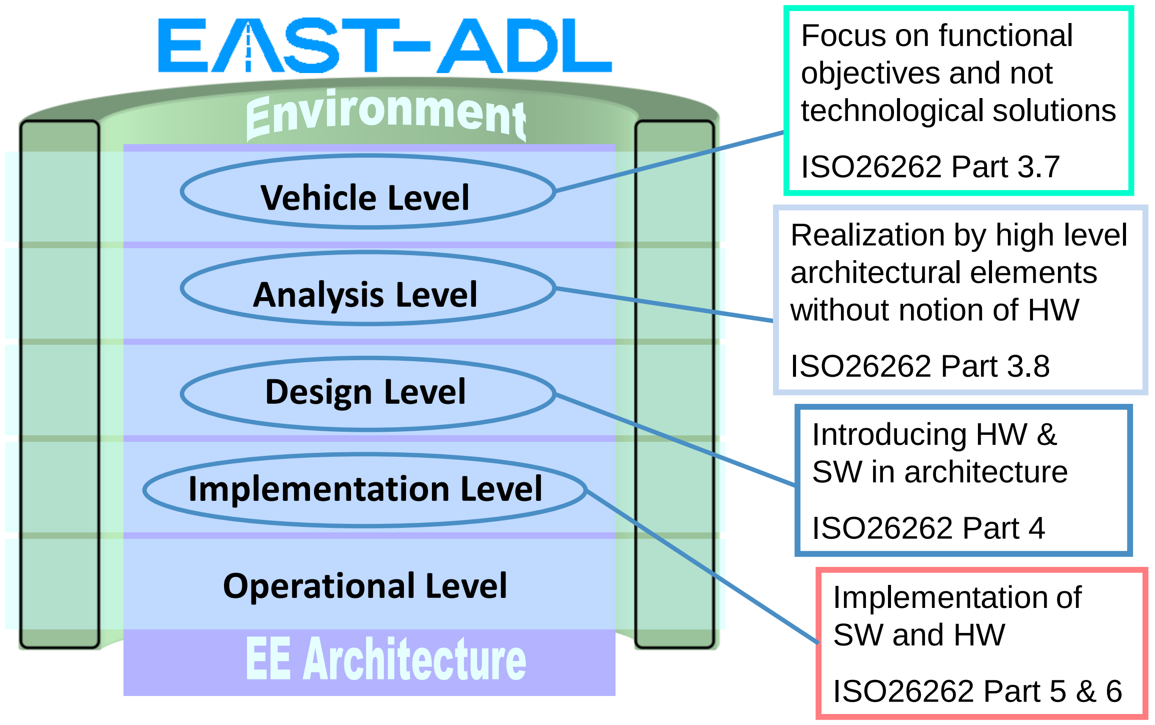

EAST-ADL
Environment
Vehicle Level
Analysis Level
Design Level
Implementation Level
Operational Level
EE Architecture
Focus on functional objectives and not technological solutions
ISO26262 Part 3.7
Realization by high level architectural elements without notion of HW
ISO26262 Part 3.8
Introducing HW & SW in architecture
ISO26262 Part 4
Implementation of SW and HW
ISO26262 Part 5 & 6

Figure 4. Mapping of ISO26262 information to EAST-ADL abstraction levels.

Following a top-down approach, the safety analysis starts at the Vehicle Level, beginning with the identification and description of the *item*. An item, as defined in ISO 26262, is a system or array of systems or functions that is of particular concern in regards to functional safety. Through hazard analysis and risk assessment activities, it is possible to preliminarily evaluate at Vehicle Level the "safety relevance" of the item under safety analysis, to define the safety goal (top-level safety requirement) for each hazardous event (hazard evaluated in different scenarios) and to classify them in terms of ASIL. Moreover, AnalysisLevel and DesignLevel of EAST-ADL support respectively the *functional safety concept* and the *technical safety concept* definition of ISO26262.

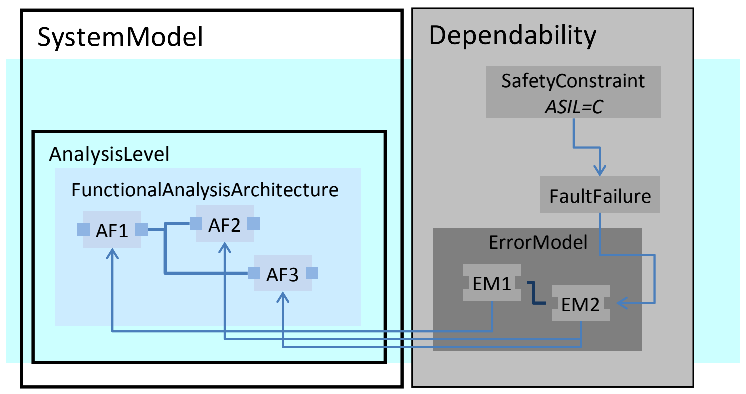


Figure 5. EAST-ADL error model as a separate architecture view extending the nominal architecture model.

EAST-ADL error modeling allows capturing detailed information about the failure behavior of the system and thus supports a safety analysis to determine whether technical safety requirements are met. This *ErrorModel* describes the generation and propagation of failures through the system. The relationships of local error behaviors are captured by means of explicit error propagation ports and connections. Within an error model, the syntax and/or semantics of existing external formalisms can be adopted for a precise description of the error logic. The specification captures what output failures of the target architecture component are caused by what faults of this component. This, together with the error propagation links, makes it possible to perform safety simulations and analyses through external analysis tools. In an architecture specification, an error is allowed to propagate via design specific architectural relationships when such relationships also imply behavioral or operational dependencies (e.g. between software and hardware).

The error modeling is treated as a separate analytical view (see Fig. 5). It is not embedded in a nominal architecture model but seamlessly integrated with the architecture model through the EAST-ADL meta-model. This separation of concerns in modeling is considered necessary in order to avoid some undesired effects of error modeling, e.g. relating to the comprehension and management of nominal design, reuse, and system synthesis (e.g. code generation).

Given an error model, the analysis of the causes and consequences of failure behaviors can be automated through tools. There is currently a (prototype) analysis plug-in in the Eclipse environment allowing the integration of the HiP-HOPS tool (Hierarchically Performed Hazard Origin and Propagation Studies) for static safety analysis in terms of FFA, FTA, and FMEA. The analysis leverage includes fault trees from functional failures to software and hardware failures, minimal cut sets, FMEA tables for component errors and their effects on the behaviors and reliability of the entire system.

In EAST-ADL, a safety requirement derived from the safety analysis has attributes specifying the hazard to be mitigated, the safety integrity level (ASIL), operation state, fault time span, emergency operation times, safety state, etc. The safety requirement is then traced to or used to derive other nominal requirements, e.g. relating to safety functions and performance.

4.7 Variability Modeling

EAST-ADL variability management starts on the Vehicle Level, where model range Features and variability are represented. At this point, the purpose of variability management is to provide a highly abstract overview of the variability in the system such as the complete system together with dependencies between these variabilities. A *variability* in this sense is a certain aspect of the complete system that changes from one variant of the complete system to another. “Abstract” here means that, for an individual variability, the idea is not to specify how the system varies with respect to this variability but only that the system shows such variability. For example, the front wiper may or may not have an automatic start. At Vehicle Level, the impact of this variability on the design is not defined; only the fact that such variability exists is defined by introducing an optional Feature named *RainControlledWiping*. This is subsequently validated and refined during analysis and design.

One or more Feature Models may be defined on the Vehicle Level: the so-called core Technical Feature Model is used to define the complete system’s variability on a global level from a technical perspective, whereas one or more optional Product Feature Models can be used to define views on this technical variability which can be tailored to a particular view-point or purpose, e.g. the end-customer perspective.

While the details of how variability is actually realized in the system are largely suppressed at the Vehicle Level, they are the focus of attention when managing variability in other areas of the development process. In fact, specific variability may lead to modifications in any development artifact, such as requirements specifications and functional models. Here, describing that a specific variability occurs is not sufficient; it is necessary to describe how each variation affects and modifies the corresponding artifact.

The purpose of Feature Modeling is to define the commonalities and variabilities of the product variants within the scope of a product line. Feature models are normally used on a high level of abstraction, as described above for Vehicle Level variability. However, in EAST-ADL, they are also used on Analysis and Design levels and acquire a much more concrete meaning there.

Configuration decision modeling, on the other hand, is aimed at defining configuration: the configuration of a Feature Model, f_T – i.e. the selection and deselection of its Features – is defined in terms of the configuration of another Feature Model, f_S. A configuration decision model can thus be seen as a link from f_S to f_T that allows us to derive a configuration of f_T from any given configuration of f_S. In EAST-ADL, this mechanism is used to define how a certain configuration on a higher abstraction level affects the binding of variability in lower-level components.

Variability management on the artifact level is driven by the variability captured at the Vehicle Level. This means that the main driver for variability and also variability instantiation is the Vehicle Level Feature Model. Variability on the artifact level essentially consists of the definition of variation points within these artifacts. In addition, Feature Models can be attached to functions in order to expose the variability within these functions and hide the actual structuring, representation and binding of this variability within a function. This way, the benefits of information hiding can now be applied to the variability representation and variability binding within the containment hierarchy of functions in the EAST-ADL Functional Analysis Architecture and Functional Design Architecture (called compositional variability management).

4.8 Behavior Constraint Modeling

The reasoning and analysis of dependability and performance involve many aspects in a system's lifecycle. To this end, EAST-ADL allows precise and integrated annotations of various behavioral concerns related to requirements, application modes and functions, implementation and resource deployment, and anomalies. The approach is architecture centric as all behavior annotations are formally connected to a set of standardized system artifacts and lifecycle phases. This is fundamental for many overall design decisions, such as requirements engineering, component compositionality and composability, design refinements, safety engineering, and maintenance. From a wider perspective, this language support enables an integration of many existing modeling and analysis technologies, such as those from computer science and electronic engineering, by making it possible to trace and maintain the related engineering concerns and analytical information coherently using EAST-ADL.

Based on a hybrid-system semantics, the EAST-ADL support for the annotations of behavioural concerns consists of three categories of behavior constraints:

- Attribute Quantification Constraint – relating to the declarations of value attributes and the related acausal quantifications (e.g., U=I*R).
- Temporal Constraint – relating to the declarations of behaviour constraints where the history of behaviours on a timeline is taken into consideration.
- Computation Constraint – relating to the declarations of cause-effect dependencies of data in terms of logical transformations (for data assignments) and logical paths.

Each of these behaviour constraints can be associated with time conditions given in terms of logical time, of which the exact semantics is given by the existing EAST-ADL support for timing definition (e.g. the triggering, and port data sending and receiving events of a function). Owing to the formal semantics, one can explicitly define the model transformation from EAST-ADL behavior model to other model formats of external analysis methods and tools, such as hazard analysis, response time analysis, model checking, test-case generation, etc.

5 Methodology

The purpose of the EAST-ADL methodology is to give guidance for the adoption of EAST-ADL, i.e. how to use the language for the construction, validation and reuse of models for automotive embedded software. The purpose is thus not to impose a specific development process, but to show sequences of steps that can produce sound and useful EAST-ADL models. The EAST-ADL methodology provides understanding for the EAST-ADL language and serves as building blocks for a more complex and complete process definition.

The EAST-ADL methodology is organized in phases that are derived from a typical V-model for automotive systems development, see Figure 6. The development flow is idealized to allow compact and systematic description, but will in practice be subject to iterations, top-down or bottom-up application as appropriate.

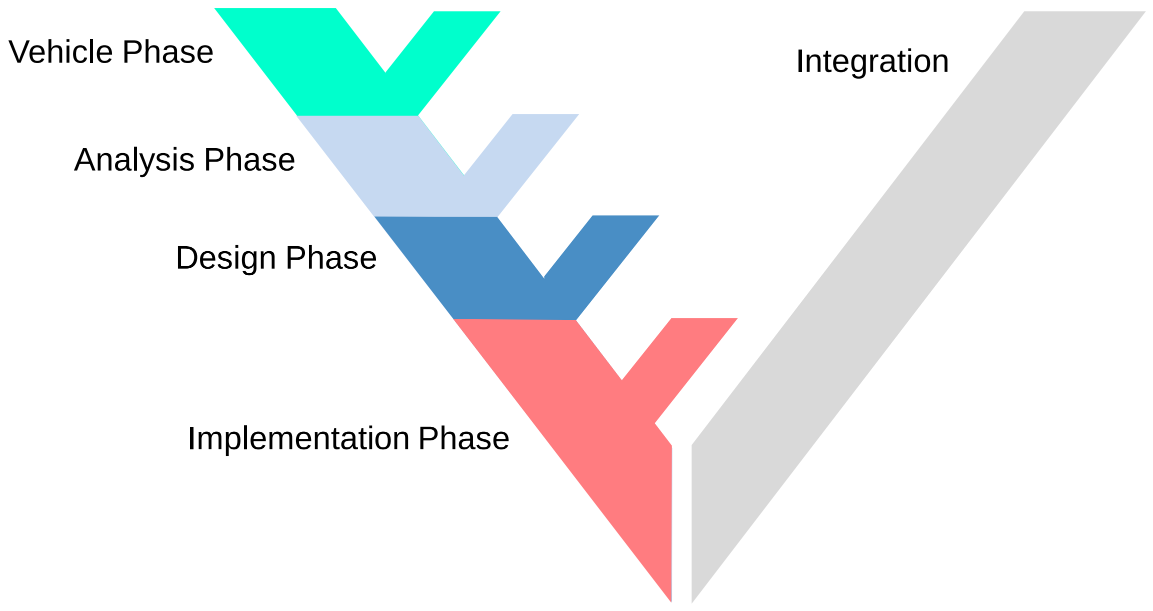


Figure 6. Visualization of automotive system development according to the V-model.

The core aspects of each phase is decribed below:

- The Vehicle phase involves analysis of external requirements based on which a Technical Feature Model is constructed. This tree structure shall be organized in an adequate way and also capture necessary or intended Feature configurations. In addition, for each Feature a set of requirements is specified.
- The Analysis phase results in a FunctionalAnalysisArchitecture which specifies a realization of the Features. The solution is a logical representation of the system to be developed and there is no distinction between hardware or software or about the implementation of communication.
- The Design phase involves defining the FunctionalDesignArchitecture specifying a solution to the requirements in terms of efficient and reusable architectures, i.e. sets of (structured) HW/ SW components and their interfaces, a hardware architecture, and a mapping from functional components to HW/SW components. The architecture must satisfy more detailed constraints.

- The Implementation phase results in the HW/SW implementation and configuration of the final solution. This part is mainly a reference to the concepts of AUTOSAR, which provides standardized specifications at this level of automotive software development.

To relate specific methodological aspects like safety and timing to the core activites, a generic method pattern has been applied for each phase:

1. Refine, Introduce and Validate Requirements
2. Create Solution
3. Attach Requirements to Solution
4. Create supporting models
5. Analyze
6. Verify
7. Specify Requirements

The set of steps is the same for each phase, and also for each aspect (safety, timing, variability, etc.). The core and each of the complementary aspects forms “swimlanes” in each phase, see Figure 7. The principle is that the user assesses the steps related to the core and each relevant aspect, and then implicitly “weaves” an appropriate set of steps for her or his needs. The notation for the methodology description is Business Process Modeling Notation (BPMN).

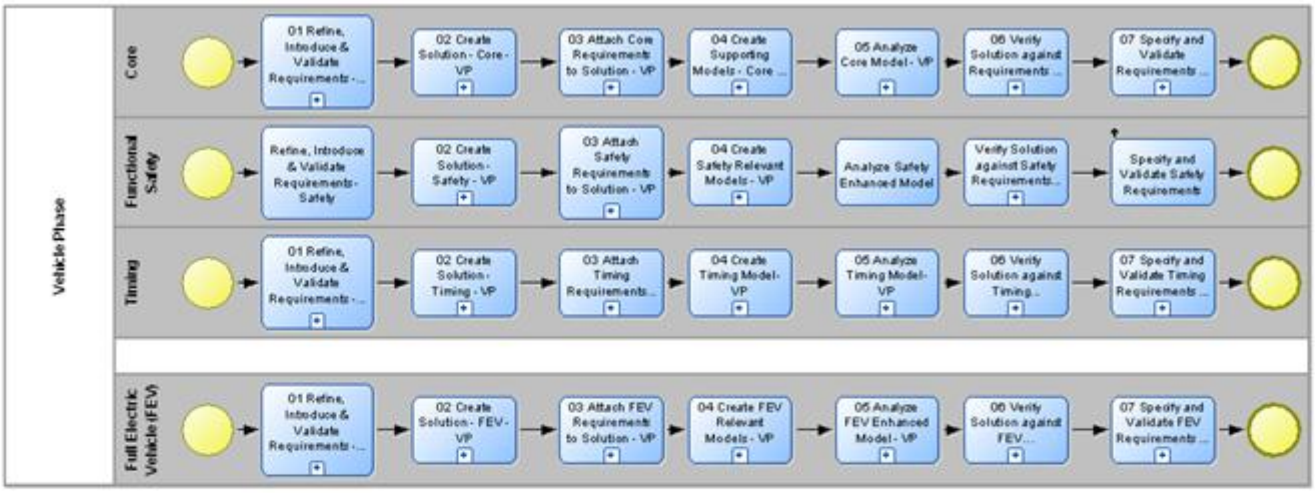

Vehicle Phase
Core
01 Refine, Introduce & Validate Requirements - ...
02 Create Solution - Core - VP
03 Attach Core Requirements to Solution - VP
04 Create Supporting Models - Core ...
05 Analyze Core Model - VP
06 Verify Solution against Requirements ...
07 Specify and Validate Requirements ...
Functional Safety
Refine, Introduce & Validate Requirements - Safety
02 Create Solution - Safety - VP
03 Attach Safety Requirements to Solution - VP
04 Create Safety Relevant Models - VP
Analyze Safety Enhanced Model
Verify Solution against Safety Requirements...
Specify and Validate Safety Requirements
Timing
01 Refine, Introduce & Validate Requirements - ...
02 Create Solution - Timing - VP
03 Attach Timing Requirements...
04 Create Timing Model - VP
05 Analyze Timing Model - VP
06 Verify Solution against Timing...
07 Specify and Validate Timing Requirements ...
Full Electric Vehicle (FEV)
01 Refine, Introduce & Validate Requirements - ...
02 Create Solution - FEV - VP
03 Attach FEV Requirements to Solution - VP
04 Create FEV Relevant Models - VP
05 Analyze FEV Enhanced Model - VP
06 Verify Solution against FEV...
07 Specify and Validate FEV Requirements ...

Figure 7. An example of metholdology "Swimlanes" in Vehicle phase

While the methodology tries to be comprehensive in handling the construction phases, the integration activities are only covered inasmuch as they involve V&V activities and the relation to V&V-artifacts defined in the construction phases.

6 Support for the development of FEVs

Electrification is the dominant trend of the automotive industry. Hybrid-electric vehicles (HEVs) and Full Electric Vehicles (FEVs) will become more popular in the future to alleviate the crisis of fuel and pollution. The challenge associated with this trend is larger flexibility and hence complexity in vehicle embedded control systems. The complexity comes from the large number of system configurations, communication patterns, and dynamic reconfigurations. The behavior constraint package of EAST-ADL must be able to facilitate the modeling and analysis of such complex behaviors.

A unique topic of HEVs and FEVs is the efficient management of the electrical energy, which may be stored in battery or ultra-capacitor. The electrical energy is used to propel the vehicle and load the electric auxiliaries. Smart control methods and structures are studied to optimally use the limited electrical energy in the storage in order to reduce the fuel consumption, extend the range, and keep the drivability. The behavior constraint package allows the designer to model and analyze the architecture of the energy management control strategy in HEVs and FEVs.

The development of FEVs requires that some specific aspects concerning the electric and electronic system shall be dealt with, which imply the need of modeling, analyzing and designing the system according to several specific requirements. It is also useful to follow a development process able to provide an effective guideline, which addresses the different aspects, thus helping to meet the requirements and cover efficiently the specific needs.

Therefore, EAST-ADL has some extensions to support the development of FEVs. The main purpose is to allow the application of the various standards and regulations that are specific of FEVs. In particular, the following subjects are addressed:

High voltage

This is a key issue and concerns electric insulation, electric shocks, bonding and grounding. Several standards establish design and test rules, and require proper provisions to ensure safety, also by means of insulation monitoring system, warning and recovery actions. The standards considered are in particular ISO6469-2 and EN 61851.

Propulsion

Propulsion is a function to be developed according to the general methodology valid for any automotive application. In addition, some specific points have to be taken into account, such as the operating modes and the drivetrain interlock.

Regenerative braking

Special care has to be taken for the integration of the Regenerative Braking System with ABS, depending also on the operating mode for the intervention of RBS. Regulation R13 H deals with the interaction between the two systems. Testing is covered by FMVSS n. 135.

Regenerative Energy Storage System

Several standards are focused on this subject, especially ISO 6469-1, J2289, ISO 8714, which require introduction of some protection devices such as overcurrent interruption, over-discharge detection provisions, proper fuses and connectors.

Charging

The process guides the designer as to adopt the charging modes, to define the operation states and to meet the grounding and insulation requirement so as to comply with EN 61851 and ISO 6469-3. Charge coupler, in particular, could be compliant with SAE J2777, as concerns control pilot, proximity detection, charge management and indicators. Communication with the charging station should comply with SAE J1772, SAE J1773, and SAE J2293.

Anti-theft system

This system is required to prevent the unauthorized use of electric vehicles by means of locking motor operation and steering. The requirement comes from FMVSS No. 114 and R 116, and is intended to ensure safety by limiting the risk of improper use.

Vehicle performance

Several standards deal with EV performance including terms and definitions, test conditions and test procedures. The performance factors particularly considered are energy, range and speed. Some of the reference standards are ISO 8715, ISO8714, EN 1821-1, EN 1986-1, ISO 12405-2.

Hazard Analysis and Risk Assessment

Although the hazard analysis is a task to perform in the safety life cycle, specific points are considered such as regenerative braking, insulation, charging system, battery system, according to some of the above mentioned standards, which require to perform the hazard analysis and adopt proper safety measures.

7 Related Approaches

One key aspect of the development of EAST-ADL is to benefit from existing methods and techniques and also to influence emerging approaches. Whenever possible, existing and state-of-the-art solutions were reused and integrated in the language. This favors the wide use of the language, allows the use of available tools and prepares for a sound standardization process.

Efforts like AUTOSAR [2], TIMMO [6], and ISO 26262 [4] are sources both for the alignment of domain specific challenges and for the integration of technologies and methodologies in the development of EAST-ADL.

AUTOSAR is a de-facto standard for automotive embedded systems and addresses the needs for a process-safe integration of functions. It provides a standardized platform for the specification and execution of application software, an integration method for software components and hardware resources, and also the interchange formats that these require. While adopting AUTOSAR for the implementation level abstractions, the EAST-ADL language complements the AUTOSAR initiative by providing higher-level abstractions, analysis and life cycle management support. In effect, it allows an AUTOSAR-compliant software architecture being extended with models relating to the design of functionality, timing and safety, the structuring and allocation of application, as well as the management of variability, requirements, traceability and verification and validation.

AUTOSAR is used to represent the final software architecture of automotive embedded systems. As such, it defines the software components, their interfaces, execution timing, middleware (basic software) interactions, etc. The model is sufficiently detailed to automatically generate and configure the platform software and integrate on ECUs.

The EAST-ADL function design architecture acts as the functional specification of the AUTOSAR software architecture. As such, it carries functional and non-functional requirements stemming from user needs, control design, safety design, re-use, etc. Software components may have to be organized differently, have different interfaces, timing, interaction, etc. in order to meet the architectural constraints of the software architecture. Using an EAST-ADL functional model, such implementation specific adjustments can be made in the AUTOSAR model without replacing the fundamental properties.

Defining a software architecture requires a large effort with much detail in the solution. The EAST-ADL functional model is a way to quicker make architectural exploration. The Design Level models can then be used to autogenerate much of the content at implementation level.

EAST-ADL integrates the results of TIMMO, which is an ITEA project focusing on the timing constraints and timing properties in automotive real-time systems. TIMMO has developed a formal description language, TADL, and a methodology for dealing with the timing concerns on the basis of EAST-ADL1. It has been developed in a close collaboration with AUTOSAR. The follow-up project TIMMO-2-USE is further developing the TADL language, in close collaboration with the MAENAD project, developing EAST-ADL.

The emerging international standard ISO 26262 [4] is carefully considered in EAST-ADL. The key content includes an automotive safety lifecycle, an automotive specific approach for determining risk classes and deriving safety requirements based on ASILs (Automotive Safety Integrity Levels), and a set of requirements for validation and confirmation measures to ensure a sufficient and acceptable level of safety being achieved.

To support behavior modeling, EAST-ADL provides dedicated behavior elements that facilitate the description of the relationship between behavioral and structural models. The EAST-ADL functions have synchronous execution semantics, and language concepts are available to define their triggering and timing. By clearly distinguishing between component execution and component logical computation, EAST-ADL allows the integration of behavior models from off-the-shelf tools like SCADE, ASCET, Simulink, etc., according to lifecycle stages and stakeholder needs. For continuous-time behavior (e.g., for the vehicle dynamics under control), related modeling techniques from Modelica, which combines acausal modeling with object-oriented thinking, have been adopted. The Functional Mockup interface, used for co-simulation and model exchange via Functional Mockup Units (FMUs) has been investigated, and a prototype transformation tool has been developed. EAST-ADL also provides tool prototypes for model transformation to Simulink and the SPIN (Simple PROMELA Interpreter) model checker.

A further standardization effort being taken into consideration is the SAE "Architecture and Analysis Description Language" (AADL), which has its roots in the avionics domain. Compared to EAST-ADL, AADL has a more narrow scope: no explicit support is provided for variability management or requirements refinements and traceability. Specifics for automotive systems such as the networks are weakly supported. The AADL is not designed for mass-produced systems and therefore has less emphasis on optimized overall solutions e.g. by considering compact runtime systems. For the automotive domain, the clash with AUTOSAR concepts is also a problem. However, wherever applicable, AADL concepts were reused, e.g. for dependability modeling.

EAST-ADL allows the adoptions of existing formalisms for the underlying semantics and provides support for model transformation and tool interoperability with the external safety analysis techniques. In particular, HiP-HOPS and the AADL's Error Model Annex have been carefully considered in the development of EAST-ADL. They both enable the modeling of system failure behavior and allow analysis of that behavior by using tools.

A tool plug-in for HiP-HOPS has been developed to support both FTA and FMEA. Other approaches to model-based safety analysis and verification that have been investigated for the development of EAST-ADL include ISSAC and its predecessor ESACS in the aerospace industries (where the goal was to develop a formal methodology and tools for the safety analysis of complex aeronautical systems), the ASSERT project (with similar goals but more focused on software intensive systems specified in AADL), the SETTA project (focusing on the use of time-triggered architectures in automotive systems), and the SAFEDOR project (which aimed to develop new practices for the safety assessment of maritime systems).

SPEEDS (Speculative and Exploratory Design in Systems Engineering) is a European project aiming at providing support for modeling and analysis of complex embedded systems through the usage of formal analysis tools. EAST-ADL complements the SPEEDS approach with automotive architecture and lifecycle information. The techniques of SPEEDS have been considered in EAST-ADL for behavior modeling (i.e., with the hybrid automata variant) and for a more formal specification of requirements and constraints (i.e., with temporal logics scripts for contracts of functionality, safety, and timing).

MARTE is a UML profile for Modeling and Analysis of Real-Time and Embedded systems. MARTE models real-time constraints and other embedded systems characteristics, such as memory capacity and power consumption. MARTE supports modeling and analysis of component-based architectures, as well as a variety of different computational paradigms (asynchronous, synchronous, and timed). The EAST-ADL UML-profile is released as an annex to MARTE, done in the ATESST2 and ADAMS projects.

The OMG Systems Modeling Language (OMG SysML) is a general-purpose graphical modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and facilities. Compared with EAST-ADL, SysML is more generic and high-level, so EAST-ADL can be seen as a specialization and subset of SysML for automotive embedded systems. In fact, the first versions of EAST-ADL and SysML were defined in parallel with some interaction between the teams. The EAST-ADL function architecture with ports and datatypes are influenced by SysML, as well as the requirements modeling.

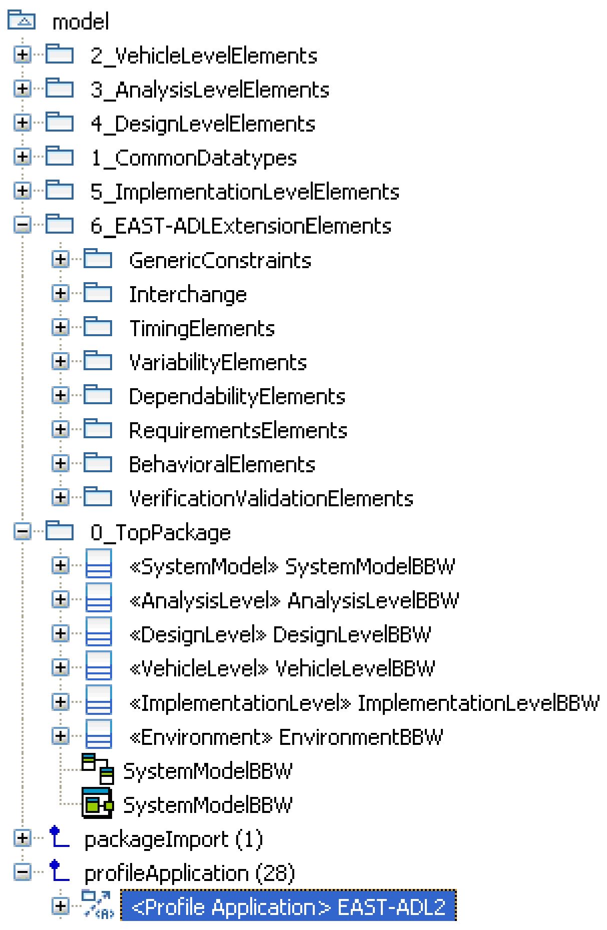
There are also many other research oriented architecture description languages or frameworks supporting the formal specification and analysis of software systems. For example, Wright (by Carnegie Mellon University) is based on CSP to perform formal verifications including deadlock detection and behavioral refinement. SaveCCM (by Mälardalen University) is a component-based modeling language tailored for automotive embedded control applications, which exploits the real-time model checker UPPAAL for specifying and verifying real-time constraints. While helpful for developing automotive embedded systems, these approaches are limited to software aspect and hence lack the support to the design of complex embedded systems in a broader perspective, which further requires the information of requirements, functional design, hardware architecture, resource constraint, communication relationship, and software to hardware binding. On the contrary, facilitating system integration in the context of automotive OEMs is the strength of EAST-ADL. In addition, the behavior constraint specification of EAST-ADL is not bound to one analysis tool. It is comprehensive and fiexible for utilizing various mature analysis tools with complementary objectives, such as Simulink, SPIN, UPPAAL, and HiP-HOPS. In particular, the support for behavior modeling by EAST-ADL, based on hybrid automata, is much effective than many state-of-the-art approaches. For instance, Darwin (by Imperial College London) is a component-based ADL supporting both structural and behavioral modeling of parallel software systems. The behavioral specification of Darwin is however limited to discrete-event formalism and LTL properties. For example, Darwin cannot specify the dynamics of the state of charge (SoC) of a battery according to the current through it. This type of information is simply out of the scope of Darwin. CHARMY (by University of L'Aquila) is a design and verification framework for checking the potential design inconsistencies between the behavior specifications of individual components and the logical constraints on the interactions of the components. The EAST-ADL support, however, is more specific. For example, the behavior of the elementary function must be deterministic and the communication must be asynchronous data transfer. These restrictions in EAST-ADL greatly simplify the complexity of SPIN transformation.

8 Example Model

On the following pages, various diagrams from an EAST-ADL model will be shown. The model and diagrams are created by using the Papyrus UML tool.

8.1 Overall Model

Figure 8 provides a package structure overview of the expected EAST-ADL modeling elements for the braking system architecture, as well as its associated requirements, variability and other non-functional constraints (e.g., timing and dependability), and verification & validation (V&V) cases. The *SystemModel* (within the *0_TopPackage*) contains the entire braking electrical/electronic system architecture, for which specifications at various abstraction levels are applied. Figure 9 provides a graphical representation of this multi-level braking electrical/electronic system specification and its related Environment Model (*EnvironmentBBW*).



```
model
  2_VehicleLevelElements
  3_AnalysisLevelElements
  4_DesignLevelElements
  1_CommonDatatypes
  5_ImplementationLevelElements
  6_EAST-ADLExtensionElements
    GenericConstraints
    Interchange
    TimingElements
    VariabilityElements
    DependabilityElements
    RequirementsElements
    BehavioralElements
    VerificationValidationElements
  0_TopPackage
    «SystemModel» SystemModelBBW
    «AnalysisLevel» AnalysisLevelBBW
    «DesignLevel» DesignLevelBBW
    «VehicleLevel» VehicleLevelBBW
    «ImplementationLevel» ImplementationLevelBBW
    «Environment» EnvironmentBBW
    SystemModelBBW
    SystemModelBBW
  packageImport (1)
  profileApplication (28)
    <Profile Application> EAST-ADL2
```

Figure 8: An overview of packages of an EAST-ADL model in Papyrus.

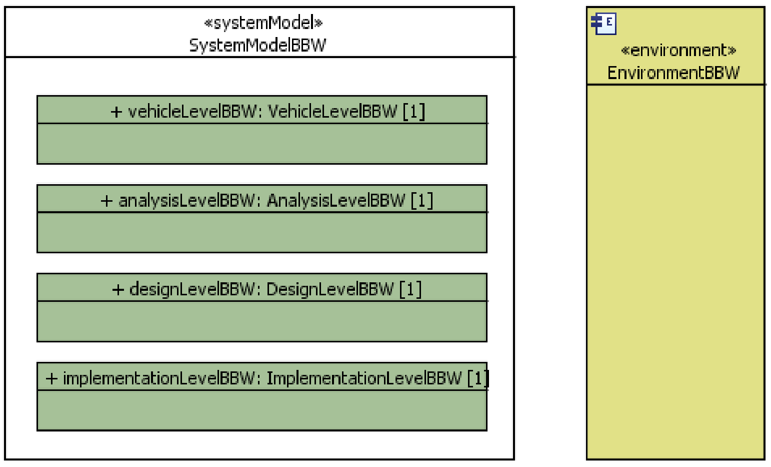

«systemModel»
SystemModelBBW
+ vehicleLevelBBW: VehicleLevelBBW [1]
+ analysisLevelBBW: AnalysisLevelBBW [1]
+ designLevelBBW: DesignLevelBBW [1]
+ implementationLevelBBW: ImplementationLevelBBW [1]
«environment»
EnvironmentBBW

Figure 9: The braking electrical/electronic system and its environment in Papyrus.

EAST-ADL supports requirements, V&V cases, and the annotations of variability and other non-functional constraints through separate modeling packages shown in Figure 10. A requirement model specifies the conditions or capabilities that must be met or possessed by a system or its component. In a model-based approach, requirements are derived, refined, mapped, validated and verified along with the progress of system design. The specifications of variability and other non-functional constraints augment the multi-level system architecture specification with analytical information (e.g. timing, reliability, and safety integrity) for early quality predictions and contract declarations. Normally, an analytical model should have its level of abstraction according to its target artifacts.

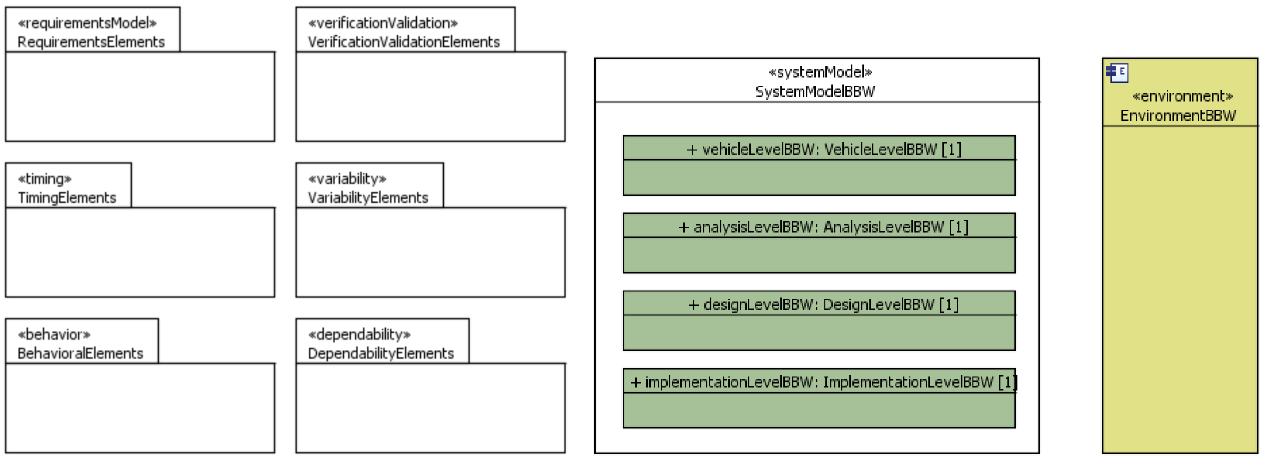


Figure 10: An overview of system model and related EAST-ADL packages for the specifications of requirements, V&V cases, and the annotations of variability and other non-functional constraints in Papyrus.

8.2 Vehicle level

A Vehicle Level specification constitutes the topmost system description and manages the Features of an entire product family. In Figure 11, the Technical Feature tree of the target braking system is shown. Each Vehicle Feature (*VehicleFeature*) denotes a functional characteristic, such as the functions, or non-functional properties, to be supported. While a braking control Feature (*BrakingControl*) is needed for the vehicle longitudinal control, regenerative braking control

(*RegenerativeBraking*) is a Feature for power control in FEV, allowing the kinetic energy produced by braking to be converted to electrical energy and stored in capacitor or/and battery. As shown in Figure 11, the relations of Features are supported by Feature Links (*FeatureLink*). In a Feature link definition, the precise semantics of a Feature relationship is given by the type attribute (*Kind*) and the direction attribute (*isBidirectional*).

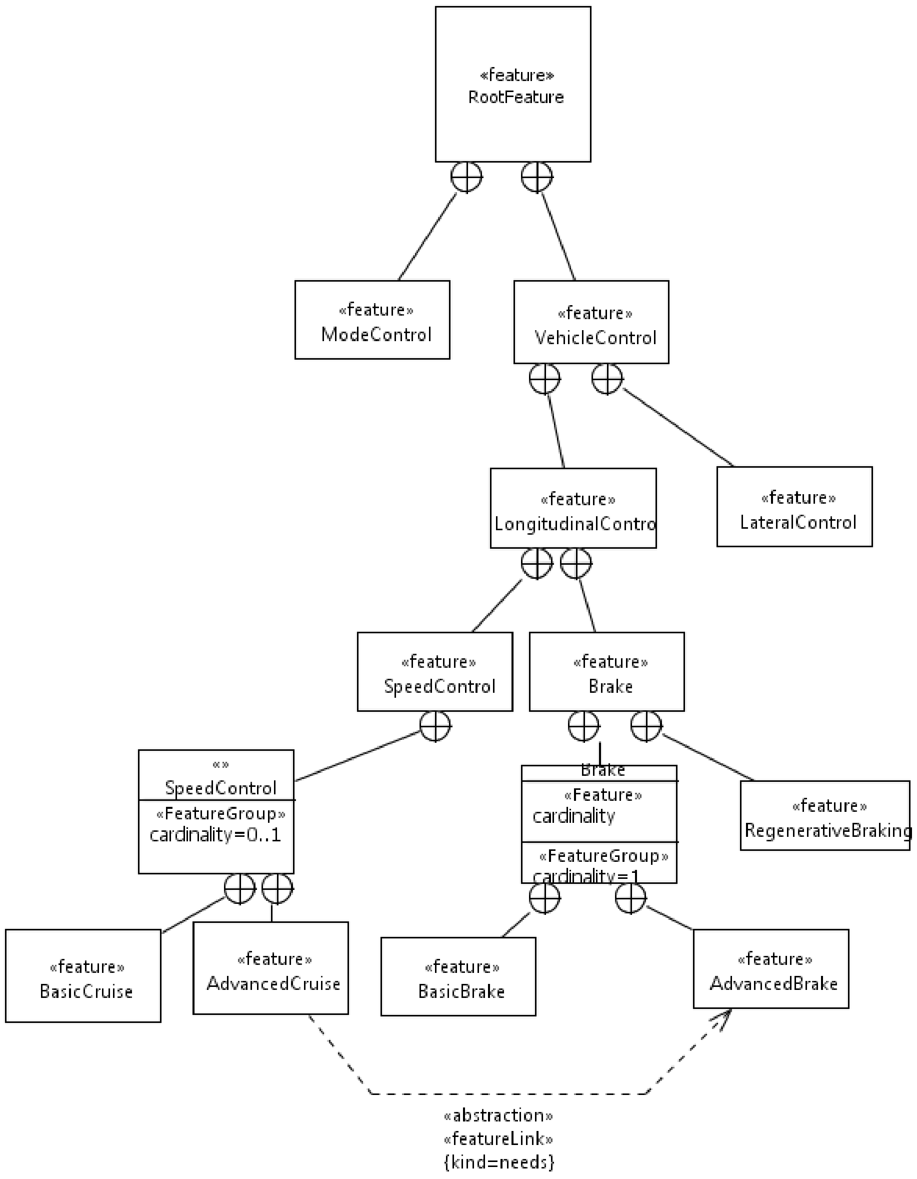


Figure 11. Vehicle Feature Model of the Regenerative Braking System in Papyrus.

Requirements at the Vehicle Level are directly based on system use cases and allocated to vehicle Features denoting the expected system functions. See Table 1 for a list of requirements on braking control. By EAST-ADL, the relationships of a requirement in regard to other requirements, system artifacts, more detailed analytical models, and V&V cases are explicit supported.

Table 1: Top-level braking control requirements.

ID	Description
Req#1_BaseBraking	"The system shall provide a base brake functionality where the driver indicates that he/she wants to reduce speed and the braking system starts decelerating the vehicle"
Req#2_DriverBrakeRequest	"The driver shall be able to request braking"
Req#3_Anti-LockBraking	"The system shall be an anti-lock braking system (ABS) by preventing the wheels from locking while braking"
Req#4_BrakeReactionTime	"The time from the driver's brake request until the actual start of the deceleration shall be ≤ 300ms.(Value derived from expert judgment)"
Req#5_TimeToStandstill	"The time to stadstill shall follow the recommendations in EU braking systems Directive 71/320 EEC. The Swdish Road Administration claims that a factor of 3 (on braking distance) is acceptable for ice"
Req#6_OperationofBrakePedal	"The Operator shall be able to vary the desired braking force using the brake pedal. A fully pressed pedal means maximum brake force."
Req#7_BrakeRelease	"When the brake pedal is not pressed, the brake shall not be active."

While a Feature tree model specifies the composition of system functions and their logical dependencies, it often implies the refinement of Vehicle Level requirements. With EAST-ADL, the derived/derived by relationship of requirements is given by a dedicated requirement relationship: *DeriveRequirement*. When such a requirement relationship is declared, a modification of the supplier requirement would have effects on the derived client requirements. Figure 12 shows the requirements model capturing four derived requirements and their relationships to a common supplier requirement and to each other.

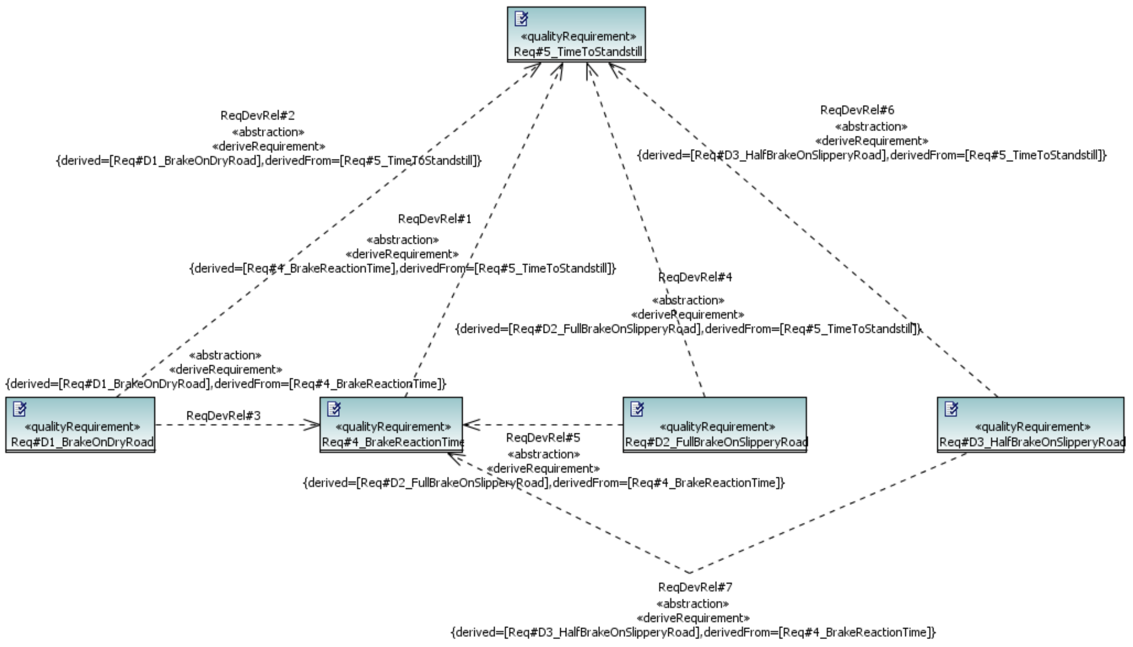

«qualityRequirement»
Req#5_TimeToStandstill
ReqDevRel#2
«abstraction»
«deriveRequirement»
{derived=[Req#D1_BrakeOnDryRoad],derivedFrom=[Req#5_TimeToStandstill]}
ReqDevRel#6
«abstraction»
«deriveRequirement»
{derived=[Req#D3_HalfBrakeOnSlipperyRoad],derivedFrom=[Req#5_TimeToStandstill]}
ReqDevRel#1
«abstraction»
«deriveRequirement»
{derived=[Req#4_BrakeReactionTime],derivedFrom=[Req#5_TimeToStandstill]}
ReqDevRel#4
«abstraction»
«deriveRequirement»
{derived=[Req#D2_FullBrakeOnSlipperyRoad],derivedFrom=[Req#5_TimeToStandstill]}
«abstraction»
«deriveRequirement»
{derived=[Req#D1_BrakeOnDryRoad],derivedFrom=[Req#4_BrakeReactionTime]}
«qualityRequirement»
Req#D1_BrakeOnDryRoad
ReqDevRel#3
«qualityRequirement»
Req#4_BrakeReactionTime
«qualityRequirement»
Req#D2_FullBrakeOnSlipperyRoad
«qualityRequirement»
Req#D3_HalfBrakeOnSlipperyRoad
ReqDevRel#5
«abstraction»
«deriveRequirement»
{derived=[Req#D2_FullBrakeOnSlipperyRoad],derivedFrom=[Req#4_BrakeReactionTime]}
ReqDevRel#7
«abstraction»
«deriveRequirement»
{derived=[Req#D3_HalfBrakeOnSlipperyRoad],derivedFrom=[Req#4_BrakeReactionTime]}

Figure 12: A model of braking performance requirements in Papyrus.

Figure 13 shows the allocations of functional and non-functional requirements to the braking control and its sub-Features through the *Satisfy* links.

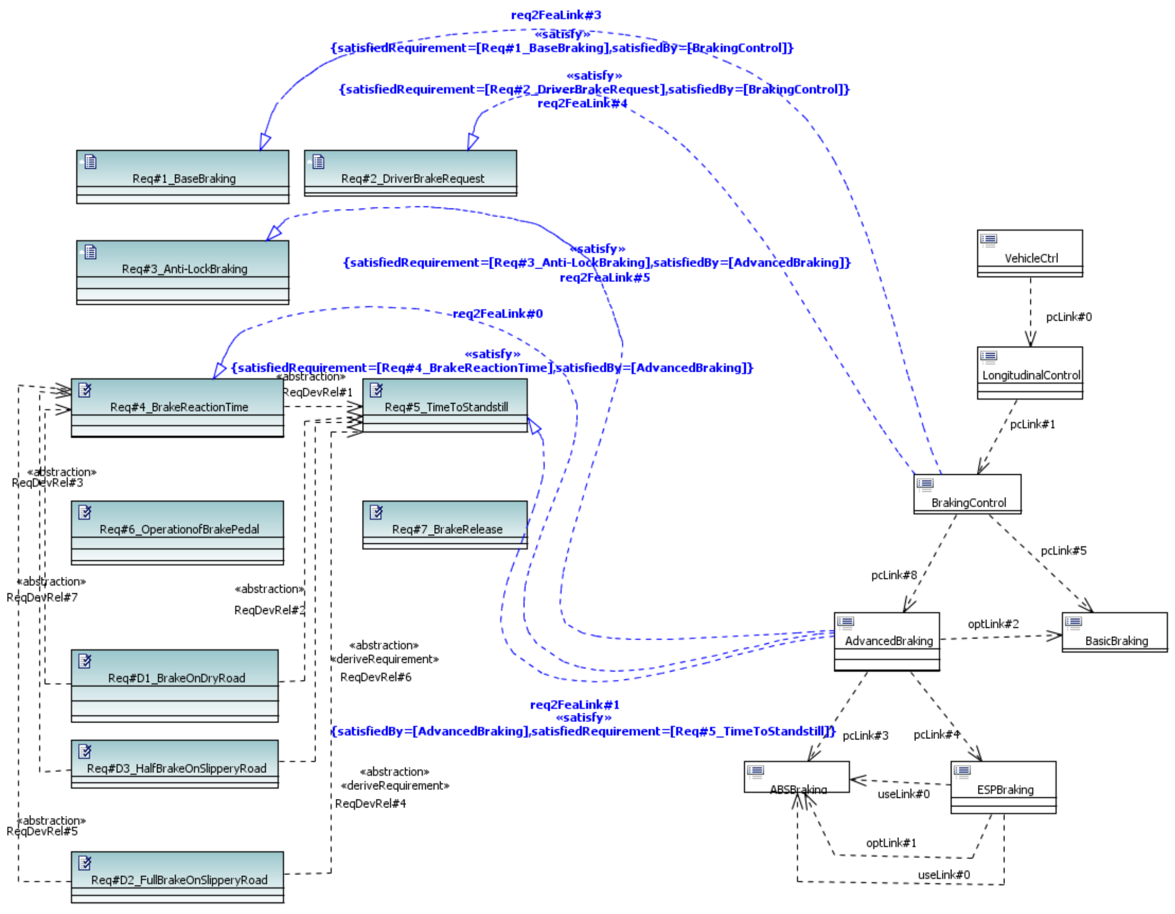


Figure 13: Linking braking requirements to Vehicle Features in Papyrus.

In EAST-ADL, a Satisfy relationship signifies the relationship between a requirement and an architectural element intending to satisfy the requirement. Requirements can also be inherited along with the Feature configuration hierarchy. For example, the requirements *Req#1_BaseBraking* and *Req#2_DriverBrakeRequest*, shown in Figure 13, should also be satisfied by the children of *BrakingControl*, such as the *AdvancedBraking* and the *BasicBraking.*

8.3 Analysis Level

As a step towards system realization, the Vehicle Level Features are realised by some interconnected abstract functions at the Analysis Level, specifying the corresponding input functions, application functions, and output functions for each Vehicle Level function in an implementation independent way. For the target braking system, the vehicle Features of concern are implemented by a set of Analysis Functions shown in Figure 14 and Figure 15.

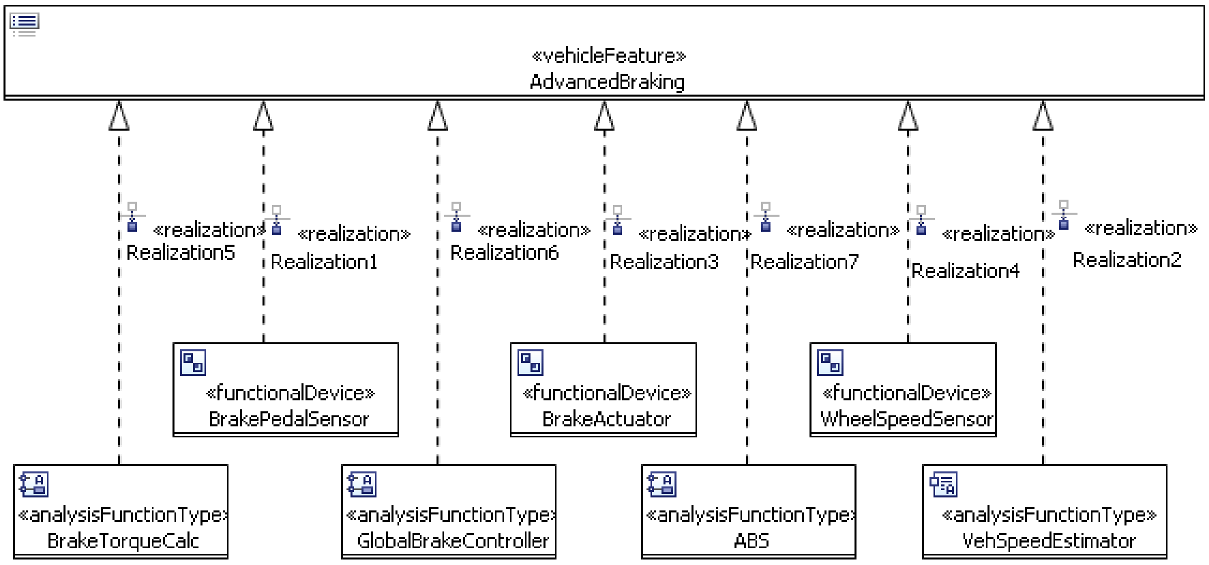


Figure 14: Advanced Braking Feature and the specification of its functional realizations in Papyrus.

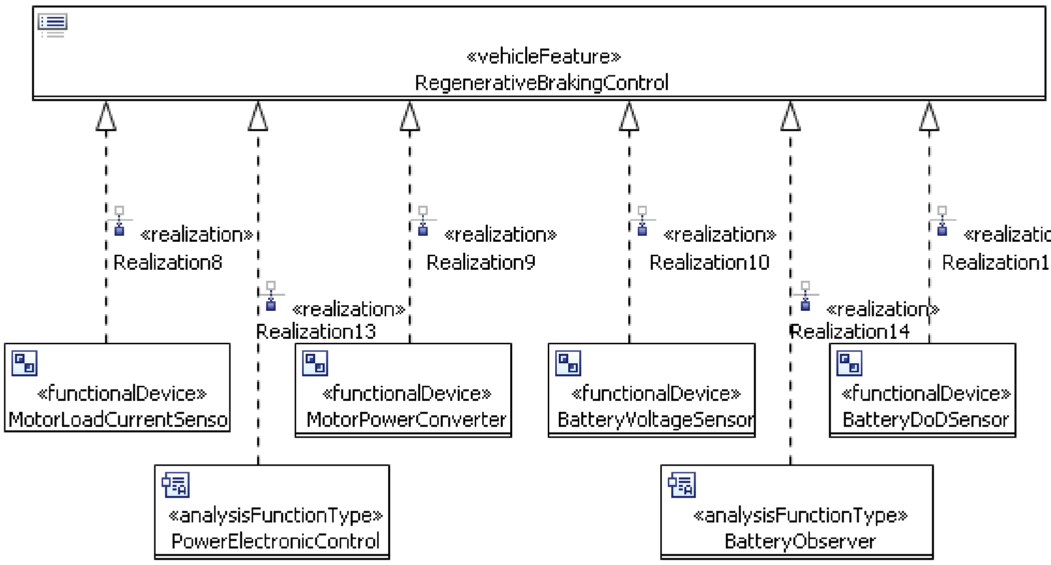
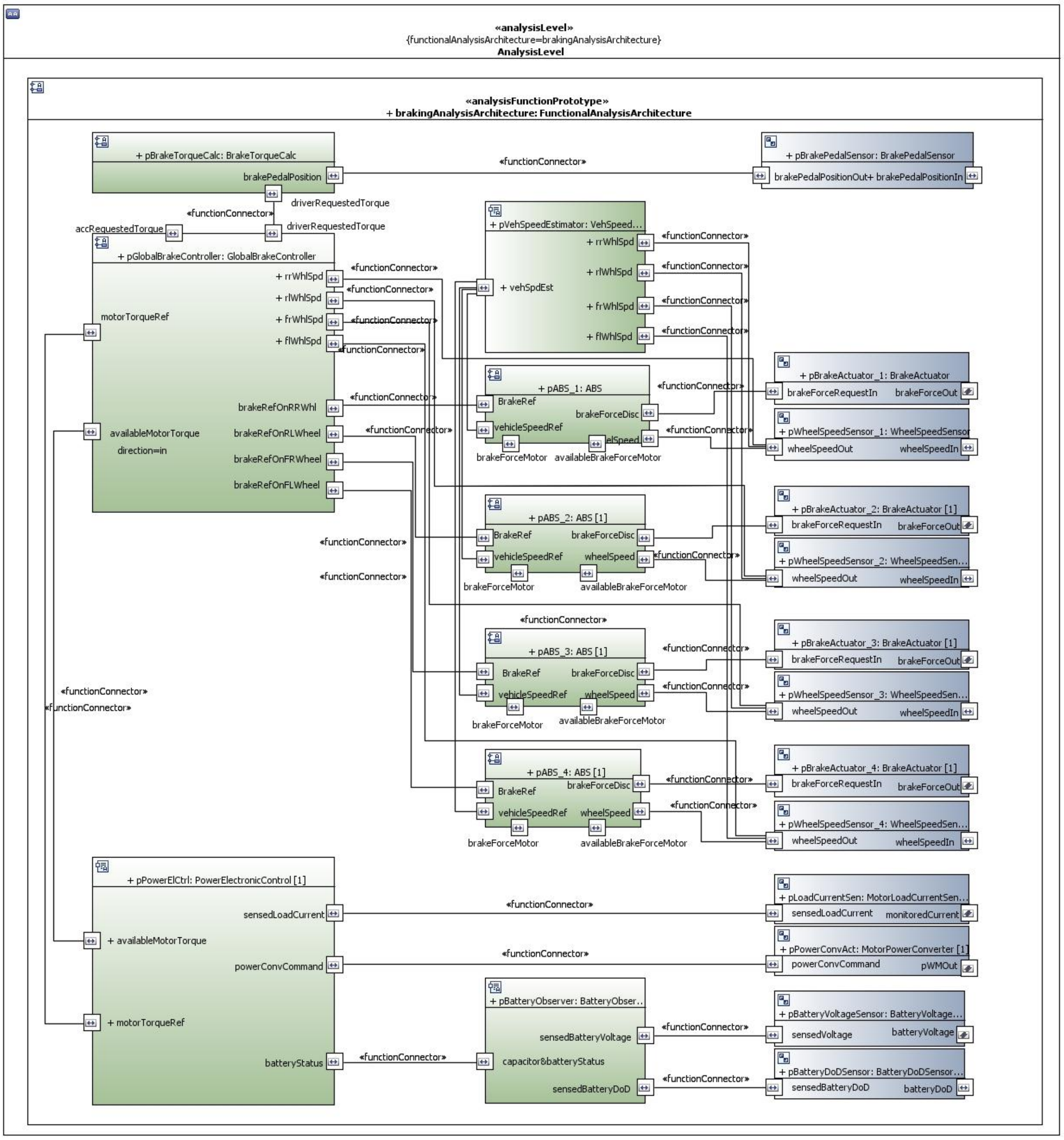


Figure 15:Regenerative Braking Control Feature and the specification of its functional realizations in Papyrus.

Figure 16 shows the specification of functional architecture in EAST-ADL for the braking system (See also D6.1.1 for an overview the functional operation concept).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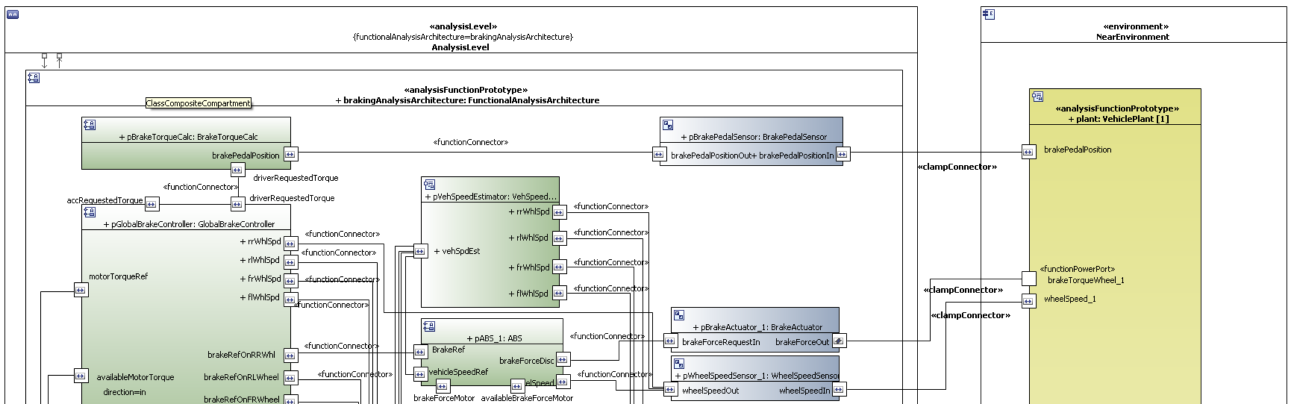
AnalysisLevel
«analysisFunctionPrototype»
+ brakingAnalysisArchitecture: FunctionalAnalysisArchitecture
+ pBrakeTorqueCalc: BrakeTorqueCalc
brakePedalPosition
+ pBrakePedalSensor: BrakePedalSensor
brakePedalPositionOut
+ brakePedalPositionIn
«functionConnector»
driverRequestedTorque
accRequestedTorque
+ pGlobalBrakeController: GlobalBrakeController
motorTorqueRef
availableMotorTorque
direction=in
+ rrWhlSpd
+ rlWhlSpd
+ frWhlSpd
+ flWhlSpd
brakeRefOnRRWhl
brakeRefOnRLWheel
brakeRefOnFRWheel
brakeRefOnFLWheel
+ pVehSpeedEstimator: VehSpeed...
+ vehSpdEst
+ pABS_1: ABS
+ pABS_2: ABS [1]
+ pABS_3: ABS [1]
+ pABS_4: ABS [1]
BrakeRef
vehicleSpeedRef
brakeForceDisc
wheelSpeed
brakeForceMotor
availableBrakeForceMotor
+ pBrakeActuator_1: BrakeActuator
+ pBrakeActuator_2: BrakeActuator [1]
+ pBrakeActuator_3: BrakeActuator [1]
+ pBrakeActuator_4: BrakeActuator [1]
brakeForceRequestIn
brakeForceOut
+ pWheelSpeedSensor_1: WheelSpeedSensor
+ pWheelSpeedSensor_2: WheelSpeedSen...
+ pWheelSpeedSensor_3: WheelSpeedSen...
+ pWheelSpeedSensor_4: WheelSpeedSen...
wheelSpeedOut
wheelSpeedIn
+ pPowerElCtrl: PowerElectronicControl [1]
sensedLoadCurrent
+ availableMotorTorque
powerConvCommand
+ motorTorqueRef
batteryStatus
+ pLoadCurrentSen: MotorLoadCurrentSen...
monitoredCurrent
+ pPowerConvAct: MotorPowerConverter [1]
pWMOut
+ pBatteryObserver: BatteryObser...
sensedBatteryVoltage
capacitor&batteryStatus
sensedBatteryDoD
+ pBatteryVoltageSensor: BatteryVoltage...
sensedVoltage
batteryVoltage
+ pBatteryDoDSensor: BatteryDoDSensor...
batteryDoD

Figure 16: Functional Analysis Architecture specification of the Regenerative Braking System in Papyrus.

In EAST-ADL, system boundaries are explicitly defined by means of Functional Devices (*FunctionalDevice*). Through Functional Devices, an Analysis Function interacts with the physical environment. Figure 17 shows the connections between Functional Devices and the physical environment.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{functionalAnalysisArchitecture=brakingAnalysisArchitecture}
AnalysisLevel
«analysisFunctionPrototype»
+ brakingAnalysisArchitecture: FunctionalAnalysisArchitecture
+ pBrakeTorqueCalc: BrakeTorqueCalc
+ pBrakePedalSensor: BrakePedalSensor
+ pVehSpeedEstimator: VehSpeed...
+ pGlobalBrakeController: GlobalBrakeController
+ pABS_1: ABS
+ pBrakeActuator_1: BrakeActuator
+ pWheelSpeedSensor_1: WheelSpeedSensor
«functionConnector»
«clampConnector»
«environment»
NearEnvironment
«analysisFunctionPrototype»
+ plant: VehiclePlant [1]
brakePedalPosition
«functionPowerPort»
brakeTorqueWheel_1
wheelSpeed_1

Figure 17: Connecting Analysis Functions with Environment in Papyrus.

To define the timing requirements and timing design, constructs like TimingConctraint, EventChain and Event are available in EAST-ADL.

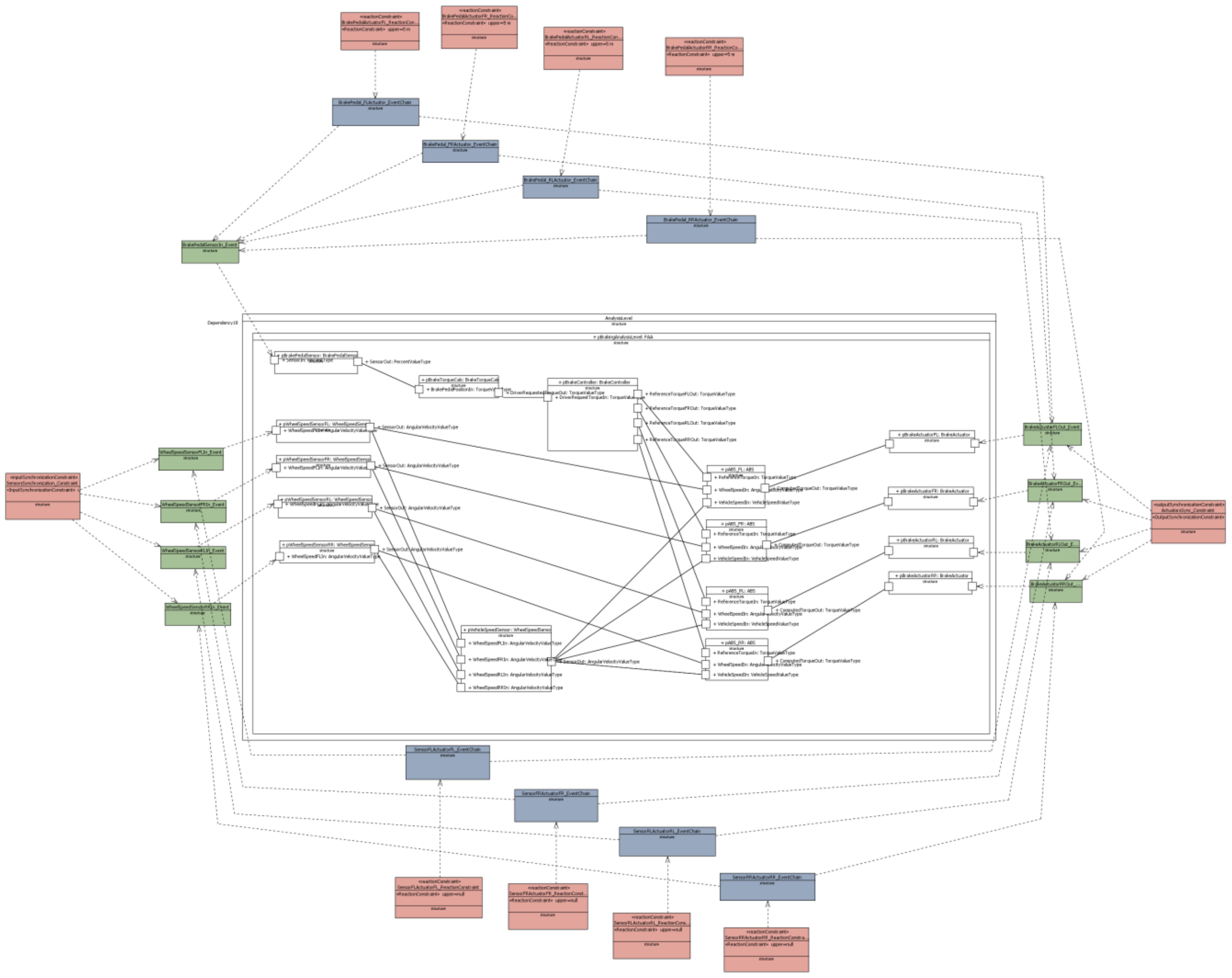


Figure 18. Synchronization and End-to-end timing from pedal to brake actuators

8.4 Design Level

The Design Level architecture further details the Analysis Level design by taking the software and hardware resources into consideration. (See also D6.1.1 for an overview the related design concept).

Currently, the documentation corresponds to a single wheel brake by wire model. Work is under way to extend to a full four-wheel model.

8.4.1 Functional Design Architecture

Figure 19 shows the FunctionalDesignArchitecture. The model focuses on the base braking and does not include energy regeneration functionality.

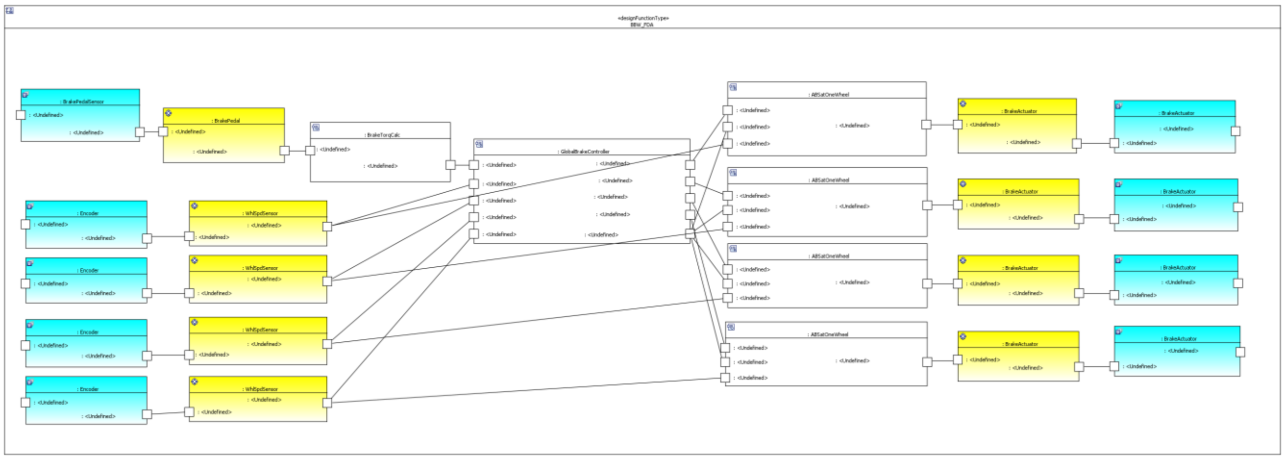


Figure 19. Functional Design Architecture of the Regenerative Braking System in Papyrus.

Figure 20 shows the period times of the included functions.

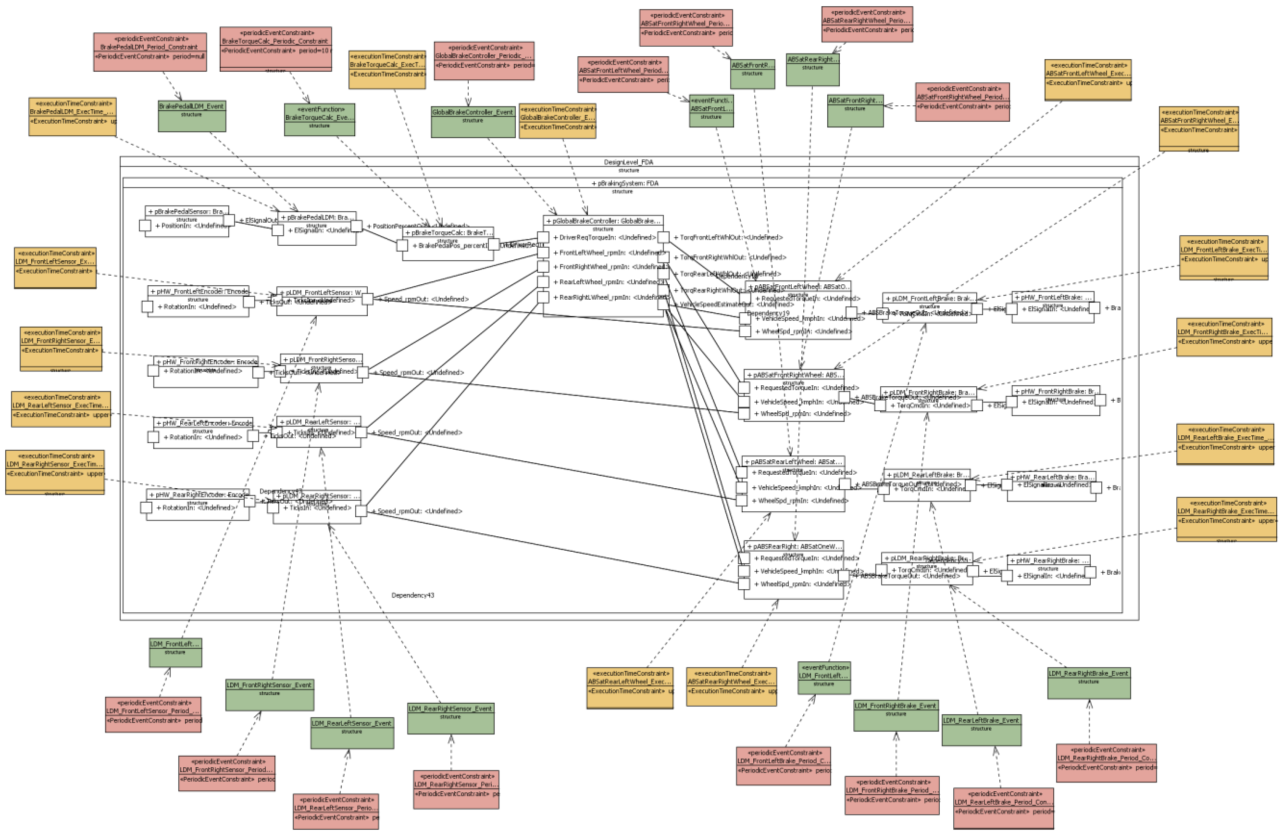
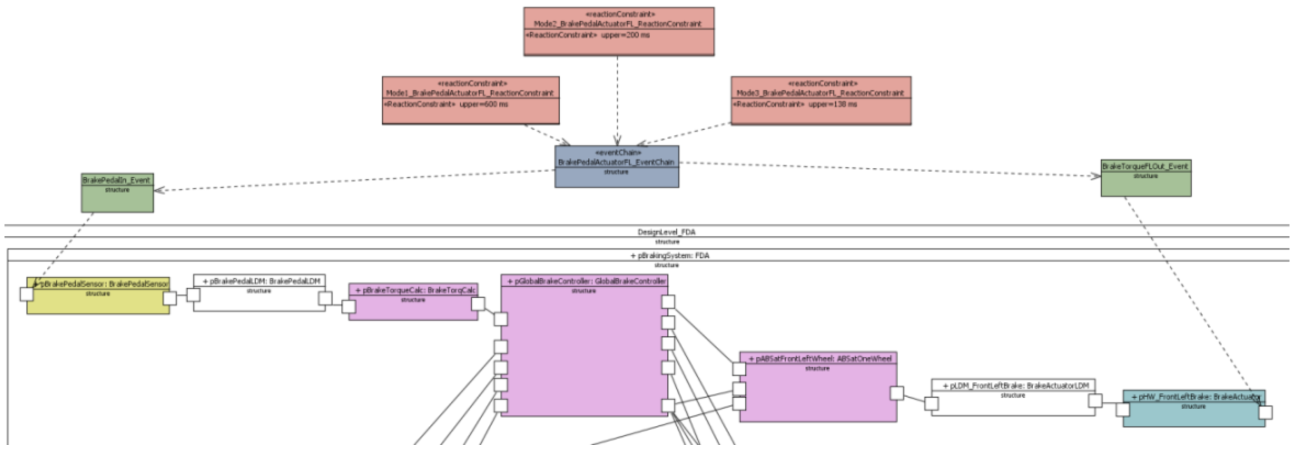


Figure 20. Period times of functions

Figure 21 (close-up) and Figure 22 (overall) shows timing constraints for end-to-end response requirements of the brake functionality. Figure 22 also shows synchronization requirements and a brake-down of the end-to-end timing budget.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Mode2_BrakePedalActuatorFL_ReactionConstraint
«ReactionConstraint» upper=200 ms
«reactionConstraint»
Mode1_BrakePedalActuatorFL_ReactionConstraint
«ReactionConstraint» upper=600 ms
«reactionConstraint»
Mode3_BrakePedalActuatorFL_ReactionConstraint
«ReactionConstraint» upper=138 ms
«eventChain»
BrakePedalActuatorFL_EventChain
structure
BrakePedalIn_Event
structure
BrakeTorqueFLOut_Event
structure
DesignLevel_FDA
structure
+ pBrakingSystem: FDA
structure
+ pBrakePedalSensor: BrakePedalSensor
structure
+ pBrakePedalLDM: BrakePedalLDM
structure
+ pBrakeTorqueCalc: BrakeTorqCalc
structure
+ pGlobalBrakeController: GlobalBrakeController
structure
+ pABSatFrontLeftWheel: ABSatOneWheel
structure
+ pLDM_FrontLeftBrake: BrakeActuatorLDM
structure
+ pHW_FrontLeftBrake: BrakeActuator
structure

Figure 21. Functional Design Architecture with end-to-end timing

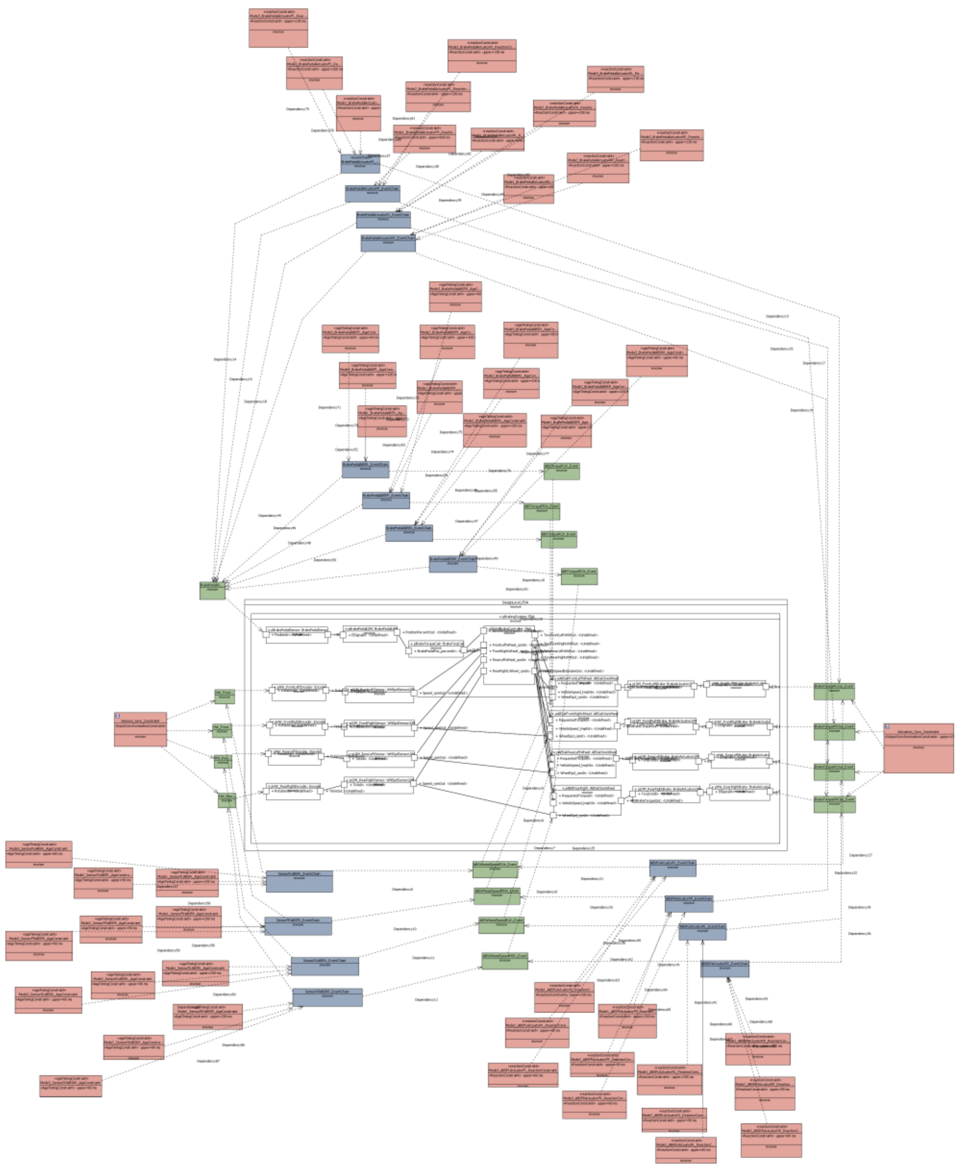

Figure 22. Functional Design Architecture with end-to-end timing

8.4.2 Hardware Design Architecture

Figure 23 shows an initial HardwareDesignArchitecture.

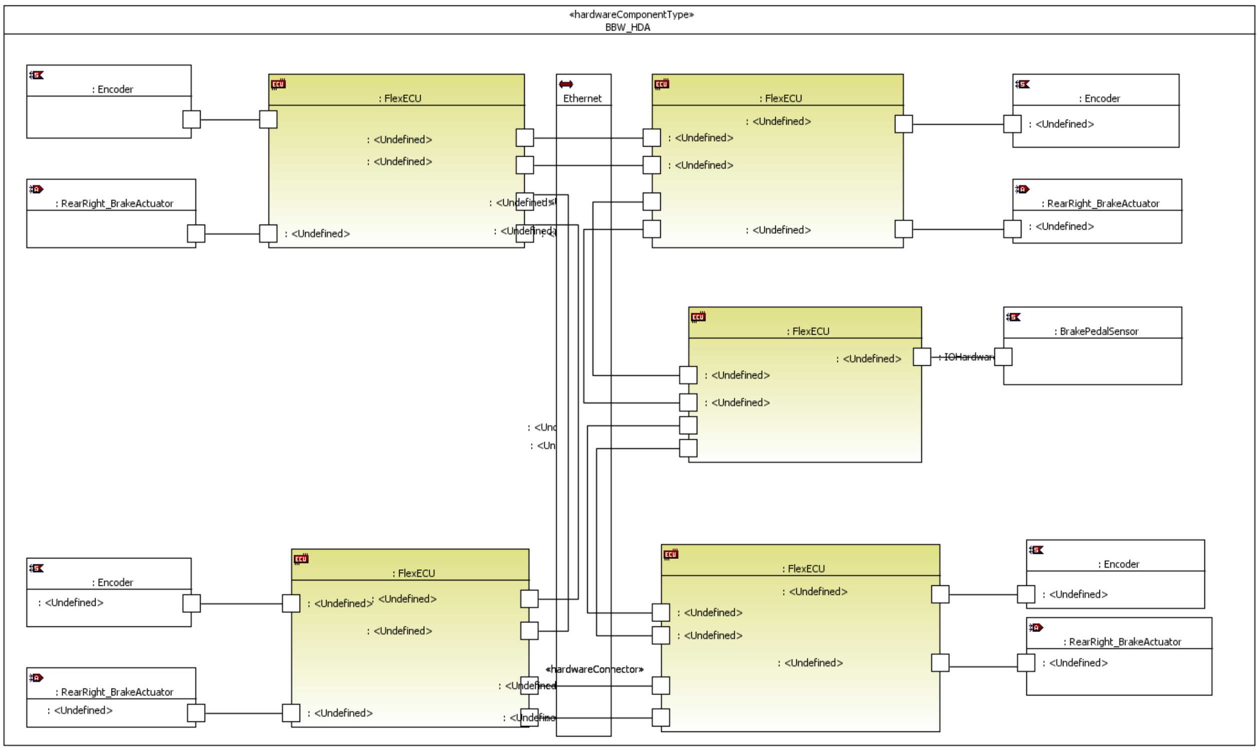

Figure 23: Hardware Design Architecture of the Braking System in Papyrus.

8.4.3 Allocation

Allocation at the Design Level is represented in Figure 24, where function prototypes of the FunctionalDesignArchitecture are allocated to nodes in the HardwareDesignArchitecture.

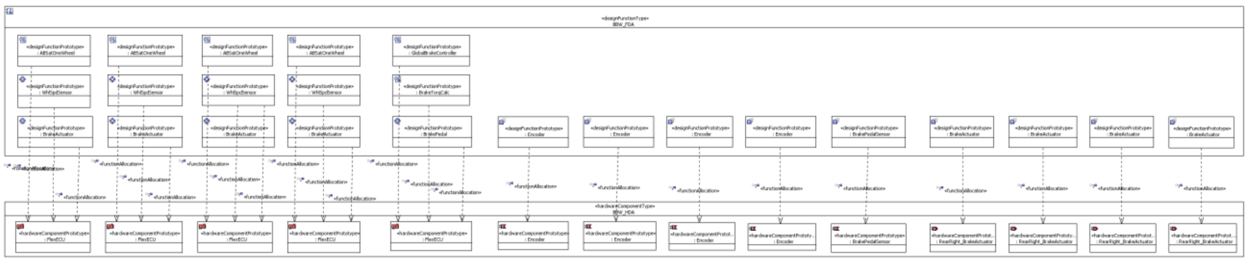

Figure 24: Function-to-node Allocation in the Braking System in Papyrus.

8.5 Implementation Level

The implementation level modeling relies on AUTOSAR model elements, which are normally edited in AUTOSAR tools. Below is a Papyrus Model based on an AUTOSAR UML Profile.

8.5.1 AUTOSAR Software Component Template

Figure 25 shows an AUTOSAR software composition for the brake-by-wire system. The components are automatically generated according to the pattern “one elementary function – one runnable – one atomic Software component”. For this reason the name and structure from Design Level remains, but in a later refinement, the structure would be adjusted to better cope with the architectural constraints of the software implementation.

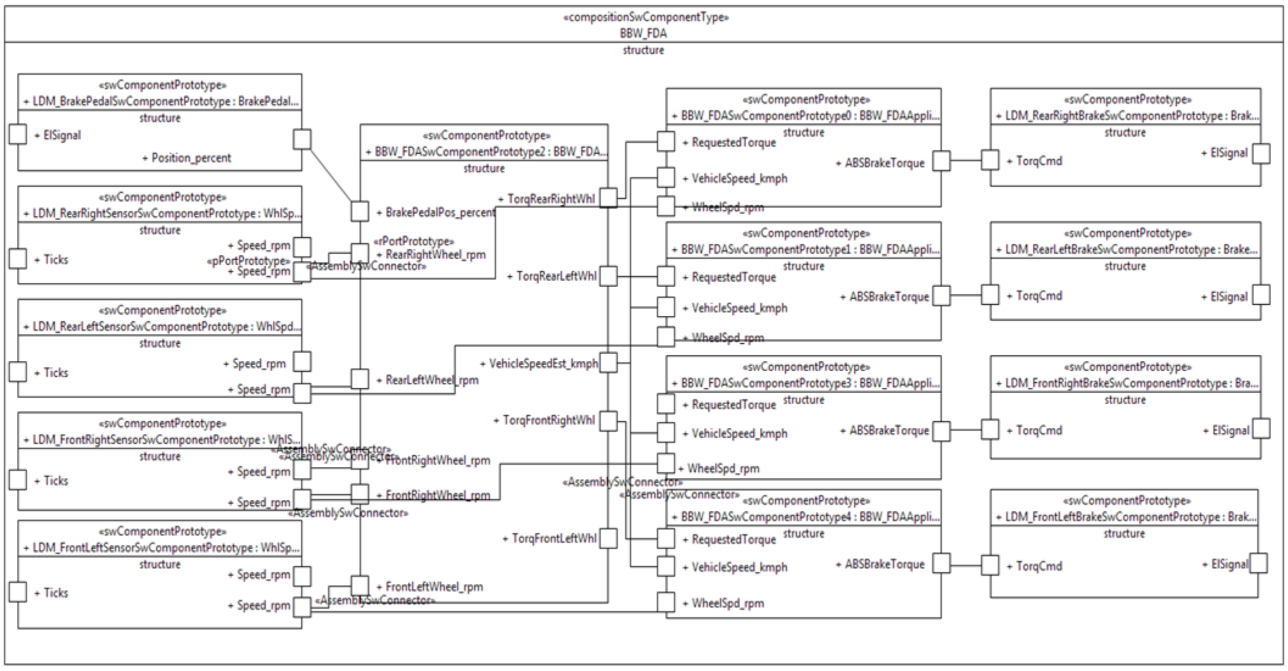
«compositionSwComponentType»
BBW_FDA
structure
«swComponentPrototype»
+ LDM_BrakePedalSwComponentPrototype : BrakePedal...
+ ElSignal
+ Position_percent
+ LDM_RearRightSensorSwComponentPrototype : WhlSp...
+ LDM_RearLeftSensorSwComponentPrototype : WhlSpd...
+ LDM_FrontRightSensorSwComponentPrototype : WhlS...
+ LDM_FrontLeftSensorSwComponentPrototype : WhlSp...
+ Ticks
+ Speed_rpm
«pPortPrototype»
«rPortPrototype»
«AssemblySwConnector»
+ BBW_FDASwComponentPrototype2 : BBW_FDA...
+ BrakePedalPos_percent
+ RearRightWheel_rpm
+ RearLeftWheel_rpm
+ FrontRightWheel_rpm
+ FrontLeftWheel_rpm
+ TorqRearRightWhl
+ TorqRearLeftWhl
+ VehicleSpeedEst_kmph
+ TorqFrontRightWhl
+ TorqFrontLeftWhl
+ BBW_FDASwComponentPrototype0 : BBW_FDAAppli...
+ BBW_FDASwComponentPrototype1 : BBW_FDAAppli...
+ BBW_FDASwComponentPrototype3 : BBW_FDAAppli...
+ BBW_FDASwComponentPrototype4 : BBW_FDAAppli...
+ RequestedTorque
+ VehicleSpeed_kmph
+ WheelSpd_rpm
+ ABSBrakeTorque
+ LDM_RearRightBrakeSwComponentPrototype : Brak...
+ LDM_RearLeftBrakeSwComponentPrototype : Brake...
+ LDM_FrontRightBrakeSwComponentPrototype : Bra...
+ LDM_FrontLeftBrakeSwComponentPrototype : Brak...
+ TorqCmd
+ ElSignal

Figure 25. AUTOSAR Software Component Template of the Braking System

9 ACKNOWLEDGMENT

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[2] AUTOSAR Development Partnership: AUTOSAR web site. http://www.autosar.org/

[3] EAST-ADL Association Members: EAST-ADL Association web site. http://www.east-adl.info/

[4] International Organization for Standardization: *Road Vehicles – Functional Safety – Part 1 to 9*. International Standard ISO 26262.

[5] MAENAD Consortium: MAENAD Project home page. http://www.maenad.eu/

[6] TIMMO Consortium: TIMMO 2 USE Project web site. http://www.timmo-2-use.org/