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Functional Modelling of Systems with Multiple Operation Modes: Case Study on an Active Spoiler System

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Abstract

This article presents the application of the Enhanced Sequence Diagram (ESD) for the analysis of the functionality of a system with shape-changing aspects in the context of its multiple operational modes, considering an active rear spoiler as a case study. The article provides new insights on the ESD support for model-based capture and articulation of functional requirements across multiple operation modes of the same system, with appropriate detail on attributes and metrics, and the alignment of these attributes and metrics in line with the concept of time through scope lines. The article also provides a comprehensive argument and discussion, exemplified based on the case study, for the support that the ESD provides for early systems functional and architecture analysis, within the context of a broader model-based Failure Mode Analysis methodology.

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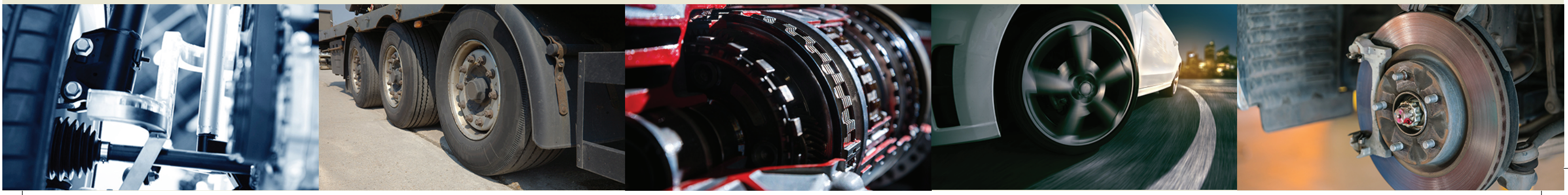


1. Introduction

1.1. Problem Statement and Motivation

Automotive systems development has seen a significant complexity increase due to technology advancements and the increased focus on the introduction of features to enhance safety, comfort, and refinement of the vehicle. Systems engineering integration challenges stem from the now ubiquitous interdisciplinary nature of the cyber-physical systems [1] and the interdisciplinarity present in engineering teams collaborating in Product Development [2]. While Model-Based Systems Engineering (MBSE) environment [3] is increasingly adopted to manage systems engineering integration, the development of approaches to bridge the gap between MBSE and the engineering methods widely employed to support robustness and Failure Mode Avoidance (FMA) in systems design and product development are still valuable and needed. This article focuses on the description of such a method—referred to as the Enhanced Sequence Diagram (ESD) [4], employed to address a known difficult problem for both MBSE and conventional engineering design approaches, i.e., the modelling of the functional logic for a system with multiple operation modes.

Many modern automotive systems have multiple use cases as modes of operation, where modes can be referred to various functions provided by the system to the user directly and indirectly, and hence involving different functional requirements [5]. The need for studies on functional modelling of complex systems with multiple operation modes is well recognized in literature [5, 6, 7, 8, 9, 10]. It is recognized that transitions between modes can contribute to the increase of the system complexity due to the switchable and dynamic behaviors [5].

From a classic engineering analysis perspective, function analysis methods (e.g., [11]) provide the practitioners with a clear sequence of steps to apply on a system. These methods focus on the device-centric analysis of the system, i.e., the way of working of the system is analyzed in the context of one of its main function flows. Therefore, these methods cannot easily capture the distinct modes of operation in relation to other functions of the system. MBSE methods can describe the logic of different modes of operation based on function-related activities, but they do not provide an easy and systematic way of integrating models of different operation modes to ensure the robust capture of requirements and functional and architecture models that are traceable across the modes of operations of the system. From an automotive OEM point of view, this leads to further methodological challenges in terms of the identification and the evaluation of risks based on the existing Function FMA methodology [12]. There is a need for a methodology that enables practitioners to capture functional requirements with integrity based on the systems analysis within an MBSE environment.

The ESD detailed in [4] aimed to address the need for such a methodology in relation to the gap between the MBSE methods and the well-established methods for functional modelling in engineering design. The ESD examples in [4] focused on the introduction of both new technology and advanced control feature as a new operation mode on an existing hybrid propulsion system, which is common practice in product development projects [13, 14] and is also a methodological challenge in technology development and innovation across industry domains [15].

This article aims to further enhance the ESD approach, illustrate its deployment in the context of a system with multiple modes of operation, and show how this analysis supports an effective approach to Function Failure Mode Analysis and Avoidance of the system, supporting robustness and reliability early in the system design process. Specifically, in this work, we focus the analysis on a material functional flow and consider the shape-changing perspective, related to the change of geometrical shape of the system based on user or system operational requirements. Functional analysis of such systems, in particular systems (e.g., morphing airfoil) with complex behaviors relating to aeroelasticity (i.e., the science of the interaction between aerodynamic forces and nonrigid structures), has been identified as problematic by several scholars [5, 16]. An active rear spoiler (ARS) system is used as a case study in this article with the aim of (i) providing a deeper understanding of functional analysis of such systems with a focus on shape change of a single component (i.e., spoiler) in relation to multiple operation modes and (ii) providing practitioners with guidance on the use of ESD in the Function Failure Mode Analysis and Avoidance of the system.

1.2. Overview of Related Literature

From functional requirements perspective, functional reasoning revolves around modelling the flows through the system in industrial practice. The analysis of systems with multiple operation modes using flow-based functional modelling requires the integration of the flows of material, energy, and information related to the operation modes into a single functional model and the activation of a selection of functions in respect of an operation mode. Functional models of operation modes of a system may not necessarily consist of the same function chain (a set of connected functions capturing the decomposition structure at a given hierarchical level); however, functions of these models can possess the same inputs-outputs (e.g., electrical energy), which need to be transmitted or transformed through the system. The inclusion of function specifications, the attributes, and metrics of inputs/outputs of each function in function modelling of a system enables the practitioner to differentiate between ways of achievement of operation modes which may be related to switching to a different technology (e.g., powering a hybrid electric vehicle by fuel or electric) or just changing the value of an attribute of a system/subsystem/component (e.g., different configurations/shapes of a car boot in relation to user requirements).

The framework of Pahl and Beitz [11], adopted in mechanical engineering literature (e.g., [17, 18, 19]) and in interdisciplinary design approaches (e.g., [20]), represents a functional model of technical systems in terms of the flows of material, energy, and information/signal. The information contained in the verb-object description of functions in this modelling scheme neglects the specifications of functions. This also applies to the recent works in engineering design literature that utilized flow-based function modelling formalized by [17], e.g., [21, 22, 23].

MBSE modelling environment provides an effective way of modelling functional related activities. Behavior diagrams of System Modelling Language (SysML) [24], a prevalent MBSE tool for model-based development of multidisciplinary systems [25, 26, 27], capture functional requirements of a system's use cases. Sequence diagrams (SD), activity diagrams, and state machine diagrams are used in the realization of these use cases. These methods capture function specifications in different ways. Inputs and outputs of activity in activity diagrams are called parameters, which may have a value type or block, while state machines can include variables such as heat. SD represent the exchanges of the messages including arguments, which can be values such as numbers. [28] argue that it is also possible to indicate the passage of material and energy through arguments of the message. However, a systematic method to develop a functional model of a system in the context of its multiple operation modes is lacking, including taking into consideration the impact of a diagram for a use case on another diagram of the different use cases of the same system.

The idea of deriving state-based diagrams (i.e., UML/SysML state machines and its predecessor Statecharts) from SD has been the subject of intensive research efforts in both industry and academia in the last two decades; see, e.g., [29, 30, 31, 32]. There are a variety of motivations behind the need for the transitions from SD to state-based diagrams. [33] pointed out the transition from requirements scenarios to component design. [30, 34] suggest that SD are generally used in the early stages of conceptual design; therefore synthesis of statecharts from SD was natural. [35] argued that the transition can increase the effectiveness of the overall software development process. Several other researchers [32, 36, 37, 38, 39] indicated that SD describes a specific aspect of a system's operation based on the behavior of a complete set of objects (e.g., SD for "Drive Vehicle" including interactions between "Driver" and "Vehicle"), while state-based diagrams can provide a complete view of all scenarios in an integrated model of a single object's behavior (e.g., state machine diagram for "Drive Vehicle" with transitions between "vehicle on" and "vehicle off" states). As in the conventional SD, the ESD focuses on the analysis of a particular use case of a system as a mode of operation. However, the ESD provides a more detailed and rigorous analysis of functional requirements of a complex multidisciplinary system by being based on the integration of a flow-based functional requirements reasoning and schema with the system operational analysis based on an SD.

1.3. Paper Structure

The structure of the article is as follows: Section 2 provides an overview of the ESD, including its schemata and the representation of functions and flows; Section 3 describes the application of the ESD methodology on the automotive case study of an ARS, while Section 4 focuses on the use of the ESD in the Function FMA along with the introduction of a new perspective of deriving state-based diagrams from sequence-based diagrams and the syntheses of these state-based diagrams for researchers or practitioners who are interested in this topic. Section 5 discusses key aspects of the ESD in function modelling and architecture analysis of the ARS as a shape-changing structure and the impact of the ESD in the Function Failure Mode Analysis and Avoidance. Section 6 concludes the article.

2. Enhanced Sequence Diagram

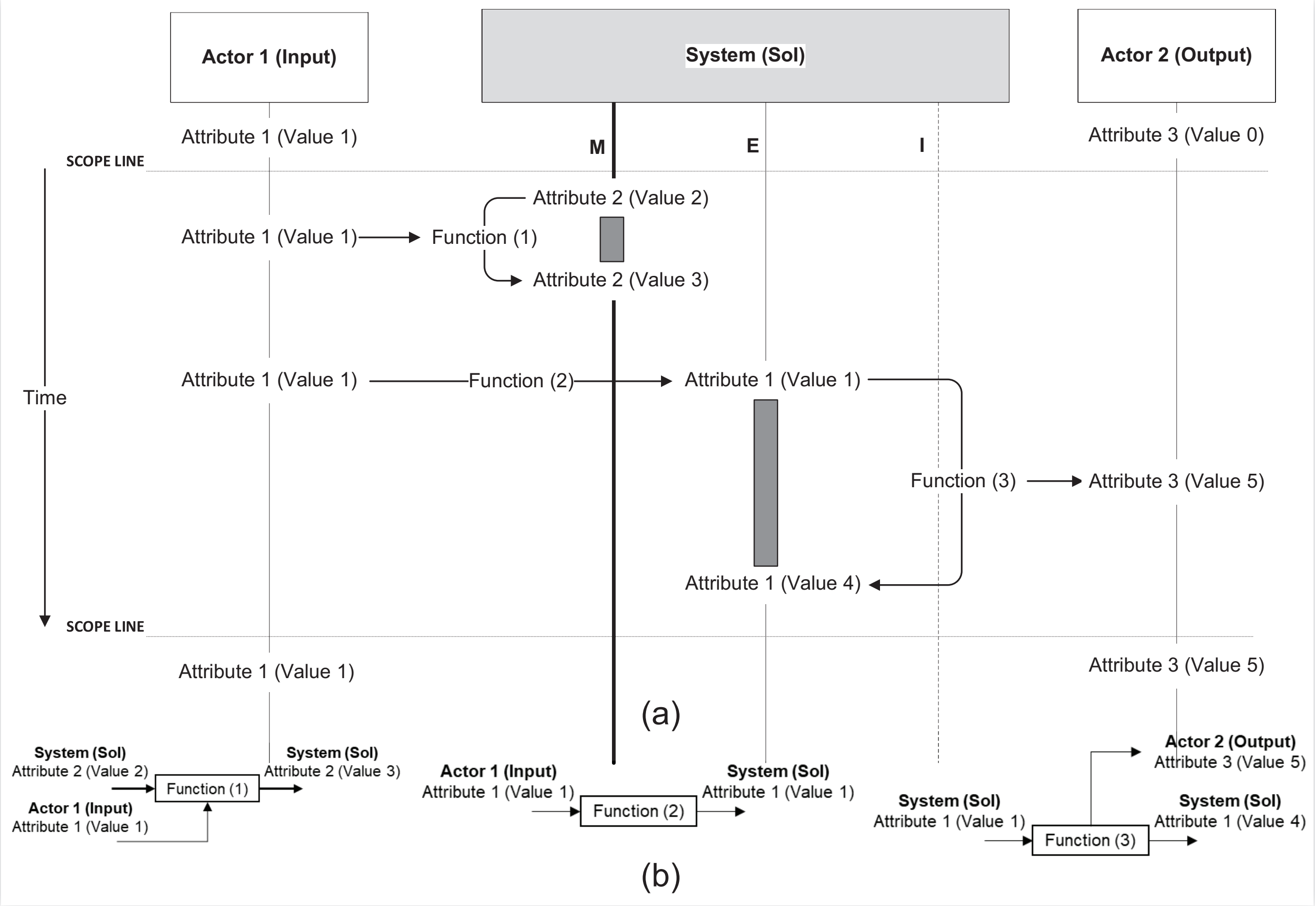
SysML is considered as one of the most popular tools in MBSE in terms of engineering applications [25]. SysML SD supports MBSE by capturing the functional logic of a system use case as transmission/transaction type functions. These diagrams support the analysis of a system with numerous modelling possibilities such as alternatives, options, and breaks [40]. SD has been adopted by various software packages and used with increased functionality. For example, scenario diagrams (e.g., operational scenario) of Capella are mainly inspired by the SysML SD [41]. Until very recently (in March 2021) MathWorks introduced SD in System Composer for its use in MBSE. Component and system-level behavior of a system in System Composer can be described as the interaction between components in a sequence of message exchanges by using SD. SD can be used with architecture models and can be integrated with Simulink with traceability throughout Model-Based Design. They also support the identification and the documentation of requirements through the definition of profiles and stereotypes [42].

The idea of the ESD, first outlined in [43], and further developed by [4, 44], is to augment a conventional SD with the ability to capture flow-based information to provide better support for function and architecture analysis and requirements capture. This section introduces the ESD schema and concept; Section 2.1 covers the representation of the elements of the ESD and introduces definitions and conventions, while Section 2.2 details the representation of functions and flows in the ESD.

2.1. ESD Schemata

Engineered systems fulfill their functions through operations, which can take place concurrently or sequentially, and these operations are thought of in terms of the flows of material,

FIGURE 1 (a) ESD schema [4], (b) corresponding flow-based schema for Functions 1-3.



energy, or information/signal [11]. Figure 1(a) illustrates the fundamental representation principle for the main operations and flows in the ESD. The corresponding flow-based representations for Functions 1-3 are shown in Figure 1(b) based on the representation convention of Pahl and Beitz [11].

A conventional SD focuses on the analysis of systems where all exchanges are signal/information and represents these exchanges in terms of information on a single dominant flow. Therefore, the conventional SD cannot not provide sufficient information in the analysis of multidisciplinary systems with a combination of multiple flows of material, energy, and information. The ESD augments the SD in the following aspects for the analysis of systems consisting of a combination of the flows of material, energy, and information:

- The replacement of an SD “lifeline” (representing operations on a single flow of information) with a “flowline” (representing the flows of material and energy in addition to information, with associated operations). With respect to the representation convention of [11], these flowlines are represented by dotted line (the flow of information/signal), thinner continuous line (the flow of energy), and thicker continuous line (the flow of material) as shown in Figure 1(a).
- The ability to relate an actor to multiple flowlines of the same or different kind. Both the System of Interest (SoI) and the actors can hold multiple flowlines of Material, Energy, and Information. The SoI in Figure 1(a) is represented with three flowlines of Material, Energy, and Information.
- In terms of architecture development, one or more flowlines can be related to an internal actor in the SoI, and these actors can be conceptualized as subsystems or components along with the capture of the operations’ sequence in the system.
- Like the SD, the ESD elaborates on the functionality of one use-case/operation mode of a system. However, the ESD introduces the concept of “Scope Line” to link ESDs of different use cases of a system. A scope line denotes the boundaries of a system use case. The initial and/or the final value(s) of the attribute(s) of relevant actors (i.e., input/output actors and internal actors of the SoI) are represented as states at the boundary of the scope lines.

The representation principles of the ESD are in line with Unified Modelling Language (UML)/SysML SD as shown in Figure 1(a). Flowlines are represented as vertical lines that descend from the base of the actors and SoI. Similarly, both an actor and an SoI are denoted by rectangles.

2.2. ESD Representation of Functions and Flows

Figure 1(a) represents two main types of operations (conversion and transmission) and three main types of flows (connecting, branching, and transmission) taking place in technical systems, as follows:

a. Conversion (transformation) operation and connecting flow, illustrated by Function 1
b. Transmission (transaction) operation and transmission flow, illustrated by Function 2
c. Branching flow, illustrated by Function 3 based on a conversion operation

These types of operations and flows provide prescriptive guidelines on the use of the ESD in the functional analysis of complex systems with a combination of multiple types of operations on flows. The SoI and the input/output actors are conceptualized as states, which are described in terms of objects with measurable attributes. An open arrow is used to denote a function, connecting the input state to the output state. A function is articulated in a verb + noun format where the verb reflects the operation on the object attribute(s) and the noun represents the object or the object attribute.

A conversion operation changes the attributes of an object that the function is applied to. It is defined in terms of a "triad" of an input state (SoI with Attribute 2/Value 2), an output state (SoI with Attribute 2/Value 3), and another state (conceptually defined as a design element/solution—Actor 1 with Attribute 1/Value 1) as shown with Function 1 in Figure 1(a). The achievement of the conversion operations requires the connection of the flows of additional resources to relevant flowlines to complete the triad, showing the way of achievement of the function. The arrow from Attribute 1 (Value 1) of Actor 1 pointed to Function 1 completes the triad by showing that Actor 1 is necessary for the fulfillment of Function 1, which provides the transition from the input state to the output state. This "connecting flow" is related to the conceptual "design solution" for the delivery of the function on the related flowline where the conversion operation takes place. The SoI with its input values (Attribute 2/Value 2) interacts with the Actor 1 (with Attribute 1/Value 1) to achieve the transition to the output state (SoI with Attribute 2/Value 3). In line with the principles of a standard SD, the duration of the transformation is shown in the flowline sequence by a bar whose length is indicative of the time over which the conversion functions act, as shown in Figure 1(a). It is not possible to show the duration of time on a flow-based presentation, as shown by Function 1 and Function 3 in Figure 1(b).

A transmission operation in the ESD changes the location of an object/object attribute through the applied function. Transmission flow for this operation is illustrated with a straight open arrow, as shown by Function 2 in Figure 1(a). Function 2 represents the transmission of Attribute 1 (Value 1) from Actor 1 to the SoI. If the duration of the transmission event is not negligible, the event can be represented as a transformation as shown by Function 1 in Figure 1(a).

A branching flow in the ESD is used to illustrate considerable losses during conversion and transmission functions. Function 3 in Figure 1(a) shows a branching flow for a conversion operation. The transmission of part of the SoI's Attribute 1 on the energy flowline to the Actor 2 changes both the value of SoI's Attribute 1 from Value 1 to Value 4 and the value of the Attribute 3 of the Actor 2 to Value 5 in Figure 1(a). [4] introduced join and fork nodes for the representation of different combinations of multiple flows.

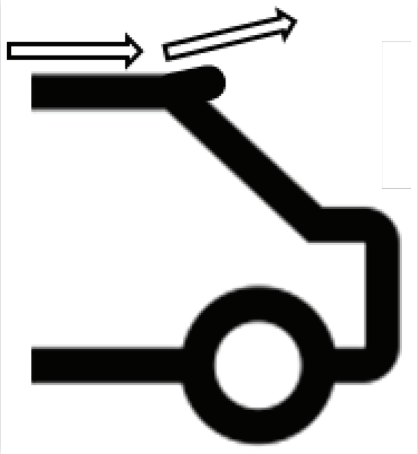
The ESD captures the attributes associated with interactions between both the external and internal actors and between internal actors in terms of operations on flows for the fulfillment of the function(s) associated with a system use case. A structured and coherent analysis of other use cases of the same system requires the consideration of relevant states of these actors. The following section provides a detailed illustration of this based on the deployment of the ESD methodology to analyze an ARS.

3. Case Study: ESD Analysis for an ARS with Multiple Operation Modes

3.1. Overview of the ARS System

As an automotive aerodynamic device, the function of a rear spoiler is to "spoil" unfavorable air movement (generally described as turbulence or drag) passing over the vehicle body, as shown by arrows in Figure 2. A rear spoiler increases fuel

FIGURE 2 A rear spoiler "spoiling" unfavorable air movement [45].



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efficiency and aerodynamic stability of the vehicle by reducing the aerodynamic drag of the vehicle body.

An "active" rear spoiler automatically adjusts its angle according to the vehicle conditions, changing the spoiling effect on the vehicle. ARS mostly operate automatically in response to the change in vehicle speed and other inputs. The driver can often deploy the spoiler manually if desired (such as for aesthetic purposes) but may not be able to retract the spoiler above a particular speed if the control of the vehicle could be affected dangerously.

3.2. ESD Methodology for the ARS System

Figure 3 summarizes the modes of operation of the ARS analyzed in this article. As shown in Figure 3, the change of the modes of operation of the ARS is related to the values of three inputs taken from the vehicle in this article: Vehicle Velocity (VV), Drag Coefficient (D), and Spoiler Angle (θ). "Vehicle" refers to relevant subsystems of the vehicle (such as the battery or ECU). More inputs can be considered (such as the yaw rate of the vehicle body), as pointed out by [46]. The ARS converts these inputs into a control signal for the adjustment of the spoiler, which spoils the air and notifies the state of the spoiler to the driver. Certain values for θ and thresholds for VV and D are presented to differentiate between operation modes. In relation to "Normal Speed" and "High Speed" operation modes, "Retracted" mode can be divided into "Retract at Normal Speed" and "Retract at High Speed."

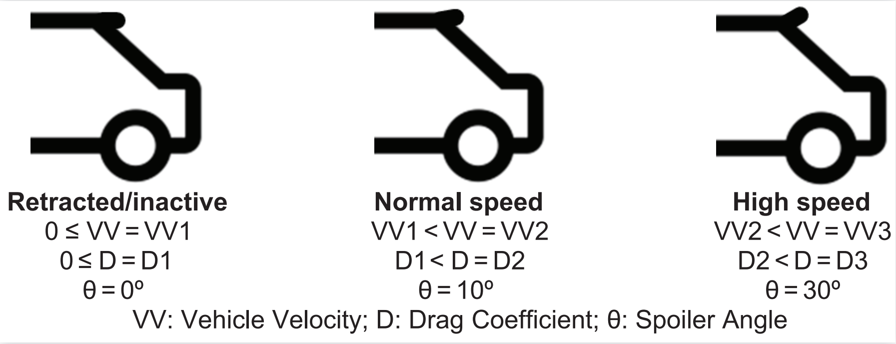
The use-case diagram in Figure 4 illustrates these operation modes as use cases to capture the functionality of the spoiler. As shown in Figures 3 and 4, the functionality of the ARS revolves around the movement of the spoiler. The variation between the operation modes is at different variables of relevant actors rather than different functional models—in other words, functional models of these modes share the same functional model; however, the attribute values of relevant internal and external actors of the ARS will be different. These require the consideration of quantification of actor's states, described in terms of measurable attributes in the ESD, in relation to the functional model of each operation mode.

Vehicle, Driver, and Air are the actors required for the fulfillment of the use cases, i.e., the movement of the spoiler. The actors "Vehicle" and "Driver" are related to all use cases, while the actor "Air" is only associated with the state of the spoiler at relevant vehicle speeds, as illustrated in Figure 4. The ESD is used in the analysis of a system in a structured sequence:

i. The development of a use diagram.
ii. The analysis of each use case is in turn based on a black-box analysis. A concise articulation of input/output states and transformative function of relevant use case with reference to its actors are introduced as a black-box based on the System State Flow Diagram (SSFD) function representation [47].
iii. The function decomposition analysis for each use case, based on a proposed architecture or the assumption of a standard architecture depending on the aim of the analysis, such as the analysis of an existing system or the improvement of an existent system.
iv. The use of the ESDs of the system to support function failure mode analysis and avoidance, which prompts further analysis (functional, architecture, etc.) of the system.

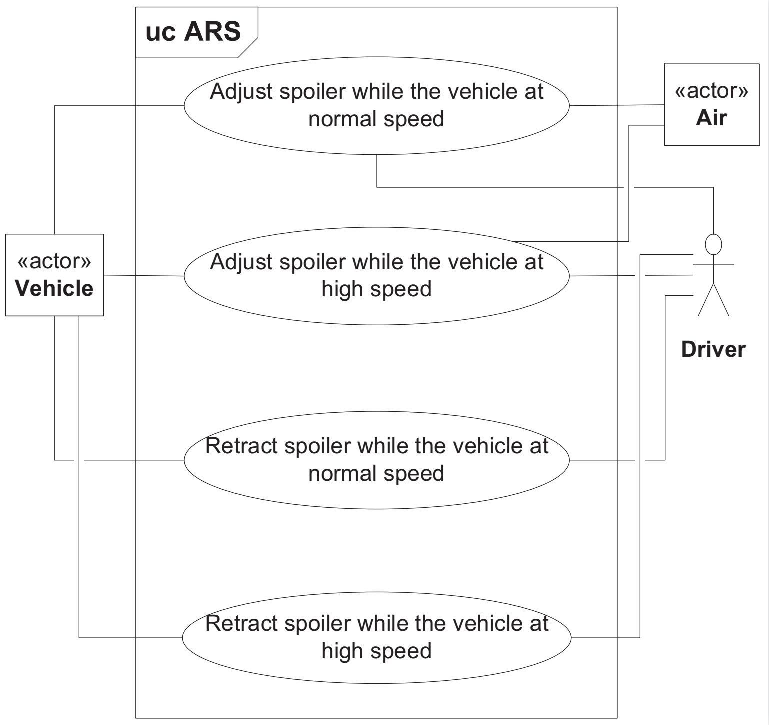
The following sections focus on i-iii by being based on the analysis of four modes of operation of the ARS shown as use cases in Figure 4 in conjunction with different conditions of the vehicle to reflect the functionality of the spoiler's different configurations based on this methodology. Sections 3.3 and 3.4 describe "adjust spoiler" and "retract spoiler" at normal speed, respectively. Section 3.5 outlines both use cases for the operation at high speed, while Section 3.6 details the establishment of links between multiple operation modes in the ESD.

FIGURE 3 Modes of operation of the ARS [45].



Adapted from Ref. [45]. Image by Ervin Bolat and licensed under the. Creative Commons Attribution 3.0 license (https://creativecommons.org/licenses/by/3.0/)

FIGURE 4 Use-case diagram for the ARS.



3.3. Operation Mode 1: Adjust Spoiler While the Vehicle is at Normal Speed

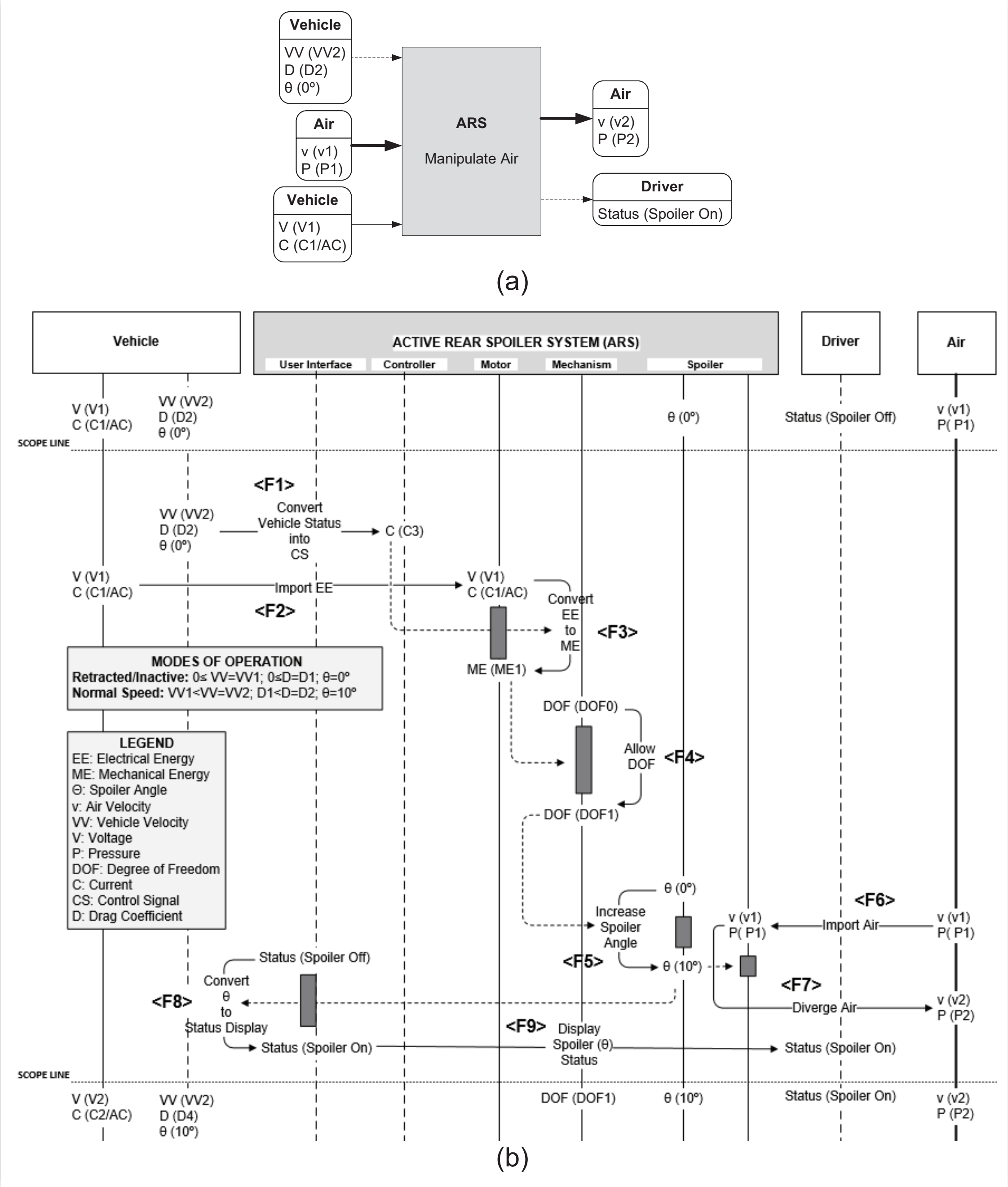
Figure 5 illustrates the development of the ESD for "Adjust spoiler while the vehicle is at normal speed" use case. Figure 5(a) shows a black-box representation of the system based on the SSFD, while Figure 5(b) represents the ESD based on this black box.

Figure 5(a) shows that the system deals with the manipulation of air (from V1; P1 to V2; P2) across the body of the vehicle. The ESD in Figure 5(b) identifies and represents the way of achievement of the black-box function "Manipulate Air" in relation to "Adjust spoiler while the vehicle is at normal speed" use case by decomposing the black-box function into subfunctions based on a known architecture of an ARS consisting of User Interface, Controller, Motor, Mechanism, and Spoiler subsystems. All activities of each of these subsystems are represented on separate flowlines. The angle of the spoiler to manipulate the flow of air is adjusted based on the inputs of energy (V1; C1) and information (VV2; D2; 0°) from the vehicle. The system notifies the status of the spoiler to the driver (Spoiler On). We can reason out intermediate states between the input states and the output states based on the description of the physical phenomena [48] that regulate the changes of the actors' attributes. Functional requirements can be directly extracted from the ESD in the "verb + noun (object)" format. The diagram in Figure 5(b) includes the following functional requirements:

- **<F1> Convert Vehicle Status into Control Signal (CS):** This is an information/signal conversion function achieved by the Controller by transforming Vehicle attributes (VV2/D2/0°) into a control signal (C3).
- **<F2> Import Electrical Energy (EE):** This is a transmission function for the Motor that brings in EE (V1/C1) from the vehicle.
- **<F3> Convert EE to Mechanical Energy (ME):** The motor transforms the imported EE from the vehicle (V1/C1) into ME (ME1).
- **<F4> Allow Degree of Freedom (DOF):** ME (ME1) from the motor enables the mechanism to control its movement in one or more directions (DOF1).
- **<F5> Increase Spoiler Angle:** The mechanism changes the angle of the spoiler (10°).
- **<F6> Import Air:** The spoiler causes the move of the flow of air (v1/P1) over its body.
- **<F7> Diverge Air:** The spoiler breaks up the flow of air (v2/P2).
- **<F8> Convert Spoiler Angle (θ) to Status Display:** Spoiler angle (10°) changes attribute values of the User Interface from Status (Spoiler Off) to (Spoiler On).
- **<F9> Display Spoiler (θ) Status:** This transmission function displays spoiler status to the driver.

The ESD diagram also facilitates the complete articulation of functional requirements in the "subject + shall + verb

FIGURE 5 (a) Black box and (b) ESD for “Adjust spoiler while the vehicle is at normal speed” use case.



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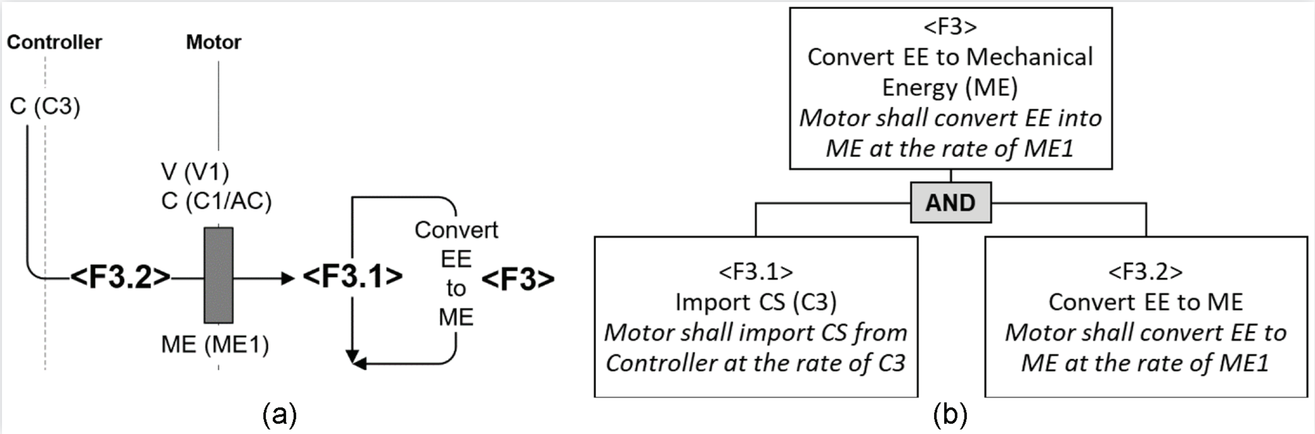
+ object” format [49, 50] in relation to exchanges that take place in terms of change/transfer of actor’s attributes. This enables the practitioner to put more emphasis on other stakeholders required for the achievement of function through change/transfer of actor’s attributes, i.e., input(s), output(s), and design element for the fulfillment of the function. For example, <F5> can be articulated as “Mechanism shall increase spoiler angle to 10°.”

The way of achievement of functional requirements can be detailed through the ESD. For example, as shown in Figure 6(a), <F3> in Figure 5 consists of two parts: <F3.1> and <F3.2>. The fulfilment of <F3> requires the connection of the flow of CS from Controller to Motor. This requires to the practitioner to consider the achievement of <F3.1> and <F3.2> concurrently as <F3.2> depends on <F3.1>. Figure 6(b) represents this as an “AND” gate where <F3.1> and <F3.2> are shown at both “verb + noun (object)” format and “subject + shall + verb + object” format (in italic).

Unlike other internal actors, the spoiler in Figure 5 is associated with two flowlines of energy and two functions related these flowlines: “Increase Spoiler Angle” related to the position of the spoiler and “Diverge Air” related to the design

FIGURE 6 The analysis of <F3> based on the ESD.



of the spoiler. Similarly, the external actor vehicle has one flowline of energy and one flowline of information.

3.4. Operation Mode 2: Retract Spoiler While the Vehicle is at Normal Speed

Following operation mode 1 in Section 3.3, there are two possible scenarios based on the use case diagram in Figure 4:

1. The speed of the vehicle goes from "normal" to "high," which triggers "Adjust spoiler while the vehicle is at high speed" mode.
2. The speed of the vehicle decreases and this activates "Retract spoiler while the vehicle is at normal speed" mode.

This use-case scenario, as shown in Figure 7, is based on (2)—the VV and D decreases (from VV2 to VV1 and D4 to D1) with time, i.e., the driver slows down the vehicle while the vehicle at normal speed. The system retracts the spoiler based on the obtained vehicle attributes.

From a Product Development point of view, the functional logic and functional requirements for this operation mode are the same as with the "Adjust spoiler while the vehicle is at normal speed" use case to a large extent. The same subsystems/internal actors with the same functions represented in ESD of Operation Mode 1 deliver this functionality. The task is to identify attribute values of the internal and external actors. In terms of functional requirements, two differences between ESDs of Operation Mode 1 and Operation Mode 2 are as follows:

i. The exclusion of "Import Air" and "Diverge Air" functions in Figure 7 as air is not the external actor of the "Retract spoiler while the vehicle is at normal speed" use case. The vehicle attribute "drag coefficient" reflects the effect of air on the vehicle;
ii. The replacement of the "Increase Spoiler Angle" function of Spoiler with "Decrease Spoiler Angle", shown as <F10> in Figure 7.

3.5. Operation Modes 3 and 4: Adjust and Retract Spoiler While the Vehicle is at High Speed

These operation modes are based on the same working principles with Operation Mode 1 and Operation Mode 2, respectively. Operation Mode 3 "Adjust spoiler while the vehicle is at high speed" represents the behavior of the spoiler if the driver speeds up the vehicle from the "retracted" state (VV1) to the state of high speed (VV3). Appendix 1.a represents ESD for this operation mode.

Coherent with ESD of Operation Mode 1 in Figure 5(b), the system needs to address the transfer and transformation of attribute values for operation mode 3 via the same functions and the actors. Similarly, in line with Figure 7, Appendix 1.b shows that the system retracts the spoiler if the speed of the vehicle drops to a certain level and attribute values of relevant actors change accordingly.

3.6. Integration of Multiple Operation Modes in the ESD

The flow and type of operation modes of an ARS may be varied depending on the environment, the state of the vehicle, and driver preference. This case study focused on operation modes of the spoiler based on the assumption that the flow of the spoiler state will follow the order in Figure 8. Dotted arrows point to the operation modes.

Figure 8 shows the flow of the spoiler state in terms of state transitions on a state machine diagram. The state of the spoiler changes from spoiler off to spoiler on/normal speed or spoiler on/high speed before the retraction of the spoiler.

FIGURE 7 ESD for “Retract spoiler while the vehicle is at normal speed” use case.

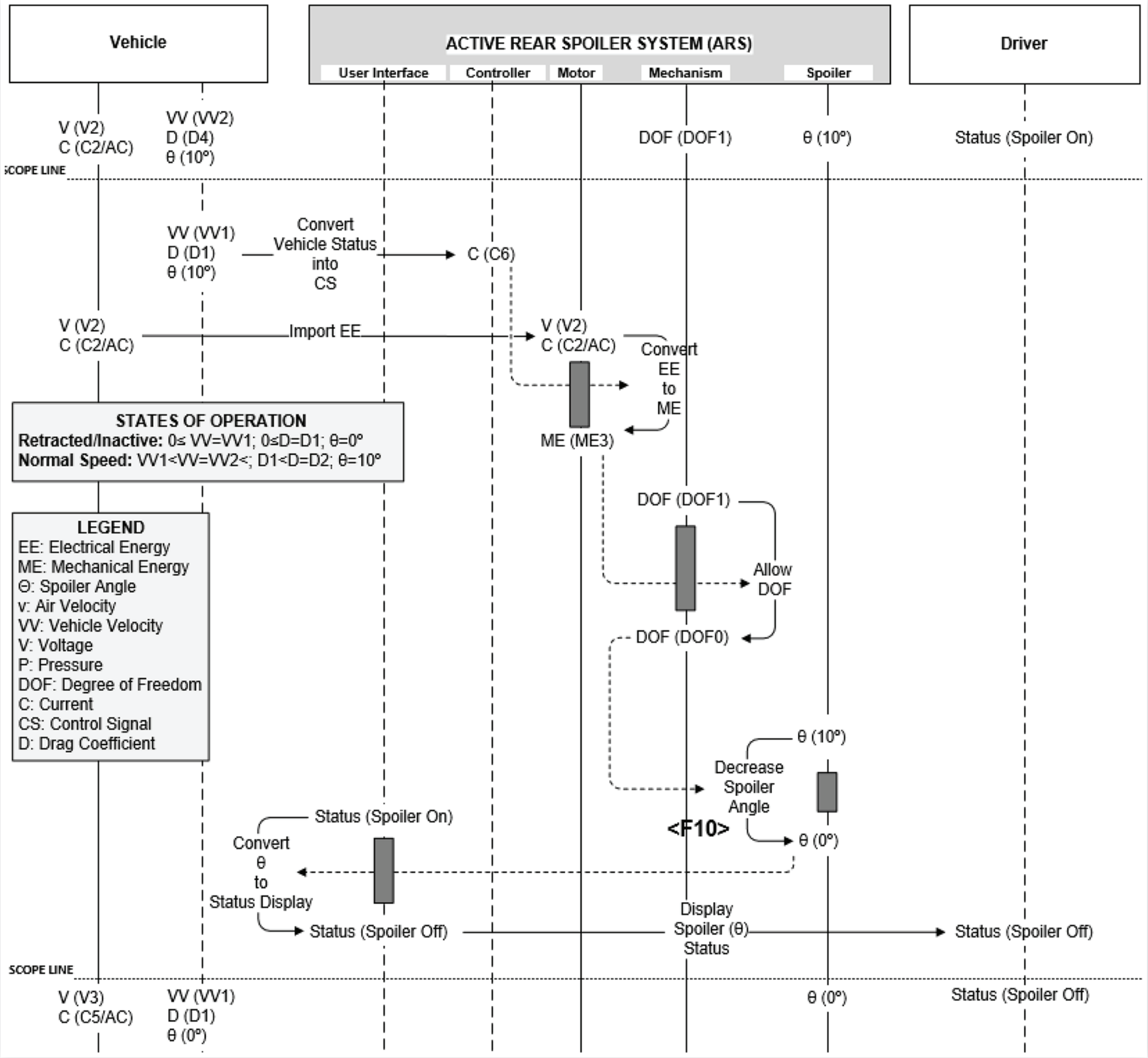


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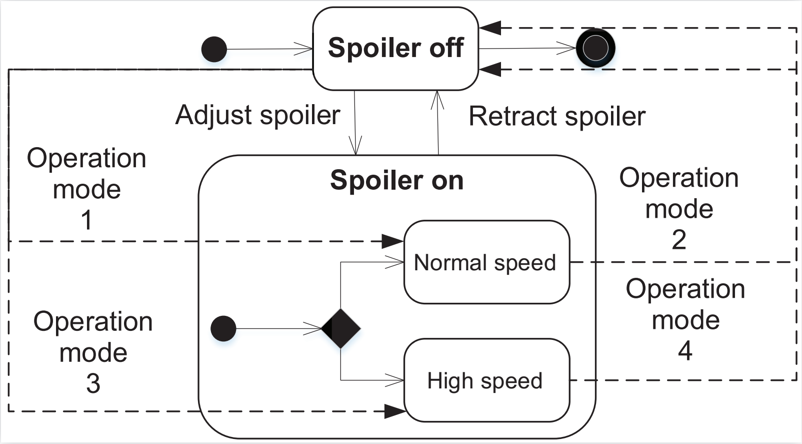
FIGURE 8 The flow of spoiler states.



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Scope lines facilitate the establishment of relationships between the external and the internal actors, as well as between internal actors to realize the operation modes in Figure 8. Figure 9 illustrates this relationship for Operation Mode 1 and Operation Mode 2 based on the attribute values of the internal and external actors.

Figure 9 represents attributes with their values held by Vehicle, Mechanism, Spoiler, and Driver as output and input states at the boundary of the scope lines of Operation Mode 1 and Operation Mode 2, respectively. The role of scope lines in the development of ESDs of Operation Mode 1 and Operation Mode 2 shown in Figure 9 applies to the development of ESDs for Operation Mode 3 and Operation Mode 4. In this case, scope lines show the relationship between the input states of "Adjust spoiler while the vehicle is at normal speed" and "Adjust spoiler while the vehicle is at high speed" operation modes, as shown in Figure 10.

The spoiler moves from "retracted" state to "normal speed" and "high speed" state in Operation Mode 1 and Operation Mode 3, respectively. Therefore, the initial attribute values (VV and D) of the vehicle and the air are not the same for these operation modes.

FIGURE 9 The role of scope lines in the development of ESDs—relationship between input and output states.

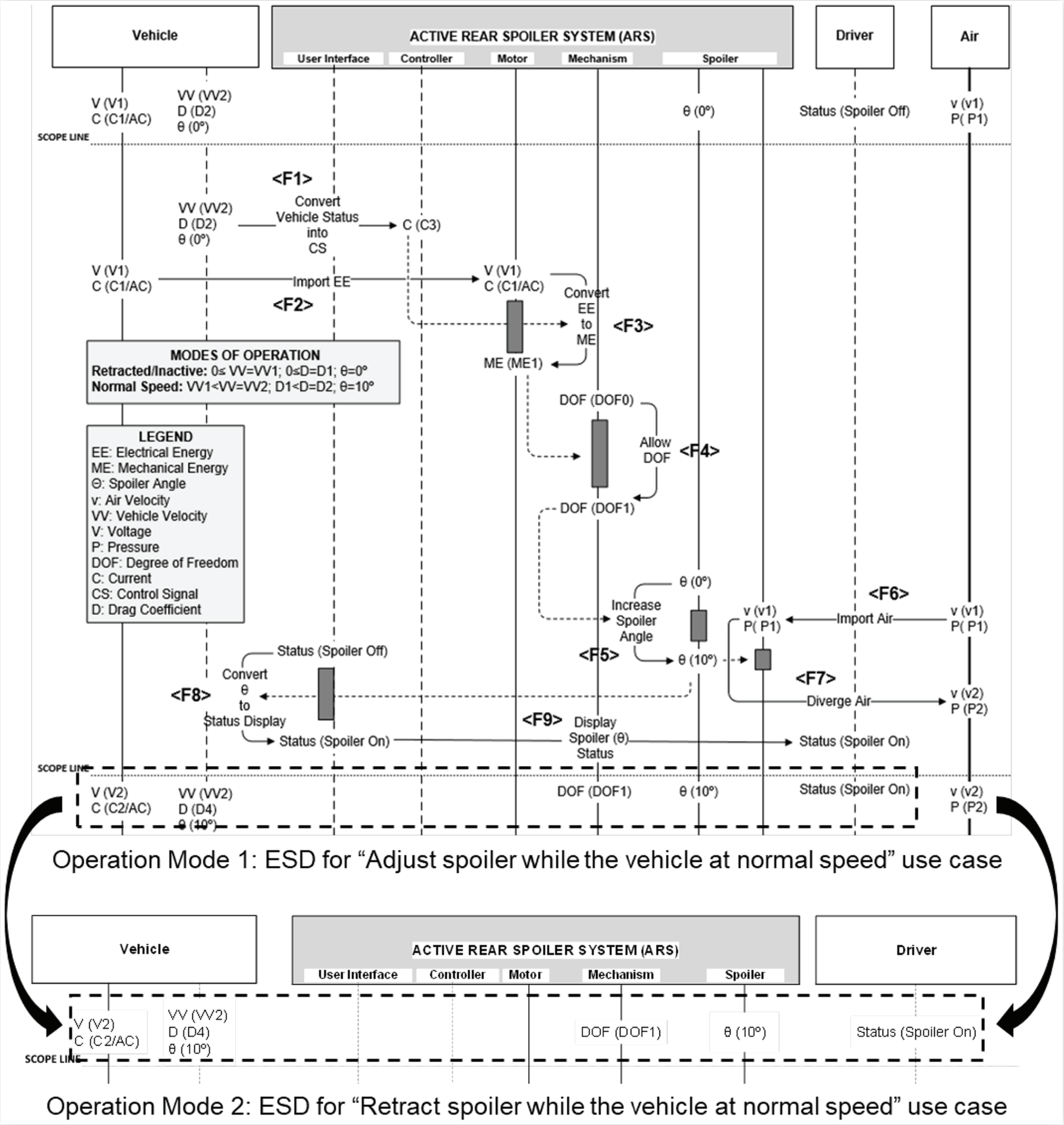

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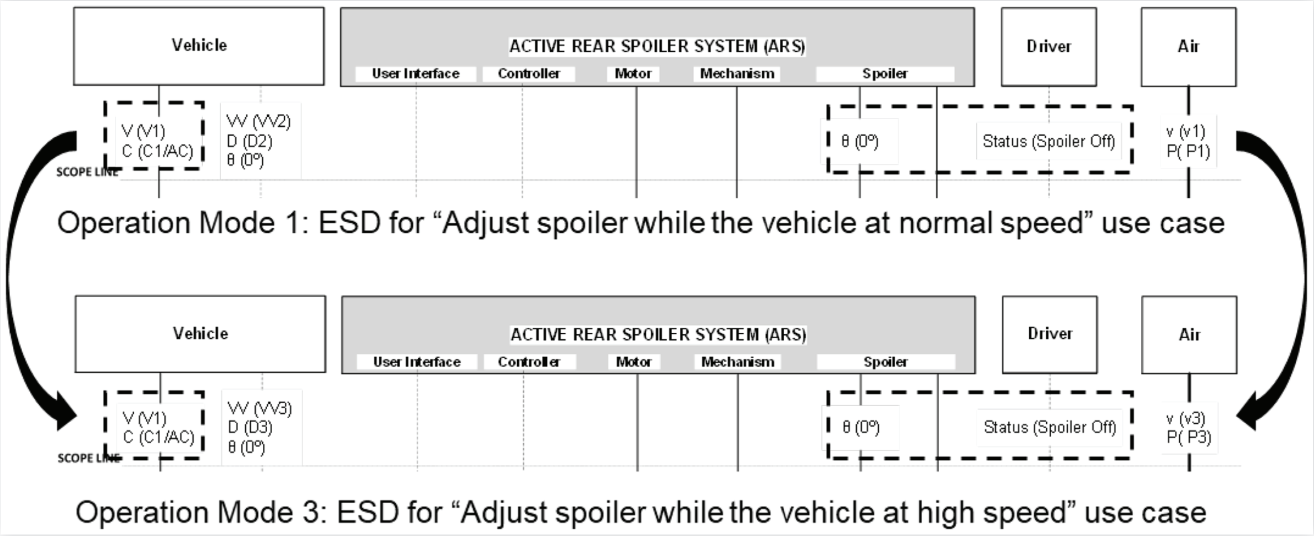
FIGURE 10 The role of scope lines in the development of ESDs—relationship between input states.



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4. Integration of ESD with Model-Based Function FMA

There is a significantly increased interest in the integration of the FMA methodologies [51, 52, 53] with the MBSE to enhance the effectiveness of product development (see, for example, [54, 55]). We will be discussing the support that the ESD methodology is offering for model-based function failure analysis within a systems engineering context early in the product development, based on the FMA methodology described in [12].

This section starts by introducing the development of an SSFD based on the ESD for an operation mode and the synthesis of SSFDs for various operation modes of the same system into a single functional model based on the ARS case study. While the ESD focuses on functional modelling of one operation mode of a system in respect of the other operation modes of the same system, the synthesis of SSFDs enables the capture of functional models of different operation modes in a single diagram, which provides an integrated "logical model" of the system.

The SSFD [47], underpinned by the state-based modelling and states description through attributes, provides systematic guidance to the analyst in carrying out exchange-based articulation of functional requirements along with their specifications. The functional model of the ARS extracted from the ESD can be shown as an SSFD. Figure 11 represents this based on <F3> in Figure 5(b) for the "Adjust spoiler while the vehicle is at normal speed" use case.

Figure 12 shows a complete SSFD for the "Adjust spoiler while the vehicle is at normal speed" use case based on its ESD in Figure 5(b).

As shown by numbered functions with in Figure 5(b), functions in ESD are mapped top-down in relation to interactions between the actors and the system. This reflects the time sequence characteristic of the SD by relating the time dimension to the function reasoning based on operations on flows. The development of an SSFD based on ESD enables the SSFD to ensure that time and parameter dependency are appropriately captured in the system functional model. Unlike the ESD in Figure 5(b), numbered functions with in Figure 12 are mapped from down to top as the auxiliary flows with associated functions should take place first for the fulfillment of the function(s) on the main flow. For example, F3 cannot take place without the output of F1. This addresses an important gap in flow-based functional modelling frameworks (including established frameworks such as Functional Basis of Stone and Wood) where time is not appropriately captured in the functional flow representation.

The representation of the initial and the final value(s) of the attribute(s) of the actors as states at the boundary of the scope lines in the ESD facilitates the synthesis of SSFD functional models derived from ESDs for the ARS's use cases into a single overall system model through the identification of the states that couple for the individual SSFD function models. By doing so, it is possible to illustrate the activation of a selection of functions in respect of a particular operation mode in the overall functional model of the system via the conditional fork node introduced in the SSFD. Figure 13 illustrates the SSFD functional model of the ARS, including all operation modes shown in Figure 4. Another industrial case study of the synthesis of functional models from operation modes using the SSFD has been described by [56] with a focus on a nested systems approach.

The structure of the ESD (the flowlines, functions, and associated design elements) underpins the identification and

FIGURE 11 The development of an SSFD from an ESD.

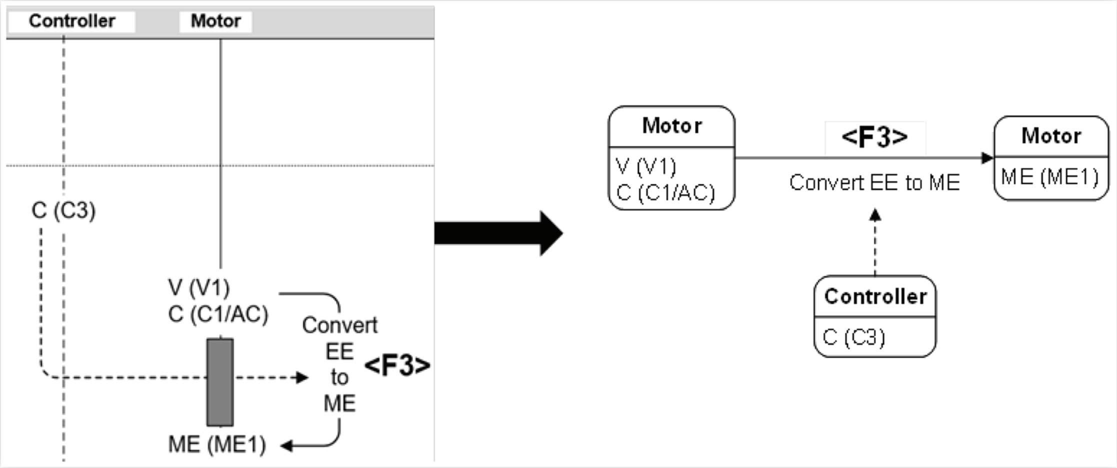

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FIGURE 12 SSFD for “Adjust spoiler while the vehicle is at normal speed” use case.

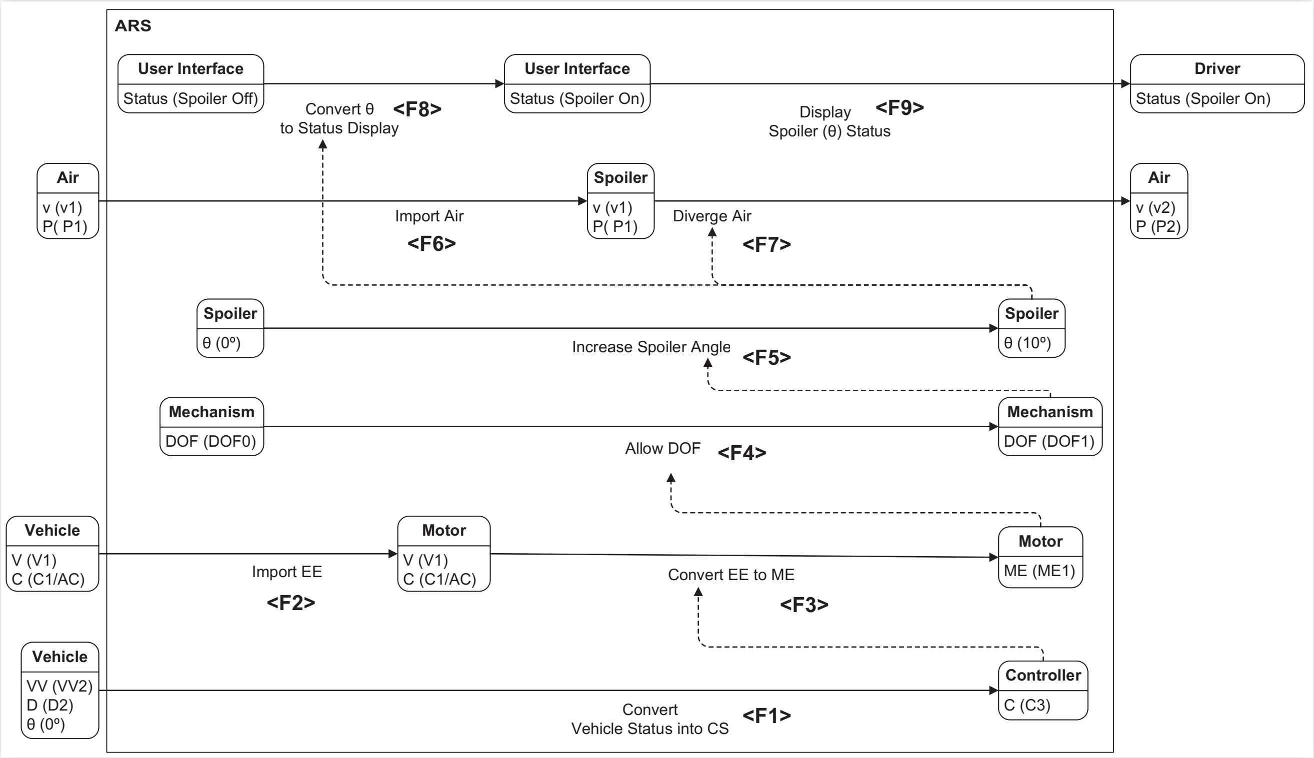

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FIGURE 13 Integrated ARS SSFD system function model—including all operation modes.

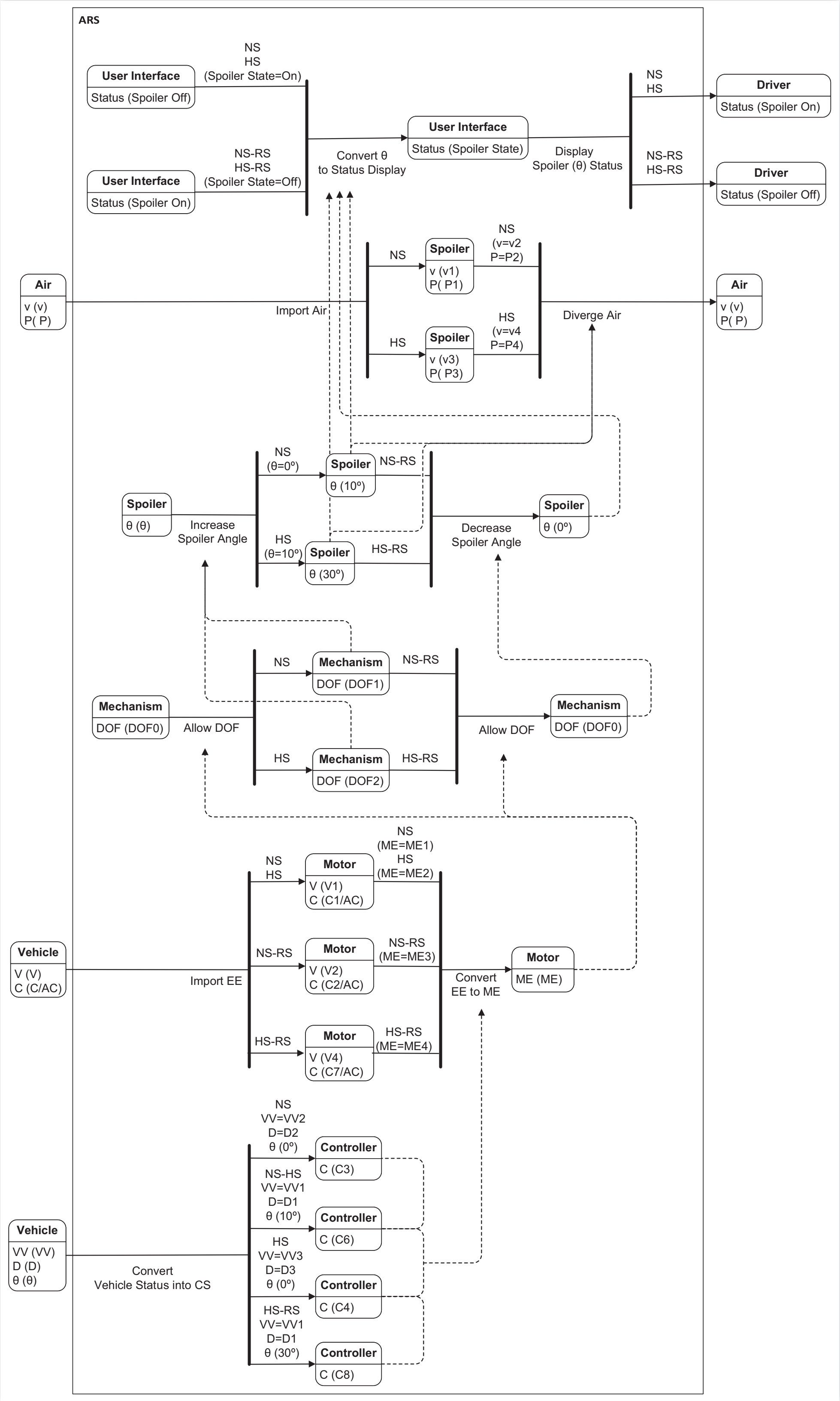

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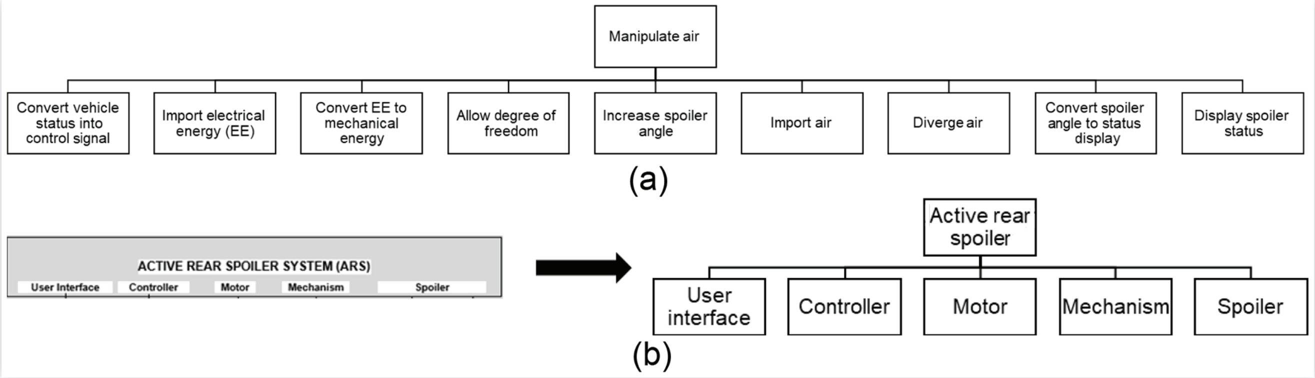
FIGURE 14 The development of function tree (a) and structure tree (b) from the ESD.



the evaluation of risks based on the existing Function FMA methodology (e.g., [57]).

A function tree provides a fundamental engineering understanding of how a system achieves its function through subfunctions. Figure 14(a) shows a conventional function tree extracted from the functional decomposition defined through the ESD and the SSFD of "Adjust spoiler while the vehicle is at normal speed" use case in Figures 5(b) and 12, respectively. Similarly, an architecture tree can be derived from the ESD of the same use case as in Figure 14(b).

A boundary diagram shows a graphical representation of a system, showing both the internal components and the external interfaces for the operation of the system in relation to the flows of material, energy, and information. The allocation of flowlines (of material, energy, and information) and functions to components in the ESD provides a basis for the development of a system boundary diagram, as shown in Figure 15 for "Adjust spoiler while the vehicle is at normal speed" use case. The diagram in Figure 15 includes the design elements identified on the ESD with the flow's energy, material, and information. Vehicle's relevant subsystems and air are shown as the inputs to the system boundary, while "spoiled" air and "informed" driver are represented as the outputs from the system boundary.

The ESD underpins the development of the interface analysis template (IAT), described by [49] and further enhanced and customized for use in practice by [57], to capture requirements of a system based on interface reasoning. Figure 16 represents this based on <F1> and <F2> of ESD for Adjust spoiler while the vehicle is at normal speed" use case.

Other functional and architectural requirements of these interfaces can be identified via the IAT. The decomposition of <F3> into <F3.1> and <F3.2> in Figure 6 can be considered in this respect. As regards Figure 16, the achievement of both <F1> and <F2> can be detailed by identifying related interaction operations and functional requirements. Figure 16 shows this in gray rows: (i) the gray row on the top focuses on the move of EE from vehicle to motor, that is, it approaches to <F1> from the vehicle's side in relation to Vehicle-Motor interface; (ii) the gray row on the bottom addresses the need for bringing the CS from the Vehicle. As shown in Figure 16, functional requirements for the Vehicle-Controller interface

FIGURE 15 ARS boundary diagram for "Adjust spoiler while the vehicle is at normal speed" use case.

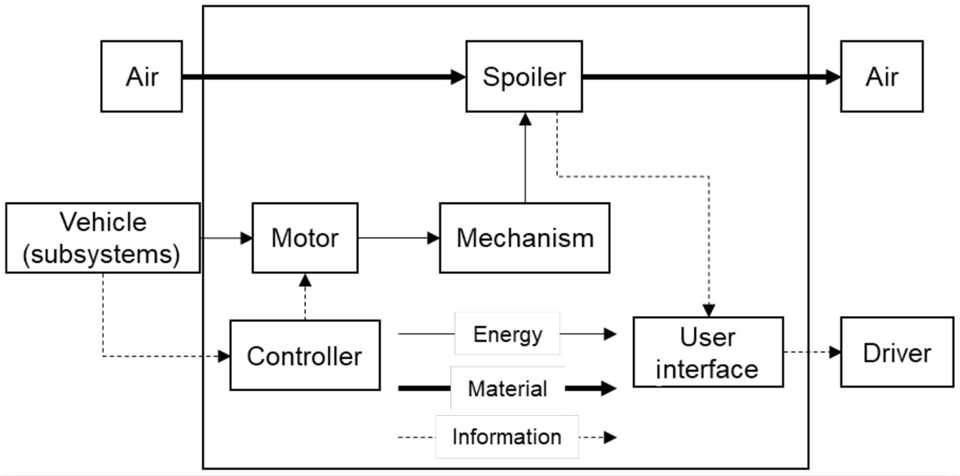
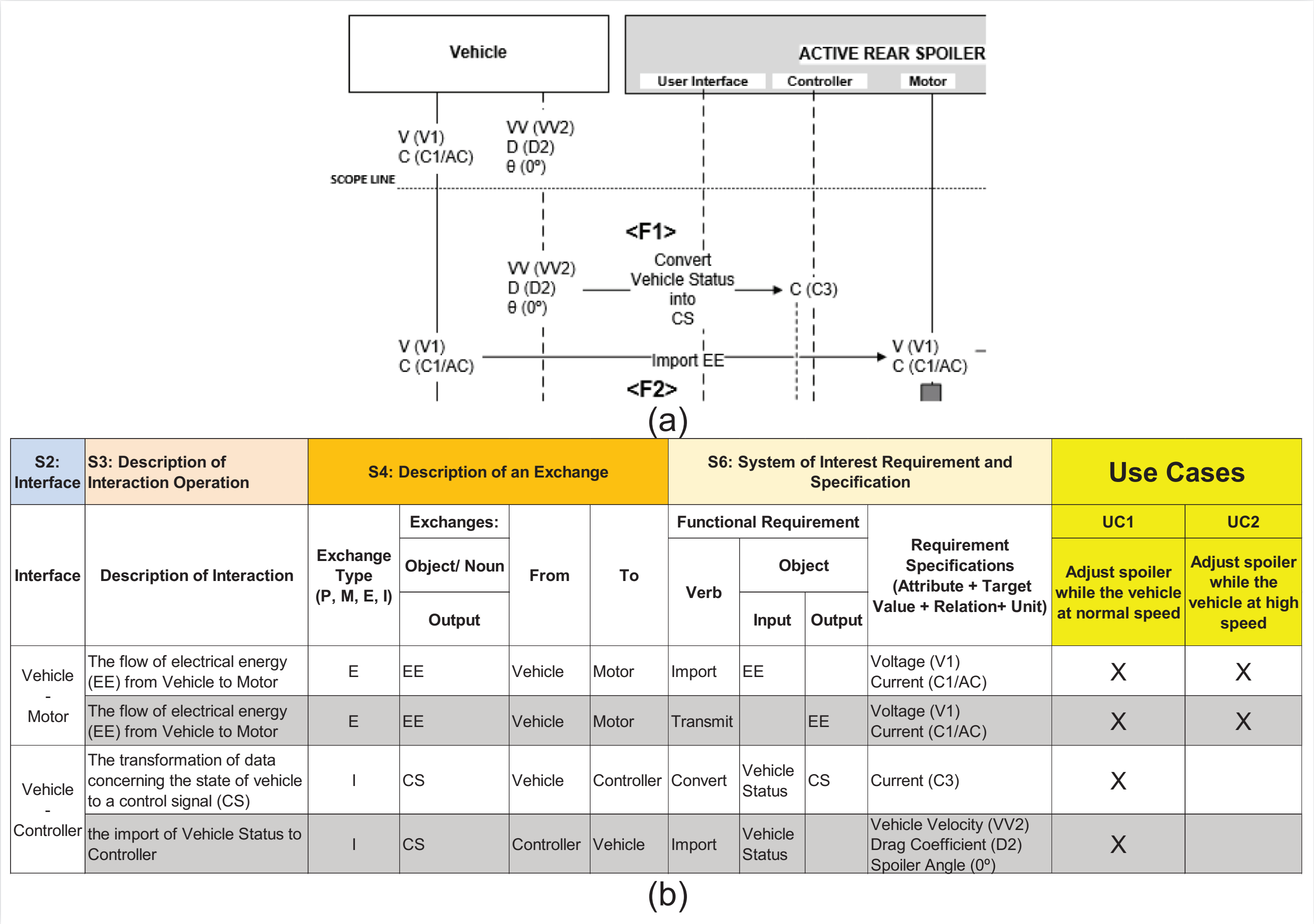


FIGURE 16 (a) An excerpt from ESD for "Adjust spoiler while the vehicle is at normal speed" use case. (b) Interface analysis based on (a).



(a)

S2: Interface	S3: Description of Interaction Operation	S4: Description of an Exchange				S6: System of Interest Requirement and Specification				Use Cases	
			Exchanges:			Functional Requirement				UC1	UC2
Interface	Description of Interaction	Exchange Type (P, M, E, I)	Object/ Noun Output	From	To	Verb	Object Input	Output	Requirement Specifications (Attribute + Target Value + Relation+ Unit)	Adjust spoiler while the vehicle at normal speed	Adjust spoiler while the vehicle at high speed
Vehicle - Motor	The flow of electrical energy (EE) from Vehicle to Motor	E	EE	Vehicle	Motor	Import	EE		Voltage (V1) Current (C1/AC)	X	X
	The flow of electrical energy (EE) from Vehicle to Motor	E	EE	Vehicle	Motor	Transmit		EE	Voltage (V1) Current (C1/AC)	X	X
Vehicle - Controller	The transformation of data concerning the state of vehicle to a control signal (CS)	I	CS	Vehicle	Controller	Convert	Vehicle Status	CS	Current (C3)	X	
	the import of Vehicle Status to Controller	I	CS	Controller	Vehicle	Import	Vehicle Status		Vehicle Velocity (VV2) Drag Coefficient (D2) Spoiler Angle (0°)	X	

(b)

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are associated with both Operation Mode 1 (UC1) and Operation Mode 3 (UC2).

The ESD can enhance function failure reasoning via the IAT, and this can lead to the development of a Failure Mode and Effects Analysis (FMEA) type analysis. Figure 17 represents the flow of information from the ESD through the IAT for <F2> for the development of such an analysis.

5. Discussion

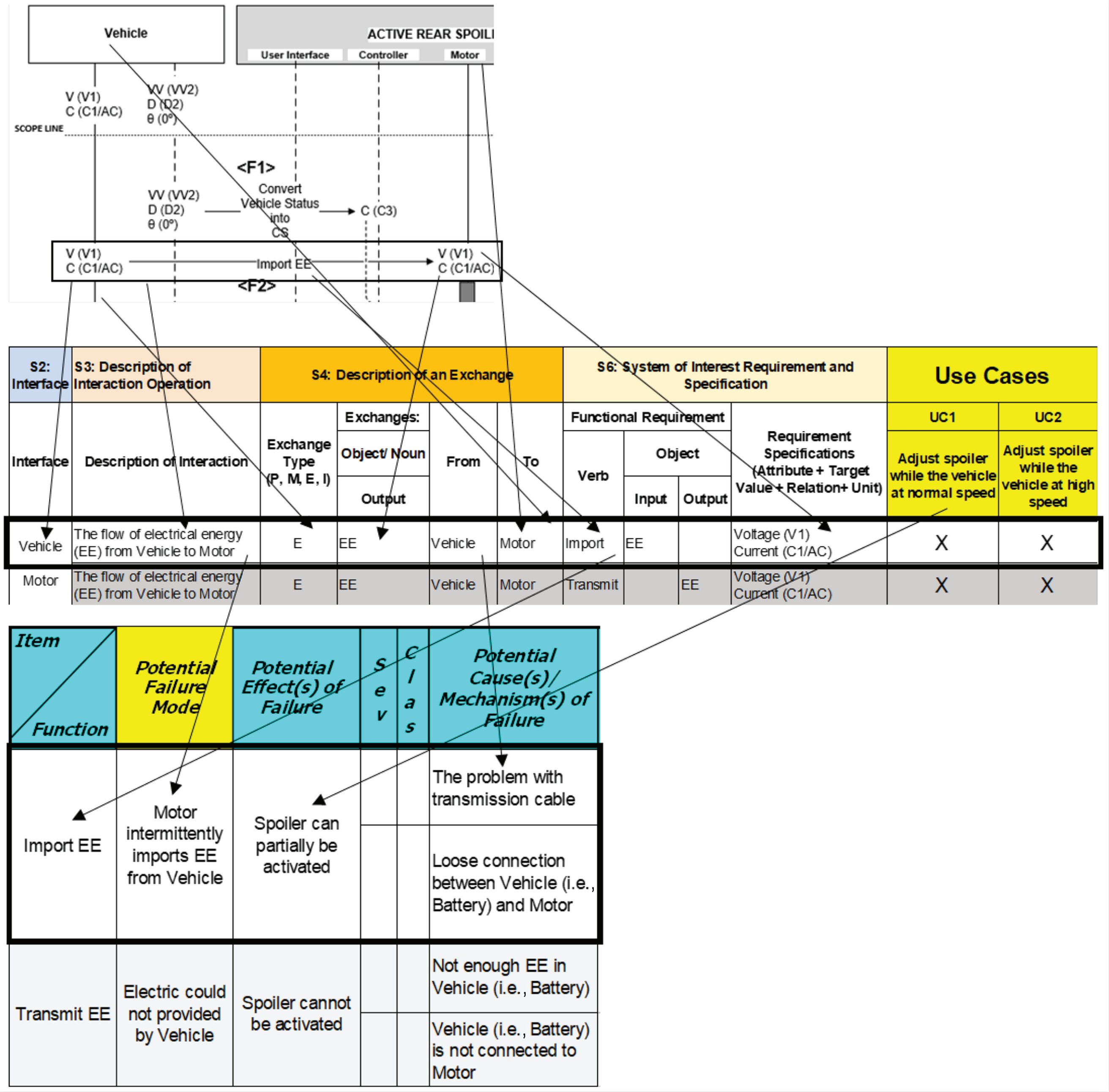
A system with multiple operation modes can change its configuration state from one to another. The change of the configuration state can lead to the introduction of a different technology to fulfill the system's function (e.g., powering a hybrid electric vehicle only by electric) or the change in the state of a specific component/subsystem (e.g., temperature control mode of a hair dryer).

The change in the state of a specific component (or a subsystem) means the change of its measurable attributes (such as size, position, and temperature) to fulfill functional requirements related to different operation modes. The ESD complements the approach commonly seen in literature and used by systems engineers in this respect, where functional analysis of a system is not carried out in the context of its multiple operation modes systematically. Sequences of multiple operation modes are coupled in respective functional model representations through the coherent alignment of attributes and values. Scope lines facilitate the coupling of operation modes by representing input and output attributes of actors with their values in ESDs of relevant use cases, as shown in Figures 9 and 10.

The representation of time in a graphical functional model coherent with the principles of standard SD supports the use of the ESD in the analysis of the dynamic behavior of complex physical systems. ESDs of the ARS in Sections 3.3-3.5 show which components and subsystems need to achieve one or more than one function through a change of the attribute values at different times. Table 1 represents the case for the spoiler.

The spoiler changes its position at different velocities and pressures of air. As shown in Table 1, the spoiler in the ESDs

FIGURE 17 Flow of information from the ESD to an FMEA analysis through the IAT.



S2: Interface	S3: Description of Interaction Operation	S4: Description of an Exchange				S6: System of Interest Requirement and Specification				Use Cases	
			Exchanges:			Functional Requirement				UC1	UC2
Interface	Description of Interaction	Exchange Type (P, M, E, I)	Object/ Noun Output	From	To	Verb	Object Input	Object Output	Requirement Specifications (Attribute + Target Value + Relation+ Unit)	Adjust spoiler while the vehicle at normal speed	Adjust spoiler while the vehicle at high speed
Vehicle	The flow of electrical energy (EE) from Vehicle to Motor	E	EE	Vehicle	Motor	Import	EE		Voltage (V1) Current (C1/AC)	X	X
Motor	The flow of electrical energy (EE) from Vehicle to Motor	E	EE	Vehicle	Motor	Transmit		EE	Voltage (V1) Current (C1/AC)	X	X

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Clas	Potential Cause(s)/ Mechanism(s) of Failure
Import EE	Motor intermittently imports EE from Vehicle	Spoiler can partially be activated			The problem with transmission cable
					Loose connection between Vehicle (i.e., Battery) and Motor
Transmit EE	Electric could not provided by Vehicle	Spoiler cannot be activated			Not enough EE in Vehicle (i.e., Battery)
					Vehicle (i.e., Battery) is not connected to Motor

TABLE 1 Mapping of spoiler's functional requirements to the inputs, the outputs, and operation modes.

	Input			Output	
Operation mode	**Attribute**	**Value**	**Function**	**Attribute**	**Value**
1	Spoiler angle	0°	Increase spoiler angle	Spoiler angle	10°
3		0°			30°
2		10°	Decrease spoiler angle		0°
4		30°			0°
1	Air velocity	v1	Import air	Air velocity	v1
3		v3			v3
1	Air pressure	P1		Air pressure	P1
3		P3			P3
1	Air velocity	v1	Diverge air	Air velocity	v2
3		v3			v4
1	Air pressure	P1		Air pressure	P2
3		P3			P4

of Operation Mode 1 and Operation Mode 3 includes two more functional requirements for the manipulation of the flow of the air: "Import Air" and Diverge Air." The same functional requirements are related to different operational states that are dependent on different values of the same attributes in the ARS. The ESD enables the capture of this through a coherent mapping of transformations and transmission functions in terms of the measurable attributes of the actors. Functional requirements in Table 1 reflect the requirements of the spoiler both as a component and as a feature. "Increase/Decrease Spoiler Angle" is related to the operation of the spoiler in relation to other parts of the ARS, whereas "Import/Diverge Air" is about the design of the spoiler, i.e., shape.

The ESD provides opportunities for structure sharing, which is a challenge in the design of products with multiple modes [7]. Table 1 shows the allocation of four functional requirements to the spoiler. A component may also require addressing only one functional requirement in relation to operational states that are dependent on different values of the same attributes. For example, the function of "Mechanism" only is to satisfy the functional requirement of "allow DOF" but also provide this function at different times for different attribute values of its input and the output for four use cases analyzed in Section 3. Only by satisfying these criteria can this mechanism be selected.

The ESD also facilitates the architecture development of a system. This is an important feature in the development of a new system or feature at the early-stage conceptual analysis [14]. Functional models and architecture could be evolved, and furthermore, they could be converged with different embodiment choices. For example, flowlines and functions of Motor and Mechanism can be allocated to a single subsystem. Adaptable design, introduced by [58] and further developed by numerous researchers (e.g., [59, 60]), promotes the idea of replacing multiple products with one product with a set of replaced or added certain modules. The ESD can also be used to support adaptable design based on the same methodology. In a similar vein, as illustrated and discussed by [4], the subsystem can be decomposed into its components as the ESD facilitates the transition between levels of abstraction. For example, the analysis of the controller can be further deployed to the nested functional decomposition analysis and representation of its components (e.g., for the design and analysis of sensors).

In the case of the graphical representation itself, all ESDs were completed using Microsoft Visio. We acknowledge that further development needs to be done (including compatibility with relevant MBSE/SysML packages) to promote the take-up of the ESD by practitioners.

Figure 17 shows that the ESD provides a coherent way to the development of FMEA through the IAT. The role of the ESD in the practice of function failure mode analysis and avoidance can be summarized as follows:

- The ESD supports the development of the system model through the generation of Function Tree, Structure Tree, and System Boundary Diagram.
- Functional requirements of the system can be extracted from the ESD in a structured way, and these requirements can be fed into IAT, which leads to a more detailed analysis of these requirements.
- The development of FMEA based on IAT provides a detailed analysis of the system by documenting potential failure modes with their causes and other relevant details.

The development of the IAT underpinned by the ESD in the identification of other functional requirements of a component/subsystem supports the identification of a combination of failure modes on FMEA. Gray rows in Figure 17 shows this by documenting functional requirement related to the achievement of <F2> and relating this functional requirement along with interface information to a failure in the same component, namely, the spoiler.

6. Conclusions

This article presented further methodological development and insights into the ESD, in conjunction with a case study related to functional analysis of a single component with a shape-changing aspect. This both validated the applicability of the ESD in the analysis of such systems and contributed to existing knowledge of functional analysis of such a system in the context of its multiple operation modes in a systematic way. The use of the ESD to support model-based Function Failure Mode Analysis and Avoidance was also shown to address methodological challenges in the identification and evaluation of risks during product development in the automotive industry.

The analysis of an ARS system through the ESD shows its capability to analyze operation modes of a system with the same functional requirements that are dependent on the transmission and conversion of the same attributes with different values. This also illustrates the applicability of the ESD across the flows of different types (i.e., energy, information, and material), and engineering disciplines (e.g., mechanical and electrical). The concept of Scope Lines enables the coupling of ESDs of operation modes of the same system by facilitating the coherent alignment of attributes and values and therefore capturing and representing function sequences. This facilitates the analysis of the dynamic behavior of systems whose operational modes are dependent on different attribute values.

Both the development of a flow-based diagram, SSFD, from the ESD for an operation mode and the synthesis of SSFDs from ESDs of different operation modes of the same system into a single functional model may be of assistance to the practitioners who are interested in this topic. The development of SSFD from ESD enables the SSFD to capture the time dimension in the function reasoning, which is an important gap in flow-based functional modelling frameworks. Scope lines in the ESD facilitate the identification of the coupling of the individual SSFD that leads to the aggregation of SSFDs for operation modes of the same system into a single functional model. The SSFD enables the activation of relevant functions in relation to a particular operation mode in the context of the overall functional model of the system encompassing multiple operation modes.

The development of FMEA from the ESD through the IAT provides a systematic way of identifying a combination of failure modes of a system or a component on FMEA. This paves the way for the use of ESD in relation to requirement-based testing, design verification, and validation of systems at the conceptual design stage.

Our future work focuses on the automation of ESD and its integration with other methods through relevant MBSE packages to make the ESD more accessible to practitioners.

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References

1. Hehenberger, P., Vogel-Heuser, B., Bradley, D., Eynard, B. et al., "Design, Modelling, Simulation and Integration of Cyber Physical Systems: Methods and Applications," *Comput Ind* 82 (2016): 273-289, https://doi.org/10.1016/j.compind.2016.05.006.
2. Lindemann, U., Maurer, M., and Braun, T., *Structural Complexity Management: An Approach for the Field of Product Design* (Berlin: Springer Verlag, 2009), https://doi.org/10.1007/978-3-540-87889-6.
3. INCOSE, "Systems Engineering Vision 2020," INCOSE-TP-2004-004-02, September 2007.
4. Yildirim, U. and Campean, F., "Functional Modelling of Complex Multi-Disciplinary Systems Using the Enhanced Sequence Diagram," *Res Eng Design* 31 (2020): 429-448, https://doi.org/10.1007/s00163-020-00343-8.
5. Liu, C., Hildre, H.P., Zhang, H., and Rolvag, T., "Conceptual Design of Multi-Modal Products," *Research in Engineering Design* 26, no. 3 (2015): 219-234, https://doi.org/10.1007/s00163-015-0193-0.
6. Goebel, R., Sanfelice, R., and Teel, A., *Hybrid Dynamical Systems: Modeling, Stability, and Robustness* (Princeton, NJ: Princeton University Press, 2012), ISBN:9780691153896.
7. Liu, C., Hildre, H.P., Zhang, H., and Rolvag, T., "Product Architecture Design of Multi-Modal Products," *Res Eng Design* 27 (2016): 331-346, https://doi.org/10.1007/s00163-016-0221-8.
8. Burkacky, O., Deichmann, J., and Stein, J.P., "Automotive Software and Electronics 2030: Mapping the Sector's Future Landscape," McKinsey, accessed August 2019, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/mapping-the-automotive-software-and-electronics-landscape-through-2030.
9. Mokhtarian, H., Coatanéa, E., and Paris, H., "Function Modeling Combined with Physics-Based Reasoning for Assessing Design Options and Supporting Innovative Ideation," *Artificial Intelligence for Engineering Design,*

Analysis and Manufacturing 31, no. 4 (2017): 476-500, https://doi.org/10.1017/S0890060417000403.

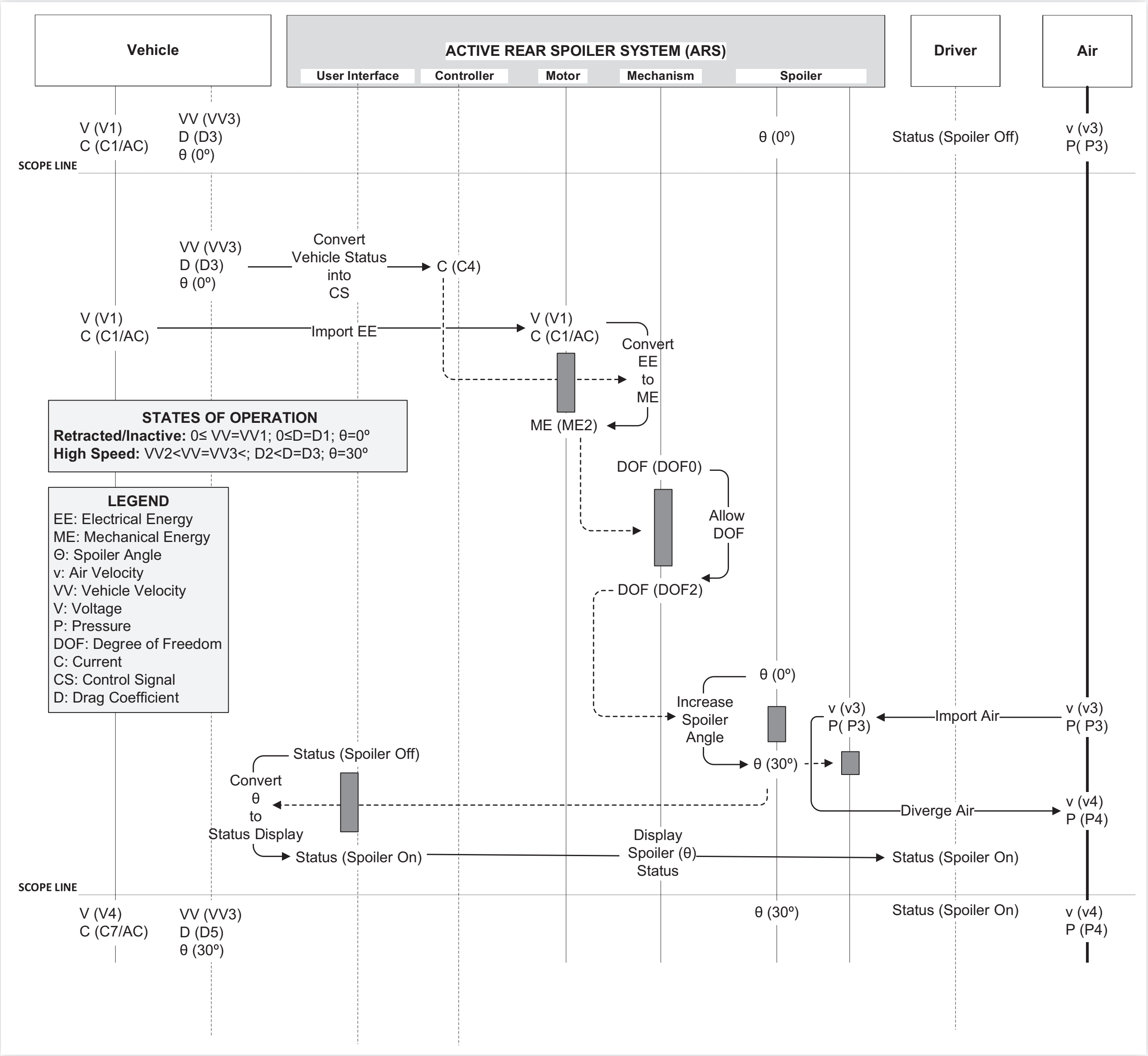
10. Zhao, M., Chen, Y., Chen, L., and Xie, Y., "A State-Behavior-Function Model for Functional Modeling of Multi-State Systems," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 233, no. 7 (2019): 2302-2317, https://doi.org/10.1177/0954406218791640.
11. Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.H., *Engineering Design: A Systematic Approach*, 3rd ed. (London: Springer, 2007), https://doi.org/10.1007/978-1-84628-319-2.
12. Campean, I., Henshall, E., and Rutter, B., "Systems Engineering Excellence Through Design: An Integrated Approach Based on Failure Mode Avoidance," *SAE Int. J. Mater. Manf.* 6, no. 3 (2013): 389-401, https://doi.org/10.4271/2013-01-0595.
13. Eigner, M., Dickopf, T., and Huwig, C., "An Interdisciplinary Model Based Design Approach for Developing Cybertronic Systems," Paper presented at in *the DESIGN Conference*, Dubrovnik, Croatia, vol. 16-19, May 2016, 1647-1656.
14. Albers, A., Rapp, S., Spadinger, M., Richter, T. et al., "The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and Their Interrelations," *Proc Design Soc Int Conf Eng Design* 1, no. 1 (2019): 1693-1702, https://doi.org/10.1017/dsi.2019.175.
15. Campean, F., Delaux, D., Sharma, S., and Bridges, J., "Reliability Research Roadmapping Workshop: Implications for Engineering Design," in *DESIGN Conference 2020*, Cavtat, Croatia, October 26-29, 2020, https://doi.org/10.21278/idc.2020.0000.
16. Schultz, J., Sen, C., Caldwell, B., Mathieson, J. et al., "Limitations to Function Structures: A Case Study in Morphing Airfoil Design," in *Proceedings of the ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 5: 22nd International Conference on Design Theory and Methodology; Special Conference on Mechanical Vibration and Noise*, Montreal, Quebec, Canada, August 15-18, 2010, 405-417, ASME, https://doi.org/10.1115/DETC2010-28559.
17. Stone, R.B. and Wood, K.L., "Development of a Functional Basis for Design," *J Mech Des* 122 (2000): 359-370, https://doi.org/10.1115/1.1289637.
18. Ullman, D.G., *The Mechanical Design Process*, 4th ed. (New York: McGraw-Hill, 2010)
19. Ulrich, K.T. and Eppinger, S.D., *Product Design and Development*, 3rd ed. (New York: McGraw-Hill/Irwin, 2003)
20. Cross, N., *Engineering Design Methods: Strategies for Product Design*, 4th ed. (Chichester: Wiley, 2008)
21. Short, A.R., Van Bossuty, D.L., "Rerouting Failure Flow Using Logic Blocks in Functional Models for Improved System Robustness: Failure Flow Decision Functions," in *Proceedings of the 20th International Conference on Engineering Design (ICED15)*, Milan, Italy, July 27-30, 2015.
22. Soria Zurita, N.F., Stone, R.B., Onan Demirel, H., and Tumer, I.Y., "Identification of Human-System Interaction Errors during Early Design Stages Using a Functional Basis Framework," *ASME J. Risk Uncertainty Part B: Mechanical Engineering* 6, no. 1 (2020): 011005, https://doi.org/10.1115/1.4044787.
23. Gill, A., Summers, J., and Turner, C., "Comparing Function Structures and Pruned Function Structures for Market Price Prediction: An Approach to Benchmarking Representation Inferencing Value," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 31, no. 4 (2017): 550-566, https://doi.org/10.1017/S0890060417000543.
24. OMG, "OMG Systems Modeling Language (OMG SysML™) Specification Version 1.6," OMG, accessed August 2019, https://sysml.org/.res/docs/specs/OMGSysML-v1.6-19-11-01.pdf.
25. Albers, A. and Zingel, C., "Challenges of Model-Based Systems Engineering: A Study towards Unified Term Understanding and the State of Usage of SysML," in *Proceedings sf Smart Product Engineering: The 23th CIRP Design Conference*, Bochum, Germany, 2013, 83-92, https://doi.org/10.1007/978-3-642-30817-8_9.
26. Barbieri, G., Fantuzzi, C., and Borsari, R., "A Model-Based Design Methodology for the Development of Mechatronic Systems," *Mechatronics* 24, no. 7 (2014): 833-843, https://doi.org/10.1016/j.mechatronics.2013.12.004.
27. Huldt, T. and Stenius, I., "State-of-Practice Survey of Model-Based Systems Engineering," *Systems Engineering* 22 (2019): 134-145, https://doi.org/10.1002/sys.21466.
28. Friedenthal, S., Moore, A., and Steiner, R., *A Practical Guide to SysML: The Systems Modeling Language*, 2nd ed. (Burlington: Morgan Kaufmann, 2012), https://doi.org/10.1016/C2013-0-14457-1.
29. Whittle, J. and Schumann, J., "Generating Statechart Designs from Scenarios," in *Proceedings of the 2000 International Conference on Software Engineering. ICSE 2000 the New Millennium*, Limerick, Ireland, 2000, 314-323, https://doi.org/10.1145/337180.337217.
30. Harel, D., Kugler, H., and Pnueli, A., "Synthesis Revisited: Generating Statechart Models from Scenario-Based Requirements," in: Kreowski, H.J., Montanari, U., Orejas, F., Rozenberg, G. et al. (Eds), *Formal Methods in Software and Systems Modeling. Lecture Notes in Computer Science*. Vol. 3393, (Berlin: Springer, 2005), https://doi.org/10.1007/978-3-540-31847-7_18.
31. Gronmo, R. and Moller-Pedersen, B., "From Sequence Diagrams to State Machines by Graph Transformation," in: Tratt, L. and Gogolla, M. (Eds), *Theory and Practice of Model Transformations. ICMT 2010. Lecture Notes in Computer Science*. Vol. 6142, (Berlin: Springer), https://doi.org/10.1007/978-3-642-13688-7_7.
32. Piques, J.-D., "SysML for Embedded Automotive Systems: SysCARS Methodology," Paper presented at in *Embedded Real Time Software and Systems (ERTS2014)*, Toulouse, France.
33. Whittle, J., Saboo, J., and Kwan, R., "From Scenarios to Code: An Air Traffic Control Case Study," in *25th*

International Conference on Software Engineering. Proceedings, Portland, OR, 2003, 490-495, https://doi.org/10.1109/ICSE.2003.1201227.

34. Latronico, E. and Koopman, P., "Representing Embedded System Sequence Diagrams as a Formal Language," in: Gogolla, M. and Kobryn, C. (Eds), *"UML" 2001—The Unified Modeling Language. Modeling Languages, Concepts, and Tools. UML 2001. Lecture Notes in Computer Science*. Vol. 2185, (Berlin: Springer), 2001.
35. Liang, H., Dingel, J. and Diskin, Z., "A Comparative Survey of Scenario-Based to State-Based Model Synthesis Approaches," in *5th International Workshop on Scenarios and State Machines, SCESM*, 2006.
36. Glinz, M., "An Integrated Formal Model of Scenarios Based on Statecharts," in: Schäfer, W. and Botella, P. (Eds), *Software Engineering—ESEC '95. ESEC 1995. Lecture Notes in Computer Science*. Vol. 989, (Berlin: Springer), https://doi.org/10.1007/3-540-60406-5_19.
37. Maier, T. and Zündorf, A., "The Fujaba Statechart Synthesis Approach," in *2nd International Workshop on Scenarios and State Machines: Models, Algorithms, and Tools, ICSE*, Portland, Oregon, 2003.
38. Vasilache, S. and Tanaka, J., "Synthesis of State Machines from Multiple Interrelated Scenarios Using Dependency Diagrams," *Journal of Systemics, Cybernetics and Informatics* 3, no. 3 (2005): 18-25, https://doi.org/10.1.1.113.8512.
39. Wei, B., Delugach, H.S., and Wang, Y., "From State Diagrams to Sequence Diagrams: A Requirements Acquisition Approach," *International Journal of Computers and Applications* 41, no. 2 (2019): 89-111, https://doi.org/10.1080/1206212X.2017.1408982.
40. Berkenkötter, K., "Using UML 2.0 in Real-Time Development—A Critical Review," in *SVERTS Workshop at the UML Conference*, 2003, https://www.verimag.imag.fr/EVENTS/2003/SVERTS/.
41. Roques, P., *Systems Architecture Modeling with the Arcadia Method: A Practical Guide to Capella* (London: ISTE Press, 2018)
42. Mathworks, *System Composer™ User's Guide (R2021b)* (The MathWorks, Inc., Apple Hill Drive Natick, MA, 2021)
43. Yildirim, U., "Function Modelling of Complex Multidisciplinary Systems: Development of a System State Flow Diagram Methodology for Function Decomposition of Complex Multidisciplinary Systems," PhD thesis, University of Bradford, 2015.
44. Campean, F. and Yildirim, U., "Enhanced Sequence Diagram for Function Modelling of Complex Systems," *Procedia CIRP* 60 (2017): 273-278, https://doi.org/10.1016/j.procir.2017.01.053.
45. Bolat, E., "Rear Spoiler Warning," accessed June 2021, https://thenounproject.com/term/rear-spoiler-warning/457502/.
46. Barber, C.J., Active spoiler for a motor vehicle. US Patent 10,035,548B2, July 31, 2018.
47. Yildirim, U., Campean, F., and Williams, H., "Function Modeling Using the System State Flow Diagram," *Artif Intell Eng Des Anal Manuf* 31, no. 4 (2017): 413-435, https://doi.org/10.1017/S0890060417000294.
48. Umeda, Y., Ishii, M., Yoshioka, M., Shimomura, Y. et al., "Supporting Conceptual Design Based on the Function-Behavior-State Modeller," *Artif Intell Eng Des Anal Manuf* 10, no. 4 (1996): 275-288, https://doi.org/10.1017/S0890060400001621.
49. Uddin, A., Campean, F., and Khan, M.K., "Application of the Interface Analysis Template for Deriving System Requirements," in *Proceedings of International Design Conference (DESIGN)*, Dubrovnik, Croatia, May 16-19, 2016, 543-552.
50. INCOSE, "The Guide for Writing Requirements," INCOSE-TP-2010-006-03, INCOSE Requirements Working Group, 2019.
51. Clausing, D.P., "Operating Window: An Engineering Measure for Robustness," *Technometrics* 46, no. 1 (2004): 25-29, https://doi.org/10.1198/004017004000000077.
52. Davis, T.P., "Science, Science, Engineering, and Statistics," *Appl. Stochastic Models Bus. Ind.* 22, no. 5-6 (2006): 401-430.
53. Zhou, J., "Reliability and Robustness Mindset in Automotive Product Development for Global Markets," SAE Technical Paper 2005-01-1212, 2005, https://doi.org/10.4271/2005-01-1212.
54. Qamar, A., Meinhart, M., and Walley, G., "Model Based Systems Engineering to Support Failure Mode Avoidance for Driver Assistance Systems," in *2017 IEEE Aerospace Conference*, 2017, 1-9, https://doi.org/10.1109/AERO.2017.7943639.
55. Shirvani, F., Scott, W., Kennedy, G.A.L., and Campbell, A.P., "Enhancement of FMEA Risk Assessment with SysML," *Australian Journal of Multi-Disciplinary Engineering* 15, no. 1 (2019): 52-61, https://doi.org/10.1080/14488388.2019.1664211.
56. Campean, F., Yildirim, U. and Henshall, E., "Synthesis of Functional Models from Use Cases Using the System State Flow Diagram: A Nested Systems Approach," Paper presented at in *the 15th International Design Conference*, Dubrovnik, Croatia, May 21-24, 2018, 2833-2844, https://doi.org/10.21278/idc.2018.0543.
57. Campean, F., Williams, H., Uddin, A., and Yildirim, U., *Robust Engineering Systems Analysis through Failure Mode Avoidance, Short Course Lecture Notes* (Bradford, UK: University of Bradford, 2017)
58. Gu, P., Hashemian, M., and Nee, A.Y.C., "Adaptable Design," *CIRP Annals* 53, no. 2 (2004): 539-557, https://doi.org/10.1016/S0007-8506(07)60028-6.
59. Zhang, J., Chen, Y., Xue, D. et al., "Robust Design of Configurations and Parameters of Adaptable Products," *Front. Mech. Eng.* 9 (2014): 1-14, https://doi.org/10.1007/s11465-014-0296-8.
60. Cong, J., Chen, C.-H., and Zheng, P., "Design Entropy Theory: A New Design Methodology for Smart PSS Development," *Advanced Engineering Informatics* 45 (2020): 101124, https://doi.org/10.1016/j.aei.2020.101124.

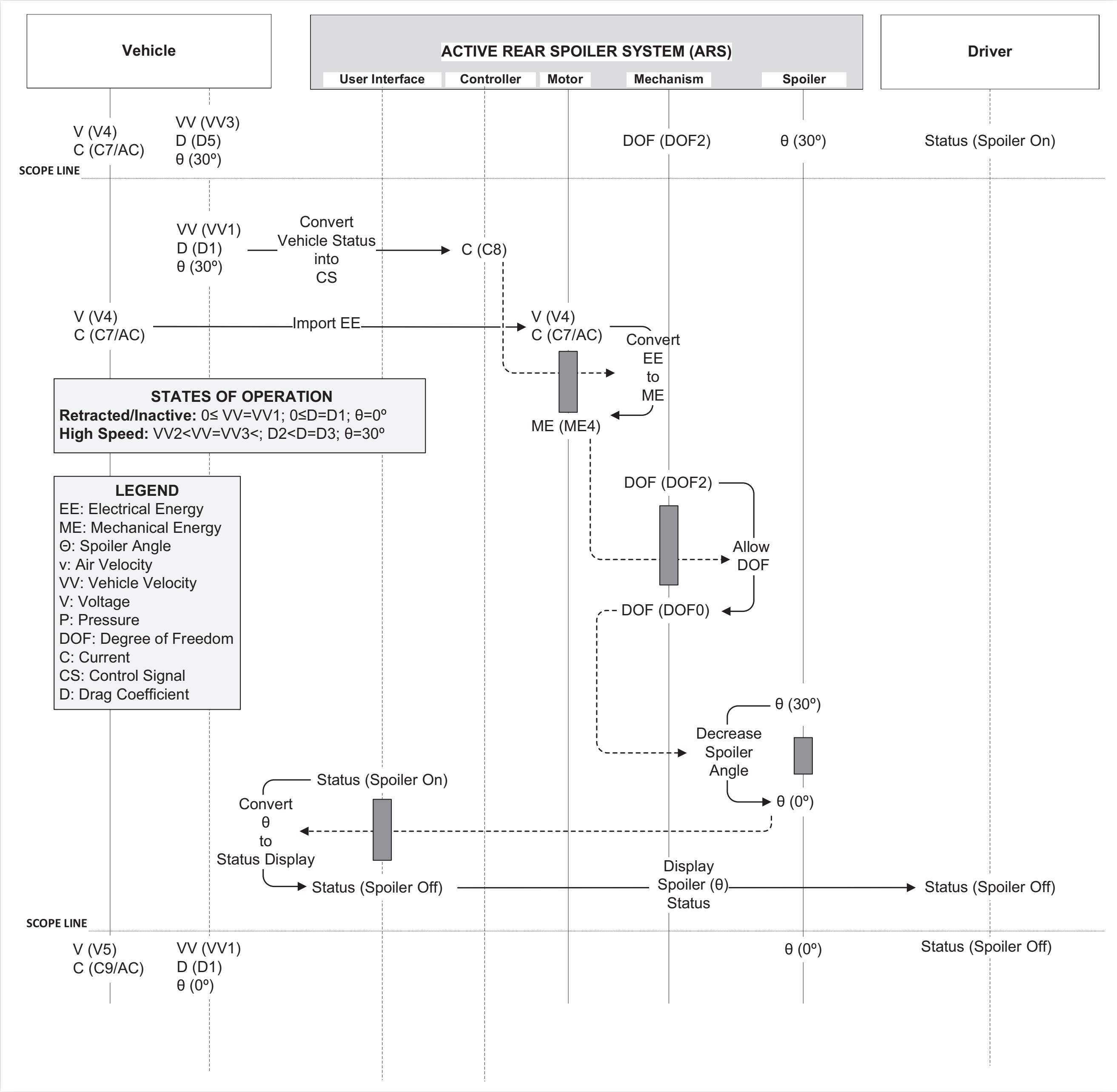
A. Appendix 1.a

ESD for “Adjust spoiler while the vehicle is at high speed” use case.



B. Appendix 1.b

ESD for “Retract (b) spoiler while the vehicle is at high speed” use case.



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