U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

NHTSA

DOT HS 812 576 August 2018

Functional Safety Assessment of a Generic Steer-by-Wire Steering System With Active Steering and Four-Wheel Steering Features

Notice

Suggested APA Format Citation:

Becker, C., Brewer, J., Arthur, D., & Attioui, F (2018, August). *Functional safety assessment of a generic steer-by-wire steering system with active steering and four-wheel steering features* (Report No. DOT HS 812 576). Washington, DC: National Highway Traffic Safety Administration.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No.0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2018	July 2015 – March 2016

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Functional Safety Assessment of a Generic Steer-by-Wire Steering System With Active Steering and Four-Wheel Steering Features	Intra-Agency Agreement DTNH22-14-V-00136 51HS6CA100
6. AUTHORS Christopher Becker, John Brewer, Larry Yount, David Arthur, and Fouad Attioui	
7. PERFORMING ORGANIZATION NAME AND ADDRESS John A. Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-NHTSA-16-06
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT HS 812 576

11. SUPPLEMENTARY NOTES
Paul Rau was Contracting Officer Representative for this project.

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161, www.ntis.gov.	

13. ABSTRACT
This report describes the research assessing the functional safety of foundational steering systems,. specifically, steer-by-wire (SbW) systems. This study also considers the additional active steering and four-wheel steering features, which could potentially be incorporated into some SbW systems. This study follows the Concept Phase process in the ISO 26262 standard and applies hazard and operability study, functional failure modes and effects analysis, and systems theoretic process analysis methods. in total, this study identifies five vehicle-level safety goals and 81 SbW system functional safety requirements (an output of the ISO 26262 process). This study uses the results of the analysis to develop potential test scenarios and identify possible areas for diagnostic trouble code coverage.

14. SUBJECT TERMS	15. NUMBER OF PAGES
steer-by-wire, SbW, active steering, four wheel steering, 4WS, hazard and operability study, HAZOP, failure modes and effects analysis, FMEA, systems theoretic process analysis, STPA, ISO 26262, hazard analysis, risk assessment, and safety requirements.	304
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

Foreword

NHTSA's Automotive Electronics Reliability Research Program

The mission of the National Highway Traffic Safety Administration is to save lives, prevent injuries, and reduce economic costs due to motor vehicle crashes. As part of this mission, NHTSA researches methods to ensure the safety and reliability of emerging safety-critical electronic control systems in motor vehicles. The electronics reliability research area focuses on the body of methodologies, processes, best practices, and industry standards that are applied to ensure the safe operation and resilience of vehicular systems. More specifically, this research area studies the mitigation and safe management of electronic control system failures and making operator response errors less likely.

NHTSA has established five research goals for the electronics reliability research program to ensure the safe operation of motor vehicles equipped with advanced electronic control systems. This program covers various safety-critical applications deployed on current generation vehicles, as well as those envisioned on future vehicles that may feature more advanced forms of automation and connectivity. These goals are:

1. Expand the knowledge base to establish comprehensive research plans for automotive electronics reliability and develop enabling tools for applied research in this area;
2. Strengthen and facilitate the implementation of safety-effective voluntary industry-based standards for automotive electronics reliability;
3. Foster the development of new system solutions for ensuring and improving automotive electronics reliability;
4. Research the feasibility of developing potential minimum vehicle safety requirements pertaining to the safe operation of automotive electronic control systems; and
5. Gather foundational research data and facts to inform potential future NHTSA policy and regulatory decision activities.

This Report

This publication is part of a series of reports that describe NHTSA's initial work in the automotive electronics reliability program. This research specifically supports the first, second, fourth, and fifth goals of NHTSA's electronics reliability research program by gaining understanding on both the functional safety requirements for automated lane centering (ALC) control systems and related foundational systems, and how the industry standard may enhance safety.

Specifically, this report describes the research effort to assess the functional safety and derive safety requirements related to a generic steer-by-wire (SbW) steering system that includes features such as active steering and four-wheel steering. This supports the overall project objective of assessing the functional safety of ALC systems, and the foundational steering and braking control systems upon which these ALC systems are based. The analysis described in this report follows the Concept Phase of the ISO 26262 standard [2].

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

4WS	four-wheel steering
A/D	analog/digital
ALC	automated lane centering
ASIL	automotive safety integrity level
CAN	controller area network
CF	causal factor
CPU	central processing unit
DTC	diagnostic trouble code
DVI	driver-vehicle interface
EEPROM	electronically erasable programmable read-only memory
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ESD	electrostatic discharge
FARS	Fatality Analysis Reporting System
FMEA	failure mode effects analysis[1]
FMVSS	Federal Motor Vehicle Safety Standard
FTTI	fault tolerant time interval
GES	General Estimates System
HAZOP	Hazard and Operability Study
I/O	input/output
IC	integrated circuit
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
kph	kilometers per hour
QM	quality management
RAM	random access memory
ROM	read-only memory
SAE	SAE International, formerly the Society of Automotive Engineers
SbW	steer-by-wire
SG	safety goal

[1] Editor's Note: The term "Failure Mode Effects Analysis," FMEA, was coined by the Department of Defense in 1949 in a military standard called MIL-P-1629, which later morphed into MIL-STD-1629 and its amended forms, cited in this report. Over the years, the term itself has changed, sometimes using "Modes," plural, instead of "Mode," and sometimes inserting the word "and," to Failure Mode *and* Effects Analysis. It is clear in the original that the term means the effects of a failure mode, not a failure mode or modes AND effects thereof. As such, the term must remain unitary as "failure mode effects," and the totality as an analysis of those effects. Thus, NHTSA prefers to use "failure mode effects analysis" as it preferred term in respect to father and son, MIL-P-1629 and MIL-STD-1629, without necessarily asserting that other forms of the term are "wrong." Variant terms are left as they are when quoting or citing a source, but is changed or "corrected" as well as lowercased (because it is a generic form of analysis) in text.

STPA	system-theoretic process analysis
TBD	to be determined
UCA	unsafe control action
UNECE	United Nations Economic Commission for Europe
VOQ	vehicle owner questionnaire

EXECUTIVE SUMMARY

The National Highway Traffic Safety Administration established the electronics reliability research area to study the mitigation and safe management of electronic control system failures and operator response errors. This project supports NHTSA's electronics reliability research area by:

- Expanding the knowledge base for automated lane centering systems and the foundational steering and braking systems upon which ALC relies.
- Providing an example for implementing a portion of the voluntary, industry-based functional safety standard, ISO 26262.
- Deriving example functional safety requirements.
- Providing research to inform potential future NHTSA policy and regulatory decision activities.

As advanced driver assistance systems and other automated technologies are introduced into the Nation's fleet, the safety of these systems will depend in part on the safety of the underlying foundational vehicle systems. While emerging technologies may be designed in accordance with the ISO 26262 functional safety standard, many foundational systems currently deployed are legacy systems that predate ISO 26262 [2].

This report describes research by the Volpe National Transportation Systems Center in conjunction with NHTSA to derive functional safety requirements related to a recent version of one such foundational system — foundational steering as implemented in a steer-by-wire system. Foundational steering systems, together with foundational brake systems, form the basis for automated lateral control technologies, such as ALC.

The primary purpose of this work is to study and analyze the potential hazards that could result from cases of electrical or electronic failures impacting the functions of vehicular control systems. The study follows the ISO 26262 process to identify the integrity requirements of these functions at the concept level, independent of implementation variations. This study also considers potential causes that could lead to such functional failures and documents the technical requirements the ISO 26262 process suggests with respect to the identified automotive safety integrity level of the item under consideration. While this study does not go into implementation strategies to achieve these ASILs, the ISO 26262 process provides a flexible framework and explicit guidance for manufacturers to pursue different methods and approaches to do so. Manufacturers employ a variety of techniques, such as ASIL decompositions, driver warnings, fault detection mechanisms, plausibility checks, redundancies, etc. to achieve the necessary ASILs that effectively mitigate the underlying safety risks.

In order to assess the SbW system, this study applies a method for developing a Functional Safety Concept by following the Concept Phase (Part 3) of the ISO 26262 standard.[2] The following outlines the analysis approach used in this study along with these key findings.

1. Defining the scope and functions of a generic SbW system. The SbW system considered in this study includes additional features such as active steering and four-wheel steering. in addition to executing the driver's steering command, the SbW system is also capable of implementing steering requests from other vehicle systems, such as ALC.

2. Performs a vehicle-level hazard analysis using both the HAZOP study and the STPA method. By integrating the hazards identified in both the HAZOP study and STPA, the process establishes six vehicle-level hazards.

3. Applies the ASIL assessment[3] approach in the ISO 26262 standard to evaluate the risks associated with each of the identified hazards. The vehicle-level hazards identified for the SbW system ranged from ASIL A to ASIL D; ASIL D is the most severe ASIL.

4. Performs safety analysis using both the Functional Failure Mode Effects Analysis and the STPA method.

5. Derives 81 functional safety requirements for the SbW system and components by combining the results of the two safety analyses[4] (functional FMEA and STPA) following the Concept Phase in the ISO 26262 standard.[5]

6. Identifies 145 generic diagnostic trouble codes (DTCs) listed in the SAE Recommended Practice J2012[6] that are relevant to the SbW system.

7. Develops seven example test scenarios that could be used to validate the safety goals and functional safety requirements.

The results of this report may be used to:

---

[2] The Concept Phase of the ISO 26262 standard is the initial stage of the development process and can be implemented before the specifics of the system design are known.

[3] The ASIL is established by performing a risk analysis of a potential hazard that looks at the Severity, Exposure, and Controllability of the vehicle operational situation.

[4] The HAZOP study is not used directly in deriving the functional safety requirements. The HAZOP study is used to identify the relevant vehicle-level hazards, which are then assigned ASILs that cascade down to the functional safety requirements.

[5] All requirements presented in this report are intended to illustrate a set of requirements that could be derived from the safety analysis results. These safety requirements are not intended to represent NHTSA's official position or requirements on the SbW system.

[6] The SAE standard J2012 defines the standardized DTCs that on-board diagnostic systems in vehicles are required to report when malfunctions are detected.

- Demonstrate how the Concept Phase of ISO 26262 may be implemented, including integration of multiple analysis methods.
- Establish a baseline functional safety concept for future development of SbW systems.
- Provide research data for future NHTSA activities with respect to SbW systems.
- Illustrate how the analysis results may be used to develop potential test scenarios to validate the safety goals and functional safety requirements.

1 INTRODUCTION

1.1 Research Objectives

In conjunction with NHTSA, the Volpe National Transportation Systems Center is conducting a research project to assess the functional safety of automated lane centering systems in light vehicles.[7] These ALC systems are largely implemented through foundational braking and/or steering control systems. Therefore, the reliability of the ALC technology depends in part on the reliability of these foundational braking and steering systems. The foundational braking and steering systems are shared resources that may also be used to implement commands from other longitudinal and lateral control systems such as adaptive cruise control, forward collision avoidance, and emergency steer assist.

This project is part of NHTSA's electronics reliability research program for ensuring the safe operation of motor vehicles equipped with advanced electronic control systems. The objectives of this project are:

1. Identify and describe various ALC, foundational braking, and foundational steering system implementations, including system variations related to the five levels of automation defined in the SAE Standard J3016[8] [1].
2. Determine the hazards and their severity levels pertaining to the functional safety of ALC controls and related foundational systems, and identify safety requirements and constraints.
3. Assess diagnostic and prognostic needs.
4. Identify performance parameters and recommend functional safety test scenarios.

---

[7] Light vehicles include passenger cars, vans, minivans, SUVs, and pickup trucks with gross vehicle weight ratings of 10,000 pounds or less.

[8] The five levels of automated driving systems include:

- Level 1 automation where the vehicle is controlled by the driver, but some driving assist features may be included in the vehicle that can assist the human driver with either steering or braking/accelerating, but not both simultaneously.
- Level 2 automation where the vehicle has combined automated functions, like speed control and steering simultaneously, but the driver must remain engaged with the driving task and monitor the environment at all times.
- Level 3 automation where an automated driving system on the vehicle can itself perform all aspects of the driving task under some circumstances. The driver is still a necessity, but is not required to monitor the environment when the system is engaged. The driver is expected to be takeover-ready to take control of the vehicle at all times with notice.
- Level 4 automation where the vehicle can perform all driving functions under certain conditions. A user may have the option to control the vehicle.
- Level 5 automation where the vehicle can perform all driving functions under all conditions. The human occupants never need to be involved in the driving task.

5. Review human factors considerations, including driver-vehicle interface requirements and the need for driver awareness and training resources.

In addition to assessing the functional safety of ALC systems, this research project will study the functional safety of two foundational steering system variants — electric power steering and steer-by-wire— and a conventional hydraulic brake system with electronic stability control and anti-lock brakes.

1.2 Steer-by-Wire System

This report covers the study of the SbW system. Although several manufacturers and Tier-1 suppliers have performed research on SbW systems, only one production vehicle currently offers SbW as a feature.

The SbW system electronically transmits the driver's steering input to the steering actuator assembly. During normal operation, SbW systems do not have a mechanical connection between the driver and the front-wheels. Figure 1 depicts a generic SbW system and its key components.

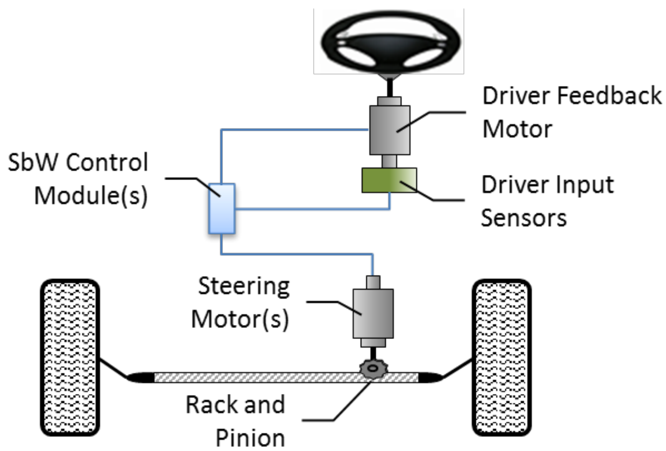


Figure K-1. Depiction of a Generic SbW System

In particular, this study assesses two types of SbW systems.

- A *"full" SbW system* electrically transmits the driver's steering input to the wheels. Furthermore, "full" SbW systems do not include a steering column or other means of mechanically transmitting the driver's steering input to the wheels, including mechanical backup subsystems.
- An *intermediate SbW system* electrically transmits the driver's steering input to the wheels. However, intermediate SbW systems retain the steering column as a mechanical backup subsystem in the event of a failure of the electronic portion of the SbW system.

In addition to providing steering, the generic SbW system considered in this study includes two additional features: active steering and four-wheel steering. These additional features may not be included in all SbW systems. The active steering feature enables the SbW system to adjust the steering response to the driver's input as a function of vehicle speed and to provide steering independent of the driver's input. The 4WS feature operates the rear-wheel orientation based on the driver's steering input and vehicle speed. These features are described in more detail in Section 3.4 of this report.

This study reviewed some of the current safety issues related to SbW systems. This study included a review of crash data in the General Estimates System and Fatality Analysis Reporting System to understand the crash types at least partially attributable to steering system related failures. NHTSA's recall and vehicle owner questionnaire databases were also reviewed to identify potential failure modes related to SbW systems. The findings from the review of current safety issues are included in Appendix A.

1.3 Report Outline

This report documents the approach and the findings of the analysis of the SbW system. in addition to this Introduction, the report contains the following sections.

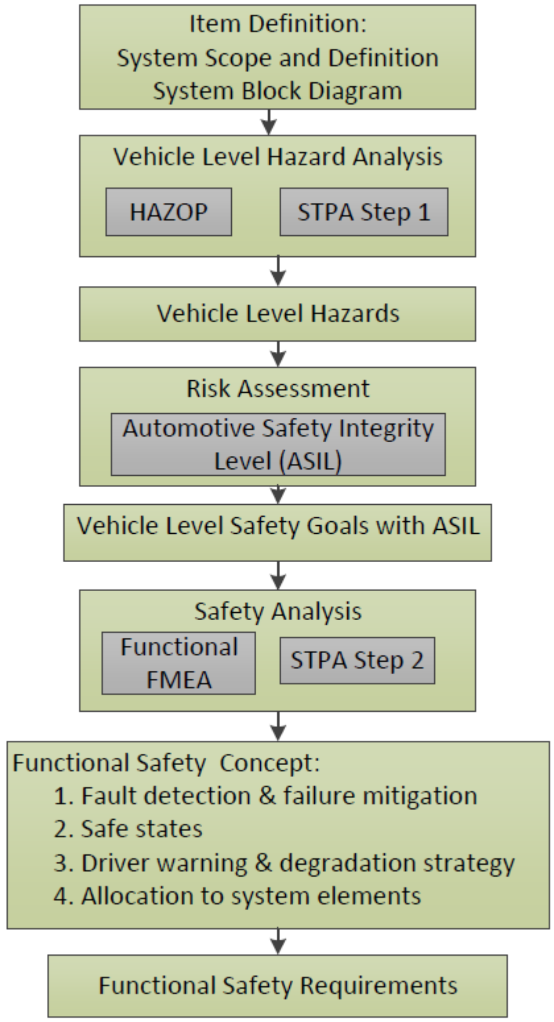
- **Section Two**: details the analysis approaches, including descriptions of the hazard and safety analysis methods used in this study.
- **Section Three**: provides the description of a generic SbW system that includes features such as Active Steering and 4WS. It also defines the analysis scope and assumptions used in this study.
- **Section Four**: details the vehicle-level hazard analysis approaches and results.
- **Section Five**: documents the risk assessment of the identified vehicle-level hazards.
- **Section Six**: summarizes the vehicle-level safety goals derived from the hazard analysis and risk assessment.
- **Section Seven**: details the safety analysis that supports the functional safety concept and the safety requirements.
- **Section Eight**: describes the functional safety concept.
- **Section Nine**: lists the functional safety requirements.
- **Section Ten**: identifies common diagnostic trouble codes covering the SbW system and discusses the need for additional diagnostics for the SbW system.
- **Section Eleven**: provides recommendations for functional safety test scenarios.

2 ANALYSIS APPROACH

The primary purpose of this work is to study and analyze the potential hazards that could result from cases of electrical or electronic failures impacting the functions of vehicular control systems. The study follows the ISO 26262 process to identify the integrity requirements of these functions at the concept level, independent of implementation variations. ISO 26262 is a functional safety process adapted from the International Electrotechnical Commission Standard 61508, and is intended for application to electrical and electronic systems in motor vehicles (Introduction in Part 1 of ISO 26262). Part 3 of ISO 26262 describes the steps for applying the industry standard during the concept phase of the system engineering process.

This study also considers potential causes that could lead to such functional failures and documents the technical requirements the ISO 26262 process suggests with respect to the identified automotive safety integrity levelof the item under consideration. While this study does not go into implementation strategies to achieve these ASILs, the ISO 26262 process provides a flexible framework and explicit guidance for manufacturers to pursue different methods and approaches to do so. Manufacturers employ a variety of techniques, such as ASIL decompositions, driver warnings, fault detection mechanisms, plausibility checks, redundancies, etc. to achieve the necessary ASILs that effectively mitigate the underlying safety risks.

Figure 2 illustrates the safety analysis and safety requirements development process in this project, which is adopted from the Concept Phase (Part 3) of ISO 26262.



HAZOP: Hazard and Operability study
STPA: Systems-Theoretic Process Analysis

- **STPA Step 1**: Identify Unsafe Control Actions
- **STPA Step 2**: Identify Causal Factors

FMEA: Failure Mode Effects Analysis

Note: ISO 26262 does not recommend or endorse a particular method for hazard and safety analyses. Other comparable and valid hazard and safety analysis methods may be used at the discretion of the analyst/engineer.

Figure K-1. Safety Analysis and Requirements Development Process

2.1 Analysis Steps

As depicted in Figure 2, this project involves the following steps:

1. Define the system:
    a. Identify the system boundary. Clearly state what components and interactions are within the system boundary, and how the system interacts with other components and systems outside of the system boundary.
    b. Understand and document how the system functions.
    c. Develop system block diagrams to illustrate the above understandings and to assist the analysts in the rest of the process.
    d. Record any assumptions about the system operation or configuration made when defining the system.
2. Carry out the hazard analysis using both the HAZOP [3] and the STPA method [4]. The output of the hazard analysis step is a list of vehicle-level hazards. If the methods do not use a common list of hazards at the outset, an additional step may be necessary to synthesize the hazards identified in the HAZOP study and STPA.
3. Apply the ISO 26262 risk assessment approach to the identified vehicle-level hazards, and assign an ASIL to each hazard as defined in ISO 26262.
4. Generate vehicle-level safety goals, which are vehicle-level safety requirements based on the identified vehicle-level hazards. The ASIL associated with each hazard is also transferred directly to the corresponding vehicle-level safety goal. If a safety goal satisfies more than one vehicle-level hazard, the more stringent ASIL is applied to the safety goal.
5. Perform safety analyses on the relevant system components and interactions as defined in the first step of this process. This project uses both a functional FMEA [5] and STPA to complete the safety analysis. Note that only single-point faults were considered when performing the safety analysis.
6. Follow the ISO 26262 process to develop a functional safety concept and functional safety requirements at the system and component levels, based on results from the functional FMEA and STPA, ISO 26262 guidelines, and industry practice experiences.

Once the functional safety concept and functional safety requirements are derived, these are used along with the safety analysis results to develop potential test scenarios and performance parameters.

This report describes how the HAZOP study, functional FMEA, and STPA methods were applied to a generic SbW system that includes active steering and 4WS features.

2.2 Hazard and Safety Analysis Methods

This project uses multiple analysis methods to generate a list of hazard and safety analysis results[9]. These methods are described in this section.[10]

2.2.1 Hazard and Operability Study

This study uses the HAZOP study as one of the methods for identifying vehicle-level hazards. Figure 3 illustrates the analytical steps of the HAZOP study.

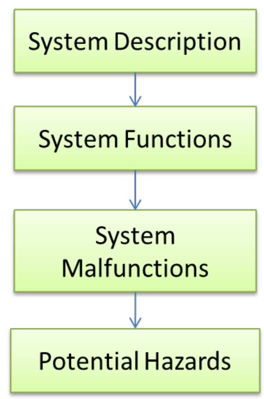


Figure K-1. HAZOP Study Process

This study performs the HAZOP study steps in Figure 3 as follows:

1. Define the system of study and the scope of the analysis. Draw a block diagram to illustrate the system components, system boundary, and interfaces. This step is accomplished in the first step of the overall project (Figure 2).
2. List all of the functions that the system components are designed to perform. This step is also accomplished in the first step of the overall project (Figure 2).
3. For each of the identified functions, apply a set of guidewords that describe the various ways in which the function may deviate from its design intent. IEC 61882[11] lists 11 suggested guidewords, but notes that the guidewords can be tailored to the particular system being analyzed [3]. The HAZOP study implemented in this project uses the following seven malfunction guidewords.
    - Loss of function

[9] ISO 26262 does not recommend or endorse specific methods for hazard or safety analysis. Comparable and valid hazard and safety analysis methods may be used at the discretion of the analyst/engineer.
[10] This report provides more details on the STPA than other methods because the application of the STPA method to automotive electronic control systems is relatively new. Unlike HAZOP and Functional FMEA, a standard approach has not been defined and published for STPA. Therefore, this report provides more descriptions in order to better explain how the analysis is performed.
[11] IEC 61882:2001, *Hazard and operability studies (HAZOP studies) - Application guide*, provides a guide for HAZOP studies of systems using the specific set of guide words defined in this industry standard; and also gives

- More than intended
- Less than intended
- Intermittent
- Incorrect direction
- Not requested
- Locked function

The combination of a system function and guideword may have more than one interpretation. in these situations, the analyst may identify more than one malfunction.

4. Assess the effect of these functional deviations at the vehicle level. If a deviation from an intended function could potentially result in a vehicle-level hazard, the hazard is then documented.

2.2.2 Functional Failure Modes and Effects Analysis

The FMEA is a bottom-up reliability analysis method that relies on brainstorming to identify failure modes and determine their effects on higher levels of the system. There are several types of FMEAs, such as system or functional FMEAs, design FMEAs, and process FMEAs. This study uses a functional FMEA in the safety analysis to identify failure modes at the function level that could lead to the vehicle-level hazards. The failure modes identified by the functional FMEA are used to derive the safety requirements.

Standard J1739 by SAE provides guidance on applying the functional FMEA method [5]. The analysis includes the following steps.

1. List each function of the item on an FMEA worksheet.
2. Identify potential failure modes for each item and item function.
3. Describe potential effects of each specific failure mode and assign a severity to each effect.
4. Identify potential failure causes or mechanisms.
5. Assign a likelihood of occurrence to each failure cause or mechanism.
6. Identify current design controls that detect or prevent the cause, mechanism, or mode of the failure.
7. Assign a likelihood of failure detection to the design control.

This study applies the first four steps listed above for the functional FMEA. Since this study is implemented at the concept phase and is not based on a specific design, the FMEA does not assume controls or mitigation measures are present; there is no data to support Steps 5 through 7. The completed functional FMEA worksheet is intended to be a living document that would be continually updated throughout the development process.

---

guidance on application of the technique and on the HAZOP study procedure, including definition, preparation, examination sessions, and resulting documentation.

2.2.3 Systems-Theoretic Process Analysis

The STPA is a top-down systems engineering approach to system safety [4]. in STPA, the system is modelled as a dynamic control problem, where proper controls and communications in the system ensure the desired outcome for emergent properties such as safety. in the STPA framework, a system will not enter a hazardous state unless an unsafe control action is issued by a controller, or a control action needed to maintain safety is not issued. Figure 4 shows a process flow diagram for the STPA method.

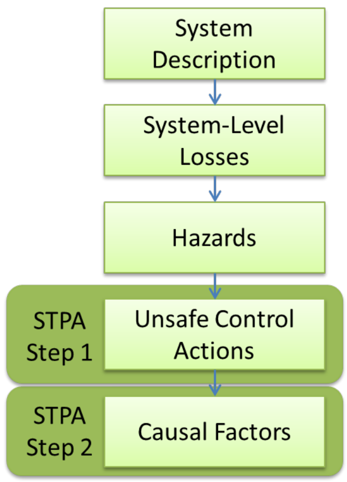


Figure K-1. STPA Process

This project performs STPA following these steps:

1. Define the system of study and the scope of the analysis:
    a. Draw a hierarchical control structure of the system that captures the feedback control loops (controller, sensors, actuators, controlled process, and communications links). This control structure is a generic representation of the system, based on common implementation strategies.
    b. Identify the system boundary and interfaces with other vehicle systems and the external environment.

   This step is accomplished in the first step of the overall project (Figure 2).

2. Define the loss or losses at the system level that should be mitigated. STPA defines system-level losses as undesired and unplanned events that result in the loss of human life or injury, property damage, environmental pollution, etc. [4]. For this project, one loss was considered: occurrence of a vehicle crash.
3. Identify a preliminary list of vehicle-level hazards. STPA defines a hazard as a system state or set of conditions that, together with a particular set of adverse environmental conditions, will lead to a system-level loss [4]. in this project, a preliminary hazard list is

generated based on engineering experience and a literature search. This list is refined during STPA Steps 1 and 2.

4. **STPA Step 1**: Identify potential UCAs issued by each of the system controllers that could lead to hazardous states for the system. Four sub-steps are involved:

   a. For each controller in the scope of the system, list all of the relevant control actions it can issue.

   b. For each control action, develop a set of context variables[12]. Context variables and their states describe the relevant external control inputs to the control system and the external environment that the control system operates in, which may have an impact on the safety of the control action of interest. The combinations of context variable states are enumerated to create an exhaustive list of possible states. This approach is based on a recent enhancement to the STPA method [6] that enumerates the process variable states during STPA Step 1. Process variables refer to variables that the control algorithm uses to model the physical system it controls. However, this study is not based on a specific design and a detailed process model algorithm is not available. Therefore, this study modifies this approach to focus on context variables instead of process variables.

   c. Apply the UCA guidewords to each control action. The original STPA literature includes four such guidewords [4]. This study uses a set of six guidewords for the identification of UCAs as illustrated in Figure 5.

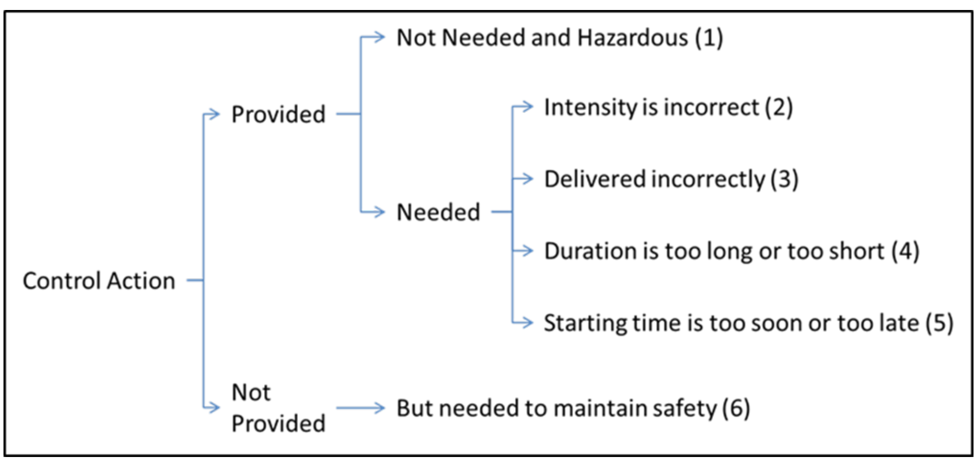


Figure K-2. Guidewords for UCAs

[12] The context variables describe the context in which a controller issues a control action. For example, the control command "provide steering torque in the Θ direction" may operate in the context of the driver's steering command and steering commands from other vehicle systems.

For each control action, assess each of the six guidewords against each of the context variable combinations to determine if it could lead to any of the preliminary vehicle-level hazards. If this step identifies new hazards, add them to the vehicle-level hazard list initiated in the previous step.

d. Apply logical reduction to the resulting UCA matrix using the Quine-McCluskey minimization algorithm [7] in order to reduce the number of UCA statements.

STPA Step 1 produces a list of UCAs that can be used to derive safety requirements for software control logic and initiate the STPA Step 2 analysis.

5. **STPA Step 2:** Determine CFs for each UCA identified in STPA Step 1.

   Analyze each component and interaction in the control structure representation of the system to determine if the component or the interaction may contribute to one of the UCAs identified in STPA Step 1. STPA literature provides 17 guidewords to assist the analyst in identifying CFs [4]. This project uses an expanded list of 26 guidewords for identifying CFs. Appendix B provides the list of CF guidewords and detailed causes under each guideword that are used in this project.

As discussed above, there are two main analysis steps in STPA (Figure 4). This project applies STPA Step 1 in the hazard analysis stage of the study and STPA Step 2 as part of the safety analysis stage (Figure 2).

3 SYSTEM DEFINITION

3.1 System Analysis Scope

NHTSA has established two Federal Motor Vehicle Safety Standards — FMVSS 203 and FMVSS 204 — establishing crashworthiness parameters to minimize injury to vehicle occupants from steering system components in the event of a crash. However, there is no FMVSS that specifies minimum performance parameters for steering systems. Furthermore, these FMVSSs may have limited applicability to "full" SbW systems that do not include steering columns.

The United Nations Economic Commission for Europe establishes the *Uniform Provisions Concerning the Approval of Vehicles with Regard to Steering Equipment* [8]. The UNECE regulation defines the "main steering system" as:

> *"the steering equipment of a vehicle which is mainly responsible for determining the direction of travel."*

According to the UNECE regulation, steering equipment may consist of:

- The *steering control*, which is the "part of the steering equipment which controls its operation." This includes the driver-operated control, such as a steering wheel, but may also include steering equipment that is not operated with direct intervention by the driver.
- The *steering transmission*, which includes "all components which form a functional link between the steering control and the road wheels." This includes both the control transmission (e.g., control signals transmitted to steering equipment) and energy transmission (e.g., transmission of necessary power to adjust the road wheels).
- The *steered wheels*, which are the wheels that "may be altered directly or indirectly in relation to the longitudinal axis of the vehicle in order to determine the direction of movement of the vehicle." For the generic SbW system described in this report, the term "front-wheels" refers to the front road wheels of the vehicle. The term "rear-wheels" refers to the rear road wheels of the vehicle that may be steered in vehicles equipped with the 4WS feature.
- The *energy supply*, which are the "parts of the steering equipment that provide it with energy, regulate that energy and where appropriate, process and store it." For the SbW, this includes the power supply, wiring, etc.

The scope of this analysis generally conforms to the UNECE definition, and includes all components involved in transmission of forces from both the driver-operated control and electronic control system to the road wheels. However, the scope of this study terminates at the transmission of steering forces to the road wheels. Transfer of forces from the road wheels to the road surface is out-of-scope for this study. This includes tire wear, wheel alignment, or other mechanical failures that may prevent the road wheels from transferring the appropriate lateral forces to the road surface.

This analysis also considers incoming steering requests from other vehicle systems that may be implemented through the SbW system. However, this analysis assumes that these other vehicle systems are operating correctly. Failures in other vehicle systems that could result in incorrect steering requests are out of scope for this study.

The following list identifies specific elements considered to be <u>in scope</u> for this study.

1. All mechanical and electronic components necessary to transmit the driver's steering input to the road wheels, including the following.
   - Steering wheel
   - Steering wheel angle sensor
   - Steering wheel torque sensor
   - SbW control module
   - Steering motor
   - Rack and pinion
2. All mechanical and electronic components necessary to transmit feedback to the driver, including the following:
   - Driver feedback motor
3. Mechanical backup subsystem (for intermediate SbW systems only)
4. All components necessary to control the rear-wheel steering angle for 4WS (if equipped), including the following:
   - Rear-wheel motors
   - Rear-wheel position sensor
5. All connections between the components listed above, including:
   - Wired connections
   - Communication over the vehicle bus (e.g., controller area network)
6. Active steering function algorithms in the SbW control module
7. Incoming steering requests from other vehicle systems
8. Interfacing sensor signals, including:
   - Vehicle speed and individual wheel speed data
   - Yaw rate/lateral acceleration data
9. Interface with the human operator of the vehicle

The following list identifies specific failures and hazards considered to be <u>out of scope</u> for this study.

- Multiple-point failures
- Failures in the road wheels (e.g., low tire pressure, tread wear, etc.) that affect transfer of lateral forces to the road or affect feedback to the driver
- Hazards not directly caused by malfunctioning behavior specific to the electronic control system, such as fire hazards

- Failures in other vehicle systems (e.g., brake/vehicle stability system) that may lead to lateral motion related hazards
- Failures in other vehicle systems (such as ALC, automated park assist, or other vehicle systems that command steering) that may result in incorrect steering requests
- Failures in the instrument panel display (considered as an interfacing system) that prevent driver notifications from illuminating
- Failures in ancillary functions that, in some designs, may be performed by the SbW control module but are not related to steering, such as validating vehicle speed with the engine rotational speed
- Failures due to improper maintenance over the lifetime of the vehicle (e.g., incorrect parts, failure to conduct scheduled inspections, etc.)

3.2 Analysis Assumptions

In addition to the system scope defined in Section 3.1, this analysis includes several assumptions regarding the operation of the SbW system. The following list identifies the key assumptions made in this study. Each assumption is addressed by explaining how the findings from this study may apply to cases where the assumption is no longer valid, or whether additional analysis is needed.

- The generic SbW system modelled in this report includes two features, active steering and 4WS, which may not be standard equipment on all SbW systems. in addition, this analysis does not assume any design limitations on the steering authority of these features, such as limits on the allowable steering angle for the rear-wheels.
  - *Findings in this report relating to the active steering and* 4WS *(e.g., malfunctions, UCAs, faults, CFs, and safety requirements) may not apply to SbW systems that do not include these features.*
- The 4WS function is located in the SbW control module. Some designs may include a separate control module for this function.
  - *Findings in this report related to the* 4WS *function (e.g., malfunctions, UCAs, faults, CFs, and safety requirements) would apply to whichever physical component houses this feature. If the* 4WS *function is located in a separate controller from the SbW control module, additional analysis of the communication between the two modules would be necessary.*
- The vehicle speed is provided to the SbW control module by the brake/vehicle stability[13] control module. Some system architectures may obtain the vehicle speed from other components or may rely on individual wheel speeds instead of the computed vehicle speed.

[13] The vehicle stability control may include, but is not limited to, the following functions: antilock braking, electronic stability control, traction control, etc.

    - *Requirements related to vehicle speed would apply to whichever component is responsible for providing this information to the SbW control module. If individual wheel speeds are used, the vehicle speed related requirements should be modified to apply to the individual wheel speeds.*
- The driver's steering input is measured using a steering wheel torque sensor and a steering wheel angle sensor. Other system designs may use other types of sensors.
    - *Additional analysis may be required to identify safety requirements relevant to other types of steering input sensors.*
- The front-wheels are connected with each other through the steering rack and tie rods, which limit the possible front-wheel steering angle configurations (i.e., the front-wheels turn in the same direction).
    - *Additional analysis would be required for vehicles with independent front-wheel steering.*
- The tires are capable of transmitting the appropriate lateral forces to the roadway. This analysis does not assess faults that may affect the ability of the tires to transmit forces (e.g., worn treads, low pressure, etc.).
    - *Additional analysis would be required to assess faults related to the tires.*
- The driver is physically capable of operating the vehicle (e.g., the driver is not impaired, distracted, etc.). The scope of this study is limited to how the DVI may lead the driver to issue an unsafe steering command.
    - *A separate human factors study would be required to evaluate driver-centric failures that affect their ability to operate the vehicle.*
- Vehicle automation systems are not considered in the analysis of the foundational SbW system. This includes potential mode confusion that may affect the driver's steering inputs.
    - *A later stage of this project will analyze the ALC system and will include DVI considerations related to mode confusion. The findings from the ALC system analysis will be published as a separate report.*
- Safety strategies, such as redundant sensors, are not considered in the hazard analysis or safety analysis stages. They are only considered as part of the functional safety concept and are reflected in the safety requirements.
    - *Once specific design strategies have been adopted, additional hazard and safety analyses should be performed to determine if the safety measures are adequate and do not introduce additional hazards into the system. .*
- For intermediate SbW systems, the mechanical backup is engaged through a clutch that connects the steering column to the rack and pinion.
    - *Other mechanical backup subsystems may operate differently. A separate analysis would be necessary to identify failure modes unique to the specific mechanical backup subsystem employed.*

3.3 System Block Diagram

The SbW system is an electronically controlled steering system that interprets driver input via the torque and angle applied to the steering wheel, along with input from other vehicle systems, and commands actuation of a steering motors to orient the road wheels to implement directional control. This report examines SbW systems with and without a mechanical backup subsystem for significant system faults.

Figure 6 shows a block diagram representation of the SbW system considered in this study. The black dashed line delineates the SbW system boundary. The components within this boundary are common to both a "full" SbW system as well as an intermediate SbW system. The red dashed line delineates the additional components associated with the mechanical backup subsystem implemented in intermediate SbW systems.

Interfacing vehicle systems are shown in gray and are treated as black boxes with respect to the SbW system. As discussed in Section 3.1, this analysis assumes that these interfacing vehicle systems are functioning properly. Key interfaces between these systems and the SbW system are shown as lines that cross the dashed line.

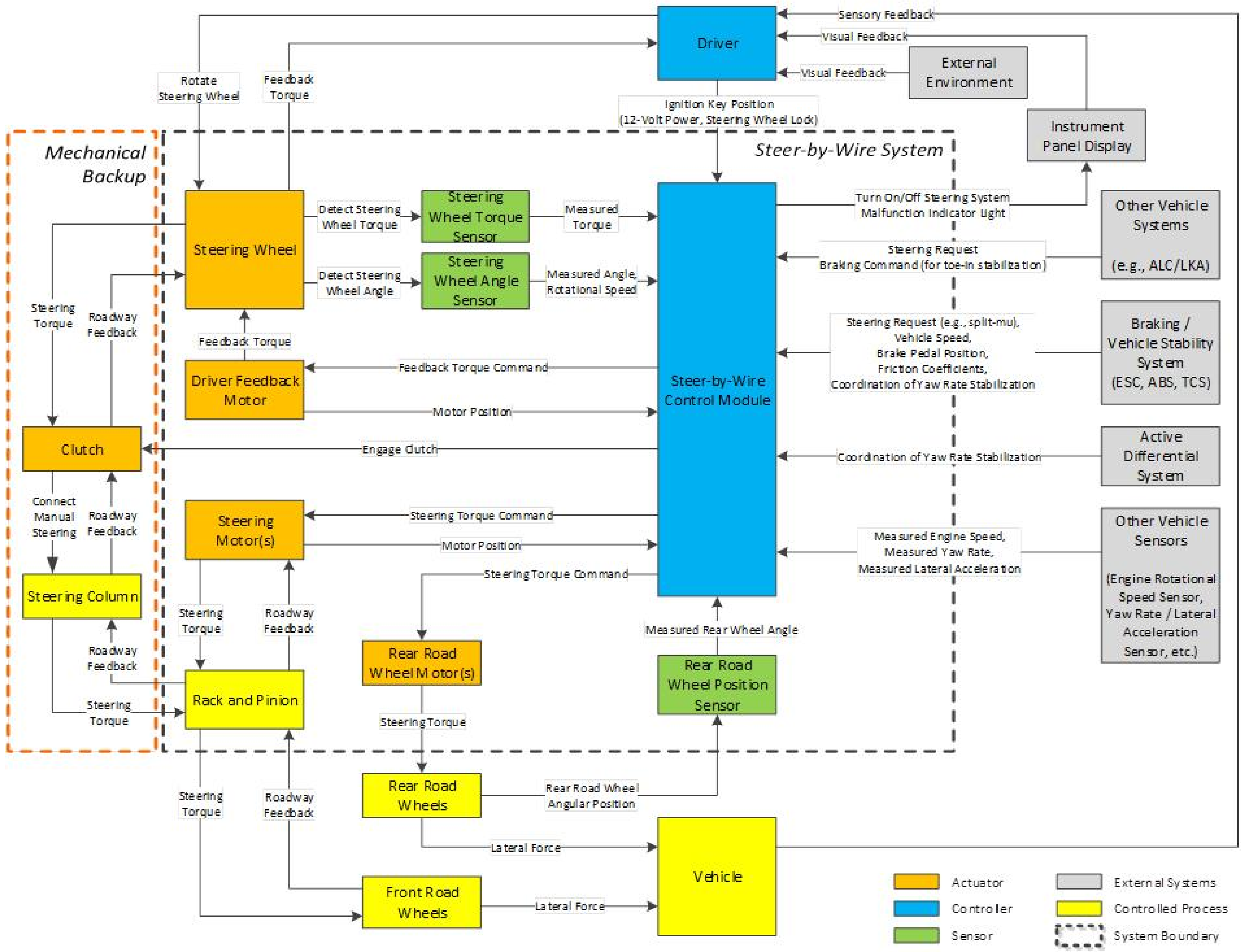


Figure K-1. Block Diagram of a Generic SbW System With Active Steering and 4WS Features

3.4 System Description

The following description outlines the functions of a SbW system [9] [10] [11] [12] [13] [14] [15] [16].

3.4.1 Driver-Operated Control and Steering Requests From Other Vehicle Systems

The steering wheel is the driver's primary interface with the SbW system. By rotating the steering wheel, the driver commands a change in the steering angle of the road wheels. This action causes the vehicle to adjust its trajectory. The steering wheel angle sensor and torque sensor measure the amount the steering wheel is rotated, the direction of rotation, and the force of the driver's steering input. These measurements are transmitted to the SbW control module, which determines the appropriate steering angle for the front-wheels to achieve the requested change in vehicle trajectory.

In addition to responding to the driver's steering input, the SbW control module also receives and implements steering requests from other vehicle systems, such as the ALC system. These steering requests may be independent of the driver's control input.

3.4.2 Steering Actuator Motor Control

The SbW control module receives the angular position and rotational speed measurements from the steering wheel angle sensor, and the torque measurement from the steering wheel torque sensor. The SbW control module uses these measurements to calculate the amount of steering actuation that the system should provide. The SbW controls the steering motor to transmit steering forces to the rack-and-pinion. The steering motor provides positional feedback to the SbW control module, allowing closed-loop control of the wheel position.

The SbW control module also uses the steering motor to implement steering adjustment requests from other vehicle systems, such as the brake/vehicle stability system or ALC system. The SbW control module arbitrates these steering requests with the driver's steering request and determines an appropriate road wheel heading based on the vehicle's current operating state. These steering adjustments may be made independent of steering inputs from the driver.

3.4.3 Mechanical Application of Steering Forces

The mechanical portion of the steering system transmits the steering torque from the steering motor to the front-wheels. The steering geometry of the front-wheels is important for maximizing the lateral forces as well as minimizing wear and tear of the tires. For example:

- Steering geometries typically conform to the Ackerman angle[14] to minimize tire slip when turning.

[14] Ackerman angle is used in the concept of Ackerman steering. While going around a corner, all the tires turn along a circle with a common center point. The intention of Ackerman geometry is to minimize the need for tires to slip sideways when following the path around a curve.

- The wheel toe setting can affect the stability of the vehicle. For example, a toe-in position can provide greater stability for the vehicle when travelling straight ahead. Figure 7 illustrates the concept of the wheel toe position.

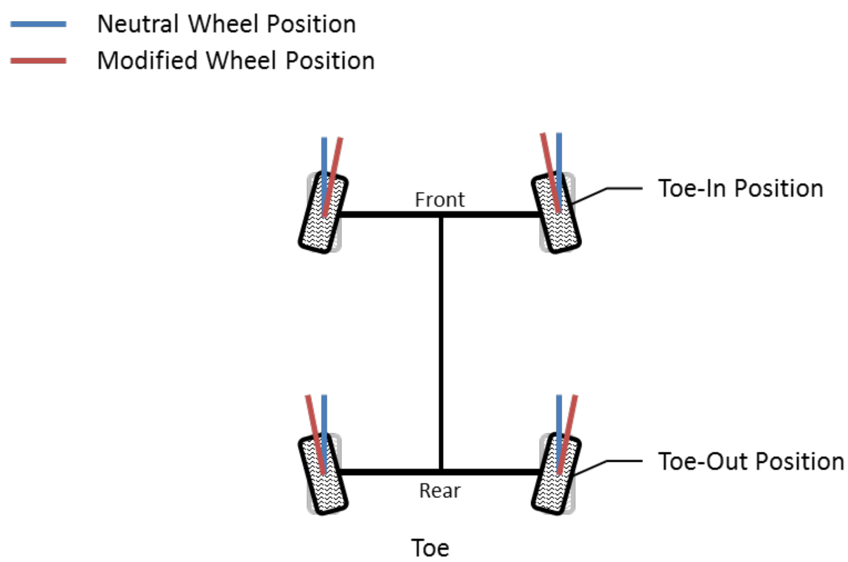


Figure K-1. Example Wheel Positions

3.4.4 Driver Feedback

In the SbW system, the driver's input device (e.g., the steering wheel) is also responsible for providing feedback to the driver. The SbW control module must determine the appropriate feedback and apply the resulting actuation to the steering wheel via the driver feedback motor. For example:

- The road surface and roughness may induce vibrations that must be transmitted to the steering wheel.
- Mechanical failures in the steering system may cause changes in the steering feel.
- The steering wheel may stop rotating when the front-wheels reach their maximum steering angle.

The positional feedback from the steering motor informs the SbW control module of road disturbances. This information may be used by the SbW control module algorithms, along with other vehicle dynamics sensor data, to determine the feedback to provide the driver.

Since the SbW system simulates all feedback to the driver via the feedback motor, the SbW algorithms may be designed to modify or reject certain types of disturbances. For example, the SbW feedback algorithms may not transmit small bumps in the road to the driver's hands for a "smoother" feel.

3.4.5 Active Steering Feature

SbW systems may incorporate an active steering feature, which enables the SbW control module to modify steering characteristics based on the vehicle's operating conditions (e.g., vehicle speed). For instance, with the active steering feature, the SbW control module may make the vehicle more responsive to the driver's steering command at low speeds. At higher vehicle speeds, the SbW control module may reduce the amount of steering provided in response to the driver's steering input to enhance the driver's precision and provide increased stability. At low vehicle speeds, the SbW control module may rely on individual wheel speed data (rather than the aggregated vehicle speed) for greater resolution of speed data.

In addition to adjusting the steering ratio, the active steering feature may also be capable of adjusting the steering angle of the road wheels independent of the driver. The SbW control module receives input from the vehicle dynamics sensors, such as yaw rate and lateral acceleration. This additional sensor data helps the SbW control module adjust the steering based on changes in the vehicle's dynamics and to reject disturbances. For example, the active steering feature may adjust the steering angle to compensate for road pull or drift (e.g., due to crosswinds), eliminating the need for the driver to continuously counter-steer. Depending on the driver feedback algorithms, these steering angle adjustments may or may not be transmitted back to the driver via the steering wheel. This feature enables the SbW to isolate the driver from certain types of road disturbances.

3.4.6 Four-Wheel Steering Feature

Traditionally, vehicles only adjust the steering angle of the front-wheels in response to steering inputs. However, vehicles with the 4WS feature can adjust both the front and rear-wheels to steer the vehicle. This can allow for greater responsiveness and improved stability.

The orientation of the rear-wheels of the vehicle may be operated by individual motors located at each wheel or a single motor at the rear axle. The rear-wheels can turn in the same direction as the front-wheels ("in-phase") to provide more stable maneuvering at high speeds. The rear-wheels can also turn in the opposite direction from the front-wheels ("reverse-phase") at low vehicle speeds to improve turning. Figure 8 depicts the in-phase and reverse-phase rear-wheel positions.

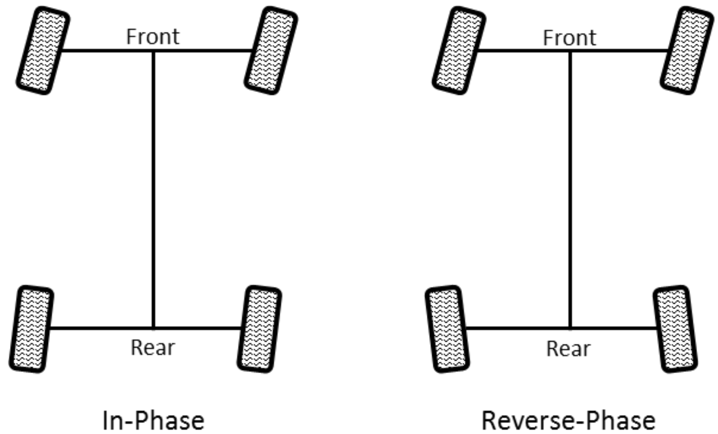


Figure K-1. Diagram of In-Phase and Reverse-Phase Rear-Wheel Positions

Finally, the rear-wheels may “toe-in” during heavy braking to improve stability. Figure 7 illustrates the concept of “toe-in.” Depending on the implementation of the rear-wheel actuator, the available rear-wheel configurations may be limited. For example, a single rear-wheel motor may not be capable of providing the “toe-in” position.

3.4.7 Fault Detection

The detection of significant faults that endanger steering control is an important aspect of the system. in the event the SbW control module detects a fault in the system, the system will still need to provide directional control for the vehicle. in the intermediate SbW system designs, the SbW system is equipped with a mechanical clutch that completes a direct mechanical connection between the steering wheel and rack and pinion. in “full” SbW systems, the design may include redundancy of the power and control components of the SbW system.

3.4.8 Related Systems: Yaw Rate Stabilization Coordination

Through the active steering feature, the SbW system may be capable of implementing yaw rate stabilization (e.g., correcting for oversteer or understeer conditions). Other vehicle systems, such as the brake/vehicle stability system and active differential system, are also capable of performing yaw rate stabilization. The SbW system and these other vehicle systems would need to coordinate their yaw rate stabilization efforts to ensure their net action results in the correct vehicle dynamics.

3.4.9 Related Systems: Ignition System

Some steering systems may lock the steering wheel when the vehicle is turned off as an anti-theft measure. The steering wheel lock prevents the steering wheel from rotating. This is typically accomplished through mechanical means, such as a solenoid or spring-loaded latch. When the ignition key (or other security device) is turned to the “on” position, the lock mechanism disengages allowing the driver to rotate the steering wheel.

4 VEHICLE-LEVEL HAZARD ANALYSIS

This study performed two types of hazard analyses — HAZOP study and STPA. Section 4.1 presents the synthesized vehicle-level hazards from both analyses. Sections 4.2 and 0 provide additional details about the HAZOP study and STPA.

4.1 Vehicle-Level Hazards

The HAZOP study and STPA each identified six vehicle-level hazards. in addition, the SAE Recommended Practice J2980[15] provides an example high-level HAZOP for the steering system that identifies three vehicle-level hazards [17]. However, the steering example provided in SAE Recommended Practice J2980 is for a power steering system and has limited applicability to a SbW system.

The majority of these hazards describe similar vehicle-level behaviors. Key differences between the hazard lists include the resolution at which hazards are defined and how specific failure modes are considered. For example, the STPA hazards differentiate between "unintended vehicle lateral motion/unintended yaw" resulting from improper arbitration of conflicting inputs to the SbW control module (e.g., between the driver and other vehicle systems) and "unintended vehicle lateral motion/unintended yaw" resulting from other causes, such as an incorrect sensor measurement. When reconciling the vehicle-level hazards between HAZOP and STPA, the analysts determined that these represent two examples of the hazard "unintended vehicle lateral motion/unintended yaw," rather than two distinct hazards.

In order to synthesize the results of the hazard analysis, the vehicle-level hazards identified in the HAZOP study and STPA, as well as SAE Recommended Practice J2980, were combined to produce the list of six hazards in Table 1. As part of this process, some of the hazard terminology was refined to provide more clarity of the hazardous vehicle state.

[15] SAE J2980, Considerations for ISO26262 ASIL Hazard Classification," presents a method and example results for determining the ASIL for automotive electrical and electronic systems.

Table 1. Synthesized List of Potential Vehicle-Level Hazards for a Steer-by-Wire System

ID	**Potential Hazard (Synthesized Term)**	**Potential Hazard Description**
H1	Unintended Vehicle Lateral Motion/Unintended Yaw	The vehicle moves laterally more than, at a faster rate than, or in the opposite direction of what is commanded by the driver or another vehicle system controller.
H2	Insufficient Vehicle Lateral Motion/Insufficient Yaw	The vehicle moves laterally, but less than or at a slower rate than what is commanded by the driver or another vehicle system controller.
H3	Loss of Vehicle Lateral Motion Control	The SbW system does not respond to steering inputs from the driver or other vehicle systems.
H4	Reduced Responsiveness to the Driver's Commands Due to Increased Rear-Wheel Drag [ii]	The rear-wheel position causes an increased drag effect, slowing the vehicle, but not at a level that results in significant vehicle deceleration. This drag effect may also affect the vehicle response if the driver is trying to steer.
H5	Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction	The feedback provided at the steering wheel is incorrect and sufficiently misleading that it causes the driver to incorrectly steer the vehicle.
H6	Intermittent Response to Driver's Control Input	The SbW system does not provide a smooth or consistent response to steering inputs. Examples of this hazard may include a jerky response to steering inputs or a delayed steering response.

4.2 Hazard and Operability Study

4.2.1 System Description

The HAZOP study uses the block diagram provided in Figure 6 to visually represent the SbW system, and identifies the SbW system functions based on the description provided in Section 3.4.

4.2.2 System Functions

The HAZOP study identifies 24 system functions for the SbW system. These functions are organized based on the system description presented in Section 3.4.

Driver-Operated Control and Steering Requests From Other Vehicle Systems

1. Senses the torque applied to the steering wheel.
2. Senses the steering wheel angle.
3. Communicates with internal subsystems and other vehicle systems, including receiving steering inputs from other vehicle systems.

Steering Actuator Motor Control

4. Electronically transmits the driver's torque from the steering wheel to the wheel angle actuators to induce lateral vehicle force.[16]
5. Modulates torque to create an on-center, straight steer by default.
6. Disables all energy sources to steering equipment when the ignition is off or once the SbW system enters a maintenance or repair mode.
7. Stores relevant data.

Mechanical Application of Steering Forces

8. Turns road wheels such that available/surplus lateral force is sufficient to achieve the desired vehicle path, including at low speeds and consistent with Ackerman angle practice.
9. Turns vehicle at highest steering wheel input angle to a to-be-determined turning circle/radius for sufficient maneuverability.
10. Turns road wheels such that tire wear and tear is minimized.
11. Absorbs environmental sounds from the tire patch and the mechanical steering system to minimize cabin noise.

[16] This function includes algorithms that determine the steering response to the driver's input, including the relationship between yaw rate and steering input, and ensuring there is no extraneous oscillation or ringing in the steering actuator or force feedback motor.

Measure and Simulate Steering System Feedback

12. Measures and simulates feedback to the driver via steering wheel when turning limit is reached by disallowing further rotation of the steering wheel.
13. Measures and simulates feedback of road feel (e.g., road surface roughness, lateral road friction, road shocks, pull from crowned roads) to the driver through the steering wheel. Note: Designers may choose to attenuate some road disturbances (e.g., to reduce minor steering wheel vibrations) while still conveying other types of feedback.
14. Detects and simulates mechanical failures from within steering system to steering wheel in driver's hands through an easily perceivable change in steering effort.

Four-Wheel Steering Feature

15. Turns the 4WS mode from on to off (or vice-versa) in 4WS-equipped vehicles.
16. Turns rear-wheels in-phase smoothly and without alarming driver when at or above the in-phase vehicle speed threshold in 4WS-equipped vehicles.
17. Turns rear-wheels in reverse-phase smoothly and without alarming driver when below the reverse-phase vehicle speed threshold in 4WS-equipped vehicles.
18. Turns the rear-wheels inward (toe-in) to supplement braking and enhance stability in 4WS-equipped vehicles.

Fault Detection

19. Provides diagnostics and fault detection.
20. Provides mitigation for system faults.
21. Electronically transmits steering system failures to the driver using all or some of the dashboard indicators, chimes, or similar alerts.
22. Provide steerability in the event of power loss or other critical fault. (Note: design solutions include multiple redundancy and/or a backup mechanical system engaged by a mechanical clutch.)

Interfacing Vehicle Systems (Ignition System)

23. Does not respond to steering wheel inputs when vehicle is off and motionless such that any steering input (torque or angle) are not communicated to the steering motor.
24. Responds to steering wheel inputs for normal functions after vehicle is accessed with security device (key, biometrics, etc.) and re-orients steering wheel to road wheels if necessary.

Functions 20 and 21 are shown here for completeness, but are not considered part of the scope for the hazard analysis. Functions 20 and 21 are part of the design to mitigate hazards resulting from other malfunctions.

4.2.3 System Malfunctions and Hazards

The seven HAZOP study guidewords presented in Section 2.2.1 were applied to each of the 24 SbW functions listed above. This process generated a list of 138 malfunctions.[17] Each of these malfunctions was then assessed to determine if they may lead to one of the vehicle-level hazards; 84 of the 138 malfunctions lead to one or more of the vehicle-level hazards.

Table 2 provides an example of how malfunctions are derived from one of the SbW functions and are assigned vehicle-level hazards. Table 3 shows the number of malfunctions identified for each of the SbW functions. Appendix C provides the complete results of the HAZOP study.

[17] This does not represent an exhaustive list of all possible SbW malfunctions. Identification of malfunctions is dependent on the item definition (e.g., system functions), the interpretation of the guidewords, and the judgment of the analyst.

Table 2. Derivation of Malfunctions and Hazards Using HAZOP Study
(Example Function: Senses Steering Wheel Torque)

HAZOP Guideword	***Malfunction***	***Potential Vehicle Level Hazard***
Loss of function	Torque cannot be sensed from steering wheel	H1: Unintended Vehicle Lateral Motion/Yaw H2: Insufficient Vehicle Lateral Motion/Yaw H3: Loss of Lateral Motion Control
More than intended	Senses more torque than the actual torque	H1: Unintended Vehicle Lateral Motion/Yaw
	Senses torque with greater frequency than needed	Not Hazardous
Less than intended	Senses less torque than the actual torque	H2: Insufficient Vehicle Lateral Motion/Yaw
	Senses torque with less frequency than needed	H1: Unintended Vehicle Lateral Motion/Yaw H2: Insufficient Vehicle Lateral Motion/Yaw
Intermittent	Senses torque intermittently	H6: Intermittent Response to Driver's Control Input
Incorrect direction	Senses torque in the opposite direction	H1: Unintended Vehicle Lateral Motion/Yaw
Not requested	Senses torque when there is no steering input	H1: Unintended Vehicle Lateral Motion/Yaw
Locked function	Senses a constant torque regardless of steering input	H1: Unintended Vehicle Lateral Motion/Yaw H2: Insufficient Vehicle Lateral Motion/Yaw

Table 3. Number of Identified Malfunctions for Each HAZOP Function

HAZOP Function	**Number of Mal-functions**	**Mal-functions Leading to Hazards**
Senses the torque applied to the steering wheel.	9	8
Senses the steering wheel angle	9	8
Communicates with internal subsystems and other vehicle systems, including receiving steering inputs from other vehicle systems.	5	3
Electronically transmits the driver's torque from the steering wheel to the wheel angle actuators to induce lateral vehicle force.	8	8
Modulates torque to create an on-center, straight steer by default.	5	5
Disables all energy sources to steering equipment when the ignition is off or once the SbW system enters a maintenance/repair mode.	5	2
Stores relevant data.	5	0
Turns road wheels such that available/surplus lateral force is sufficient to achieve the desired vehicle path, including at low speeds and consistent with Ackerman angle practice.	4	4
Turns vehicle at highest steering wheel input angle to a TBD turning circle/radius for sufficient maneuverability.	3	3
Turns road wheels such that tire wear and tear is minimized.	2	0
Absorbs environmental sounds from the tire patch and the mechanical steering system to minimize cabin noise.	3	0
Measures and simulates feedback to the driver via steering wheel when turning limit is reached by disallowing further rotation of the steering wheel.	7	6
Measures and simulates feedback of road feel to the driver through the steering wheel.	6	6
Detects and simulates mechanical failures from within steering system to the driver through an easily perceivable change in steering effort.	6	0
Turns the 4WS mode from on to off (or vice-versa) in 4WS-equipped vehicles.	5	3
Turns rear-wheels in-phase smoothly and without alarming driver when at or above the in-phase vehicle speed threshold in 4WS-equipped vehicles.	9	7
Turns rear-wheels in reverse-phase smoothly and without alarming driver when below the reverse-phase vehicle speed threshold in 4WS-equipped vehicles.	9	7
Turns the rear-wheels inward (toe-in) to enhance stability in 4WS-equipped vehicles.	7	5
Provides diagnostics and fault detection. [i]	6	0
Provides mitigation for system faults. [i]	5	0
Electronically transmits steering system failures to the driver using all or some of the dashboard indicators, chimes, or similar alerts.	6	0
Provide steerability in the event of power loss or other critical fault.	5	5
Does not respond to steering wheel inputs when vehicle is off and motionless such that any steering input (torque or angle) are not communicated to the wheel angle actuators.	5	2
Responds to steering wheel inputs for normal functions after vehicle is accessed with security device (key, biometrics, etc.) and re-orients steering wheel to road wheels if necessary.	4	2
[i] This function is only included for completeness and the identified malfunctions were not associated with potential vehicle level hazards.		

4.3 System Theoretic Process Analysis: Step 1

4.3.1 Detailed Control Structure Diagram

Figure 9 illustrates the detailed control structure diagram used in the STPA method to represent a generic SbW system (in the black dashed line) and its interfacing systems and components. These components and interfaces are common to all SbW architectures. in addition, intermediate SbW systems employ a mechanical backup subsystem, such as the clutch-based steering column shown in the red dashed line.

The low voltage (e.g., 12-volt) power supply is only shown on this diagram as an effect of the driver's action on the ignition key. However, the impact of the low voltage power supply on the operation of the system electronics is considered in detail as part of STPA Step 2.

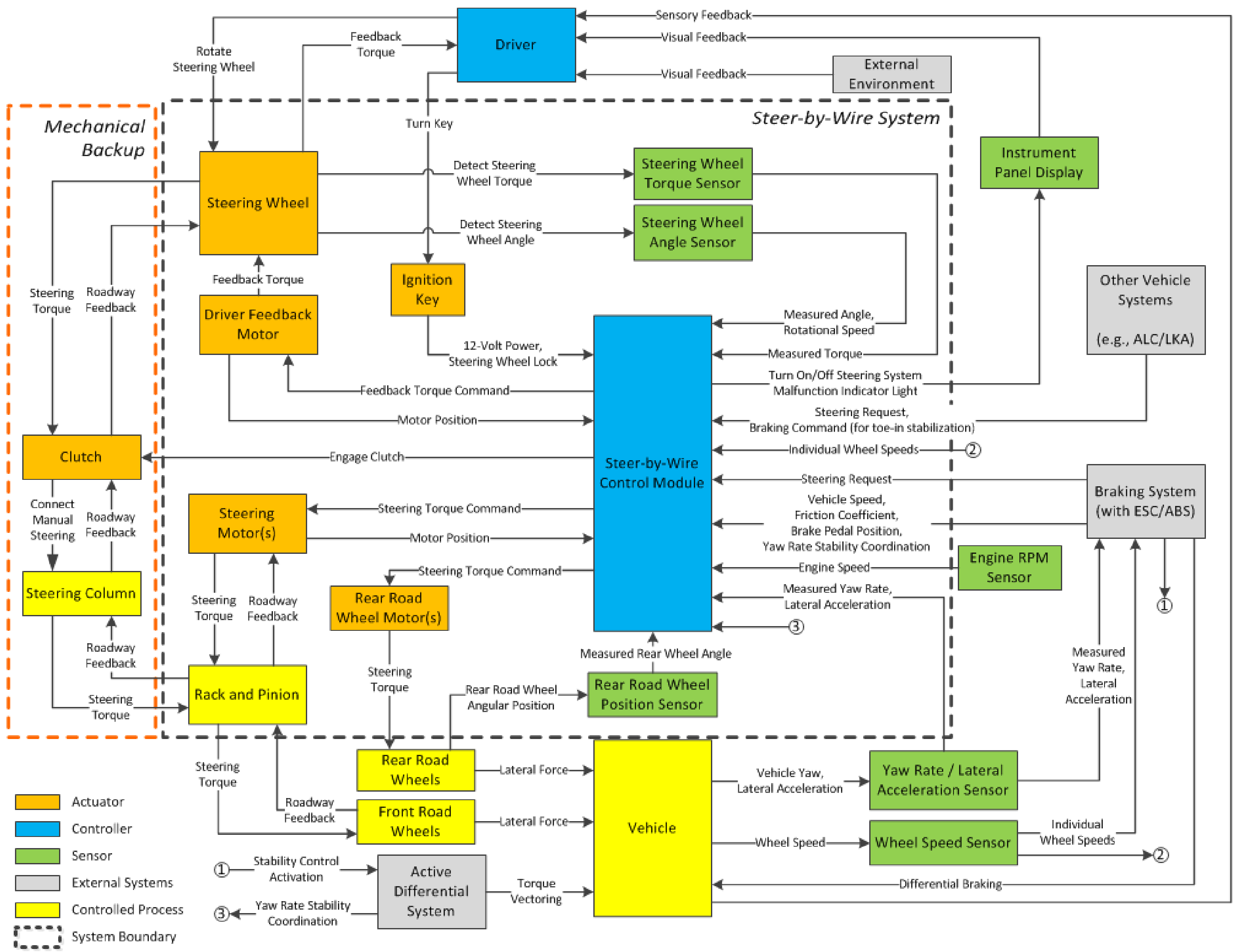


Figure K-1. Detailed Control Structure Diagram for a Generic SbW System With Active Steering and 4WS Features

4.3.2 Vehicle-Level Loss and Initial Hazards

STPA begins by identifying specific losses that the study is trying to prevent. in the STPA method, these losses result from a combination of a hazardous state along with a worst-case set of environmental conditions [4]. The vehicle-level loss relevant to this study is a vehicle crash.

An initial list of vehicle-level hazards is generated based on a literature search and engineering experiences. As the analyst identifies UCAs as part of STPA Step 1, the initial hazard list may be refined. Section 4.3.3 and Section 4.3.4 provide the details of this process. Then, the hazards generated from both the HAZOP study and STPA are synthesized to produce the hazard list shown in Table 1.

4.3.3 Control Actions and Context Variables

STPA Step 1 studies ways in which control actions in the system may become unsafe, leading to the vehicle-level hazards. The classification of a control action as safe or unsafe will depend on the state or "context" of the vehicle system at the time it is issued. For example, commanding a reverse-phase orientation for the rear-wheels may be safe (and effective) at low vehicle speeds, but potentially unsafe at high vehicle speeds. Hence, this discussion of the control actions will also identify relevant context variables.

This study identifies one control action of the driver (not technically within the SbW system scope) and six control actions issued by the SbW control module related to the SbW system functions.

The driver's control action is related to issuing the actual steering command.

- **Command Steering** – the driver commands steering by rotating the steering wheel. This command is transmitted electronically to the front-wheel steering motor through the SbW control module that determines the amount of steering motor actuation to provide.

Table 4 shows one context variable considered in assessing this control action. There are numerous conditions that could influence why the driver may issue a steering command, and it is not practical for this study to consider all possible combinations of these conditions. Therefore, this study assumes a competent driver and considers only whether the driver perceives the need for steering; this study does not analyze why the driver may arrive at that conclusion.

Table 4. STPA Context Variable for the Driver Issuing a Steering Command

Context Variable	Context Variable States
Is a Steering Adjustment Needed	Yes
	No

One control action from the SbW module is related to commanding torque from the steering motor.

- **Command Torque From the Steering Motor to Change the Front-Wheel Heading by θ degrees** – The SbW control module issues this command to increase or decrease the front-wheel steering angle in response to the driver's steering command or a steering request from other vehicle systems.

Table 5 lists two context variable states used for the analysis of the control action to command torque from the steering motor. Note that vehicle speed can be an important context variable for other steering systems (e.g., some electric power steering systems with Active Steering) as the degree of Active Steering may be affected by this speed compared to the design speed thresholds. in SbW systems however, the degree of steering wheel torque needed to implement a given amount of steering as function of speed can be incorporated into the overall steering algorithm and does not need to be considered separately here.

Table 5. STPA Context Variables for Commanding Torque From the Steering Motor

Context Variable	Context Variable States
Driver's Steering Command	No steering
	Steering in the θ direction
	Steering in the -θ direction
Steering Requests From Other Vehicle Systems	No steering request
	Steering requested in the θ direction
	Steering requested in the -θ direction
	Steering requested in both the θ and -θ directions.

For this control action, the symbol "θ" is used to convey whether the actions of the driver and steering requests from other vehicle systems are in the same direction (i.e., in the θ direction) or in the opposite direction (i.e., in the -θ direction) of the torque output from the steering motor. An alternative approach could be to consider separate control actions for clockwise and counterclockwise torque commands. However, this would result in redundant analyses since the only difference in the UCAs for the clockwise and counterclockwise cases would be the direction.

Three control actions relate to the SbW module commanding torque from the rear-wheel steering motor if the vehicle is equipped with 4WS. The SbW control module issues these commands to adjust the rear-wheel steering angle in response to the vehicle speed and the driver's steering input.

- **Command an In-Phase Rear-Wheel Heading** – the SbW control module issues this command to turn the rear-wheels in the same direction as the front-wheels to enhance vehicle stability at high vehicle speeds.

- **Command a Reverse-Phase Rear-Wheel Heading** – the SbW control module issues this command to turn the rear-wheels in the opposite direction as the front-wheels to provide improved turning at low vehicle speeds.
- **Command the Rear-Wheels to Toe-In** – the SbW control module issues this command to turn the rear-wheels inward to provide greater stability during braking.

The vehicle speed thresholds for activating in-phase steering and reverse-phase steering are determined as part of the system design. The vehicle speed boundaries for activating in-phase and reverse-phase steering are not necessarily the same. The context variables used to consider the three control actions differ slightly, and are presented in Table 6, Table 7, and Table 8.

Table 6. STPA Context Variables for Commanding the Rear-Wheels to Turn In-Phase

Context Variable	Context Variable States
Steering Torque Commanded by Driver or Other Vehicle Systems	Yes
	No
Vehicle Speed	Above Threshold Value for Activating In-Phase Steering
	Below Threshold Value for Activating In-Phase Steering
	At Threshold Value for Activating In-Phase Steering

Table 7. STPA Context Variables for Commanding the Rear-Wheels to Turn in Reverse-Phase

Context Variable	Context Variable States
Steering Torque Commanded by Driver or Other Vehicle Systems	Yes
	No
Vehicle Speed	Above Threshold Value for Activating Reverse-Phase Steering
	Below Threshold Value for Activating Reverse-Phase Steering
	At Threshold Value for Activating Reverse-Phase Steering

Table 8. STPA Context Variables for Commanding the Rear-Wheels to Toe-In

Context Variable	Context Variable States
Steering Torque Commanded by the Driver or Other Vehicle Systems	Yes
	No
Brakes Applied	Yes
	No

One control action is issued by the SbW control module to provide feedback to the driver. Since there is no mechanical connection between the driver and the road wheels during normal operation, all feedback to the driver via the steering wheel must be simulated by the SbW controller.

- **Command Steering Feedback Torque to the Driver Feedback Motor** – the SbW needs the ability to provide appropriate feedback to the driver to indicate road conditions, system failures, steering angle limits, etc.

This command is executed through a torque motor at the steering wheel that can simulate the torques that might be expected through a traditional, primarily mechanical steering system. Table 9 shows the context variables for this control action.

Table 9. STPA Context Variables for Command Steering Feedback for the Driver

Context Variable	Context Variable States
Steering Feedback to the Driver Needed	Yes
	No

The last control action of the SbW control module is specific to intermediate SbW system architectures and relates to engaging the mechanical backup system. The SbW control module may issue this control action in response to a major system fault (such as mechanical failure or power loss) to ensure that minimal steering functionality is maintained.

- **Engage Mechanical Backup Subsystem** – The SbW system must be able to initiate an alternative steering system if confronted by evidence that the primary SbW system has ceased to function as designed.

Table 10shows the context variable for this control action.

Table 10: STPA Context Variables for Engaging the Mechanical Backup System

Context Variable	Context Variable States
Steer-by-Wire System Fault	Yes
	No

4.3.4 Unsafe Control Actions

The six UCA guidewords (Figure 5) were applied to each combination of context variable states for the seven control actions listed in the previous section. The analysts then assessed whether the control action would result in a vehicle-level hazard under that particular scenario. Table 11 shows how this is done for one of the control actions – "Command a Reverse-Phase Rear-Wheel Heading." Appendix D contains all of the UCA assessment tables for the seven control actions.

Table 11. UCA Assessment Table (Example)

Control Action: Command a Reverse-Phase Rear-Wheel Heading										
Context Variables		**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Steering torque commanded (by driver or other vehicle systems)	**Vehicle speed (threshold for reverse-phase steering)** [i]	**Not provided in this context**	**Provided in this context**	**Provided, but duration is too long**	**Provided, but duration is too short**	**Provided, but the intensity is incorrect (too much)**	**Provided, but the intensity is incorrect (too little)**	**Provided, but executed incorrectly**	**Provided, but the starting time is too soon**	**Provided, but the starting time is too late**
Yes	Above threshold value	Not hazardous	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
Yes	At or below threshold value	Not hazardous	Not hazardous	H1	Not hazardous	H1	Not hazardous	H1, H2	Not applicable[ii]	H1
No	Above threshold value	Not hazardous	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
No	At or below threshold value	Not hazardous	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

[i] The vehicle speed threshold is established by each manufacturer as part of the design.
[ii] Since the context variables assume that the vehicle is already below the threshold vehicle speed, the “provided, but the starting time is too soon” UCA guideword is not applicable. Adopting the reverse-phase rear-wheel heading before the vehicle speed transitions below the threshold value is considered as part of the “provided in this context” guideword for the context variable “above threshold value..”

Vehicle-Level Hazards

H1: Potential unintended vehicle lateral motion/unintended yaw
H2: Potential insufficient vehicle lateral motion/insufficient yaw

Each cell in Table 11 represents a potential UCA. For example, application of the guideword "provided in this context" to the first row of context variables in Table 11 results in the following UCA statement.

> *The SbW control module commands the rear-wheels to turn in reverse-phase when:*
> - *steering is commanded by the driver or other vehicle systems, and*
> - *the vehicle speed is above the threshold speed value for activating reverse-phase steering.*
>
> *This may result in unintended vehicle lateral motion/unintended yaw.*

However, writing each cell of the table into a UCA statement would create a very long list of UCAs and many of these UCAs would have overlapping logical states. Therefore, this study uses the Quine-McCluskey minimization algorithm [7] to consolidate and reduce the overall number of UCA statements. STPA Step 1 identifies a total of 51 UCAs for the generic SbW system. All 51 UCAs lead to one or more vehicle-level hazard.

Table 12 provides the breakdown of these UCAs by control action.

Table 12. Number of Identified UCAs for Each STPA Control Action

STPA Control Action	Number of UCAs
Driver/Vehicle Operator	
Command Steering	7
SbW Control Module	
Command Torque From the Steering Motor to Change the Front-Wheel Heading by θ Degrees	17
Command an In-Phase Rear-Wheel Heading	6
Command a Reverse-Phase Rear-Wheel Heading	6
Command the Rear-Wheels to Toe-In	2
Command Steering Feedback Torque to the Driver Feedback Motor	7
Engage Mechanical Backup Subsystem	6

Appendix E presents a complete list of the UCAs identified in STPA Step 1. Table 13 shows an example a UCA and its associated vehicle-level hazard.

Table 13. Example UCA Statement for Commanding a Change in the Rear-Wheel Position

Hazard	Potential Insufficient Vehicle Lateral Motion/Insufficient Yaw
UCA (Example)	The SbW control module commands the rear-wheels to turn in-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is below the threshold for activating in-phase steering.

This UCA describes a situation where the SbW commands the rear-wheels to the wrong position, based on the vehicle speed. An example of this situation may be where the driver is trying to make a turn at an intersection. If the rear-wheels turn in-phase, this would increase the turning radius of the vehicle, which may prevent the vehicle from executing the turn maneuver. This could potentially result in insufficient vehicle lateral motion and insufficient yaw.

5 RISK ASSESSMENT

This study follows the risk assessment approach in ISO 26262. The assessment derives the ASIL for each of the six identified vehicle-level hazards.

5.1 Automotive Safety Integrity Level Assessment Steps

The ASIL assessment contains the following steps:

1. Identify vehicle operational situations
2. For each identified vehicle-level hazard, apply the ISO 26262 risk assessment framework:
    a. Assess the probability of exposure to the operational situation.
    b. Identify the potential crash scenario.
    c. Assess the severity of the harm to the people involved if the crash occurred.
    d. Assess the controllability of the situation and the vehicle in the potential crash scenario.
    e. Look up the ASIL per ISO 26262 based on the exposure, severity, and controllability.
3. Assign the worst-case ASIL to the hazard.

5.1.1 Vehicle Operational Situations

Operational situations are scenarios that can occur during a vehicle's life (Part 1 Clause 1.83 in ISO 26262). This study generates 14 vehicle operational situations that are provided in Appendix F. Below are two examples:

- Driving at high speeds (130 kilometers per hour (kph) > V ≥ 100 kph) on a Divided Highway

- Driving at medium speed (100 kph > V ≥ 40 kph), on city streets, with pedestrians present.

These 14 scenarios cover three variables and their states as shown in Table 14. These variables and their states were identified following current industry practices. Not all combinations of variable states in Table 14 produce viable operational situations. For example, the vehicle speed state "very high speed" combined with the roadway state "parking lot/driveway" does not produce a viable operational situation.

Table 14. Variables and States for Description of Vehicle Operational Situations

Variable	States
Vehicle Speed	Very High Speed (V ≥ 130 kph)
	High Speed (130 kph ≥ V > 100 kph)
	Medium Speed (100 kph ≥V > 40 kph)
	Low Speed (V < 40 kph)
Roadway Type	Limited Access Highway (e.g., Interstate)
	Divided Highway
	Country Road
	City Street
	Parking Lot/Driveway
Pedestrians	Present
	Not Present

5.1.2 Automotive Safety Integrity Level Assessment

ISO 26262 assesses the ASIL of identified hazards according to the severity, exposure, and controllability (Part 3 in ISO 26262).

Exposure is defined as the state of being in an operational situation that can be hazardous if coincident with the failure mode under analysis (Part 1 Clause 1.37 in ISO 26262). Table 15 is a reproduction of Table 2 in Part 3 of the ISO 26262 standard.

Table 15. Exposure Assessment

	Class				
	E0	**E1**	**E2**	**E3**	**E4**
Description	Incredible	Very low probability	Low probability	Medium probability	High probability
E = Exposure					

Severity is defined as the estimate of the extent of harm to one or more individuals that can occur in a potentially hazardous situation (Part 1 Clause 1.120 in ISO 26262). Table 16 is directly quoted from ISO 26262 Part 3 Table 1.

Table 16. Severity Assessment

	Class			
	S0	**S1**	**S2**	**S3**
Description	No injuries	Light and moderate injuries	Severe and life-threatening injuries (survival probable)	Life-threatening injuries (survival uncertain), fatal injuries
S = Severity				

Table 17 is one method for assessing severity that is provided in ISO 26262 (Part 3 Clause 7.4.3.2 and Annex B Table B.1).

Table 17. Example Method for Assessing Severity

	Class of Severity			
	S0	**S1**	**S2**	**S3**
Reference for single injuries (from AIS scale)	• AIS 0 and Less than 10% probability of AIS 1-6 • Damage that cannot be classified safety-related	More than 10% probability AIS 1- 6 (and not S2 or S3)	More than 10% probability of AIS 3-6 (and not S3)	More than 10% probability of AIS 5-6
AIS: Abbreviated Injury Scale				

ISO 26262 defines controllability as the "ability to avoid a specified harm or damage through the timely reactions of the persons[18] involved, possibly with support from external measures" (Part 1 Clause 1.19 in ISO 26262). Table 18 is ISO 26262's approach to assessing controllability (Table 3 in Part 3 in ISO 26262). Table 19 shows how ASIL is assessed based on exposure, severity, and controllability (Table 4 in Part 3 of ISO 26262).

Table 18. Controllability Assessment

	Class			
	C0	**C1**	**C2**	**C3**
Description	Controllable in general	Simply controllable	Normally controllable	Difficult to control or uncontrollable
C = Controllability				

[18] Persons involved can include the driver, passengers, or persons in the vicinity of the vehicle's exterior.

Table 19. ASIL Assessment

Severity Class	Probability Class (Exposure)	Controllability Class		
		C1	**C2**	**C3**
S1	**E1**	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	**E1**	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	**E1**	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D
QM: Quality Management **E: Exposure** **S: Severity** **C: Controllability**				

Table 20 and Table 21 provide two examples of how this study assesses the ASIL for each hazard under identified operational situations.

Table 20: Example ASIL Assessment for Hazard H1

Vehicle-Level Hazard	Potential unintended vehicle lateral motion/unintended yaw		
Operational Situation	Driving at high speed (130 kph > V ≥ 100 kph) on a country road		
Potential Crash Scenario	Vehicle head-on collision with on-coming vehicle		
ASIL Assessment	Severity	S3	Life-threatening injuries (survival uncertain) or fatal injuries
	Exposure	E4	Occurs often (>10% of driving time is not unexpected)
	Controllability	C3	Difficult to control or uncontrollable
Assigned ASIL Value	**D**		

Table 21: Example ASIL Assessment for Hazard H2

Vehicle-Level Hazard	Potential insufficient vehicle lateral motion/insufficient yaw		
Operational Situation	Driving at medium speed (100 kph > V ≥ 40 kph) on a city street, with pedestrians present		
Potential Crash Scenario	The vehicle runs into a pedestrian at medium speed.		
ASIL Assessment	Severity	S3	Life-threatening injuries (survival uncertain) or fatal injuries.
	Exposure	E4	Occurs often (>10% of driving time is not unexpected)
	Controllability	C3	Difficult to control or uncontrollable
Assigned ASIL Value	**D**		

Appendix G contains the full ASIL assessment.

5.2 Automotive Safety Integrity Level Assignment for Each Hazard

The ASIL assessment for each operational situation forms the basis for the ASIL assignment to each of the five vehicle-level hazards. ISO 26262 requires the most severe ASIL be chosen for each hazard. Table 22 shows the resulting ASIL values for each hazard.

Table 22. Vehicle-Level Hazards and Corresponding ASIL

	Hazard	ASIL
H1	Potential unintended vehicle lateral motion/unintended yaw[i]	D
H2	Potential insufficient vehicle lateral motion/insufficient yaw	D
H3	Potential loss of vehicle lateral motion control	D
H4	Potential reduced responsiveness to the driver's commands due to increased rear-wheel drag[i]	A
H5	Potential incorrect (delayed, missing, counterintuitive, etc.) feedback resulting in incorrect driver reaction	B
H6	Intermittent response to driver's control input	D

[i] Rear-wheel drag indicates a rear-wheel position (i.e., toe-in) that slows the vehicle when the brakes are not being applied

6 VEHICLE-LEVEL SAFETY GOALS

Based on the hazard analysis and risk assessment, the safety goals (i.e., vehicle-level safety requirements) are established as listed in Table 23. The safety goals correspond to the potential hazards in Table 22, although slightly reformulated:

- Hazards H1 and H2 were recombined so that SG 1 seeks to prevent unintended steering (i.e., not commanded by driver or other vehicle system) and SG 2 seeks to prevent an incorrect steering response when the driver or another vehicle system provides a steering input.
- Safety goal SG 2 also seeks to prevent an untimely steering response, including intermittent steering responses (hazard H6), by requiring the implementation of correct steering control actions within an appropriate time frame.

Safety goals SG 3, SG 4, and SG 5 correspond directly to hazards H3, H4, and H5, respectively.

Table 23. Safety Goals for the SbW System

ID	Safety Goals	ASIL
SG 1	The SbW system is to prevent unintended self-steering in any direction under all vehicle operating conditions.	D
SG 2	The SbW system is to provide the correct amount of steering within TBD seconds under all vehicle operating conditions.	D
SG 3	The SbW system is to prevent the loss of vehicle lateral motion control (i.e., steering loss) under all vehicle operating conditions	D
SG 4	The SbW system is to prevent unintended rear-wheel drag under all vehicle operating conditions.[i]	A
SG 5	The SbW system is to provide the correct amount of feedback to the driver under all vehicle operating conditions.	B

[i] Rear-wheel drag indicates a rear-wheel position (i.e., toe-in) that affects the vehicle dynamics or slows the vehicle when the brakes are not being applied. However, the drag effect may not reach the level of "deceleration."

7 SAFETY ANALYSIS

This study uses the functional FMEA and STPA to complete the safety analysis.

7.1 Functional Failure Modes and Effects Analysis

This study carried out a functional FMEA for all of the potential vehicle-level hazards identified in Table 1. Overall, the functional FMEA covers eight SbW subsystems and components, and three interfacing systems or subsystems. The functional FMEA identifies 16 failure modes and 110 potential faults. Table 24 shows a breakdown of failure modes and potential faults by the systems, subsystems, and components.

Table 24. Breakdown of Identified Failure Modes and Potential Faults

System/Subsystem/Component	Number of Failure Modes	Number of Potential Faults
SbW Subsystems and Components		
Steering wheel sensors	1	17
SbW control module	1	16
Front-wheel steering motor	1	11
Front-wheel/rack position sensor	1	17
Mechanical steering elements	1	1[i]
4WS subsystem	2	24
Mechanical backup subsystem (intermediate SbW systems)	2	5
Driver feedback mechanism	1	11
Interfacing Systems or Subsystems		
Power supply	1	3
Vehicle communication system	3	2
Interfacing system/sensors	2	3
Note: Some faults may result in one or more failure modes. [i] These faults are mechanical in nature and are not within the scope of ISO 26262.		

Table 25 shows a few examples of the functional FMEA. Appendix H provides the complete functional FMEA results

Table 25. Portion of the Functional FMEA for H1: Potential Unintended Vehicle Lateral Motion/Unintended Yaw

System/Subsystem	Potential Failure Mode	Potential Causes or Mechanisms of Failure	Safety Mechanism	
			"Full" SbW System	Intermediate SbW System
SbW Control Module	Failure of one of the SbW controllers	Hardware fault (sensors, integrated circuits (ics), circuit components, circuit boards…)	Fail-operational[19] controller configuration provides redundancy	Controllers have a minimum dual redundancy, with the mechanical backup subsystem engaged by a voter
		Internal connection fault (short or open)		
		Break in SbW input/output connections		
		Short in SbW I/O connections to ground or voltage		
		Short in SbW I/O connections to another connection		
		Signal connector connection failure		
		Power connector connection failure		
		Power-assist motor torque command calculation algorithm fault		
		Firmware crash/failure (software parameters corrupted)		
		Arbitration logic fault		

[19] Fail-operational implies that any first electronic fault does not result in a loss in the primary function of the electronic system.

7.2 Systems-Theoretic Process Analysis: Step 2

STPA Step 1 identified 51 UCAs and 6 vehicle-level hazards, which were then integrated with the HAZOP results to yield the six vehicle-level hazards described in Section 4. The goal of STPA Step 2 is to identify CFs that may lead to the UCAs, which then may result in one or more of the 6 synthesized vehicle-level hazards. Each of the 26 CF guidewords and the detailed causes (Appendix B) are applied to the components and interactions depicted in the STPA control structure diagram (Figure 9). Specifically, the STPA Step 2 analysis includes the following components and interactions:

- Components within the SbW system – defined as any component within the SbW system scope boundary shown in Figure 6.
- Interactions within the SbW system – defined as any interaction between components entirely within the SbW system scope boundary. Types of interactions include wired or communication bus connections used to transmit data, or physical connections (e.g., to transmit torque).
- Interactions with interfacing components and systems – defined as any interaction that involves a component within the SbW system boundary and a component external to the SbW system. Types of interactions include wired or communication bus connections used to transmit data, or physical connections.

The choices of these components and interactions enable the analysis to focus on the defined scope of this study while still considering critical interfaces between the SbW system and other vehicle systems. For example, the vehicle speed signal may be provided by the brake/vehicle stability control system. This analysis will consider faults in the transmission of the vehicle speed data to the SbW system (e.g., over the CAN bus). However, failures within the brake/vehicle stability control module or other parts of the brake/vehicle stability system that may lead to an incorrect vehicle speed are not considered in the analysis of the SbW system.

Each identified CF relates to one or more of the UCAs identified in STPA Step 1, providing a traceable pathway from CFs up to vehicle-level hazards (Figure 10).

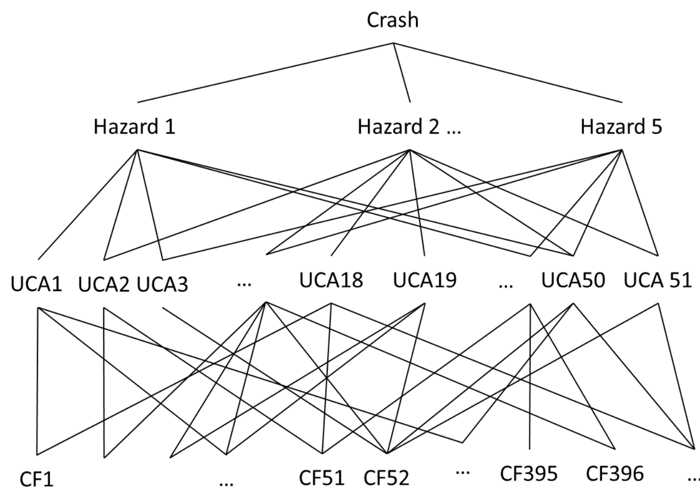


Figure K-1. Traceability in STPA Results

The STPA Step 2 analysis identifies a total of 760 unique CFs. Below is a breakdown of CFs by the type of UCAs they affect.

- 401 CFs may lead to UCAs related to the SbW control of the steering motor
- 266 CFs may lead to UCAs related to the SbW control of the rear-wheel position
- 156 CFs may lead to UCAs related to the SbW control of the driver feedback motor
- 79 CFs may lead to UCAs related to the SbW control of the mechanical backup subsystem (only applicable to Intermediate SbW Systems)
- 161 CFs may lead to UCAs related to the driver's steering input

As shown in Figure 10, a CF may lead to more than one UCA. Therefore, the totals listed above exceed the number of unique CFs identified in this study.

Table 26 shows a breakdown of the identified CFs by the 26 CF guidewords applied in this study. Appendix I provides the complete list of CFs identified in this study.

Table 26. Number of Identified Causal Factors by Causal Factor Category

Causal Factor Category	**Identified Causal Factors**
Actuation delivered incorrectly or inadequately: Actuation delayed	3
Actuation delivered incorrectly or inadequately: Hardware faulty	3
Actuation delivered incorrectly or inadequately: Incorrect connection	2
Actuator inadequate operation, change over time	25
Conflicting control action	2
Controlled component failure, change over time	6
Controller hardware faulty, change over time	9
Controller to actuator signal ineffective, missing, or delayed: Communication bus error	16
Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	30
Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	10
External control input or information wrong or missing	4
External disturbances	235
Hazardous interaction with other components in the rest of the vehicle	216
Output of controlled process contributes to system hazard	2
Power supply faulty (high, low, disturbance)	25
Process model or calibration incomplete or incorrect	19
Sensor inadequate operation, change over time	22
Sensor measurement delay	3
Sensor measurement inaccurate	3
Sensor measurement incorrect or missing	3
Sensor to controller signal inadequate, missing, or delayed: Communication bus error	30
Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	47
Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	14
Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	31

Table 27 shows three examples of CFs that may result in a UCA related to controlling the power-assist motor. in this UCA, the SbW control module commands steering in the correct direction, however, too much steering torque is commanded.

Table 27. Examples of Causal Factors for a UCA Related to Controlling the Steering Motor

Hazard	Potential unintended vehicle lateral motion/unintended yaw	
UCA (Example)	The steering system control module commands torque to change the front road wheel heading by θ degrees when: • the driver is steering in the θ direction, and • other vehicle systems are not requesting a steering adjustment or are requesting a steering adjustment in the θ direction, but too much torque is commanded.	
Potential Causal Factors (Example)	**Component**	**Potential Causal Factors**
	Steering Wheel Angle Sensor	An internal hardware failure might affect the steering wheel angle sensor and cause it to output an incorrect steering wheel angle measurement to the SbW control module.
	SbW Control Module	A programming error or flaw in software logic may affect how the SbW control module reconciles multiple steering requests in the same direction (e.g., add torques).
	Brake/Vehicle Stability System to SbW Control Module	A bus overload or bus error between the brake/vehicle stability system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.

1. The first example CF in Table 27 describes a failure of the steering wheel angle sensor that results in an incorrect measurement of the driver's steering input. If the SbW control module receives the incorrect steering input, the controller may request more steering than intended by the driver.
2. The second example CF in Table 27 describes a fault in the SbW control module's arbitration algorithm for resolving multiple torque requests in the same direction. For example, the SbW control algorithm may implement a steering request from another vehicle system as a torque overlay added to the driver's steering input, resulting in a net steering output that is greater than what the driver may expect.
3. The third example CF in Table 27 describes a fault in the communication bus, which could affect the vehicle speed information from being transmitted to the SbW control module (e.g., for an active steering feature). For example, if the SbW control module does not receive an updated vehicle speed, the control algorithm may compute the steering torque using outdated vehicle speed data that is lower than the vehicle's actual speed.

8 FUNCTIONAL SAFETY CONCEPT

ISO 26262 defines functional safety as *the absence of unreasonable risk due to hazards caused by malfunctioning behavior of electric/electronic systems* (Part 1 Clause 1.51 in ISO 26262). Functional safety is one aspect of the overall system safety. The primary focus of functional safety is to address systemic protection from electronic faults, which may include adding functionality to the system to specifically address safety. in particular, functional safety covers the safety behaviors or safety measures implemented by the system, such as fault detection, physical or systemic redundancy, or transitioning to a safe state, that reduce the overall risk due to faults in the electronic system. [2] [18]

The objective of the functional safety concept is to derive a set of functional safety requirements from the safety goals, and to allocate them to the preliminary architectural elements of the system, or to external measures (Part 3 Clause 8.1 in ISO 26262). Figure 11 illustrates how the functional safety concept takes into consideration the results from the safety analysis; applies safety strategies, industry practices, and engineering experiences; and derives a set of safety requirements following the established process in ISO 26262.

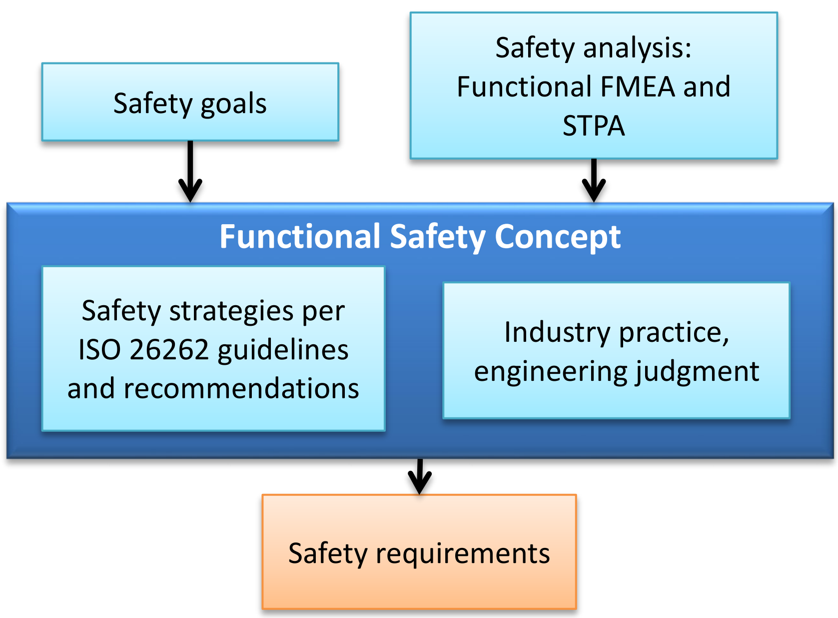


Figure K-1. Functional Safety Concept Process

8.1 Safety Strategies

As stated in ISO 26262 Part 3 Clause 8.2, "*the functional safety concept addresses:*

- *Fault detection and failure mitigation;*
- *Transitioning to a safe state;*
- *Fault tolerance mechanisms, where a fault does not lead directly to the violation of the safety goals and that maintains the item in a safe state (with or without degradation)*
- *Fault detection and driver warning in order to reduce the risk exposure time to an acceptable interval (e.g., engine malfunction indicator lamp, anti-lock brake fault warning lamp);*
- *Arbitration logic to select the most appropriate control request from multiple requests generated simultaneously by different functions*."

Typical safety strategy elements may include the following:

1. Ensure that the critical sensors' inputs to the main controller are valid and correct (redundant measurements paths).
2. Validate[20] the health of the main controller (using an auxiliary processor).
3. Ensure the validity and correctness[21] of critical parameters (mitigate latent faults through periodic checks).
4. Ensure the validity and correctness of the critical communication signals internal and external to the SbW system (quality factors[22]).
5. Ensure that the correct steering actuation (in terms of magnitude and direction) is delivered to the road wheels at the correct time.
6. Ensure that low-voltage power is available until the safe state is reached under all safety hazards conditions.
7. Mitigate the safety hazards when an unsafe condition is detected.
8. Ensure that the safe state is reached on time when a hazard is detected.
9. Ensure driver warnings are delivered when an unsafe condition is detected.
10. Ensure the correctness and timeliness of the arbitration strategy.

8.2 Architectural Requirements

Since SbW systems do not have a direct mechanical connection between the driver and the front-wheels during normal operation, a key component of the functional safety concept is ensuring that the driver retains a minimum level of steering capability following any first electronic fault

[20] "Validate" means to ensure that the value of a parameter or the state of an element falls within a valid set of values or states.
[21] "Correctness" means that the value of a parameter is the correct one from the valid set.
[22] Quality factors refer to techniques for error detection in data transfer and communication including checksums, parity bits, cyclic redundancy checks, error correcting codes, etc.

in the SbW system. This study provides examples of two architectural strategies that could achieve this requirement: “Fail Operational” and “Fail Safe.”

8.2.1 Fail Operational

An electronic system is “Fail Operational” if any first electronic fault is detected and does not result in a loss of any primary electronic system functionality that is essential to the safety of the system. [19] in the case of a “full” SbW system, this means ensuring that the SbW system continues to provide steering in response to the driver’s steering commands without violating any of the system’s safety goals.

Following any first electronic fault, if the degraded system is no longer fail operational to any subsequent fault, the system transitions to a status of fail-safe. Essentially, the system can safely sustain a minimum of two fully independent electronic faults prior to loss of primary system functionality and transition to an associated “safe state.” Independence of the effects of these faults must be validated using techniques such as common mode analysis.

Redundancy is commonly used ensure a fail-operational architecture. Redundancy can be physical redundancy, such as multiple fully redundant computing elements that “vote” their outputs. Thus, when one element is “out-voted,” a fault is presumed and that element is blocked from asserting control on the system. Alternatively, “analytical redundancy” may be used. By using independent data streams, encoding methods, and evaluation algorithms, fault effects associated with data corruption can be identified and mitigated.

Figure 12 shows examples of key fail-operational concepts as applied to a SbW system.[23] It depicts one common fail-operational architecture, “triplex,” with a three-way voting scheme. Alternative fail-operational architectures exist, such as “dual-dual” (not shown), which employs two pairs of controllers. If either pair detects a discrepancy between its elements, that pair of controllers is blocked from asserting control on the system.

[23] Figure 12 is provided to illustrate some of the key concepts for a fail-operational architecture and is not intended to represent an actual system design.

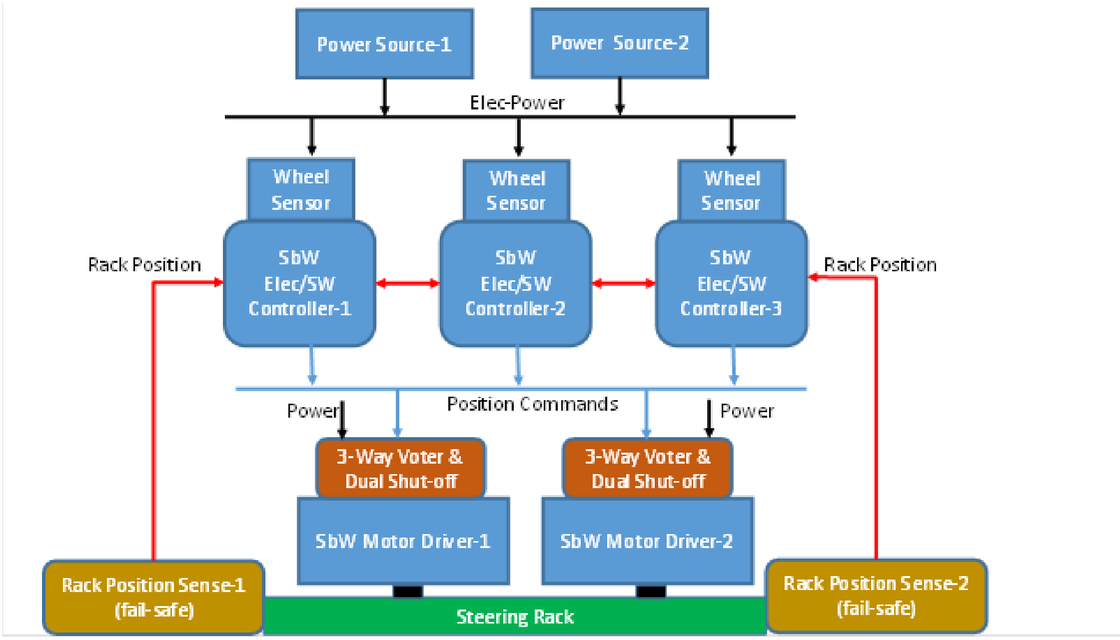


Figure K-1. Schematic of a Basic Fail-Operational "Full" Steer-by-Wire System

In the fail-operational schematic shown in Figure 12, there is no mechanical backup for the primary steering function. Instead, the configuration of controllers, sensors, power supplies, and actuators is sufficiently redundant to provide full steering capability following any single electronic failure. in addition to redundancy, detection and mitigation of electronic faults in each subsystem is another key element of the fail-operational schematic shown in Figure 12.

The cut-over to the redundant system (or removal of defective control path from contributing to the actual steering control of the vehicle) happens with sufficient speed to avoid inducing driver errors. The driver is appropriately warned of the error and that immediate service is required as the designed level of redundancy no longer exists.

8.2.2 Fail Safe

An electronic system is "Fail-Safe" if any single electronic fault is detected and results in the system transitioning to a safe-state to ensure system safety. An intermediate SbW system is an example of a fail-safe architecture, where the mechanical backup subsystem is designed to engage following detection of any first electronic fault in the SbW system.

A fail-safe system would require two fully independent electronic faults before it would lose primary system functionality. Upon the first failure, the system would transition to a safe state with limited functionality[24]. Fault effect independence must be validated through a method such

[24] For example, a mechanical backup steering system that does not implement active steering, power steering, or 4WS but may still have sufficient functionality to allow the driver to seek immediate maintenance.

as CMA. As with the fail-operational architecture, proper communication of any fault is made to the operator.

Fail-safe implies redundancy such that no single electronic fault is capable of resulting in a critical hazard. However, a fail-safe architecture may not require the same level of redundancy as a fail-operational architecture, since the system is designed to transition to a safe state immediately following detection of a fault. For example, a fail-safe architecture may only require two (redundant) controllers. If there is a disagreement due to an internal electronic fault in either of the controllers, the system transitions to a safe state. Figure 13 shows examples of key fail-safe concepts as applied to a SbW system.[25]

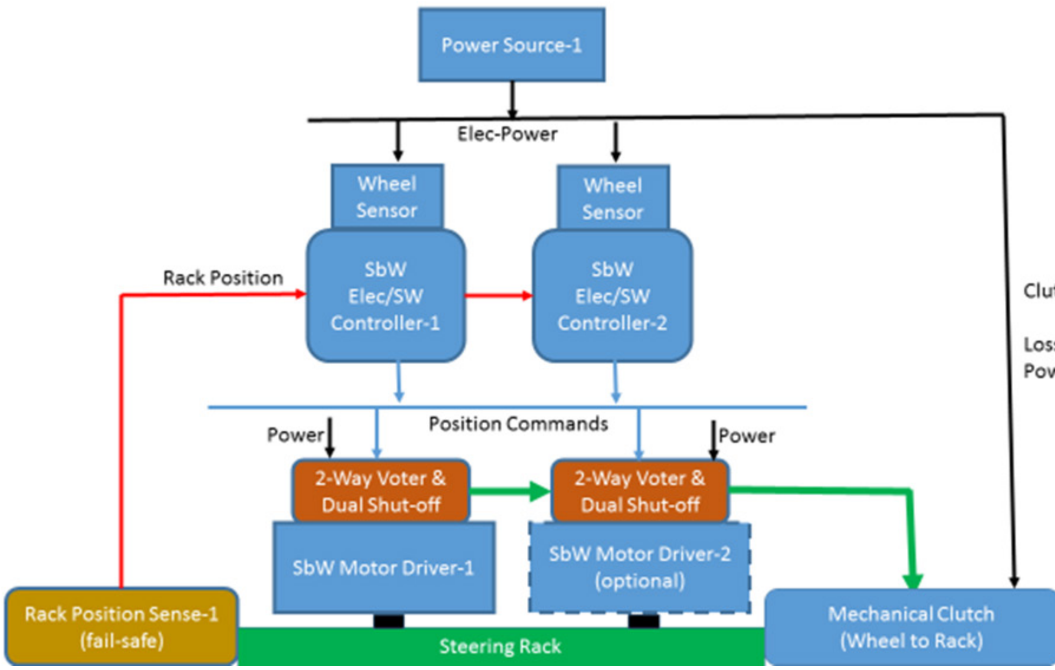


Figure K-1. Schematic of a Fail-Safe Intermediate Steer-by-Wire System

Intermediate SbW systems, such as the system shown in Figure 13, retain the mechanical steering pathway, which can be engaged following any electronic failure in the primary SbW system. The mechanical backup steering subsystem may have reduced functionality. For example, the mechanical backup may not have torque assistance (i.e., power steering) and may not support advanced features such as active steering or 4WS. Transition to the mechanical backup system would generally be combined with appropriate notification to the driver.

8.3 Example Safe States

A safe state is an operating mode of the item without an unreasonable risk. A safe state may be the intended operating mode, a degraded operating mode, or a switched off mode (Part 1 Clause

[25] Figure 13is provided to illustrate some of the key concepts for a fail-safe architecture and is not intended to represent an actual system design.

1.102 of ISO 26262). The developer of the functional safety concept attempts to maximize the availability of the vehicle while ensuring the safety of its operation. Therefore, careful consideration is given to selecting the safe states in relation to the potential failure modes.

The safe states for the SbW system can be either full operation, degraded operation (e.g., loss of certain SbW functions), or switched off mode (e.g., the SbW system is not available). Possible safe states for the SbW system may include (but are not limited to) those listed in Table 28. The objective of the safe state is to reduce the overall risk at the vehicle level. Therefore, some of the safe states presented in Table 28 include degradation of other vehicle systems, such as the propulsion system, to maximize the driver's controllability and to reduce the potential severity in the event of a collision.

Table 28. Possible SbW System Safe States

Safe State	SbW System Behavior	Example Triggering Event
1A	SbW degrades from fail-operational to fail-safe, but retains full steering availability[1]	Failure of one element (e.g., minimum triple redundancy)
1B	SbW system engages the mechanical backup subsystem[2]	Failure of one element (e.g., no redundancy)
2	Propulsion is restricted (e.g., "limp-home" mode) • Vehicle operation limited to TBD key cycles	Failure of two elements
3	Propulsion is gradually reduced until vehicle stops • Brake/torque vectoring may be used for limited steering	Failure of all redundant elements
4	Feedback motor is disabled	Failure of driver feedback mechanism
5	Rear-wheel steering is disabled • Rear-wheels are returned to straight-ahead position	Failure in the rear-wheel steering mechanism
[1] This safe state only applies for fail-operational architectures, as described in Section 8.2.1. [2] This safe state applies to the intermediate SbW systems, as described in Section		

8.4 Example Driver Warning Strategies

In addition to the safe states listed in Section 8.3, driver notification is a key element for ensuring that the driver takes the proper course of action. The following are examples of driver warning strategies commonly seen in the automotive industry.

- Amber Light: Potential violation of a safety goal is detected, but the probability of violating a safety goal is moderate.
- Red Light:
  - Potential violation of a safety goal is detected and the probability of violating a safety goal is high, or
  - Violation of a safety goal is detected.

- Audio:
  - Chime: Audible notification of the driver is implemented whenever the conditions for the red light driver warning are identified. The chime may continue until the fault is removed.
  - Specific recorded (or simulated) verbal warning to the operator.
- Messages: Messages are displayed to the driver at least with the red light driver warning. The messages include instructions to the driver in case exiting, staying away from, or ceasing operation of the vehicle is required.
- Haptic warning: Haptic warning may be an additional driver warning strategy. Dashboard lights and audible chimes are commonly used in conjunction with haptic warning. It may be beneficial to assess driver reactions to a haptic warning issued at the same time the system is attempting to reach safe state and degraded operation.

9 APPLICATION OF THE FUNCTIONAL SAFETY CONCEPT

The functional Safety Requirements for a SbW system can be apportioned to the major components in the system's architecture. Due to the architectural differences outlined in Section 8.2, each functional safety requirement is noted as whether it is applicable to "full" SbW systems and/or intermediate SbW systems. This study followed the Concept Phase (Part 3) in the ISO 26262 standard to identify 81 SbW system and component functional safety requirements SbW systems.

9.1 Vehicle-Level Safety Requirements (Safety Goals)

Vehicle-level safety requirements for the SbW system correspond to the safety goals presented in Table 23. They are summarized below, along with the recommended safety strategies.

SG 1: The SbW system is to prevent unintended self-steering in any direction under all vehicle operating conditions in accordance with ASIL D classification.

- Unintended self-steering is defined as any steering that was not initiated by the driver or other vehicle systems (which are assumed to be operating correctly).

SG 2: The SbW system is to provide the correct amount of steering within TBD seconds under all vehicle operating conditions in accordance with ASIL D classification.

- The level of steering actuation that deviates from the *requested* steering angle. Unlike SG 1, SG 2 applies in cases where either the driver or other vehicle systems initiate the steering maneuver.

SG 3: The SbW system is to prevent the loss of vehicle lateral motion control (i.e., steering loss) under all vehicle operating conditions in accordance with ASIL D classification.

- Loss of lateral motion control is defined as the absence of steering actuation in response to a steering input from the driver or other vehicle systems responsible for executing the lateral dynamic driving task in lieu of the driver.[26]

SG 4: The SbW system is to prevent unintended rear-wheel drag under all vehicle operating conditions in accordance with ASIL A classification.

SG 5: The SbW system is to provide the correct amount of feedback to the driver under all vehicle operating conditions in accordance with ASIL B classification.

[26] This safety goal does not apply in situations where the SbW system does not respond to the command from an assist-type vehicle system, but continues to respond to the driver's steering input. For example, if the driver's steering input overrides an Automated Lane Centering system, this would not constitute "loss of lateral motion control."

In addition to any specific safety strategies listed for the safety goals above, the following general safety strategies are to be followed for each of the safety goals:

- The SbW system is to prevent or detect faults and failures that could lead to the vehicle-level hazards.
- In case of the detection of any failure that could lead to vehicle-level hazards, the SbW system is to transition into a safe state within the fault tolerant time interval (FTTI).
    - The FTTI is to be set based on established empirical data, system analysis, or engineering judgment.
    - The safe state is to be appropriate for the detected failure.
- In case of the detection of any failure that could lead to vehicle-level hazards, a warning is to be sent to the driver, and when necessary, any actions required by the driver are to be communicated to them.

9.2 Functional Safety Requirements for a SbW System

Following the Concept Phase (Part 3) in the ISO 26262 standard, this study identifies 81 functional safety requirements for a SbW system and its components. The distribution of these requirements is as follows.

1. General SbW System – 18 requirements
2. SbW Control Module – 16 requirements
3. Driver Steering Input Sensor – 8 requirements
4. Driver Feedback Assembly – 6 requirements
5. Steering Actuator Assembly – 13 requirements
6. Power Source – 6 requirements
7. Communication System – 6 requirements
8. Interfacing System – 3 requirements
9. Rear-Wheel Assembly – 3 requirements
10. Mechanical Backup Steering Assembly – 2 requirements

Table 29 shows examples of safety requirements associated with the SbW control module, the safety analysis results from which the requirements are derived, and how the vehicle-level safety goal (SG 1) is allocated to one of the components in the system. The safety analysis identifies many failure modes and CFs for the SbW control module that could potentially lead to the violation of SG 1. Two SbW control module failures are chosen as examples in Table 29 to illustrate the development process of the safety requirements.

Table 29. Examples of Safety Requirements for the SbW Control Module

<table>
<tr><td>Safety Goal</td><td>SG 1: The SbW system is to prevent unintended self-steering in any direction under all vehicle operating conditions in accordance with ASIL D classification.</td></tr>
<tr><td>ASIL</td><td>D</td></tr>
<tr><td>Component</td><td>SbW control module</td></tr>
<tr><td>Safety Analysis (Examples)</td><td>• Hardware fault (sensors, ICs, etc.)
• Arbitration algorithm fault</td></tr>
<tr><td>Safety Strategy</td><td>Potential Safety Requirements (Examples)</td></tr>
<tr><td>Detection</td><td>Detect electronic failures in SbW control module.</td></tr>
<tr><td>Fault Tolerance</td><td>Design the SbW control module for full SbW systems to be fail-operational to a failure rate appropriate for the specified ASIL.</td></tr>
<tr><td>Safe State</td><td rowspan="2">Upon detection and isolation of any first electronic fault in the SbW control module:
• Transition to safe state 1A and issue an amber light driver warning if the remaining SbW system elements can support full torque availability to the specified ASIL.
• Transition to safe state 2 and issue a red light driver warning if the remaining SbW system elements cannot support full torque availability to the specified ASIL.</td></tr>
<tr><td>Warning</td></tr>
</table>

The rest of this section lists the 81 SbW functional safety requirements derived through this process. A functional safety requirement may have more than one ASIL associated with it, because the same requirement may cover more than one safety goal and these safety goals may have various levels of ASILs. The requirement may be implemented using different ASIL classification if independence among the implementation solutions can be demonstrated (Part 9 Clause 5.2 of ISO 26262).

9.2.1 General SbW System Functional Safety Requirements

This study derived 18 general functional safety requirements related to the SbW system. These requirements may cover the whole SbW system or may apply to all components within the SbW system. Each of the general SbW system functional safety requirements is listed in Table 30 along with the safety goals supported by the requirement and the associated ASILs.

Table 30. General Functional Safety Requirements

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
1.1	1, 2, 3, 4, 5	A, B, D	Detect mechanical and electronic failures in the SbW system within TBD time frame, depending on function affected by the fault and any associated requirements to achieve a safe state.	●	●

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
1.2	1, 2, 3, 4, 5	A, B, D	Periodically validate the integrity of the SbW system. (e.g., once at the beginning or end of each key-cycle). • This may include verifying sensor and actuator calibration data, or stored maps. • For intermediate SbW systems, this includes verifying the integrity of the mechanical backup subsystem.	●	●
1.3	1, 2, 3	D	Deliver the correct level of steering under all vehicle operating conditions.	●	●
1.4	1, 2, 3	D	Deliver steering in the correct direction under all vehicle operating conditions.	●	●
1.5	1, 2, 3	D	Deliver steering at the correct time under all vehicle operating conditions.	●	●
1.6	1	D	Do not provide steering without a steering input from either the driver or other vehicle systems.	●	●
1.7	1, 2, 3	D	Verify redundant elements against common cause failures (e.g., using CMA).	●	●
1.8	1, 2, 3	D	Upon detection and isolation of any first fault in the electronic or software elements comprising the SbW system: • Transition to safe state 1A and issue an amber light driver warning if the remaining SbW system elements can support full torque availability to the specified ASIL. • Transition to safe state 2 and issue a red light driver warning if the remaining SbW system elements cannot support full torque availability to the specified ASIL.	●	
1.9	1, 2, 3	D	Upon with detection and isolation of any first fault in the electronic or software elements comprising an intermediate SbW system: • Transition to safe state 1B and issue an amber light driver warning.		●
1.10	1, 2, 3	D	Meet TBD criteria before recovering from a safe state. • Possible criteria may include self-testing and/or monitoring of correct operation of the failed element by other non-failed, redundant elements.	●	●
1.11	1, 2, 3	D	Upon detection and isolation of a second electronic or software fault affecting the same layer of redundancy as the first fault: • Transition to safe state 2 and issue a red light driver warning if the second fault can be identified via real-time, in-line testing methodology.[27] • Transition to safe state 3 and issue a red light driver warning if the remaining SbW system elements if the second fault cannot be detected via real-time, in-line testing methodology.[27]	●	

[27] Methods to reduce latency of faults to meet ASIL metrics targets, such as periodic background testing.

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
1.12	1, 2, 3	D	Upon with detection and isolation of a fault in the intermediate SbW system affecting the mechanical backup when the system is already in safe state 1B: • Transition to safe state 3 and issue a red light driver warning.		●
1.13	1, 2, 3, 4, 5	A, B, D	Notify the driver of mechanical or electronic faults in the SbW system with warnings or alerts appropriate to the ASIL for the fault.	●	●
1.14	1, 2, 3, 4, 5	A, B, D	Meet requirements for resistance to environmental hazards as specified by regulatory authorities or industry best practices. Examples of environmental hazards may include: • Electrostatic discharge, electromagnetic interference, magnetic interference, heat, moisture, corrosion, and contamination ingress, and single-event effects	●	●
1.15	1, 2, 3, 4, 5	QM	Log diagnostic trouble codes as appropriate for all fault scenarios	●	●
1.16	1, 2, 3, 4, 5	No ASIL	Demonstrate that the hardware architectural Single Point Fault and Latent Fault metrics targets per ISO 26262 are met for each safety goal.	●	●
1.17	1, 2, 3, 4, 5	No ASIL	Adhere to ASIL B classification for diagnostic mechanisms for ASIL D related elements, ASIL A classification for diagnostic mechanisms for ASIL C related elements, and QM for diagnostic mechanisms for ASIL B and A related requirements.	●	●
1.18	1, 2, 3, 4, 5	QM	The SbW system is to log and save the following data every time a transition to a safe state is executed due to a violation of a safety goal: • The diagnostics information of the faults including the time at which the fault was detected and the nature of the fault. • The time interval from the detection of the fault to reaching a safe state. • The time the system degradation strategy started, including the start and end of each phase if applicable and the values of the system metrics for each phase (i.e., torque output level). The time the driver warning strategy started, including the start and end of each phase if applicable and the values of the system metrics for each phase.	●	●

9.2.2 SbW Control Module Functional Safety Requirements

This study derived 16 functional safety requirements related to the SbW control module. Each of the SbW control module functional safety requirements is listed in Table 30 along with the safety goals supported by the requirement and the associated ASILs.

Table 31. Functional Safety Requirements for the SbW Control Module

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
2.1	1, 2, 3, 4, 5	A, B, D	Design the SbW control module for full SbW systems to be fail-operational to a failure rate appropriate for the specified ASIL.	●	
2.2	1, 2, 3, 4, 5	A, B, D	Design the SbW control module for intermediate SbW systems to be fail-safe to a failure rate appropriate for the specified ASIL.		●
2.3	1, 2, 3, 4, 5	A, B, D	Detect electronic failures in SbW control module.	●	●
2.4	1, 2, 3	D	Upon detection and isolation of any first electronic fault in the SbW control module: • Transition to safe state 1A and issue an amber light driver warning if the remaining SbW system elements can support full torque availability to the specified ASIL. • Transition to safe state 2 and issue a red light driver warning if the remaining SbW system elements cannot support full torque availability to the specified ASIL.	●	
2.5	1, 2, 3	D	Upon with detection and isolation of any first electronic fault in the SbW control module for intermediate SbW systems: • Transition to safe state 1B and issue an amber light driver warning.		●
2.6	1, 2, 3	D	Upon detection and isolation of a second electronic or software fault in the SbW control module affecting the same layer of redundancy as the first fault: • Transition to safe state 2 and issue a red light driver warning if the second fault can be identified via in-line testing methodology. [28] • Transition to safe state 3 and issue a red light driver warning if the remaining SbW system elements if the second fault cannot be detected via real-time, in-line testing methodology.[28]	●	
2.7	1, 2, 3	D	Upon with detection and isolation of a fault in the intermediate SbW system affecting the mechanical backup when the system is already in safe state 1B: • Transition to safe state 3 and issue a red light driver warning.		●
2.8	1, 2, 3	D	Include an arbitration strategy for steering requests from the driver and other vehicle systems.	●	●
2.9	1, 2, 3	D	Clearly define the arbitration strategy for the SbW system when the driver's steering request conflicts with the requests or inputs of safety relevant systems.	●	●
2.10	5	B	Calculate feedback to the driver based on the vehicle handling and wheel/roadway interface characteristics (e.g., friction). [1]	●	●
2.11	5	B	Provide feedback to the driver within TBD ms time. [1]	●	●

[28] Methods to reduce latency of faults to meet ASIL metrics targets, such as periodic background testing.

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
2.12	1, 2, 3, 4, 5	A, B, D	Comply with ASIL D classification for SG 1, SG 2, and SG 3; ASIL B classification for SG 5; and ASIL A classification for SG 4 for all electrical hardware and software elements associated with the controlling the steering actuator, unless otherwise specified.	●	●
2.13	1, 2, 3, 4, 5	No ASIL	Institute diagnostics for the safety related functionality for the SbW control module with a level of coverage corresponding to the ASIL of the safety goal that is affected. Adhere to ISO 26262 diagnostics coverage guidelines for low, medium, and high coverage levels in order to comply with the hardware architectural metrics targets.	●	●
2.14	1, 2, 3, 4, 5	A, B, D	Apply software safety and design requirements to preclude safety critical software design or implementation issues with maximum failure rates appropriate to the ASIL. [1]	●	●
2.15	1, 2, 3, 4, 5	A, B, D	Correctly specify all required algorithms for the system prior to software implementation, including algorithms that arbitrate between steering inputs (e.g., between driver input and that of other vehicle systems like ALC). [1]	●	●
2.16	1, 2, 3, 4, 5	D	Design the system to comply with current industry cybersecurity best practices. [1]	●	●
[1] These requirements fall outside the scope of the ISO 26262 concept phase (Part 3).					

9.2.3 Driver's Steering Input Sensors Functional Safety Requirements

This study derived eight functional safety requirements related to the sensor measuring the driver's steering input. Each of the functional safety requirements for the driver's steering input sensors is listed in Table 32 along with the safety goals supported by the requirement and the associated ASILs.

Table 32. Functional Safety Requirements for the Driver's Steering Input Sensors

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
3.1	1, 2, 3, 4	A, D	Design the sensors measuring the driver's steering input in a "full" SbW system to be fail-operational with a failure rate appropriate for the specified ASIL.	●	
3.2	1, 2, 3, 4	A, D	Design the sensors measuring the driver's steering input in an intermediate SbW system to be fail-safe with a failure rate appropriate for the specified ASIL.		●
3.3	1, 2, 3, 4	A, B, D	Detect electronic failures in the sensors measuring the driver's steering input.	●	●

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
3.4	1, 2, 3	D	Upon detection and isolation of any first electronic fault in the sensors measuring the driver's steering input in a "full" SbW System: • Transition to safe state 1A and issue an amber light driver warning if the remaining SbW system elements can support full torque availability to the specified ASIL. • Transition to safe state 2 and issue a red light driver warning if the remaining SbW system elements cannot support full torque availability to the specified ASIL.	●	
3.5	1, 2, 3	D	Upon with detection and isolation of any first electronic fault in the sensors measuring the driver's steering input for an intermediate SbW system: • Transition to safe state 1B and issue an amber light driver warning.		●
3.6	1, 2, 3	D	Upon detection and isolation of a second electronic fault the sensors measuring the driver's steering input in a "full" SbW system that affects the same layer of redundancy as the first fault: • Transition to safe state 2 and issue a red light driver warning if the second fault can be identified via real-time, in-line testing methodology. [29] • Transition to safe state 3 and issue a red light driver warning if the remaining SbW system elements if the second fault cannot be detected via real-time, in-line testing methodology.[29]	●	
3.7	1, 2, 4	A, D	Ensure the driver's steering input is valid and correct.[1] • This includes correctly measuring steering wheel position through the full range of rotation (e.g., indexing for rotations greater than 360 degrees).	●	●
3.8	1, 2, 4	A, D	The steering wheel to road wheel position is to be verified (e.g., if the steering wheel is in the center position, the road wheel position is to be straight ahead) with TBD frequency.	●	●
[1] These requirements fall outside the scope of the ISO 26262 concept phase (Part 3).					

9.2.4 Driver Feedback Assembly Functional Safety Requirements

This study derived six functional safety requirements related to providing feedback to the driver. Each of the functional safety requirements for the driver feedback assembly is listed in Table 33 along with the safety goals supported by the requirement and the associated ASILs.

[29] Methods to reduce latency of faults to meet ASIL metrics targets, such as periodic background testing.

Table 33. Functional Safety Requirements for the Driver Feedback Assembly

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
4.1	5	B	Design the feedback actuator to be fail-safe with a failure rate appropriate for the specified ASIL.	●	●
4.2	5	B	Detect electronic failures that result in incorrect driver feedback.	●	●
4.3	5	B	Upon detection and isolation of any first fault in feedback actuator: • Transition to safe state 4 and issue an amber light driver warning.	●	●
4.4	5	B	Ensure that any failure of the driver feedback assembly (e.g., feedback motor) does not inhibit the driver's ability to operate the steering system. • This includes ensuring that failures in the driver feedback assembly do not bind the steering wheel.	●	●
4.5	5	B	Communicate the feedback motor position to the SbW control module.	●	●
4.6	5	B	Ensure the feedback motor position measurement is valid and correct.	●	●

9.2.5 Steering Actuator Assembly Functional Safety Requirements

This study derived 13 functional safety requirements related to providing steering actuation for the front-wheels. Each of the functional safety requirements for the steering actuator assembly is listed in Table 34 along with the safety goals supported by the requirement and the associated ASILs. The steering actuator assembly includes:

- the steering motor,
- the rack position sensor, and
- mechanical components, such as the rack and pinion.

Table 34. Functional Safety Requirements for the Steering Actuator Assembly

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
5.1	1, 2, 3	D	Design the steering motor for a "full" SbW system to be fail-operational with a failure rate appropriate for the specified ASIL.	●	
5.2	1, 2, 3	D	Design the steering motor for an intermediate SbW system to be fail-safe with a failure rate appropriate for the specified ASIL.		●
5.3	1, 2, 3	D	Detect electronic failures in the steering motor.	●	●
5.4	1, 2, 3	D	Design the rack position sensor for a "full" SbW system to be fail-operational with a failure rate appropriate for the specified ASIL.	●	

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
5.5	1, 2, 3	D	Design the rack position sensor for an intermediate SbW system to be fail-safe with a failure rate appropriate for the specified ASIL.		●
5.6	1, 2, 3	D	Detect electronic failures in the rack position sensor.	●	●
5.7	1, 2, 3	D	Upon detection and isolation of any first electronic fault in the steering actuator assembly in a "full" SbW System: • Transition to safe state 1A and issue an amber light driver warning if the remaining SbW system elements can support full torque availability to the specified ASIL. • Transition to safe state 2 and issue a red light driver warning if the remaining SbW system elements cannot support full torque availability to the specified ASIL.	●	
5.8	1, 2, 3	D	Upon with detection and isolation of any first electronic fault in the steering actuator assembly for an intermediate SbW system: • Transition to safe state 1B and issue an amber light driver warning.		●
5.9	1, 2, 3	D	Upon detection and isolation of a second electronic fault in the steering actuator assembly for a "full" SbW system that affects the same layer of redundancy as the first fault: • Transition to safe state 2 and issue a red light driver warning if the second fault can be identified via real-time, in-line testing methodology. [30] • Transition to safe state 3 and issue a red light driver warning if the remaining SbW system elements if the second fault cannot be detected via real-time, in-line testing methodology.[30]	●	
5.10	1, 2, 3	D	Upon with detection and isolation of a fault in the intermediate SbW system affecting the mechanical backup when the system is already in safe state 1B: Transition to safe state 3 and issue a red light driver warning.		●
5.11	1, 2, 3	D	Design the mechanical portion of the SbW system to meet the failure rate appropriate for the specified ASIL	●	●
5.12	1, 2, 3	D	Validated the integrity of the mechanical portion of the SbW system at TBD frequency	●	●
5.13	1, 2, 3	D	Design the interface between the steering motors and steering rack to ensure that failure of a steering motor does not prevent any remaining functioning steering motor from implementing safe control of the steering rack. • This includes mechanical failures of the steering motor that may jam the steering rack • This requirement covers cases where the steering motor may be disabled, non-functional, or electronically turned-off (e.g., power removed from the motor).	●	●

[30] Methods to reduce latency of faults to meet ASIL metrics targets, such as periodic background testing.

9.2.6 Power Supply Functional Safety Requirements

This study derived six functional safety requirements related to providing power to the SbW system. Each of the functional safety requirements for the SbW system power supply is listed in Table 35 along with the safety goals supported by the requirement and the associated ASILs.

Table 35. Functional Safety Requirements for the Power Supply

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
6.1	3	D	Design the power supply for a "full" SbW system to be fail-operational with a failure rate appropriate for the specified ASIL.	●	
6.2	1, 2, 3, 4, 5	A, B, D	Design the power supply for an intermediate SbW system to be fail-safe with a failure rate appropriate for the specified ASIL.		●
6.3	1, 2, 3, 4, 5	A, B, D	Detect electronic failures in the power supply.	●	●
6.4	1, 2, 3, 4, 5	A, B, D	Upon detection and isolation of any first electronic fault in the power supply in a "full" SbW System: • Transition to safe state 1A and issue an amber light driver warning if the remaining SbW system elements can support full torque availability to the specified ASIL. • Transition to safe state 2 and issue a red light driver warning if the remaining SbW system elements cannot support full torque availability to the specified ASIL.	●	
6.5	1, 2, 3, 4, 5	A, B, D	Upon with detection and isolation of any first electronic fault in the power supply for an intermediate SbW system: • Transition to safe state 1B and issue an amber light driver warning.		●
6.6	1, 2, 3, 4, 5	A, B, D	Upon detection and isolation of a second electronic fault in the power supply for a "full" SbW system that affects the same layer of redundancy as the first fault: • Transition to safe state 3 and issue a red light driver warning.	●	

9.2.7 Communication System Functional Safety Requirements

This study derived six functional safety requirements related to the vehicle's communication system supporting the SbW system. This includes both communication between subsystems in the SbW system as well as communication with interfacing vehicle systems and sensors that provide safety-critical data to the SbW system. Each of the functional safety requirements for the vehicle communication system is listed in Table 36 along with the safety goals supported by the requirement and the associated ASILs.

Table 36. Functional Safety Requirements for the Vehicle Communication System

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
7.1	1, 2, 3, 4, 5	A, B, D	Design the communication system for a "full" SbW system to be fail-operational with a failure rate appropriate for the specified ASIL.	●	
7.2	1, 2, 3, 4, 5	A, B, D	Design the communication system for an intermediate SbW system to be fail-safe with a failure rate appropriate for the specified ASIL.		●
7.3	1, 2, 3, 4, 5	A, B, D	Detect electronic failures in the vehicle's communication system	●	●
7.4	1, 2, 3, 4, 5	A, B, D	Upon detection and isolation of any first electronic fault in the communication system in a "full" SbW System: • Transition to safe state 1A and issue an amber light driver warning if the remaining SbW system elements can support full torque availability to the specified ASIL. • Transition to safe state 2 and issue a red light driver warning if the remaining SbW system elements cannot support full torque availability to the specified ASIL.	●	
7.5	1, 2, 3, 4, 5	A, B, D	Upon with detection and isolation of any first electronic fault in the communication system for an intermediate SbW system: • Transition to safe state 1B and issue an amber light driver warning.		●
7.6	1, 2, 3, 4, 5	A, B, D	Upon detection and isolation of a second electronic fault in the communication system for a "full" SbW system that affects the same layer of redundancy as the first fault: • Transition to safe state 2 and issue a red light driver warning if the second fault can be identified via real-time, in-line testing methodology. [31] • Transition to safe state 3 and issue a red light driver warning if the remaining SbW system elements if the second fault cannot be detected via real-time, in-line testing methodology.[31]	●	

9.2.8 Interfacing Systems Functional Safety Requirements

This study derived three functional safety requirements related to interfacing vehicle systems capable of requesting steering adjustments. The functional safety requirements related to interfacing vehicle systems are listed in Table 37, along with the safety goals supported by the requirement and the associated ASILs.

[31] Methods to reduce latency of faults to meet ASIL metrics targets, such as periodic background testing.

Table 37. Functional Safety Requirement for Interfacing Vehicle Systems

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
8.1	1, 2	D	All requests or commands for steering torque from interfacing vehicle systems are to be sent to the SbW control module.	●	●
8.2	1, 2	D	Validate any steering requests sent to the SbW control module from interfacing vehicle systems with the capability to request steering adjustments.	●	●
8.3	1, 2	D	All interfacing systems are to inform the SbW system in case of any failure that may cause the system to transition into a degraded mode of operation that affects the safe functioning of the SbW system.	●	●

9.2.9 Four-Wheel Steering Functional Safety Requirements

This study derived three functional safety requirements related to the 4WS feature that may be included in some SbW systems. These requirements only apply to SbW systems equipped with the 4WS feature. The functional safety requirements related to the 4WS feature are listed in Table 38, along with the safety goals supported by the requirement and the associated ASILs.

Table 38. Functional Safety Requirement for the Four-Wheel Steering Feature

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
9.1	4	A	Control the rear-wheel position to prevent violation of any safety goals.	●	●
9.2	4	A	Ensure smooth transitions between in-phase and reverse-phase rear-wheel positions so as not to alarm the driver	●	●
9.3	4	A	Upon with detection in the 4WS system (e.g., software execution, actuator fault, communication fault, etc.): • Transition to safe state 5 and issue an amber light driver warning.	●	●

9.2.10 Mechanical Backup Steering Assembly Functional Safety Requirements

This study derived two functional safety requirements related to the mechanical backup steering subsystem used in intermediate SbW systems; these requirements only apply to intermediate SbW systems. The functional safety requirements related to the mechanical backup steering assembly are listed in Table 39, along with the safety goals supported by the requirement and the associated ASILs.

Table 39. Functional Safety Requirement for the Mechanical Backup Steering Assembly

FSR ID	SG	ASIL	Functional Safety Requirement	"Full" SbW System	Inter-mediate SbW System
10.1	3	D	Validate the availability of the mechanical backup steering assembly with TBD frequency to support the specified ASIL.		●
10.2	3	D	Ensure the steering effort necessary to operate the mechanical backup steering does not exceed the steering effort to operate a conventionally steered passenger vehicle without power assist.		●

10 DIAGNOSTICS AND PROGNOSTICS

10.1 Metrics for Diagnostics

The diagnostics presented in this section are limited to the sensing and evaluation elements of the SbW system and critical interfaces, as described in Section 3.1. While failures in other vehicle systems may be amenable to diagnostic evaluation, this report focuses on methodologies for identifying existing and potential problems within the SbW system and critical interfaces.

Many diagnostic functions are characterized by detecting when a key parameter strays out of its normal operating range. In any electronic system, short-term anomalies are possible in both the electronic components and the communications network. The safety analysis for a system should identify FTTIs over which a fault has to be identified and mitigated. For many serious malfunctions, these FTTIs are significantly less than one second. Therefore rechecking abnormal readings may help the SbW system verify diagnostic system integrity. A SbW system might also use three-level monitoring, as described in Appendix K, to monitor the main controllers. However, in a full SbW system the fail-operational architecture (e.g., controller redundancy with a three-way voting mechanism) is the primary strategy for detecting and mitigating faults in the system.

Diagnostics covering the safety-related functionality of the SbW system are to be instituted with a level of coverage corresponding to the ASIL of the safety goal that is affected. The SbW system design is to adhere to ISO 26262 diagnostics coverage guidelines. Diagnostics coverage levels are associated with the number of failure modes detected by the specific technique. For example, a low diagnostics coverage level for a sensor might only detect out-of-range and stuck-in-range conditions. A medium diagnostics coverage level for a sensor might also detect offsets, in addition to out-of-range and stuck-in-range conditions. A high diagnostics coverage level might detect oscillations in addition to offsets, out-of-range, and stuck-in-range conditions.

Diagnostics coverage supports several metrics required by ISO 26262, including the hardware architectural metrics and the evaluation of safety goal violations due to hardware failures. ISO 26262 specifies how to implement diagnostic coverage for the safety-related functionality of critical SbW sensors, harnesses, and connectors based on the ASIL of the safety goal that is affected.

Diagnostics coverage may include the following.

- All system controllers (including redundant controllers):
  - CPU
  - Processor memory
  - Arithmetic Logic Unit
  - Registers
  - A/D converter

    - Software program execution
    - Connections (I/O) faults (short or open circuits)
    - Power supply
- Critical communication bus messages
- Harnesses and connectors (short or open circuits)

10.2 Common Diagnostic Trouble Codes for the SbW System

10.2.1 Assessment of Selected Generic Diagnostic Trouble Codes

DTCs are part of a safety system that senses, diagnoses, and controls situations, using driver warnings when appropriate. SAE Recommended Practice J2012 defines certain DTCs that on-board diagnostic (OBD) systems are required to report [20]. SAE J2012 does not contain any DTCs specific to SbW systems. However, there are several general steering-related DTCs that could still apply to SbW systems.

SAE J2012 uses a five-digit format for DTCs. For example, powertrain codes always start with the letter P, whereas network codes start with U," chassis codes start with C," and body system codes start with B. The second digit is numeric - typically 0, 1, 2, or 3. Predefined SAE (i.e., "controlled" non-OEM-specific) powertrain codes have a 0 or 2 as the second digit. Manufacturer-defined powertrain codes have a 1 or 3 in the second digit. For instance, P0XXX and P2XXX are SAE-controlled powertrain codes while P1XXX and P3XXX are unique to the manufacturer. Predefined SAE network codes, chassis codes, and body system codes have a 0 as the second digit whereas manufacturer-specific network codes, chassis codes, and body system codes have a 1 or 2 as the second digit. Thus, the first two digits can generally be used to determine whether the SbW system DTCs are SAE-controlled codes.

The codes are characterized by the phenomenon they represent. Some DTCs indicate an existing or emerging hazardous state, while others indicate a situation that requires attention to prevent the system from moving toward an unsafe state. System responses to DTCs, such as issuing a driver warning transitioning to a safe state is determined by the manufacturer.

Review of SAE J2012 identified 11 DTCs that cover SbW-related components and interfaces. SAE J2012 includes additional steering-related DTCs. However, these DTCs reference power steering and steering column modules, which do not apply to SbW. SAE J2012 also includes 134 DTCs that cover critical SbW system interfaces.

Table 40 and Table 41 provide a breakdown of these DTCs by the SbW system component or connection, and interfacing system or subsystem. Appendix K summarizes the DTCs relevant to the SbW system.

Table 40. Breakdown of Identified DTCs by SbW System Component or Connection

SbW System Component or Connection	Number of DTCs
Steering Wheel Angle Sensor	8
Steering Wheel Torque Sensor	2
Variable Effort Steering	1

Table 41. Breakdown of Identified SbW-Relevant DTCs by Interfacing System or Subsystem

SbW System Component or Connection	Number of DTCs
Brake Pedal Switch/Position Sensor	4
Brake Pressure Sensor	3
Brake/Stability Control System	7
Communication Bus	72
Differential Control Module	4
Ignition/Start System	8
Instrument Panel System	5
Vehicle Battery	1
Vehicle Speed Sensor	11
Wheel Speed Sensor	15
Yaw Rate/Lateral Acceleration Sensor	4

10.2.2 Potential Additional Generic Diagnostic Trouble Code Needs

SAE J2012 does not include DTC coverage of the entire SbW system. Many of the DTCs provided in Appendix L are included in SAE J2012 because of their relevance to the brake/vehicle stability system. The SbW system requirements in Section 9 suggest additional DTCs for the SbW system, which could be incorporated into SAE J2012 as part of the generic DTC coverage. These possible DTC coverage areas are listed in Table 42 The 41 DTCs in Table 42 are based on similar DTC types listed in SAE J2012. For SbW systems using a clutch-based mechanical backup, six additional possible DTC coverage areas are listed in Table 43.

Table 42. Possible Areas for Additional DTC Coverage for a SbW System

Phenomenon	System or Component
Internal SbW Control Module Memory Check Sum Error	SbW Control Module
SbW Control Module Programming Error	SbW Control Module
Internal SbW Control Module KAM Error	SbW Control Module
Internal SbW Control Module RAM Error	SbW Control Module
Internal SbW Control Module ROM Error	SbW Control Module
SbW Control Module Processor	SbW Control Module
SbW Control Module Performance	SbW Control Module

Phenomenon	System or Component
Internal SbW Control Module Monitoring Processor Performance	SbW Control Module
Internal SbW Control Module A/D Processing Performance	SbW Control Module
Internal SbW Control Module Main Processor Performance	SbW Control Module
SbW Control Module Vehicle Options Error	SbW Control Module
Lost Communication With SbW Control Module	SbW Control Module
Invalid Data Received From SbW Control Module	SbW Control Module
SbW Motor Failure	Steering Motor, Driver Feedback Motor, and Rear-Wheel Motor
SbW Motor Relay Circuit	Steering Motor, Driver Feedback Motor, and Rear-Wheel Motor
SbW Motor Position Sensor Circuit	Steering Motor and Driver Feedback Motor
SbW Motor Position Sensor Circuit Range/Performance	Steering Motor and Driver Feedback Motor
SbW Motor Position Sensor Circuit Low	Steering Motor and Driver Feedback Motor
SbW Motor Position Sensor Circuit High	Steering Motor and Driver Feedback Motor
SbW Motor Position Sensor Circuit Intermittent/Erratic	Steering Motor and Driver Feedback Motor
SbW Rear-Wheel Position Sensor Circuit	Rear-Wheel Position Sensor
SbW Rear-Wheel Position Sensor Circuit Range/Performance	Rear-Wheel Position Sensor
SbW Rear-Wheel Position Sensor Circuit Low	Rear-Wheel Position Sensor
SbW Rear-Wheel Position Sensor Circuit High	Rear-Wheel Position Sensor
SbW Rear-Wheel Position Sensor Circuit Intermittent	Rear-Wheel Position Sensor
SbW Steering Wheel Angle Sensor Circuit	Steering Wheel Angle Sensor
SbW Steering Wheel Angle Sensor Circuit Range/Performance	Steering Wheel Angle Sensor
SbW Steering Wheel Angle Sensor Circuit Low	Steering Wheel Angle Sensor
SbW Steering Wheel Angle Sensor Circuit High	Steering Wheel Angle Sensor
SbW Steering Wheel Angle Sensor Circuit Intermittent	Steering Wheel Angle Sensor
SbW Steering Wheel Torque Sensor Circuit	Steering Wheel Torque Sensor
SbW Steering Wheel Torque Sensor Circuit Range/Performance	Steering Wheel Torque Sensor
SbW Steering Wheel Torque Sensor Circuit Low	Steering Wheel Torque Sensor
SbW Steering Wheel Torque Sensor Circuit High	Steering Wheel Torque Sensor
SbW Steering Wheel Torque Sensor Circuit Intermittent	Steering Wheel Torque Sensor
Torque Sensor Zero Point Adjustment is Not Initialized	Steering Wheel Torque Sensor
Torque Sensor Zero Point Adjustment Incomplete	Steering Wheel Torque Sensor

Phenomenon	System or Component
Sensor Reference Voltage Circuit/Open	All SbW Sensors
Sensor Reference Voltage Circuit Low	All SbW Sensors
Sensor Reference Voltage Circuit High	All SbW Sensors
Lost Communication with Steering Wheel Lock Module	Steering Wheel Lock Module

Table 43. Possible Areas for Additional DTC Coverage for a SbW Mechanical Backup

Mechanical Backup Clutch Relay Control Circuit	Mechanical Backup
Mechanical Backup Clutch Relay Control Circuit Stuck Off	Mechanical Backup
Mechanical Backup Clutch Relay Control Circuit Stuck On	Mechanical Backup
Mechanical Backup Clutch Circuit Open	Mechanical Backup
Mechanical Backup Clutch Circuit Intermittent	Mechanical Backup
Excessive Clutch Slippage	Mechanical Backup

11 PERFORMANCE PARAMETERS AND TEST SCENARIOS

This section describes potential test scenarios based on the each of identified vehicle-level hazards and results of the hazard and safety analyses. These test scenarios may be used to verify that the functional safety requirements are achieved. Each test scenario includes the following:

- **Test Goals**: Each of the safety goals identified in this study serves as the testing goal for a test scenario. The test objective is to ensure that the safety goal is not violated.
- **Driving Scenarios**: The driving scenario is developed using a combination of the vehicle's operating situation and key inputs to the system. Together, this represents the situation under which the system should avoid entering a hazardous state when a fault is injected. The two components of the driving scenario are described below.
    - Operational situations are generated as part of the ASIL assessment and describe the operating environment of the vehicle. The operational situations considered in these test scenarios are based on the variables listed in Table 14. in particular, the ASIL operating scenarios that lead to the highest ASIL value for a hazard may represent worst-case driving situations under which the system should avoid entering a hazardous state. Note that test procedures may deviate from the "worst case" driving situation in the ASIL assessment for the purposes of testing safety. For example, test procedures may be developed that implement lower vehicle speeds if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.
    - The context variables used for deriving the UCAs represent key inputs to the system. Certain system behaviors are expected based on the combinations of these context variables to avoid entering a hazardous state.
- **Fault Injection**: The CFs identified in STPA, and failure modes and faults identified in the functional FMEA may be used as the basis for determining faults to inject at the component and connection levels. Examples of potential faults that could be introduced to the system include inducing hardware failures in system components, transmitting erroneous measurements from sensors, or issuing incorrect controller commands (e.g., to simulate a flaw in the software algorithm).
- **Expected Safe Behavior**: The test scenarios can be evaluated by monitoring for expected safe behaviors. The following are examples of possible safe behaviors:
    - The system may transition into one of the identified safe states within the FTTI. As described in Section 8.3, safe states are operating modes of the system that do not present an unreasonable risk.
    - The system's controller may still be capable of issuing the correct command when a fault is injected. For example, if the SbW control module may be capable of using other sensor data to determine the correct amount of steering-assist when there's a disruption in the voltage supply to one of the SbW sensors.

Although the role of the driver was considered in the hazard and safety analyses, the test scenarios presented in this section focus on the behavior of the electronic control system. Evaluation of driver behavior when certain faults are injected into the vehicle would require a human factors study.

11.1 Potential Test Scenarios for SG 1

Safety Goal 1 states that the SbW system prevent unintended self-steering in any direction under all vehicle operating conditions. Table 44 describes two possible driving scenarios to test this safety goal. Both driving scenarios are based on the same operational situation, identified as the worst-case scenario from the ASIL assessment. The driving scenarios differ based on the system input.

Table 44. Example Driving Scenarios for SG 1

Test Goal		The SbW system is to prevent unintended self-steering in any direction under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving at high speeds ($130 \text{ kph} > V \geq 100 \text{ kph}$),[32] light or heavy traffic, good visibility, and good road conditions
	System Input #1	• Driver is not issuing a steering command. • Other vehicle systems are not issuing a steering command.
	System Input #2	Driver issues a steering command.

- *Driving Scenario 1:* Neither the driver nor other vehicle systems issue a steering command while driving at high speeds with light or heavy traffic, good visibility, and good road conditions. This test scenario is intended to determine if an induced fault may cause the SbW system to issue a steering command when there is no request for steering.
- *Driving Scenario 2:* The driver issues a steering command while driving at high speeds in light or heavy traffic, under good visibility, and with good road conditions. This test scenario is intended to determine if an induced fault may cause the SbW system to issue a steering command in the opposite direction of the driver's steering request.

For each of the two test scenarios listed in Table 44, potential faults could be simulated in the SbW system to determine if these faults result in violation of the safety goal. The induced faults presented in Table 45 and Table 46 are examples of potential faults that can be derived from the STPA and functional FMEA results. The lists of potential faults in Table 45 and Table 46 are not intended to be exhaustive. The full STPA and functional FMEA results in Appendix H and Appendix I can be used to identify additional faults to include in the test scenarios.

[32] High speed is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 45. Examples of Simulated Faults to Test SG 1 Under Driving Scenario 1

Test Goal		The SbW system is to prevent unintended self-steering in any direction under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving at high speeds (130 kph > V ≥ 100 kph)[33], light or heavy traffic, good visibility, and good road conditions
	System Input	• Driver is not issuing a steering command. • Other vehicle systems are not issuing a steering command.
Injected Fault (Examples)	SbW Control Module	• Subject the SbW control module to a range of EMI and ESD disturbances. *(CF #48, 58)* • Simulate short circuits in the SbW control module. *(CF #64)* • Issue a steering request from the SbW control module to the steering motor (e.g., simulated software fault). *(CF #853, 1187)*
	Steering Wheel Angle Sensor	• Disrupt the power supply to the steering wheel angle sensor. *(CF #701)* • Transmit a non-zero steering wheel angle measurement to the SbW control module. *(CF #686, 688)*
	Incoming Connection From Other Vehicle Systems	Issue an errant signal on the communication bus that mimics a steering request. *(CF #45, 46)*
	Incoming Connection From Yaw Rate Sensor	Transmit a non-zero yaw rate measurement to the SbW control module. *(CF #553, 554, 557, 563, 564)*
	Steering Motor	Simulate a short circuit to battery voltage. *(CF #1431)*
	Rear-Wheel Position Sensor	• Transmit a non-zero rear-wheel measurement to the SbW control module. *(CF #894, 896, 906)* • Subject the connection from the rear-wheel position sensor to the SbW control module to a range of EMI and ESD disturbances. *(CF #1032, 1033)*
Expected Safety Strategies	"Full" SbW System	• Detects fault and does not provide steering. • Transitions to safe state 1A or safe state 2.
	Intermediate SbW System	• Detects fault and does not provide steering. • Transitions to safe state 1B.

[33] High speed is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 46. Examples of Simulated Faults to Test SG 1 Under Driving Scenario 2

Test Goal		The SbW system is to prevent unintended self-steering in any direction under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving at high speeds (130 kph > V ≥ 100 kph)[34], light or heavy traffic, good visibility, and good road conditions
	System Input	Driver is issuing a steering command.
Injected Fault (Examples)	SbW Control Module	• Subject the SbW control module to a range of EMI and ESD disturbances. *(CF #48, 58)* • Simulate short circuits in the SbW control module. *(CF #64)* • Issue a steering request from the SbW control module to the power-assist motor in the wrong direction (e.g., simulate a software fault). *(CF #858)*
	Steering Wheel Angle Sensor	• Disrupt the power supply to the steering wheel angle sensor. *(CF #701)* • Transmit the reversed steering wheel angle measurement to the SbW control module (e.g., θ° clockwise instead of counterclockwise). *(CF #686, 688)*
	Incoming Connection From Other Vehicle Systems	Issue steering requests from another vehicle system that conflict with the direction of the driver's steering input. Issue the requests with varying levels of priority (i.e., test the SbW system's arbitration logic). *(CF #1167, 1168)*
	Incoming Connection From Yaw Rate Sensor	Transmit a yaw rate measurement to the SbW control module in the opposite direction of the driver's steering command. *(CF #563, 564)*
	Steering Motor	Simulate reversed polarity from the vehicle power supply to the motor. *(CF #1646, 1654)*
Expected Safety Strategies	"Full" SbW System	• Detects fault and does not provide steering. • Transitions to safe state 1A or safe state 2.
	Intermediate SbW System	• Detects fault and does not provide steering. • Transitions to safe state 1B.

11.2 Potential Test Scenarios for SG 2

Safety Goal 2 states that the SbW system provide the correct amount of steering under all vehicle operating conditions. This includes providing a steering response within the correct time interval following a steering input. Table 47 describes two possible driving scenarios to test this safety goal. The driving scenarios differ based on the system input.

[34] High speed is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 47. Example Driving Scenarios for SG 2

Test Goal		The SbW system is to provide the correct amount of steering under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving high speeds (130 kph > V ≥ 100 kph)[35], light or heavy traffic, good visibility, and good road conditions.
	System Input #1	• Driver issues a steering command. • Vehicle speed is constant.
	System Input #2	• Driver issues a steering command. • Vehicle speed transitions across the threshold for reverse-phase/in-phase rear-wheel steering.

- *Driving Scenario 1:* The vehicle speed is steady, so the test scenario is not influenced by changes in the steering mode as a function of vehicle speed. This test scenario is intended to determine if an induced fault may cause the SbW system to provide the incorrect amount of steering actuation.
- *Driving Scenario 2:* The driver issues a steering command as the vehicle crosses the speed threshold for operating the rear-wheels in the reverse-phase and in-phase positions. This test scenario is intended to determine if an induced fault may affect transition of the rear-wheel positions, resulting in unexpected vehicle dynamics.

For each of the test scenarios listed in Table 47, potential faults could be simulated in the SbW system to determine if these faults result in violation of the safety goal. The induced faults presented in Table 48 and Table 49 are examples of potential faults that can be derived from the STPA and functional FMEA results. The lists of potential faults in Table 48 and Table 49 are not intended to be exhaustive. The full STPA and functional FMEA results in Appendix H and Appendix I can be used to identify additional faults to include in the test scenarios.

[35] High speed is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 48. Examples of Simulated Faults to Test SG 2 Under Driving Scenario 1

Test Goal		The SbW system is to provide the correct amount of steering within TBD seconds under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving at medium to very high speeds (40 kph ≤ V)[36], light or heavy traffic, good visibility, and good road conditions.
	System Input	• Driver issues a steering command. • Vehicle speed is constant.
Injected Fault (Examples)	SbW Control Module	• Subject the SbW control module to a range of EMI and ESD disturbances. *(CF #48, 58)* • Simulate short circuits in the SbW control module. *(CF #64)* • Issue a steering request from the SbW control module to the steering motor with the wrong actuation magnitude (simulated software fault). *(CF #849)* • Store the incorrect vehicle speed to steering motor torque maps in the SbW control module. *(CF #859)*
	Steering Wheel Angle Sensor	• Disrupt the power supply to the steering wheel angle sensor. *(CF #701)* • Transmit a steering wheel angle measurement to the SbW control module that is higher than the actual steering wheel position. *(CF #686, 688, 698, 831)* • Simulate a hardware fault that limits the steering wheel angle sensor measurement to a single 360° rotation. *(CF #1191)*
	Incoming Connection From Other Vehicle Systems	Issue steering requests from another vehicle system in the same direction as the driver's steering input. Issue the requests with varying levels of priority (i.e., test the SbW system's arbitration logic). *(CF #1166)*
	Incoming Connection From Vehicle Speed Sensor	• Simulate a loss of vehicle speed data. *(CF #1314, 1315, 1320, 1322)* • Transmit the incorrect vehicle speed data to the SbW control module. *(CF #1315, 1318, 1323)*
	Steering Motor	• Introduce a delay in the steering motor position feedback to the SbW control module. *(CF #1431, 1433, 1435)* • Disrupt the power supply to the steering motor. *(CF #1443)*
Expected Safety Strategies	"Full" SbW System	• Detects fault and does not provide steering. • Transitions to safe state 1A or safe state 2.
	Intermediate SbW System	• Detects fault and does not provide steering. • Transitions to safe state 1B.

Table 49. Examples of Simulated Faults to Test SG 2 Under Driving Scenario 2

Test Goal		The SbW system is to provide the correct amount of steering within TBD seconds under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving at medium to very high speeds (40 kph ≤ V)[37], light or heavy traffic, good visibility, and good road conditions.
	System Input	• Driver issues a steering command. • Vehicle speed transitions across the threshold for reverse-phase/in-phase rear-wheel steering.
Injected Fault (Examples)	SbW Control Module	• Subject the SbW control module to a range of EMI and ESD disturbances. *(CF #48, 58)* • Simulate short circuits in the SbW control module. *(CF #64)* • Issue a steering request from the SbW control module to turn the rear-wheels reverse-phase above the vehicle speed threshold (e.g., simulate a software fault). *(CF #1044)*
	Incoming Connection From Vehicle Speed Sensor	Delay providing the SbW control module with updates to the vehicle speed data. *(CF #1320, 1321, 1322)*
	Rear-Wheel Position Sensor	• Store the wrong calibration data for the rear-wheel position sensor. *(CF #74)* • Simulate a loss of power supply to the rear-wheel position sensor. *(CF #907)* • Simulate short circuits in the connection between the rear-wheel position sensor and SbW control module. *(CF #1004, 1005, 1008)*
	Rear-Wheel Motor	Simulate an over-temperature condition in the rear-wheel motor while the rear-wheels are in either the in-phase or reverse-phase position. *(CF #1118, 1120)*
Expected Safety Strategies	• "Full" SbW System • Intermediate SbW System	• SbW system detects the fault and provides the correct rear-wheel orientation. • Transitions to safe state 5

[36] The medium to very high speed range is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

[37] The medium to very high speed range is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

11.3 Potential Test Scenarios for SG 3

Safety Goal 3 states that the SbW system prevent the loss of steering under all vehicle operating conditions. This study derives a possible driving scenario to test this safety goal. The operational situation shown in Table 50 includes a vehicle speed range covering several operating scenarios in the ASIL assessment that all result in ASIL D.

Table 50. Example Driving Scenario for SG 3

Test Goal		The SbW system is to prevent the loss of vehicle lateral motion control (i.e., steering loss) under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving at medium to high speed (130 kph > V ≥ 40 kph)[38] with light or heavy traffic, good visibility, and good road conditions.
	System Input	Driver issues a steering command.

- *Driving Scenario 1:* The driver issues a steering command at medium to high vehicle speeds in light or heavy traffic, under good visibility, and with good road conditions. This test is intended to determine if an induced fault may cause the SbW system to become unresponsive to steering inputs (i.e., the vehicle maintains its last trajectory).

The induced faults presented in Table 51 are examples of potential faults that can be derived from the STPA and functional FMEA results. The lists of potential faults in Table 51 are not intended to be exhaustive. The full STPA and functional FMEA results in Appendix H and Appendix I can be used to identify additional faults to include in the test scenario.

[38] The medium to high speed range is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 51. Examples of Simulated Faults to Test SG 3 Under Driving Scenario 1

Test Goal		The SbW system is to prevent the loss of vehicle lateral motion control (i.e., steering loss) under all vehicle operating conditions.
ASIL		D
Driving Scenarios	Operational Situation	Driving at medium to high speed ($130 \text{ kph} > V \geq 40 \text{ kph}$)[39] with light or heavy traffic, good visibility, and good road conditions.
	System Input	Driver issues a steering command.
Injected Fault (Examples)	SbW Control Module	• Subject the SbW control module to a range of EMI and ESD disturbances. *(CF #48, 58)* • Simulate short circuits in the SbW control module. *(CF #64)* • Simulate a loss of power to the SbW control module. *(CF #56)* • Simulate an over-temperature condition in the SbW control module CPU. *(CF #65, 66)*
	Steering Wheel Angle Sensor	• Transmit a steering wheel angle measurement that is outside the calibration range. *(CF #517)* • Simulate a loss of power to the steering wheel angle sensor. *(CF #669)* • Prevent transmission of the steering wheel angle measurement to the SbW control module. *(CF #580, 585, 587, 598, 602, 1239)*
	Steering Motor	• Simulate a loss of power supply to the steering motor. *(CF #1442)* • Simulate an open circuit in the connection from the SbW control module to the steering motor. *(CF #1652)*
	Mechanical Clutch[1]	• Simulate an open circuit in the connection from the SbW control module to the mechanical clutch. *(CF #1599)* • Simulate a short to battery in the connection from the SbW control module to the mechanical clutch. *(CF #1599)*
Expected Safety Strategies	"Full" SbW System	• SbW system detects the fault and ensures the operability of steering. • Transitions to safe state 1A.
	Intermediate SbW System	• Detects fault and transitions to safe state 1B. • If the mechanical backup is also affected, the SbW system detects the faults and transitions to safe state 3.
[1] These injected faults would only apply to SbW systems with a mechanical backup. These faults assume a second fault		

11.4 Potential Test Scenarios for SG 4

Safety Goal 4 states that the SbW system prevent rear-wheel drag under all vehicle operating conditions. This study derived a possible driving scenario to test this safety goal, which is shown in Table 52.

Table 52. Example Driving Scenario for SG 4

Test Goal		The SbW is to prevent rear-wheel drag under all vehicle operating conditions.
ASIL		A
Driving Scenarios	Operational Situation	Driving at high speed (130 kph > V ≥ 100 kph)[40] with heavy traffic, good visibility, and good road conditions.
	System Input	• Driver issues a steering command. • Brake pedal is in the at-rest (i.e., undepressed) position.

- *Driving Scenario 1:* The driver issues a steering command and is not applying the brakes, while the vehicle is travelling at high speeds in heavy traffic, under good visibility, and with good road conditions. This test scenario is intended to determine if an induced fault could cause the rear-wheels to toe-in by an amount that reduces the vehicle's speed or otherwise affects the vehicle dynamics.

The induced faults presented in Table 53 are examples of potential faults that can be derived from the STPA and functional FMEA results. The lists of potential faults in Table 53 are not intended to be exhaustive. The full STPA and functional FMEA results in Appendix H and Appendix I can be used to identify additional faults to include in the test scenarios.

[39] The medium to high speed range is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

[40] High speed is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 53. Examples of Simulated Faults to Test SG 4 Under Driving Scenario 1

Test Goal		The SbW is to prevent rear-wheel drag under all vehicle operating conditions.
ASIL		A
Driving Scenarios	Operational Situation	Driving at high speed (130 kph > V ≥ 100 kph)[41] with heavy traffic, good visibility, and good road conditions.
	System Input	• The driver issues a steering command. • The brake pedal is in the at-rest (i.e., undepressed) position.
Injected Fault (Examples)	SbW Control Module	• Subject the SbW control module to a range of EMI and ESD disturbances. *(CF #48, 58)* • Simulate short circuits in the SbW control module. *(CF #64)* • Issue a command to the rear-wheel motor to toe-in to the maximum degree (e.g., simulate a software fault). *(CF #999)*
	Incoming Connection From Other Vehicle Systems	Issue a signal to the SbW control module that mimics a braking command from another vehicle system. *(CF #45, 1315, 1316, 1324)*
	Rear-Wheel Position Sensor	Simulate short circuits in the connection between the rear road wheel position sensor and SbW control module. *(CF #1004, 1005, 1008)*
	Rear-Wheel Motor	Simulate a short circuit to battery voltage. *(CF #918, 1131)*
Expected Safety Strategies	• "Full" SbW System • Intermediate SbW System	• SbW system detects the fault and prevents the rear-wheels from causing a drag effect. • Transitions to safe state 2.

11.5 Potential Test Scenarios for SG 5

Safety Goal 5 states that the SbW system provide the correct amount of feedback to the driver under all vehicle operating conditions. This study derived a possible driving scenario to test this safety goal, which is shown in Table 54.

[41] High speed is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 54. Example Driving Scenario for SG 5

Test Goal		The SbW system is to provide the correct amount of feedback to the driver under all vehicle operating conditions
ASIL		B
Driving Scenarios	Operational Situation	Driving at medium to high speeds (130 kph > V ≥ 40 kph)[42] with heavy traffic, good visibility, and good road conditions.
	System Input #1	• Driver does not issue a steering command. • Vehicle is travelling straight ahead. • A lateral disturbance is introduced (e.g., crosswind)

- *Driving Scenario 1:* The vehicle is travelling straight ahead on a smooth, level road surface at medium to high speeds in heavy traffic, under good visibility, and with good road conditions, when a lateral disturbance is introduced. This test scenario is intended to determine if an induced fault could cause the driver feedback subsystem to generate the incorrect feedback to the driver.

The induced faults presented in Table 55 are examples of potential faults that can be derived from the STPA and functional FMEA results. The lists of potential faults in Table 55 are not intended to be exhaustive. The full STPA and functional FMEA results in Appendix H and Appendix I can be used to identify additional faults to include in the test scenarios.

[42] The medium to high speed range is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

Table 55. Examples of Simulated Faults to Test SG 5 Under Driving Scenario 1

Test Goal		The SbW system is to provide the correct amount of feedback to the driver under all vehicle operating conditions.
ASIL		B
Driving Scenarios	Operational Situation	Driving at medium to high speeds (130 kph > V $\geq$ 40 kph)[43] with heavy traffic, good visibility, and good road conditions.
	System Input	• Driver does not issue a steering command. • Vehicle is travelling straight ahead. • A lateral disturbance is introduced (e.g., crosswind)
Injected Fault (Examples)	SbW Control Module	• Subject the SbW control module to a range of EMI and ESD disturbances. *(CF #48, 58)* • Simulate short circuits in the SbW control module. *(CF #64)* • Issue a command to the feedback motor in the opposite direction (e.g., simulate a software fault). *(CF #244)*
	Feedback Motor	• Simulate a short circuit to battery voltage. *(CF #1388, 1462)* • Simulate failure of one of the motor relays (e.g., welded relay) *(CF #1619)*
Expected Safety Strategies	• "Full" SbW System • Intermediate SbW System	• SbW system detects the fault and prevents the feedback motor from providing incorrect torque to the driver. • Transitions to safe state 4.

[43] The medium to high speed range is the "worst case" or most critical condition. Test procedures may be developed that implement lower vehicle speeds for the purposes of testing safety if it can be shown that failure modes are independent of speed or if the protocol implements incremental speed increases.

12 CONCLUSIONS

This study followed the Concept Phase process (Part 3) in ISO 26262 standard to derive a list of potential safety requirements for the SbW system. Specifically, this research:

1. Identified five vehicle-level safety goals and assessed their ASIL.

ID	Safety Goals	ASIL
SG 1	The SbW system is to prevent unintended[i] self-steering in any direction under all vehicle operating conditions.	D
SG 2	The SbW system is to provide the correct amount of steering within TBD seconds under all vehicle operating conditions.	D
SG 3	The SbW system is to prevent the loss of vehicle lateral motion control (i.e., steering loss) under all vehicle operating conditions	D
SG 4	The SbW system is to prevent unintended rear-wheel drag under all vehicle operating conditions.[ii]	A
SG 5	The SbW system is to provide the correct amount of feedback to the driver under all vehicle operating conditions.	B

[i] Unintended in this context is used to differentiate from intentional disabling of the SbW system as a potential safe state for the system. Specifically, the unintended loss of steering-assist is not controlled and the driver is not notified that steering-assist is not available.

[ii] Rear-wheel drag indicates a rear-wheel position (i.e., toe-in) that affects the vehicle dynamics or slows the vehicle when the brakes are not being applied. However, the drag effect may not reach the level of “deceleration.”

2. Developed the functional safety concept and identified 81 functional safety requirements by following the Concept Phase in the ISO 26262 standard, combining the results of the two safety analyses (Functional FMEA and STPA), and leveraging industry practice experiences. The breakdown of the number of requirements is as follows.
    - General SbW System – 18 requirements
    - SbW Control Module – 16 requirements
    - Driver Steering Input Sensor – 8 requirements
    - Driver Feedback Assembly – 6 requirements
    - Steering Actuator Assembly – 13 requirements
    - Power Source – 6 requirements
    - Communication System – 6 requirements
    - Interfacing System – 3 requirements
    - Rear-Wheel Assembly – 3 requirements
    - Mechanical Backup Steering Assembly – 2 requirements

3. Identified 11 generic DTCs included in SAE J2012 that provide coverage of the SbW system and 134 DTCs that provide coverage for safety-critical interfacing components and communication systems. in addition, this study identified 41 potential DTCs that could provide additional coverage of the SbW system.

4. Developed seven example test scenarios that could be used to validate the safety goals and functional safety requirements. The results from this study could also be used to develop a more comprehensive set of test scenarios.

13 REFERENCES

[1] SAE International. (2014). *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems* (SAE J3016). Warrendale, PA: SAE International, 2014.

[2] International Organization for Standardization. (2011). Road vehicles - functional safety(Final Draft). (ISO 26262). Geneva: Author.

[3] International Electrotechnical Commission. (2001). Hazard and operability studies (HAZOP Studies) - Application guide, Edition 1.0. (IEC 61882-2001). Geneva: Author.

[4] Leveson, N. (2012). *Engineering a safer world*, Cambridge, MA: MIT Press.

[5] Society of Automotive Engineers. (1994). Potential failure mode and effects analysis in design and potential failure mode and effects analysis in manufacturing and assembly processes. (SAE J1739). Warrendale, PA: Author. [Editor's note: in 2006 the Society of Automotive Engineers changed its name to SAE International.]

[6] Thomas, J. (2013). Extending and Automating a Systems-Theoretic Hazard Analysis for Requirements Generation and Analysis (Ph.D. dissertation). Cambridge, MA: Massachusetts Institute of Technology.

[7] Coudert, O. (1994). Two-level logic minimization: An overview, *Integration, the VLSI Journal, 17*(2), pp. 97-140.

[8] United Nations Economic Commission for Europe. (1988, December 1). *Regulation No. 79: Uniform Provisions Concerning the Approval of Vehicles with Regard to Steering Equipment* (Multilateral Treaty, Chapter XI, Transport and Communications, [Section] B. Road Traffic). Available at https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XI-B-16-79&chapter=11&clang=_en.

[9] AUTOSAR *Software Component Steer (Steering System),* Release 4.2.1 ed.

[10] Colwell, K. C. (2013, January). Electric Feel: Nissan Digitizes Steering, But the Wheel Remains. (Web page). Ann Arbor, MI: Car and Driver. Available at www.caranddriver.com/features/electric-feel-nissan-digitizes-steering-but-the-wheel-remains-feature

[11] General Motors Corporation. (2002). ASE 4 - Suspension and Steering: Module 3 - Rear Wheel Steering. Retrieved from www.hvcc.edu/deptweb-ats/asep/A4_SuspSteer_StudentWorkBooks/SWB_a4_m03_Final.pdf

[12] Kade, A., Bartz, D., Hudas, G., & D. G. Mikulski, D. G. (2014, October 28). *Tank Automotive Research, Development and Engineering Center Subject Matter Expert Interview on Automated Lane Centering.* [Interview].

[13] Miller, J., Seewald, A., Heitzer, H.-D., Wegner, M., Kristofik, J., & Standtke, P. (2014, October 29). Interviewees, *TRW Automotive Subject Matter Expert Interview on Automated Lane Centering.* [Interview].

[14] Pimentel, J. R. An Architecture for a Safety-Critical Steer-by-Wire System. Paper presented at *SAE 2004 World Congress & Exhibition*, Detroit, March, 2004.

[15] Heitzer, H.-D. (2003). Development of a Fault-Tolerant Steer-by-Wire Steering System. *Auto Technology, (4),* pp. 56-60.

[16] Cesiel, D., Gaunt, M. C., & Daugherty, B. Development of a Steer-by-Wire System for the GM Sequel. Paper presented at *2006 SAE World Congress*, Detroit, April 3-6, 2006.

[17] SAE International. (2015) *Considerations for ISO 26262 ASIL Hazard Classification* (SAE J2980). Warrendale, PA: Author.

[18] International Electrotechnical Commission. Functional Safety - IEC 61508 Explained (IEC 61508) Geneva: Author.Available at www.iec.ch/functionalsafety/explained/

[19] Isermann, R., Schwarz, R., & Stölzl, S. (2002, October). Fault-Tolerant Drive-by-Wire Systems, IEEE Control Systems. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

[20] Society of Automotive Engineers. (2007). *Diagnostic Trouble Code Definitions* (SAE J2012) Warrendale, PA: Author.

[21] Nissan Motor Corporation. (2013, January 14). 2014 Infinity Q50 at a Glance. (Wed page press release). Kanagawa, Japan: Author. Available at https://newsroom.nissan-global.com/releases/release-0255b33359f22007c36d7a8d14e60b48

[22] Department of Defense. (2012). Department of Defense Standard Practice: System Safety (MIT-STD-882E). Washington, DC: Author.

APPENDIX A: CURRENT SAFETY ISSUES FOR THE EPS SYSTEM

This appendix summarizes the findings from this study's review of current safety issues related to the steer-by-wire system. This study examined crash databases, and NHTSA's vehicle recall and VOQ databases to identify potential safety concerns related to the SbW system.

General Estimates System and Fatality Analysis Reporting System

In 2012, there were an estimated 5.6 million police-reported crashes involving vehicles of all types in the General Estimates System database[44] and 30,800 fatal crashes in the Fatality Analysis Reporting System database.[45] Although they represent two distinct databases, as a result of an effort to standardize the FARS and GES databases in 2010, these two databases now include similar data. The data contained in FARS are actual counts and the data in GES represent a nationally weighted sample of crashes.

Volpe analyzed the 2012 GES and FARS crash databases to identify crashes at least partially attributable to steering system issues. The GES and FARS crash databases, however, do not differentiate between different types of steering systems (e.g., electric power steering versus SbW) and do not identify specific failure modes that may have contributed to the crash. The steering system entry in these databases broadly covers tie rod ends, kingpins, power steering components, ball joints, and other steering components.

The data element "ACC_TYPE" was used to determine the crash category that best describes the type of crash that the vehicle was involved in based on the pre-crash circumstances. To determine if the vehicle had a pre-existing steering issue that may have contributed to the crash, the data element "MFACTOR" was used. More information on the coding can be found in the user's manuals of these databases.

Review of the GES database identified 9,497 crashes (0.17%) at least partially attributable to steering issues. The FARS database identified 20 crashes (0.06%) at least partially attributable to steering issues. The most common steering-related crash types identified in both databases are right roadside departures. The second most common steering-related crash types are left roadside departures.

[44] The GES database contains crash statistics on police-reported crashes across the United States involving all types of vehicles. The information comes from samples of police reports for over five million crashes that occur annually. The database is weighted to characterize a nationally representative sample. Each crash must involve at least one motor vehicle travelling on a roadway that results in property damage, injury, or death, and it must be obtained from a police report. [3]

[45] The FARS database contains information on all crashes in the United States involving at least one fatality resulting from the crash. The fatality can be either an occupant of the vehicle or a non-motorist, such as a pedestrian, and it must have occurred within 30 days of the crash. The crash must have occurred on a public roadway. [4]

NHTSA Motor Vehicle Recall Campaigns

This study identified one motor vehicle recall campaign[46] for model year 2002 through 2015 light vehicles related to SbW systems. The review covered recalls through October 8, 2014. Each recall campaign was assessed based on publically available information to determine how the SbW system may have become unsafe, contributing to a vehicle-level hazard.

The recall related to the SbW system referenced a case in which the SbW system did not provide steering when needed. in addition, the activation of the mechanical backup system occurred too late. This recall cited an external disturbance, specifically a cold ambient temperature, as the cause.

NHTSA Vehicle Owner Questionnaires

Vehicle owners can express their safety concerns to NHTSA via the vehicle owner questionnaire mechanism. NHTSA's Defects Assessment Division screens more than 30,000 VOQs annually to inform their decisions on issues requiring further investigation [5].

Volpe reviewed seven VOQs related to the SbW system. These VOQs were identified by searching the VOQ database for the term "steering" and restricting the search to production makes and models with SbW systems.

The data obtained from the VOQs were categorized in a similar manner as the recalls. Figure 1 shows the breakdown of the VOQs by UCA category. Figure 5 shows the breakdown of VOQs by CF category.

[46] Either NHTSA or the manufacturers may issue recalls due to vehicle or equipment defects once it is determined that a safety defect exists in a motor vehicle or items of motor vehicle equipment that poses a risk to safety [5]. Code of Federal Regulation Title 49 Volume 7 Part 573.6 [6] requires the manufacturer to furnish a report to NHTSA for each defect once a recall is warranted.

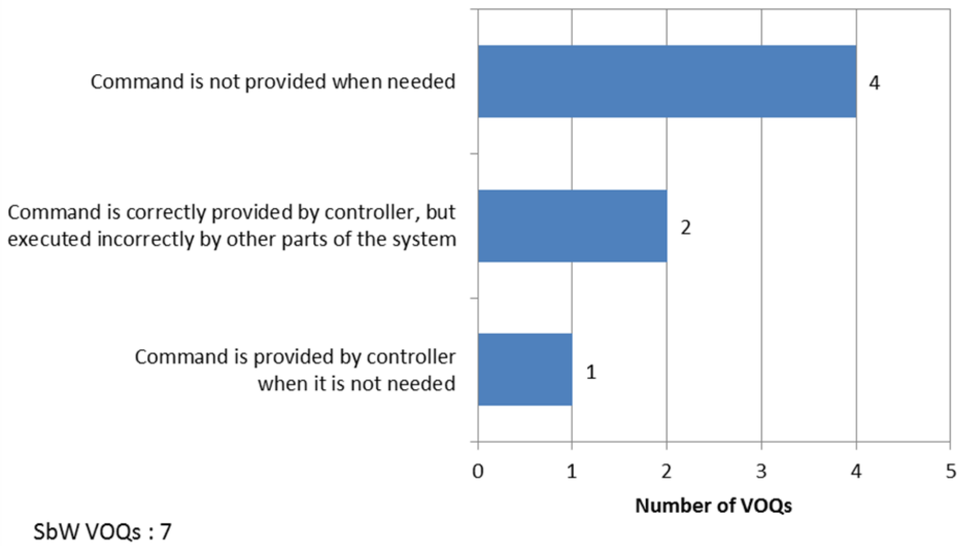


Figure A-1: Unsafe Control Action Breakdown of SbW VOQs

The majority of SbW-related VOQs described situations where the SbW system did not provide steering when expected by the driver. The majority of SbW-related VOQs did not have a specified or even speculative cause of the failure. Of the VOQs that provided a cause, external disturbances to the system were the most frequently reported cause of malfunctions. Note that VOQs are often submitted by vehicle owners based on perceived vehicle behavior and the vehicle owners submitting VOQs may not have technical expertise on how the system operates.

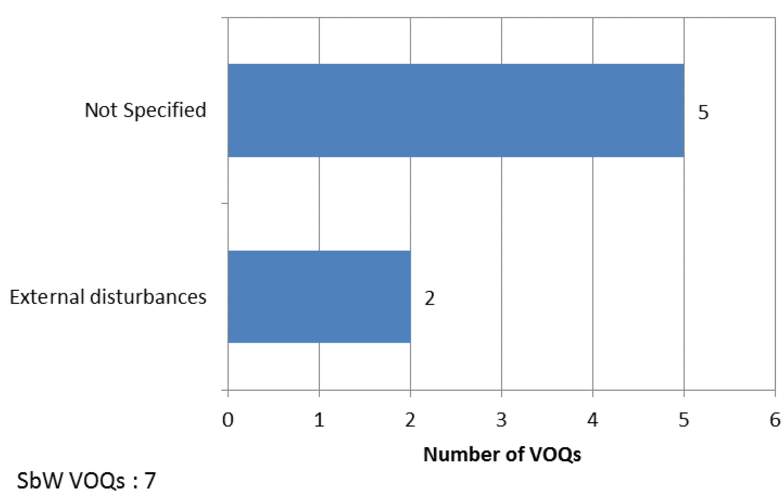


Figure A-2: Causal Factor Breakdown of EPS VOQs

APPENDIX B: STPA CAUSAL FACTOR GUIDEWORDS AND GUIDEWORDS SUBCATEGORIES

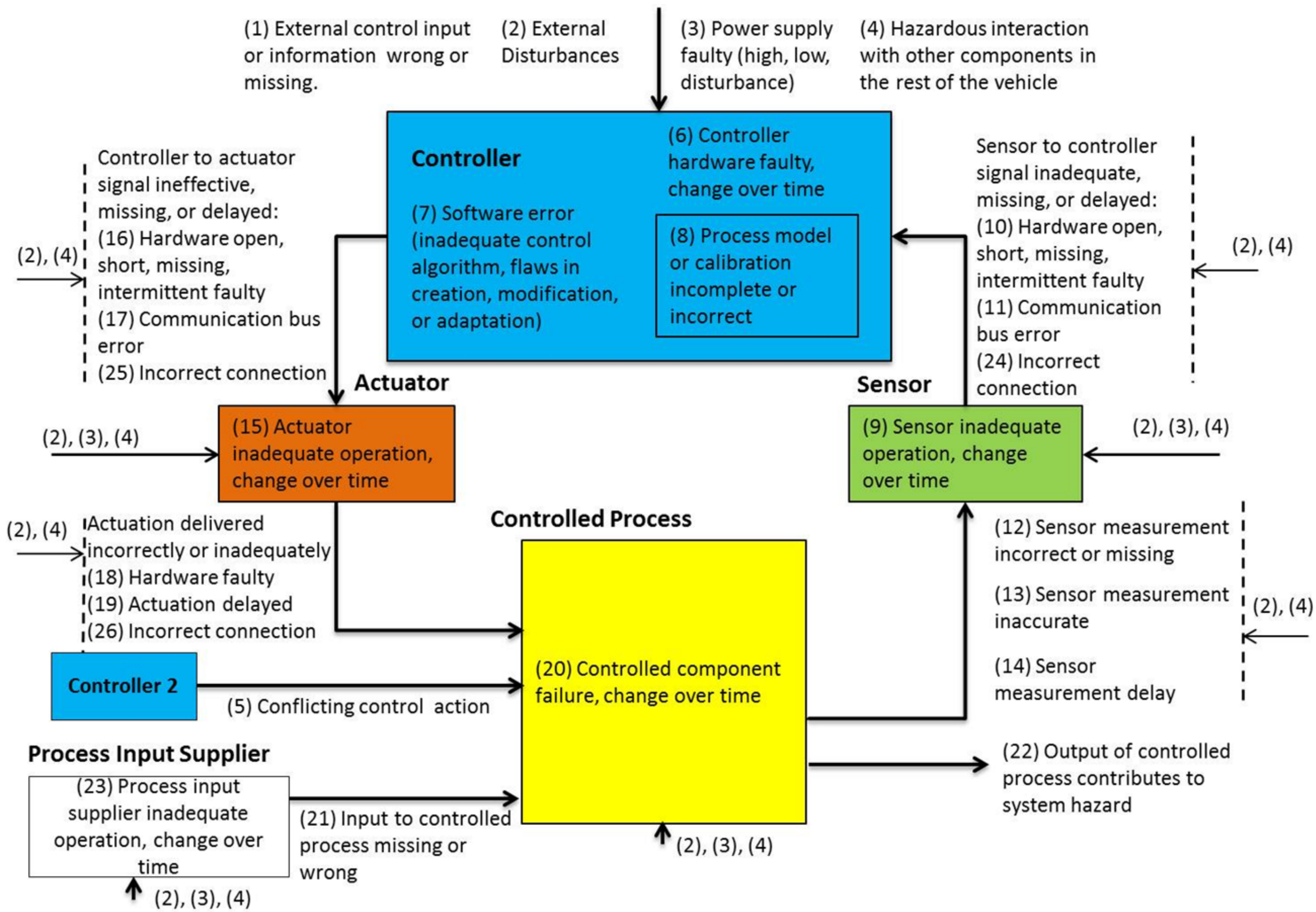


Figure B-1. Causal Factor Categories for Automotive Electronic Control Systems

Table B-1. Causal Factor Sub-categories for Automotive Electronic Control Systems

The numbering in the table below corresponds to those in Figure B-1.

Components	
Controller	**(6) Controller hardware faulty, change over time** • Internal hardware failure • Overheating due to increased resistance in a subcomponent or internal shorting • Over temperature due to faulty cooling system • Degradation over time • Faulty memory storage or retrieval • Faulty internal timing clock • Faulty signal conditioning or converting (e.g., analog-to-digital converter, signal filters) • Unused circuits in the controller
	(7) Software error (inadequate control algorithm, flaws in creation, modification, or adaptation) • Inadequate control algorithm • Flaws in software code creation
	(8) Process model or calibration incomplete or incorrect • Sensor or actuator calibration, including degradation characteristics • Model of the controlled process, including its degradation characteristics
	(2) External control input or information wrong or missing • Timing-related input is incorrect or missing • Spurious input due to shorting or other electrical fault • Corrupted signal • Malicious intruder
	(3) Power supply faulty (high, low, disturbance) • Loss of 12-volt power • Power supply faulty (high, low, disturbance)
	(2) External disturbances • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing)

	(4) Hazardous interaction with other components in the rest of the vehicle • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Moisture, corrosion, or contamination • Excessive heat from other components • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components
Sensor	**(9) Sensor inadequate operation, change over time** • Internal hardware failure • Overheating due to increased resistance in a subcomponent or internal shorting • Degradation over time • Over temperature due to faulty cooling system • Reporting frequency too low
	(3) Power supply faulty (high, low, disturbance) • Loss of 12-volt power • Reference voltage incorrect (e.g., too low, too high) • Power supply faulty (high, low, disturbance)
	(2) External disturbances • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing) • Magnetic interference
	(4) Hazardous interaction with other components in the rest of the vehicle • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Moisture, corrosion, or contamination • Excessive heat from other components • Magnetic interference • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components

Actuator	**(15) Actuator inadequate operation, change over time** • Internal hardware failure • Degradation over time • Over temperature due to faulty cooling system • Incorrectly sized actuator • Relay failure modes, including: (1) does not energize, (2) does not de-energize, and (3) welded contacts • Overheating due to increased resistance in a subcomponent or internal shorting
	(3) Power supply faulty (high, low, disturbance) • Loss of 12-volt power • Power supply faulty (high, low, disturbance)
	(2) External disturbances • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing) • Magnetic interference
	(4) Hazardous interaction with other components in the rest of the vehicle • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Moisture, corrosion, or contamination • Excessive heat from other components • Magnetic interference • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components • Unable to meet demands from multiple components (e.g., inadequate torque)
Controlled Process	**(20) Controlled component failure, change over time** • Internal hardware failure • Degradation over time
	(3) Power supply faulty (high, low, disturbance) • Loss of 12-volt power • Power supply faulty (high, low, disturbance)

Controlled Process	**(2) External disturbances** • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing) • Magnetic interference
	(4) Hazardous interaction with other components in the rest of the vehicle • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Moisture, corrosion, or contamination • Excessive heat from other components • Magnetic interference • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components • Unable to meet demands from multiple components (e.g., inadequate torque)
	(22) Output of controlled process contributing to system hazard
Process Input Supplier to Controlled Process	**(23) Process input supplier inadequate operation, change over time** • Process input supplier inadequate operation, change over time • Electrical noise other than EMI or ESD
	(3) Power supply faulty (high, low, disturbance) • Loss of 12-volt power • Power supply faulty (high, low, disturbance)
	(2) External disturbances • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing) • Magnetic interference

	(4) Hazardous interaction with other components in the rest of the vehicle • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Moisture, corrosion, or contamination • Excessive heat from other components • Magnetic interference • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components • Unable to meet demands from multiple components (e.g., inadequate torque)
Connections	
Sensor to Controller, Controller to Actuator	**(10) and (16) Hardware open, short, missing, intermittent faulty** • Connection is intermittent • Connection is open, short to ground, short to battery, or short to other wires in harness • Electrical noise other than EMI or ESD • Connector contact resistance is too high • Connector shorting between neighboring pins • Connector resistive drift between neighboring pins
	(11) and (17) Communication bus error • Bus overload or bus error • Signal priority too low • Failure of the message generator, transmitter, or receiver • Malicious intruder
	(24) and (25) Incorrect connection • Incorrect wiring connection • Incorrect pin assignment
	(2) External disturbances • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Unused connection terminals affected by moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing) • Active connection terminals affected by moisture, corrosion, or contamination

	(4) Hazardous interaction with other components in the rest of the vehicle • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Unused connection terminals affected by moisture, corrosion, or contamination • Excessive heat from other components • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components • Active connection terminals affected by moisture, corrosion, or contamination • Mechanical connections affected by moisture, corrosion, or contamination
Actuator to Controlled Process	**(18) Actuation delivered incorrectly or inadequately: Hardware faulty**
	(19) Actuation delayed
	(20) Actuator to controlled process incorrect connection
	(2) External disturbances • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Unused connection terminals affected by moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing) • Active connection terminals affected by moisture, corrosion, or contamination • Mechanical connections affected by moisture, corrosion, or contamination

	(4) Hazardous interaction with other components in the rest of the vehicle • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Unused connection terminals affected by moisture, corrosion, or contamination • Excessive heat from other components • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components • Active connection terminals affected by moisture, corrosion, or contamination • Mechanical connections affected by moisture, corrosion, or contamination

Controlled Process to Sensor	**(12) Sensor measurement incorrect or missing** Sensor incorrectly aligned/positioned **(13) Sensor measurement inaccurate** Sensor incorrectly aligned/positioned **(14) Sensor measurement delay** Sensor incorrectly aligned/positioned **(2) External disturbances** • EMI or ESD • Single event effects (e.g., cosmic rays, protons) • Vibration or shock impact • Manufacturing defects and assembly problems • Extreme external temperature or thermal cycling • Unused connection terminals affected by moisture, corrosion, or contamination • Organic growth • Physical interference (e.g., chafing) • Active connection terminals affected by moisture, corrosion, or contamination • Mechanical connections affected by moisture, corrosion, or contamination **(4) Hazardous interaction with other components in the rest of the vehicle** • EMI or ESD • Vibration or shock impact • Physical interference (e.g., chafing) • Unused connection terminals affected by moisture, corrosion, or contamination • Excessive heat from other components • Electrical arcing from neighboring components or exposed terminals • Corona effects from high voltage components • Active connection terminals affected by moisture, corrosion, or contamination • Mechanical connections affected by moisture, corrosion, or contamination
Other Controller to Controlled Process	**(5) Conflicting control action**
Process Input Supplier to Controlled Process	**(21) Input to controlled process missing or wrong**

APPENDIX C: HAZOP STUDY RESULTS

Table C- 1. Function 1: Senses the Torque Applied to the Steering Wheel

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F1-1	Torque cannot be sensed from steering wheel	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw Loss of Vehicle Lateral Motion Control
F1-2	Senses more torque than the actual torque	Unintended Vehicle Lateral Motion/Unintended Yaw
F1-3	Senses torque with greater frequency than needed	No Hazard
F1-4	Senses less torque than the actual torque	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F1-5	Senses torque with less frequency than needed	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F1-6	Intermittent sensing of torque	Intermittent Response to Driver's Control Input
F1-7	Senses torque in opposite directions	Unintended Vehicle Lateral Motion/Unintended Yaw
F1-8	Senses torque when there is none	Unintended Vehicle Lateral Motion/Unintended Yaw
F1-9	Senses a constant torque regardless of steering input	Loss of Vehicle Lateral Motion Control

Table C-2. Function 2: Senses the Steering Wheel Angle

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F2-1	Does not sense steering wheel angle	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw Loss of Vehicle Lateral Motion Control
F2-2	senses large angle while only small angle desired	Unintended Vehicle Lateral Motion/Unintended Yaw
F2-3	Senses the steering angle with more frequency than needed	No Hazard
F2-4	sensed a small angle while large angle desired	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F2-5	Senses the steering angle with less frequency than needed	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F2-6	sensing intermittently the steering wheel angle	Intermittent Response to Driver's Control Input
F2-7	Angle changes positively as opposed to negatively and vice versa	Unintended Vehicle Lateral Motion/Unintended Yaw
F2-8	Measures a change in steering angle in either direction when there is no change in the actual steering wheel angle	Unintended Vehicle Lateral Motion/Unintended Yaw
F2-9	Senses a constant steering wheel angle regardless of steering input	Loss of Vehicle Lateral Motion Control

Table C-3. Function 3: Communicates With Internal Subsystems and Other Vehicle Systems

I.D.	*Malfunction*	*Potential Vehicle Level Hazard*
F3-1	Does not communicate with subsystems	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw Loss of Vehicle Lateral Motion Control
F3-2	Communication of extraneous information to other vehicle systems	No Hazard
F3-3	Some information omitted in communication between internal subsystems and other vehicle systems	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw Loss of Vehicle Lateral Motion Control
F3-4	Communicates intermittently with subsystems	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw Loss of Vehicle Lateral Motion Control
F3-5	Communicates with internal subsystems needlessly, receives steering inputs for other vehicle systems when not requested	No Hazard

Table C-4. Function 4: Electronically Transmits the Driver's Torque From the Steering Wheel to the Steering Actuators

I.D.	*Malfunction*	*Potential Vehicle Level Hazard*
F4-1	Does not transmit torque from steering wheel indefinitely	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F4-2	Does not transmit torque from steering wheel in a timely manner	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F4-3	Transmits more torque than intended	Unintended Vehicle Lateral Motion/Unintended Yaw
F4-4	Transmits less torque than intended	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F4-5	Does not smoothly transmit torque	Intermittent Response to Driver's Control Input
F4-6	Driver's torque input is transmitted in opposite direction	Unintended Vehicle Lateral Motion/Unintended Yaw
F4-7	Torque is transmitted when steering wheel is not adjusted. (Torque is transmitted without any motion of steering wheel)	Unintended Vehicle Lateral Motion/Unintended Yaw
F4-8	Constant torque is applied regardless of steering wheel angle.	Loss of Vehicle Lateral Motion Control

Table C-5. Function 5: Modulates Torque to Create an On-Center, Straight Steer by Default

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F5-1	Does not modulate torque	Unintended Vehicle Lateral Motion/Unintended Yaw
F5-2	Torque is modulated too much	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F5-3	Torque is modulated less than desired	Unintended Vehicle Lateral Motion/Unintended Yaw
F5-4	Modulates torque intermittently	Unintended Vehicle Lateral Motion/Unintended Yaw
F5-5	Modulates torque when vehicle is turning	Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table C-6. Function 6: Disables All Energy Sources to Steering Equipment With the Ignition Is Off or Once the SbW System Enters a Maintenance or Repair Mode

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F6-1	Steering wheel equipment still powered while in maintenance mode	No Hazard
F6-2	Disables some energy sources to steering wheel while leaving some powered	No Hazard
F6-3	Disables all energy sources intermittently	No Hazard
F6-4	Disables all energy sources to steering wheel equipment when not in maintenance/repair mode	Loss of Vehicle Lateral Motion Control
F6-5	Energy sources cannot be re-enabled after maintenance/repair mode is exited	Loss of Vehicle Lateral Motion Control

Table C-7. Function 7: Stores Relevant Data

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F7-1	Does not store relevant data	No Hazard
F7-2	Stores more relevant data	No Hazard
F7-3	Does not store enough relevant data	No Hazard
F7-4	Stores some data and does not store other data	No Hazard
F7-5	Erases relevant data	No Hazard

Table C-8. Function 8: Turns Road Wheels Such That Available/Surplus Lateral Force Is Sufficient to Achieve the Desired Vehicle Path

I.D.	Malfunction	Potential Vehicle Level Hazard
F8-1	does not provide any lateral force	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F8-2	lateral force not sufficient	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F8-3	wheels turn in opposite direction (at least one wheel turns in opposite direction other than intended)	Unintended Vehicle Lateral Motion/Unintended Yaw
F8-4	wheels induce more lateral force than required	Unintended Vehicle Lateral Motion/Unintended Yaw

Table C-9. Function 9: Turns Vehicle at Highest Steering Wheel Input Angle to a TBD Turning Circle/Radius for Sufficient Maneuverability

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F9-1	does not turn vehicle at highest input angle	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F9-2	Input angle is locked at particular angle	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F9-3	turn vehicle at an input angle that is less than maximum	Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table C-10. Function 10: Turns Road Wheels Such That Tire Wear and Tear Is Minimized

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F10-1	Wheel turns is not optimized for tire wear	No Hazard
F10-2	Wheels are turned more than intended	No Hazard

Table C-11. Function 11: Absorbs Environmental Sounds From the Tire Patch and the Mechanical Steering System to Minimize Cabin Noise

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F11-1	Does not absorb environmental sounds from tire patch	No Hazard
F11-2	Environmental sounds not fully absorbed	No Hazard
F11-3	Environmental sounds absorbed at random times	No Hazard

Table C-12. Function 12: Measures and Simulates Feedback to the Driver via the Steering Wheel When the Turning Limit Is Reached

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F12-1	Does not provide any feedback to driver at turning limit	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F12-2	Provides more feedback than needed	Not Applicable
F12-3	Provides less feedback than needed (i.e., driver can still steer)	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F12-4	Intermittently provides feedback to the driver when at the turning limit	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F12-5	Limits steering in the wrong direction (e.g., prevents steering clockwise when wheels are at counterclockwise limit)	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F12-6	Provides feedback when not needed	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F12-7	Stuck at always providing feedback	Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table C-13. Function 13: Measures and Simulates Feedback of Road Feel to the Driver Through the Steering Wheel

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F13-1	Driver's steering wheel does not simulate one or more forms of road feedback normally experienced in non-SbW systems	Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
F13-2	Driver's steering wheel simulates one or more forms of road feedback at a higher intensity than normally experienced in non-SbW systems	Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
F13-3	Driver's steering wheel simulates one or more forms of road feedback at a lower intensity than normally experienced in non-SbW systems	Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
F13-4	Driver's steering wheel does not simulate one or more forms of road feedback consistently as normally experienced in non-SbW systems	Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
F13-5	Driver's steering wheel simulates one or more forms of road feedback not actually present at the road wheels	Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
F13-6	Driver's steering wheel simulates one or more forms of road feedback constantly that is not actually present at the road wheels	Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction

Table C- 14. Function 14: Detects and Simulates Mechanical Failures From Within the Steering System to the Driver Through the Steering Wheel

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F14-1	No haptic feedback is generated	No Hazard (failure of the driver warning strategy)
F14-2	More mechanical failures are transmitted than are actually present	No Hazard (failure of the driver warning strategy)
F14-3	Some mechanical failures not transmitted	No Hazard (failure of the driver warning strategy)
F14-4	Failures are transmitted intermittently	No Hazard (failure of the driver warning strategy)
F14-5	Mechanical failures are transmitted when there are none in the steering system	No Hazard (failure of the driver warning strategy)
F14-6	Haptic feedback is generated indefinitely	No Hazard (failure of the driver warning strategy)

Table C-15. Function 15: Turns the 4WS Mode From On to Off (or Vice-Versa)

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F15-1	Does not turn four wheel steering mode on	No Hazard
F15-2	Does not turn four wheel steering mode off	No Hazard
F15-3	Turns four wheel steering on and off intermittently	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F15-4	Turns on four wheel steering when not requested by driver or steering control module	Unintended Vehicle Lateral Motion/Unintended Yaw
F15-5	Turns off four wheel steering when not requested by driver or steering control module	Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table C-16. Function 16: Turns Rear Wheels In-Phase Smoothly and Without Alarming the Driver When At or Above the In-Phase Vehicle Speed Threshold

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F16-1	Does not turn rear wheels in-phase smoothly (such as lurching and/or step response)	No Hazard
F16-2	Does not turn rear wheels in-phase (remains in nominal position)	Unintended Vehicle Lateral Motion/Unintended Yaw
F16-3	Turns rear wheels in-phase intermittently (intermittent switching between different in-phase angles or between in-phase and straight ahead)	Unintended Vehicle Lateral Motion/Unintended Yaw
F16-4	Rear wheels turn out-of-phase	Unintended Vehicle Lateral Motion/Unintended Yaw
F16-5	Turns rear wheels in-phase below speed threshold	Unintended Vehicle Lateral Motion/Unintended Yaw
F16-6	Turns rear wheels in-phase with a large angle (for example, rear wheel angle > front wheel angle)	Unintended Vehicle Lateral Motion/Unintended Yaw
F16-7	Rear wheels stuck at a particular steering angle	Unintended Vehicle Lateral Motion/Unintended Yaw
F16-8	Rear wheels control stuck in in-phase mode as vehicle crosses the speed threshold	No Hazard
F16-9	Turns rear wheel in-phase slightly (too little)	No Hazard

Table C-17. Function 17: Turns Rear Wheels in Reverse-Phase Smoothly and Without Alarming the Driver When Below the Reverse-Phase Vehicle Speed Threshold

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F17-1	Does not turn rear wheels reverse-phase	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw
F17-2	Does not smoothly turn rear wheels reverse-phase	Unintended Vehicle Lateral Motion/Unintended Yaw
F17-3	Turn rear wheels reverse-phase intermittently; (intermittent switching between different reverse-phase angles or between reverse-phase and straight ahead)	Unintended Vehicle Lateral Motion/Unintended Yaw
F17-4	Turn rear wheels in reverse-phase at too high an angle	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F17-5	Rear wheels turn in-phase	Unintended Vehicle Lateral Motion/Unintended Yaw
F17-6	Turns rear wheels reverse-phase above speed threshold	Unintended Vehicle Lateral Motion/Unintended Yaw
F17-7	Rear wheels stuck at a particular steering angle	Unintended Vehicle Lateral Motion/Unintended Yaw
F17-8	Rear wheels control stuck in reverse-phase mode as vehicle crosses the speed threshold	No Hazard
F17-9	Turns rear wheels in reverse-phase slightly (too little)	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table C-18. Function 18: Turns the Rear Wheels Inward (toe-in) to Supplement Braking and Enhance Stability

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F18-1	Toe-in not actuated to supplement braking force	No Hazard
F18-2	Toe-in actuated more than intended	Increased Rear Wheel Drag
F18-3	Toe-in actuated less than intended	No Hazard
F18-4	Wheels intermittently change from toe-in to straight ahead	Insufficient Vehicle Lateral Motion/Insufficient Yaw Increased Rear Wheel Drag
F18-5	Toe-in actuated in wrong direction (toe-out) OR asymmetric toe-in	Unintended Vehicle Lateral Motion/Unintended Yaw
F18-6	Toe-in actuated when not in braking mode	Insufficient Vehicle Lateral Motion/Insufficient Yaw Increased Rear Wheel Drag
F18-7	Stuck at some toe-in angle or position	Insufficient Vehicle Lateral Motion/Insufficient Yaw Increased Rear Wheel Drag

Table C-19. Function 19: Provides Diagnostics and Fault Detection

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F19-1	Does not provide diagnostics, no faults detected when fault exists	Out of Scope for the HAZOP - This Function Is a Safety Mechanism Intended to Mitigate Hazards From Other Malfunctions.
F19-2	DTC is issued with too high of a frequency	Out of Scope for the HAZOP - This Function Is a Safety Mechanism Intended to Mitigate Hazards From Other Malfunctions.
F19-3	DTC is issued with too low of a frequency	Out of Scope for the HAZOP - This Function Is a Safety Mechanism Intended to Mitigate Hazards From Other Malfunctions.
F19-4	Provides diagnostics and detects faults intermittently	Out of Scope for the HAZOP - This Function Is a Safety Mechanism Intended to Mitigate Hazards From Other Malfunctions.
F19-5	Fault detected when no fault exists	Out of Scope for the HAZOP - This Function Is a Safety Mechanism Intended to Mitigate Hazards From Other Malfunctions.
F19-6	Vehicle stuck in diagnostic mode	Out of Scope for the HAZOP - This Function Is a Safety Mechanism Intended to Mitigate Hazards From Other Malfunctions.

Table C-20. Function 20: Provides Mitigation for System Faults

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F20-1	Does not mitigate failures at all	No Hazard
F20-2	Some faults are detected and mitigated, but not all	No Hazard
F20-3	Faults are intermittently detected, and mitigated on and off	No Hazard
F20-4	Fault is falsely detected, followed by a mitigation for a non-existent fault	No Hazard
F20-5	Mitigation is continuously provided, regardless of fault presence	No Hazard

Table C-21. Function 21: Electronically Transmits Steering System Failures to the Driver Using All or Some of the Dashboard Indicators, Chimes, or Similar Alerts

I.D.	*Malfunction*	*Potential Vehicle Level Hazard*
F21-1	Failures not electronically transmitted	No Hazard (failure of the driver warning strategy)
F21-2	More indicators are activated than intended	No Hazard (failure of the driver warning strategy)
F21-3	Some steering system failures are not electronically transmitted	No Hazard (failure of the driver warning strategy)
F21-4	Failures are transmitted intermittently	No Hazard (failure of the driver warning strategy)
F21-5	Mechanical failures are transmitted when there are none in the steering system	No Hazard (failure of the driver warning strategy)
F21-6	Warnings are continuous	No Hazard (failure of the driver warning strategy)

Table C-22. Function 22: Provide Steerability in the Event of Power Loss or Other Critical Fault

I.D.	*Malfunction*	*Potential Vehicle Level Hazard*
F22-1	Steering is not provided in the event of power loss or other critical fault.	Loss of Vehicle Lateral Motion Control
F22-2	Clutch cycles between an engaged and disengaged state when requested to be completely engaged or completely disengaged	Loss of Vehicle Lateral Motion Control
F22-3	Clutch engages when not requested	Unintended Vehicle Lateral Motion/Unintended Yaw Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
F22-4	Clutch engages more than intended.	No Hazard
F22-5	Clutch is stuck in disengaged position or engaged position regardless of engagement request	Loss of Vehicle Lateral Motion Control
F22-6	Clutch is not fully engaged and slips when requested to fully engage	Insufficient Vehicle Lateral Motion/Insufficient Yaw
F22-7	Steering is not provided in the event of power loss or other critical fault.	Loss of Vehicle Lateral Motion Control

Table C-23. Function 23: Does Not Respond to Steering Wheel Inputs When Vehicle Is Off and Motionless

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F23-1	Steering wheel responds when vehicle is off, steering wheel input is communicated to wheels	No Hazard
F23-2	Locks and unlocks the steering wheel while vehicle is off when it should lock only	No Hazard
F23-3	Steering wheel responds when vehicle is off	No Hazard
F23-4	Steering wheel unresponsive when vehicle is not off	Loss of Vehicle Lateral Motion Control
F23-5	Steering wheel unresponsive when vehicle is off, but still moving (e.g., accidentally turned off)	Unintended Vehicle Lateral Motion/Unintended Yaw Insufficient Vehicle Lateral Motion/Insufficient Yaw Loss of Vehicle Lateral Motion Control

Table C-24. Function 24: Responds to Steering Wheel Inputs for Normal Function After Vehicle Is Accessed With Security Device and Re-Orients Steering Wheel to Road Wheels if Necessary

I.D.	***Malfunction***	***Potential Vehicle Level Hazard***
F24-1	Steering wheel remains unresponsive when accessed with security device.	Loss of Vehicle Lateral Motion Control
F24-2	Intermittently issues unlock command when already responsive/unlocked	No Hazard
F24-3	Locks steering wheel when accessed with security device	Loss of Vehicle Lateral Motion Control
F24-4	Steering wheel responds even when not accessed with security device	No Hazard

APPENDIX D: UNSAFE CONTROL ACTION ASSESSMENT TABLES

Table D- 1: UCA Assessment for the "Command Torque to Change Front Road Wheel Heading by Θ Degrees" Control Action

Context Variables (Command Torque to Change Front Road Wheel Heading by Θ Degrees)		**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Driver's Steering Command	Other Vehicle Systems' Steering Command	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
None	None	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
None	In Θ Direction	H2, H5	No Hazard	H1	H2	H1	H2	H1, H2	N/A	H2
None	In -Θ Direction	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
None	In Both the Θ and -Θ Directions	H2, H5	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
In Θ Direction	None	H2, H5	No Hazard	H1	H2	H1	H2	H1, H2	N/A	H2
In Θ Direction	In Θ Direction	H2, H5	No Hazard	H1	H2	H1	H2	H1, H2	N/A	H2
In Θ Direction	In -Θ Direction	H2, H5	H3, H4	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
In Θ Direction	In Both the Θ and -Θ Directions	H2, H5	H3, H4	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
In -Θ Direction	None	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

Context Variables (Command Torque to Change Front Road Wheel Heading by Θ Degrees)		**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Driver's Steering Command	Other Vehicle Systems' Steering Command	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
In -Θ Direction	In Θ Direction	H3	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
In -Θ Direction	In -Θ Direction	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
In -Θ Direction	In Both the Θ and -Θ Directions	H3	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

Vehicle Level Hazards.

- H1: Unintended Vehicle Lateral Motion/Unintended Yaw
- H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw
- H3: Unintended Vehicle Lateral Motion/Unintended Yaw – Improper Resolution of Conflicting Steering Commands
- H4: Insufficient Vehicle Lateral Motion/Insufficient Yaw – Improper Resolution of Conflicting Steering Commands
- H5: Loss of Lateral Motion Control

Table D- 2: UCA Assessment for the "Command the Rear Wheels to Turn In-Phase" Control Action

Context Variables (Command the Rear Wheels to Turn In-Phase)		**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Steering Torque Commanded (from Driver or Other Vehicle Systems)	Vehicle Speed	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
Yes	At or Above Threshold Value for Activating In-Phase Steering	No Hazard	No Hazard	H1	No Hazard	H1	No Hazard	H1	H1	No Hazard
Yes	Below Threshold Value for Activating In-Phase Steering	No Hazard	H2	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
No	At or Above Threshold Value for Activating In-Phase Steering	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
No	Below Threshold Value for Activat	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

Context Variables (Command the Rear Wheels to Turn In-Phase)		**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Steering Torque Commanded (from Driver or Other Vehicle Systems)	Vehicle Speed	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
	ing In-Phase Steering									
Vehicle Level Hazards. • H1: Unintended Vehicle Lateral Motion/Unintended Yaw • H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw										

Table D- 3: UCA Assessment for the "Command Rear Wheels to Turn in Reverse-Phase" Control Action

Context Variables (Command Rear Wheels to Turn in Reverse-Phase)		**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Steering Torque Commanded (from Driver or Other Vehicle Systems)	Vehicle Speed	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
Yes	Above Maximum Threshold Value for Activating Reverse-Phase Steering	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
Yes	At or Below Maximum Threshold Value for Activating Reverse-Phase Steering	No Hazard	No Hazard	H1	No Hazard	H1	No Hazard	H1, H2	No Hazard	H1
No	Above Maximum Threshold Value for Activating Reverse-Phase Steering	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

No	At or Below Maximum Threshold Value for Activating Reverse-Phase Steering	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

Vehicle Level Hazards.

- H1: Unintended Vehicle Lateral Motion/Unintended Yaw
- H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table D- 4: UCA Assessment for the "Command the Rear Wheels to Toe-In" Control Action

Context Variables (Command the Rear Wheels to Toe-In)		**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Steering Torque Commanded (from Driver or Other Vehicle Systems)	Brakes Applied	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
Yes	Yes	No Hazard	H2	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
Yes	No	No Hazard	H2	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
No	Yes	No Hazard	No Hazard	No Hazard	No Hazard	No Hazard	No Hazard	H1, H2	N/A	No Hazard
No	No	No Hazard	No Hazard	No Hazard	No Hazard	No Hazard	No Hazard	H1, H2	N/A	No Hazard

Vehicle Level Hazards:

- H1: Unintended Vehicle Lateral Motion/Unintended Yaw
- H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table D- 5: UCA Assessment for the "Command Steering Feedback Torque" Control Action

Context Variables (Command Steering Feedback Torque)	**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Is Steering Feedback Needed	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
Yes	H6	No Hazard	H6	H6	H6	H6	H6	N/A	N/A
No	No Hazard	H6	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided
Vehicle-Level Hazards: • H6: Incorrect (e.g., delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction									

Table D- 6: UCA Assessment for the “Engage Mechanical Backup” Control Action

Context Variables (Command Steering Feedback Torque)	**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Steer-by-Wire Fault Present	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
Yes	H5	No Hazard	No Hazard	H2	No Hazard	H2	H2, H5	N/A	H5
No	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

This control action only applies to Intermediate SbW Systems.
Vehicle-Level Hazards:

- H1: Unintended Vehicle Lateral Motion/Unintended Yaw
- H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw
- H5: Loss of Lateral Motion Control

Table D- 7: UCA Assessment for the “Command Steering” Driver Control Action

Context Variables (Command Steering)	**Guidewords for Assessing Whether the Control Action May Be Unsafe**								
Is Steering Needed	Not provided in this context	Provided in this context	Provided, but duration is too long	Provided, but duration is too short	Provided, but the intensity is incorrect (too much)	Provided, but the intensity is incorrect (too little)	Provided, but executed incorrectly	Provided, but the starting time is too soon	Provided, but the starting time is too late
Yes	N/A[i]	No Hazard	H1	H2	H1	H2	H1, H2	N/A	H2
No	No Hazard	H1	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided	Hazardous if provided

[i] This analysis assumes a competent driver. It is expected that the driver will provide the required steering based on available cues.

Vehicle Level Hazards:

- H1: Unintended Vehicle Lateral Motion/Unintended Yaw
- H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

APPENDIX E: STPA STEP 1: UCAS AND MAPPING TO HAZARDS

Table E- 1: Unsafe Control Actions for "Command Torque to Change the Front-Wheel Heading by Θ Degrees"

Vehicle Level Hazard	**Unsafe Control Actions (Command Torque to Change the Front-Wheel Heading by Θ Degrees)**
H3	The steering system control module does not command torque to change the front road wheel heading by Θ degrees when: • the driver is steering is in the -Θ direction, and • the other vehicle systems request steering in either the Θ direction or in both the Θ and -Θ directions.
H2	The steering system control module does not command torque to change the front road wheel heading by Θ degrees when: • the driver is not steering, and • other vehicle systems are requesting steering in the Θ direction or in both the Θ and -Θ direction.
H2	The steering system control module does not command torque to change the front road wheel heading by Θ degrees when: • the driver is steering in the direction of Θ.
H1	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is not steering, and • other vehicle systems are not requesting steering, are requesting steering in the -Θ direction, or are requesting steering in both the Θ and -Θ directions.
H3, H4	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver's steering command is in the Θ direction, and • the other vehicle systems request steering in the -Θ direction or request steering in both the Θ and -Θ directions.
H1	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver's steering command is in the -Θ direction.
H1	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is steering in the Θ direction, and • other vehicle systems are not requesting a steering adjustment or are requesting a steering adjustment in the Θ direction but the steering heading is adjusted for too long (i.e., the heading changes by more than Θ degrees).
H2	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is steering in the Θ direction, and • other vehicle systems are not requesting a steering adjustment or are requesting a steering adjustment in the Θ direction but the steering heading is adjusted for too short a period (i.e., the heading changes by less than Θ degrees).
H1	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is not issuing a steering command, and • other vehicle systems request steering in the Θ direction, but the steering heading is adjusted for too long (i.e., the heading changes by more than Θ degrees).

Vehicle Level Hazard	Unsafe Control Actions (Command Torque to Change the Front-Wheel Heading by Θ Degrees)
H2	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is not issuing a steering command, and • other vehicle systems request steering in the Θ direction, but the steering heading is adjusted for too short a period (i.e., the heading changes by less than Θ degrees).
H1, H2	The steering system control module correctly issues the command for torque to change the front road wheel heading by Θ degrees, but the command is executed incorrectly.
H1	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is not issuing a steering command, and • other vehicle systems request steering in the Θ direction, but too much torque is commanded.
H1	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is steering in the Θ direction, and • other vehicle systems are not requesting a steering adjustment or are requesting a steering adjustment in the Θ direction but too much torque is commanded.
H2	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is steering in the Θ direction, and • other vehicle systems are not requesting a steering adjustment or are requesting a steering adjustment in the Θ direction but too little torque is commanded.
H2	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is not issuing a steering command, and • other vehicle systems request steering in the Θ direction, but too little torque is commanded.
H2	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is not issuing a steering command, and • other vehicle systems request steering in the Θ direction, but the command is issued too late.
H2	The steering system control module commands torque to change the front road wheel heading by Θ degrees when: • the driver is steering in the Θ direction, and • other vehicle systems are not requesting a steering adjustment or are requesting a steering adjustment in the Θ direction but the command is issued too late.

H1: Unintended Vehicle Lateral Motion/Unintended Yaw
H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw
H3: Unintended Vehicle Lateral Motion/Unintended Yaw – Improper Resolution of Conflicting Steering Commands
H4: Insufficient Vehicle Lateral Motion/Insufficient Yaw – Improper Resolution of Conflicting Steering Commands

Table E- 2: Unsafe Control Actions for "Command Torque From the Rear-Wheel Motors to Turn the Rear Wheels In-Phase"

Vehicle Level Hazard	**Unsafe Control Actions (Command Torque From the Rear-Wheel Motors to Turn the Rear Wheels In-Phase)**
H2	The steering system control module commands the rear wheels to turn in-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is below the threshold for activating in-phase steering.
H1	The steering system control module commands the rear wheels to turn in-phase when: • steering is not commanded by the driver or other vehicle systems.
H1	The steering system control module commands the rear wheels to turn in-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is at or above the threshold for activating in-phase steering, but the rear wheels heading is adjusted for too long a period (e.g., after the driver has stopped turning).
H1	The steering system control module commands the rear wheels to turn in-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is at or above the threshold for activating in-phase steering, but the rear wheels heading is changed by too much.
H1	The steering system control module correctly commands the rear wheels to turn in-phase, but the command is executed incorrectly.
H1	The steering system control module commands the rear wheels to turn in-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is at or above the threshold for activating in-phase steering, but the command is provided too soon.

H1: Unintended Vehicle Lateral Motion/Unintended Yaw
H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table E- 3: Unsafe Control Actions for "Command Torque From the Rear-Wheel Motors to Turn the Rear Wheels in Reverse-Phase"

Vehicle Level Hazard	**Unsafe Control Actions (Command Torque From the Rear-Wheel Motors to Turn the Rear Wheels in Reverse-Phase)**
H1	The steering system control module commands the rear wheels to turn in reverse-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is above the maximum speed value for activating reverse-phase steering.
H1	The steering system control module commands the rear wheels to turn in reverse-phase when: • steering is not commanded by the driver or other vehicle systems.
H1	The steering system control module commands the rear wheels to turn in reverse-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is at or below the maximum speed value for activating reverse-phase steering, but the rear wheel heading is adjusted for too long of a period (e.g., the wheels remain turned after the steering command stops).
H1	The steering system control module commands the rear wheels to turn in reverse-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is at or below the maximum speed value for activating reverse-phase steering, but the rear wheel heading is adjusted by too much.
H1, H2	The steering system control module correctly commands the rear wheels to turn in reverse-phase, but the command is executed incorrectly.
H1	The steering system control module commands the rear wheels to turn in reverse-phase when: • steering is commanded by the driver or other vehicle systems, and • the vehicle speed is at or below the maximum speed value for activating reverse-phase steering, but the command is issued too late (e.g., the rear wheels turn after the steering command stops).

H1: Unintended Vehicle Lateral Motion/Unintended Yaw
H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table E- 4: Unsafe Control Actions for "Command Torque From the Rear-Wheel Motors to Toe-In the Rear Wheels"

Vehicle Level Hazard	Unsafe Control Actions (Command Torque From the Rear-Wheel Motors to Toe-In the Rear Wheels)
H2	The steering system control module commands the rear wheels to toe-in when: • the steering is commanded by the driver or other vehicle systems.
H1, H2	The steering system control module correctly commands the rear wheels to toe-in, but the command is executed incorrectly.

H1: Unintended Vehicle Lateral Motion/Unintended Yaw
H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

Table E- 5: Unsafe Control Actions for "Command Feedback Torque From the Feedback Motor"

Vehicle Level Hazard	**Unsafe Control Actions (Command Feedback Torque From the Feedback Motor)**
H6	The steering system control module does not command torque from the driver feedback motor when: • steering feedback to the driver is needed.
H6	The steering system control module commands torque from the driver feedback motor when: • steering feedback to the driver is not needed.
H6	The steering system control module commands torque from the driver feedback motor when: • steering feedback to the driver is needed, but the duration of the command is too long.
H6	The steering system control module commands torque from the driver feedback motor when: • steering feedback to the driver is needed, but the duration of the command is too short.
H6	The steering system control module correctly commands torque from the driver feedback motor, but the command is executed incorrectly.
H6	The steering system control module commands torque from the driver feedback motor when: • steering feedback to the driver is needed, but too little torque is commanded.
H6	The steering system control module commands torque from the driver feedback motor when: • steering feedback to the driver is needed, but too much torque is commanded.

H6: Incorrect Feedback Resulting in Incorrect Driver Reaction

Table E- 6: Unsafe Control Actions for "Engage Mechanical Backup"

Vehicle Level Hazard	**Unsafe Control Actions (Command Feedback Torque From the Feedback Motor)**
H5	The steering system control module does not engage the mechanical clutch when: • there is a steer-by-wire system fault.
H1	The steering system control module engages the mechanical clutch when: • there is not a steer-by-wire system fault.
H5	The steering system control module engages the mechanical clutch when: there is a steer-by-wire system fault, but the command is provided too short a period (i.e., the clutch does not remain engaged while a fault in the steer-by-wire system persists).
H2, H5	The steering system control module correctly commands the mechanical clutch to engage, but the command is executed incorrectly.
H2	The steering system control module engages the mechanical clutch when: there is a steer-by-wire system fault, but the clutch is engaged with too little force (e.g., the clutch may not engage fully).
H5	The steering system control module engages the mechanical clutch when: there is a steer-by-wire system fault, but the command is provided too late.

H1: Unintended Vehicle Lateral Motion/Unintended Yaw
H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw
H5: Loss of Lateral Motion Control

Table E- 7: Unsafe Control Actions for the “Rotate Steering Wheel”

Vehicle Level Hazard	**Unsafe Control Actions (Rotate Steering Wheel)**
H1	The driver commands steering when: • a steering adjustment is not needed.
H1	The driver commands steering when: • a steering adjustment is needed, but too much steering is commanded.
H2	The driver commands steering when: • a steering adjustment is needed, but too little steering is commanded.
H1, H2	The driver correctly commands steering, but the command is executed incorrectly.
H1	The driver commands steering when: • a steering adjustment is needed, but the duration is too long.
H2	The driver commands steering when: • a steering adjustment is needed, but the duration is too short.
H2	The driver commands steering when: • the lateral automation system is disabled, and • a steering adjustment is needed, but the steering command is provided too late.

H1: Unintended Vehicle Lateral Motion/Unintended Yaw
H2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

APPENDIX F: OPERATIONAL SITUATIONS

1. Driving at a Very High Speed (130 kph ≤ V) on a Country Road
2. Driving at a Very High Speed (130 kph ≤ V) on a divided highway.
3. Driving at a Very High Speed (130 kph ≤ V) on a limited access highway.
4. Driving at high speed (100 kph ≤ V < 130 kph) on a country road.
5. Driving at high speed (100 kph ≤ V < 130 kph) on a divided highway.
6. Driving at high speed (100 kph ≤ V < 130 kph) on a limited access highway.
7. Driving at medium speed (40 kph ≤ V < 100 kph) on a country road.
8. Driving at medium speed (40 kph ≤ V < 100 kph) on a divided highway.
9. Driving at medium speed (40 kph ≤ V < 100 kph) on a limited access highway.
10. Driving at medium speed (40 kph ≤ V < 100 kph) on a city street, with pedestrians present.
11. Driving at low speed (V < 40 kph) on a country road.
12. Driving at low speed (V < 40 kph) on a city street, with pedestrians present.
13. Driving at low speed (V < 40 kph) in a parking lot or driveway, with pedestrians present.
14. Driving at low speed (V < 40 kph) in a parking lot or driveway, with no pedestrians present.

APPENDIX G: ASIL ASSESSMENT

Table G-1: Unintended Vehicle Lateral Motion/Unintended Yaw

Vehicle-Level Effects	Operating Scenario Description	Potential Crash Scenario	ASIL Assessment (Unintended Vehicle Lateral Motion/Unintended Yaw)			ASIL
			Exposure	Severity	Controllability	
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Limited Access Highway	Vehicle Roll-Over	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a City Street, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Medium Speed	E4	S3	C3	D
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C2	C
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a City Street, With Pedestrians Present	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C2	C

Vehicle-Level Effects	Operating Scenario Description	Potential Crash Scenario	ASIL Assessment (Unintended Vehicle Lateral Motion/Unintended Yaw)			ASIL
			Exposure	Severity	Controllability	
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Low Speed	E4	S1	C2	A
Deviation From Selected Trajectory but Resulting in No Safety Issues	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With No Pedestrians Present	No Safety Issues	E4	S0	C1	QM

Table G-2: Insufficient Vehicle Lateral Motion/Insufficient Yaw

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Insufficient Vehicle Lateral Motion/Insufficient Yaw)			ASIL
			Exposure	Severity	Controllability	
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Limited Access Highway	Vehicle Roll-Over	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a City Street, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Medium Speed	E4	S3	C3	D
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C2	C
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a City Street, With Pedestrians Present	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C2	C
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Low Speed	E4	S1	C2	A

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Insufficient Vehicle Lateral Motion/Insufficient Yaw)			ASIL
			Exposure	Severity	Controllability	
Deviation From Selected Trajectory but Resulting in No Safety Issues	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With No Pedestrians Present	No Safety Issues	E4	S0	C1	QM

Table G-3: Loss of Lateral Motion Control

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Loss of Lateral Motion Control)			ASIL
			Exposure	Severity	Controllability	
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Limited Access Highway	Vehicle Roll-Over	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a City Street, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Medium Speed	E4	S3	C3	D
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C2	C
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a City Street, With Pedestrians Present	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C2	C

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Loss of Lateral Motion Control)			ASIL
			Exposure	Severity	Controllability	
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Low Speed	E4	S1	C2	A
Deviation From Selected Trajectory but Resulting in No Safety Issues	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With No Pedestrians Present	No Safety Issues	E4	S0	C1	QM

Table G-4: Reduced Responsiveness to the Driver's Commands Due to Increased Rear Wheel Drag

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (reduced responsiveness to the driver's commands due to increased rear wheel drag)			AS IL
			Expos ure	Severit y	Controlla bility	
Reduced Controllability	Driving at a Very High Speed (130 kph ≤ V) on a Country Road	Rear-End Collision at Low Delta-V	E3	S1	C1	Q M
Reduced Controllability	Driving at a Very High Speed (130 kph ≤ V) on a Divided Highway	Rear-End Collision at Low Delta-V	E3	S1	C1	Q M
Reduced Controllability	Driving at a Very High Speed (130 kph ≤ V) on a Limited Access Highway	Rear-End Collision at Low Delta-V	E3	S1	C1	Q M
Reduced Controllability	Driving at High Speed (100 kph ≤ V < 130 kph) on a Country Road	Rear-End Collision at Low Delta-V	E4	S1	C2	A
Reduced Controllability	Driving at High Speed (100 kph ≤ V < 130 kph) on a Divided Highway	Rear-End Collision at Low Delta-V	E4	S1	C2	A
Reduced Controllability	Driving at High Speed (100 kph ≤ V < 130 kph) on a Limited Access Highway	Rear-End Collision at Low Delta-V	E4	S1	C2	A
Reduced Controllability	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Country Road	Rear-End Collision at Low Delta-V	E4	S1	C1	Q M
Reduced Controllability	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Divided Highway	Rear-End Collision at Low Delta-V	E4	S1	C1	Q M
Reduced Controllability	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Limited Access Highway	Rear-End Collision at Low Delta-V	E4	S1	C1	Q M
Reduced Controllability	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a City Street, With Pedestrians Present	Rear-End Collision at Low Delta-V	E4	S1	C1	Q M
Reduced Controllability	Driving at Low Speed (V < 40 kph) on a Country Road	Rear-End Collision at Low Delta-V	E4	S1	C1	Q M
Reduced Controllability	Driving at Low Speed (V < 40 kph) on a City Street, With Pedestrians Present	Rear-End Collision at Low Delta-V	E4	S1	C1	Q M

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (reduced responsiveness to the driver's commands due to increased rear wheel drag)			ASIL
			Exposure	Severity	Controllability	
Reduced Controllability	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With Pedestrians Present	No Accident Issue Expected	E4	S1	C1	QM
Reduced Controllability	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With No Pedestrians Present	No Accident Issue Expected	E4	S0	C1	QM

Table G-5: Incorrect (Delayed, Missing, Counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction

Vehicle-Level Effect	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Incorrect Feedback Resulting in Incorrect Driver Reaction)			ASIL
			Exposure	Severity	Controllability	
Driver Could Lose Control but Very Unlikely	Driving at a Very High Speed (130 kph ≤ V) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E3	S3	C1	A
Driver Could Lose Control but Very Unlikely	Driving at a Very High Speed (130 kph ≤ V) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E3	S3	C1	A
Driver Could Lose Control but Very Unlikely	Driving at a Very High Speed (130 kph ≤ V) on a Limited Access Highway	Vehicle Roll-Over	E3	S3	C1	A
Driver Could Lose Control but Very Unlikely	Driving at High Speed (100 kph ≤ V < 130 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at High Speed (100 kph ≤ V < 130 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at High Speed (100 kph ≤ V < 130 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a City Street, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Medium Speed	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at Low Speed (V < 40 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C1	B
Driver Could Lose Control but Very Unlikely	Driving at Low Speed (V < 40 kph) on a City Street, With Pedestrians Present	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C1	B

Vehicle-Level Effect	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Incorrect Feedback Resulting in Incorrect Driver Reaction)			ASIL
			Exposure	Severity	Controllability	
Driver Would Stop the Vehicle	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Low Speed	E4	S1	C1	QM
Driver Would Likely Stop the Vehicle	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With No Pedestrians Present	No Safety Issues	E4	S0	C1	QM

Table G-6: Intermittent System Response to Driver Controls

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Loss of Lateral Motion Control)			ASIL
			Exposure	Severity	Controllability	
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at a Very High Speed (130 kph ≤ V) on a Limited Access Highway	Vehicle Roll-Over	E3	S3	C3	C
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Radical/Immediate Deviation From Selected Trajectory	Driving at High Speed (100 kph ≤ V < 130 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Divided Highway	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a Limited Access Highway	Vehicle Roll-Over	E4	S3	C3	D
Immediate Deviation From Selected Trajectory	Driving at Medium Speed (40 kph ≤ V < 100 kph) on a City Street, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Medium Speed	E4	S3	C3	D
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a Country Road	Vehicle Head-On With On-Coming Vehicle	E4	S3	C2	C
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) on a City Street, With Pedestrians Present	Vehicle Impact With Rigid Off-Road Obstruction	E4	S3	C2	C

Vehicle-Level Effects	Operating Scenario Description	Potential Accident Scenario	ASIL Assessment (Loss of Lateral Motion Control)			ASIL
			Exposure	Severity	Controllability	
Deviation From Selected Trajectory	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With Pedestrians Present	The Vehicle Runs Into a Pedestrian at Low Speed	E4	S1	C2	A
Deviation From Selected Trajectory but Resulting in No Safety Issues	Driving at Low Speed (V < 40 kph) in a Parking Lot or Driveway, With No Pedestrians Present	No Safety Issues	E4	S0	C1	QM

APPENDIX H: FMEA

Table H- 1. System/Subsystem: Power Supply

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
Power Supply	Failure of one of the two Power Sources	H1, H2, H3, H4, H5, H6	Supply power out of range	Second power source provides redundancy	Mechanical Back-up engages
			Supply power quality failure		
			Supply power lost		

H1: Potential Unintended Vehicle Lateral Motion/Yaw
H2: Potential Insufficient Vehicle Lateral Motion/Yaw
H3: Loss of Lateral Motion Control
H4: Reduced Responsiveness to the Driver's Commands Due to Increased Rear-Wheel Drag
H5: Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
H6: Intermittent Response to Driver's Control Input

Table H- 2. System/Subsystem: Steering Wheel Sensors

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
Steering Wheel Sensors	Failure of a steering wheel sensor	H1, H2, H3, H6	Hardware fault (sensors, ICs, circuit components, circuit boards…)	Fail-op steering wheel sensor configuration provides redundancy	Wheel sensors are Fail-Safe with dual redundancy - mechanical backup is engaged by voter
			Internal connection fault (short or open)		
			Break in wheel sensor I/Os connections		
			Short in wheel sensor I/Os connections to ground or voltage		
			Short in wheel sensor I/Os connections to another connection		
			Signal connector connection failure		
			Power connector connection failure		
			Steering wheel sensor calculation algorithm fault		
			SW parameters corrupted		
			EMC/EMI fault		
			Contamination/Corrosion		
			NVH fault		
			Environmental temperature exposure failure		
			Aging (durability)		
			Manufacturing defect		
			Manufacturing variability		
			Service/Maintenance		

H1: Potential Unintended Vehicle Lateral Motion/Yaw
H2: Potential Insufficient Vehicle Lateral Motion/Yaw
H3: Loss of Lateral Motion Control
H6: Intermittent Response to Driver's Control Input

Table H- 3. System/Subsystem: Steer-by-Wire Control Module

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
SbW Control Module	Failure of one of the SbW controllers	H1, H2, H3, H4, H5, H6	Hardware fault (sensors, ICs, circuit components, circuit boards…)	Fail-operational controller configuration provides redundancy	Controllers are Fail-Safe with dual redundancy - mechanical backup is engaged by voter
			Internal connection fault (short or open)		
			Break in control module I/Os connections		
			Short in control module I/Os connections to ground or voltage		
			Short in control module I/Os connections to another connection		
			Signal connector connection failure		
			Power connector connection failure		
			Firmware crash/failure (SW parameters corrupted)		
			EMI/EMC fault		
			Contamination/Corrosion		
			NVH fault		
			Environmental temperature exposure failure		
			Aging (durability)		
			Manufacturing defect		
			Manufacturing variability		
			Service/Maintenance		

H1: Potential Unintended Vehicle Lateral Motion/Yaw
H2: Potential Insufficient Vehicle Lateral Motion/Yaw
H3: Loss of Lateral Motion Control
H4: Reduced Responsiveness to the Driver's Commands Due to Increased Rear-Wheel Drag
H5: Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
H6: Intermittent Response to Driver's Control Input

Table H- 4. System/Subsystem: Steering Actuator

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
Steering Motor	Failure of the motor driver	H1, H2, H3, H6	Internal connection fault (short or open)	3-Way Voter is Fail-Safe and removes power from the steering motor	3-Way Voter is Fail-Safe and removes power from the steering motor
			Signal connector connection failure		
			Power connector connection failure		
			HW fault in stator		
			HW fault in rotor		
			HW fault in insulation and windings		
			Over or under current		
			Manufacturing defect		
			Manufacturing variability		
			Over-emission of EMF		
			Inadequate shielding		
Rack Position Sensor	Failure of the rack position sensor	H1, H2, H3, H5, H6	Hardware fault (sensors, ICs, circuit components, circuit boards…)	Each of the two sensors is either Fail-Safe or has dual redundancy	Each of the two sensors is either Fail-Safe or has dual redundancy
			Internal connection fault (short or open)		
			Break in position sensor I/Os connections		
			Short in position sensor I/Os connections to ground or voltage		
			Short in position sensor I/Os connections to another connection		
			Signal connector connection failure		
			Power connector connection failure		
			Rack position calculation algorithm fault		
			SW parameters corrupted		
			EMC/EMI fault		

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
			Contamination/Corrosion		
			NVH fault		
			Environmental temperature exposure failure		
			Aging (durability)		
			Manufacturing defect		
			Manufacturing variability		
			Service/Maintenance		
Mechanical components (e.g., rack and pinion)	Failure of integrity of mechanical steering elements	H1, H2, H3, H5, H6	Mechanical failures are outside the scope of ISO 26262	N/A - Hardware must meet worst case ASIL requirement	N/A - Hardware must meet worst case ASIL requirement
H1: Potential Unintended Vehicle Lateral Motion/Yaw H2: Potential Insufficient Vehicle Lateral Motion/Yaw H3: Loss of Lateral Motion Control H5: Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction H6: Intermittent Response to Driver's Control Input					

Table H- 5. System/Subsystem: Vehicle Communication System

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
Comm. System	Failure of communications in the SbW system	H1, H2, H3, H4, H5, H6	Communication bus fault Wiring connection fault (short or open)	Communication system is fail-operational, and remain fail-safe after any first fault	Communication system is fail safe
Comm. System	Failure of safety-critical communications between interfacing systems and the SbW system	H1, H2, H3, H4, H5, H6	Communication bus fault Wiring connection fault (short or open)	Communication system is fail-operational, and remain fail-safe after any first fault	Communication system is fail safe

H1: Potential Unintended Vehicle Lateral Motion/Yaw
H2: Potential Insufficient Vehicle Lateral Motion/Yaw
H3: Loss of Lateral Motion Control
H4: Reduced Responsiveness to the Driver's Commands Due to Increased Rear-Wheel Drag
H5: Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction
H6: Intermittent Response to Driver's Control Input

Table H- 6. System/Subsystem: Rear-Wheel Steering Subsystem

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
Rear-Wheel Steering Motor	Failure of the rear wheel motor driver	H1, H2, H4	Internal connection fault (short or open)	The failure-rate of rear wheel steering must support ASIL requirements.	The failure-rate of rear wheel steering must support ASIL requirements.
			Signal connector connection failure		
			Power connector connection failure		
			HW fault in stator		
			HW fault in rotor		
			HW fault in insulation and windings		
			Over or under current		
			Manufacturing defect		
			Manufacturing variability		
			Over-emission of EMF		
			Inadequate shielding		
Rear Wheel Position Sensor	Failure of the rear wheel position sensor	H1, H2, H4	Hardware fault (sensors, ICs, circuit components, circuit boards…)	The failure-rate of rear wheel steering must support ASIL requirements.	The failure-rate of rear wheel steering must support ASIL requirements.
			Internal connection fault (short or open)		
			Break in position sensor I/Os connections		
			Short in position sensor I/Os connections to ground or voltage		
			Short in position sensor I/Os connections to another connection		
			Signal connector connection failure		
			Power connector connection failure		
			Rear wheel position calculation algorithm fault		
			SW parameters corrupted		
			EMC/EMI fault		

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
			Contamination/Corrosion		
			NVH fault		
			Environmental temperature exposure failure		
			Aging (durability)		
			Manufacturing defect		
			Manufacturing variability		
			Service/Maintenance		
H1: Potential Unintended Vehicle Lateral Motion/Yaw H2: Potential Insufficient Vehicle Lateral Motion/Yaw H4: Reduced Responsiveness to the Driver's Commands Due to Increased Rear-Wheel Drag					

Table H- 7. System/Subsystem: Driver Feedback Subsystem

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
Driver Feedback Motor	Failure of the driver feedback mechanism	H5	Internal connection fault (short or open)	The failure-rate of the driver feedback mechanism must support ASIL requirements.	The failure-rate of the driver feedback mechanism must support ASIL requirements.
			Signal connector connection failure		
			Power connector connection failure		
			HW fault in stator		
			HW fault in rotor		
			HW fault in insulation and windings		
			Over or under current		
			Manufacturing defect		
			Manufacturing variability		
			Over-emission of EMF		
			Inadequate shielding		
H5: Incorrect (delayed, missing, counterintuitive, etc.) Feedback Resulting in Incorrect Driver Reaction					

Table H- 8. System/Subsystem: Mechanical Backup Subsystem

Item	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms of Failure	Mitigation Strategies	
				"True" SbW	Intermediate SbW
Mechanical Backup Mechanism	Failure of the mechanical backup mechanism	H2, H3	Internal connection fault (short or open)	N/A	The failure-rate of the mechanical backup mechanism must support ASIL requirements.
			Signal connector connection failure		
			Power connector connection failure		
			HW fault in clutch		
			Mechanical fault		
	Premature engagement of the mechanical backup mechanism	H2, H3	Internal connection fault (short or open)	N/A	The failure-rate of the mechanical backup mechanism must support ASIL requirements.
			Signal connector connection failure		
			Power connector connection failure		
			HW fault in clutch		
			Mechanical fault		

Note: This item only applies to the intermediate SbW architecture.
H2: Potential Insufficient Vehicle Lateral Motion/Yaw
H3: Loss of Lateral Motion Control

APPENDIX I: STPA STEP 2: CAUSAL FACTORS

Table I- 1: Driver

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Driver)
8	Process model or calibration incomplete or incorrect	Other	The driver might get confused due to warnings from another vehicle system having the same sound, visual icon, and/or haptic feel as the steering system warnings. This might cause the driver to change their steering behavior. This can lead the driver to issue an incorrect steering command or not issue a steering command when needed.
122	Hazardous interaction with other components in the rest of the vehicle	Other	The driver might panic if inundated with vehicle system alerts (e.g., too many vehicle system warning lights activate due to a short in the dashboard circuit). This might cause the driver to change their steering behavior. This can lead the driver to issue an incorrect steering command or not issue a steering command when needed.
135	Process model or calibration incomplete or incorrect	Other	The driver might not know how a certain SbW features works. For example, the drift compensation feature might make the steering wheel stiff at high speeds and the driver might not be able to make micro adjustments, the driver might panic and issue an incorrect steering command.

Table I- 2: Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
44	External control input or information wrong or missing	Timing related input is incorrect or missing	A timing related input that is incorrect or missing might affect when the steer by wire control module issues a command. This could cause a delay or affect coordination when adjusting the feedback to the driver or adjusting the front and/or rear road wheel steering angle.
45	External control input or information wrong or missing	Spurious input due to shorting or other electrical fault	A spurious input due to shorting or another electrical fault might affect the steer by wire control module when issuing a command. This could cause a delay or affect coordination when adjusting the feedback to the driver or adjusting the front and/or rear road wheel steering angle.
46	External control input or information wrong or missing	Corrupted input signal	A corrupted input signal from another vehicle system might cause the steer by wire control module to incorrectly adjust the front and/or rear road wheel steering angle.
47	External control input or information wrong or missing	Malicious intruder	A malicious intruder might cause the steer by wire control module to incorrectly change the front and/or rear road wheel steering angle (e.g., issue a command that mimics a steering request).
48	External disturbances	EMI or ESD	EMI or ESD from the external environment might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
49	External disturbances	Single event effects (e.g., cosmic rays, protons)	Single event effects (e.g., cosmic rays, protons) from the external environment might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
50	External disturbances	Vibration or shock impact	Vibration or shock impact from the external environment might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
51	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems from the external environment might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
52	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling from the external environment might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
53	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from the external environment might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
54	External disturbances	Organic growth	Organic growth from the external environment might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
55	External disturbances	Physical interference (e.g., chafing)	Physical interference from the external environment might affect the steer by wire control module. This could affect the adjustments in feedback to the driver, and affect the transmission of torque from driver or from driver feedback motor direction or amount of steering angle change in the front road wheels, or the direction or steering angle of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
56	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of power might affect the steer by wire control module. This could affect adjustments in feedback to the driver, the direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
57	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	A power supply that is faulty (high, low, disturbance) might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
58	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from other components within the vehicle might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
59	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other components within the vehicle might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
60	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with other components within the vehicle might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
61	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from other components within the vehicle might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
62	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
63	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
1162	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components may affect the steer by wire control module. This could affect adjustments in feedback to the driver, the direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
64	Controller hardware faulty, change over time	Internal hardware failure	An internal hardware failure might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
65	Controller hardware faulty, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
66	Controller hardware faulty, change over time	Over temperature due to faulty cooling system	Over temperature due to a faulty cooling system might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
67	Controller hardware faulty, change over time	Degradation over time	Degradation over time might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
68	Controller hardware faulty, change over time	Faulty memory storage or retrieval	Faulty memory storage or retrieval might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
69	Controller hardware faulty, change over time	Faulty internal timing clock	A faulty internal timing clock might affect the steer by wire control module. This could affect timing for adjustments in feedback to the driver, changing the front road wheel steering angle, or changing the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
70	Controller hardware faulty, change over time	Faulty signal conditioning or converting (e.g., analog-to-digital converter, signal filters)	Faulty signal conditioning or converting (e.g., analog-to-digital converter, signal filters) might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
71	Controller hardware faulty, change over time	Unused circuits in the controller	Unused circuits might affect the steer by wire control module. This could affect adjustments in feedback to the driver, direction or amount of steering angle change in the front road wheels, or the direction or amount of steering angle change in the rear road wheels. • Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. • Not adjusting the front road wheels, or adjusting the front road wheels by the wrong amount or in the wrong direction may cause the steering system to respond differently than expected. • Adjusting the rear road wheels in the wrong direction or by the wrong amount may cause unexpected vehicle dynamics.
1185	Controller hardware faulty, change over time	Other	If the rear wheel steering control module is housed separately from the SbW control module, faults along the communication channel between the SbW and rear wheel steering control module (communication bus faults, wiring faults, connector faults, etc.) may affect the rear wheel steering command.
72	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Flaws in software code creation	Flaws in software code creation (e.g., automatic code generation) might affect the steer by wire control module.
73	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to delay adjusting the feedback to the driver.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
238	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	All UCAs related to the SbW control module apply
241	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may prevent the SbW control module from adjusting feedback to the driver when needed (e.g., a pull on the steering wheel may cause the driver to incorrectly countersteer).
243	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to adjust feedback to the driver at the wrong rate (e.g., adjusting the feedback too slowly/too fast may cause the driver to steer for too long/too short).
244	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to adjust feedback to the driver by the wrong amount (e.g., too much or too little) or in the wrong direction.
849	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to command torque from the steering motors for the wrong duration (e.g., too short, too long) or by the wrong amount (e.g., too much, too little).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
852	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may prevent the SbW control module from commanding torque from the steering motor when the driver or other vehicle systems request a steering adjustment.
853	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to command torque from the steering motor when the driver does not require steering and other vehicle systems are not requesting a steering adjustment.
856	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause a delay in commanding torque from the steering motor.
858	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to command torque from the steering motor in the opposite direction from the driver's or another vehicle system's request.
859	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to incorrectly adjust the amount of steering provided in response to the driver's input as a function of vehicle speed (e.g., providing more steering response at high speeds).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
999	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to command the rear wheels to toe-in when not needed (e.g., while the driver is steering or while the brakes are not applied).
1040	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to command the rear wheels to move to an in-phase or reverse-phase position when not needed (e.g., no steering input).
1042	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to adjust the a rear wheel steering angle for the wrong duration (e.g., the rear wheels have a non-zero steering angle after the driver returns the steering wheel to the center position).
1044	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to command the rear wheels to turn to the reverse-phase position when the vehicle speed is above the maximum speed value for activating reverse-phase steering.
1045	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to adjust the rear wheel steering angle with the wrong timing (e.g., the transition from in-phase to reverse-phase is not smooth).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
1047	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to command the rear wheels to turn to the in-phase position when the vehicle speed is below the minimum speed value for activating in-phase steering.
1163	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to adjust the rear wheel steering angle at the wrong rate (e.g., an abrupt change in vehicle handling).
1165	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to adjust the front or rear road wheel steering angle by the wrong amount (e.g., the steering angle changes more than requested by another vehicle system).
1166	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may affect how the SbW control module reconciles multiple steering requests in the same direction (e.g., add torques).
1167	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may affect how the SbW control module reconciles multiple steering requests in opposite directions.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
1168	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	A programming error or flaw in software logic may cause the SbW control module to incorrectly prioritize between the driver and an active safety system.
1187	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	The Active Steering feature may incorrectly determine that compensation was needed (e.g., interprets a steady non-zero input from the driver as the driver compensating for crosswinds).
1258	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	SbW control module might not be programmed to issue a warning to the driver for some situations. For example, when the rear wheels lock but the driver does not know since there was no warning from the SbW control module.
1524	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	An inadequate control algorithm might cause the steer-by-wire control module to command torque from the driver feedback motor when feedback is not needed (e.g., travelling straight ahead on a smooth road surface) resulting in an incorrect driver reaction.
1578	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	An inadequate control algorithm might cause the steer-by-wire control module to command the mechanical clutch to engage too late.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
1582	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	An inadequate control algorithm might prevent the steer-by-wire control module from engaging the mechanical clutch when needed.
1583	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	An inadequate control algorithm might cause the steer-by-wire control module to command the mechanical clutch to engage when not needed.
1584	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	An inadequate control algorithm might cause the steer-by-wire control module to command the mechanical clutch to engage for too short period of time (i.e., the clutch does not remain engaged while a fault in the steer-by-wire system persists).
1585	Software error (inadequate control algorithm, flaws in creation, modification, or adaptation)	Inadequate control algorithm	An inadequate control algorithm might cause the steer-by-wire control module to engage the mechanical clutch with too little force (e.g., the clutch may not engage fully).
74	Process model or calibration incomplete or incorrect	Sensor or actuator calibration, including degradation characteristics	Sensor or actuator calibration, including degradation characteristics, in the steer by wire control module may be incorrect. This could affect how the SbW control module adjusts feedback to the driver and affect the direction or amount by which the front and/or rear road wheel steering angle is adjusted.
75	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	Model of the controlled process, including degradation characteristics, in the steer by wire control module may be incorrect. This could affect how the SbW control module adjusts feedback to the driver and affect the direction or amount by which the front and/or rear road wheel steering angle is adjusted.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
76	Process model or calibration incomplete or incorrect	Errors in stored maps	Stored calibration maps in the steer by wire control module may be incorrect. This could affect how the SbW control module adjusts feedback to the driver and affect the direction or amount by which the front and/or rear road wheel steering angle is adjusted.
1169	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW control module may incorrectly consider the vehicle speed when determining how much steering to provide in response to the driver's input.
1170	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW control module may incorrectly consider the vehicle speed when determining whether to turn the rear road wheel's to the in-phase or reverse-phase position.
1171	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW control module's understanding of the vehicle yaw rate and lateral acceleration may be different from the actual vehicle yaw rate and lateral acceleration.
1172	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW control module's model of the vehicle dynamics may be incorrect (e.g., incorrect parameters, calibration for wrong vehicle type, etc.).
1173	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW control module may have an incorrect understanding of which other vehicle systems are capable of requesting steering adjustments. For example, if the SbW control module thinks the ALK/ALC system is disabled, it may not respond to steering requests from the ALK/ALC system.
1175	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW control module may have an incorrect understanding of the ignition key state (e.g., a disruption in the power supply causes the SbW to think the key is in the "off" position). If the SbW incorrectly thinks the driver has turned the vehicle "off," it may engage the steering wheel locking mechanism.
1176	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW may not know what yaw rate corrective actions other vehicle systems are taking (e.g., active differential or brake/stability control systems). The SbW may implement yaw stability control at the same time another vehicle system is making the same adjustments.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module)
1177	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	If the SbW may not compare the driver's steering input with the vehicle's yaw rate when computing the adjustment needed for drift compensation (e.g., crosswind compensation). This may cause the SbW to misinterpret a steady steering input from the driver as a countersteer effort.
1181	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW control module may have an incorrect understanding of the health of the steering system (e.g., whether faults are present). This may prevent the SbW control module from entering a degraded operating state or issuing a warning notification to the driver.
1251	Process model or calibration incomplete or incorrect	Other	The SbW control module adjusts the rear road wheel steering angle when power assist to the front wheels is not available (e.g., steering motor fault).
1252	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	If the rear wheel steering control module is housed separately from the SbW control module, faults along the communication channel between the SbW and rear wheel steering control module (communication bus faults, wiring faults, connector faults, etc.) may affect the rear wheel steering command.
1256	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The SbW system might deactivate itself without giving the driver enough time to react or assess the roadway conditions. This might cause the driver to issue an incorrect steering command.
1373	Process model or calibration incomplete or incorrect	Other	An incorrect software mode might affect the SbW control module torque command. For example, the vehicle might produce an incorrect torque output if the SbW control module is still set to the supplier’s factory operating mode.
1429	Process model or calibration incomplete or incorrect	Model of the controlled process, including degradation characteristics	The steer by wire control module may have an incorrect model of the road feel characteristics (e.g., friction, pull, etc.). This may cause the steer by wire control module to command incorrect (delayed, missing, counterintuitive, etc.) torque to the driver feedback motor.

Table I- 3: Steering Motor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor)
1431	Actuator inadequate operation, change over time	Internal hardware failure	An internal hardware failure might cause the steering motors to provide the incorrect steering forces to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1432	Actuator inadequate operation, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting might cause the steering motors to provide incorrect forces to the front wheels or an incorrect roadway feedback/motor position to the steer-by-wire control module resulting in incorrect driver reaction.
1433	Actuator inadequate operation, change over time	Degradation over time	Degradation over time might cause the steering motors to provide incorrect forces to the front wheels or incorrect roadway feedback/motor position to the steer-by-wire control module resulting in incorrect driver reaction.
1434	Actuator inadequate operation, change over time	Over temperature due to faulty cooling system	Over temperature due to faulty cooling system might cause the steering motors to provide incorrect forces to the front wheels or an incorrect roadway feedback/motor position to the steer-by-wire control module resulting in incorrect driver reaction.
1435	Sensor inadequate operation, change over time	Reporting frequency too low	A reporting frequency that is too low might cause a delay when the steering motors provides feedback to the steer-by-wire control module.
1436	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might cause the steering motors to incorrectly transmit torque to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1437	External disturbances	Vibration or shock impact	Vibration or shock impact might cause the steering motors to incorrectly transmit torque to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1438	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might cause the steering motors incorrectly transmit torque to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1439	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might cause the steering motors to incorrectly transmit torque to the front road wheels or provide incorrect roadway feedback to the steer-by-wire control module.
1440	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with other components might cause the steering motors to incorrectly transmit torque to the front road wheels or provide incorrect roadway feedback position to the steer-by-wire control module.
1441	External disturbances	Magnetic interference	Magnetic interference might cause the steering motors to provide incorrect (delayed, missing, counterintuitive, etc.) roadway feedback/motor position to the steer-by-wire control module resulting in incorrect driver reaction.
1442	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of 12-volt power might cause the steering motors to provide incorrect (delayed, missing, counterintuitive, etc.) roadway feedback/motor position to the steer-by-wire control module resulting in incorrect driver reaction.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor)
1443	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	A power supply that is faulty (high, low, disturbance) might cause the steering motors to provide incorrect steering force to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1444	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other components within the vehicle might cause the steering motors to incorrectly transmit steering forces to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1445	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with other components within the vehicle might cause the steering motors to incorrectly transmit steering forces to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1446	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from other components within the vehicle might cause the steering motors to incorrectly transmit steering forces to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1447	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other components within the vehicle might cause the steering motors to incorrectly transmit steering forces to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1448	Hazardous interaction with other components in the rest of the vehicle	Magnetic interference	Magnetic interference from components within the vehicle might cause the steering motors to provide incorrect (delayed, missing, counterintuitive, etc.) roadway feedback/motor position to the steer-by-wire control module resulting in incorrect driver reaction.
1449	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might cause the steering motors to incorrectly transmit steering forces to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1450	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	Corona effects from high voltage components might cause the steering motors to incorrectly transmit steering forces to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1622	External disturbances	Organic growth	Organic growth might cause the steering motors to incorrectly transmit torque to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1623	External disturbances	EMI or ESD	EMI or ESD might cause the steering motors to incorrectly transmit torque to the front road wheels or provide incorrect feedback to the steer-by-wire control module.
1624	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from other components within the vehicle might cause the steering motors to incorrectly transmit torque to the front road wheels or provide incorrect feedback to the steer-by-wire control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor)
1625	Actuator inadequate operation, change over time	Relay failure modes, including: 1) does not energize, 2) does not de-energize, and 3) welded contacts	If the steering motor allows for two way direction opreation, a relay failure might cause the steering motor to provide incorrect forces to the front wheels or an incorrect roadway feedback/motor position to the SbW control module.
1654	Power supply faulty (high, low, disturbance)	Other	The polarity to the steering motor may be reversed.

Table I- 4: Rear Road Wheel Motors

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Motors)
1116	Actuator inadequate operation, change over time	Internal hardware failure	An internal hardware failure might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1117	Actuator inadequate operation, change over time	Degradation over time	Degradation over time might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1118	Actuator inadequate operation, change over time	Over temperature due to faulty cooling system	Over temperature due to faulty cooling system might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1119	Actuator inadequate operation, change over time	Incorrectly sized actuator	Incorrectly sized rear road wheel motors might cause the rear wheel position to change by the wrong amount.
1120	Actuator inadequate operation, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1121	External disturbances	EMI or ESD	EMI or ESD might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.
1122	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.
1123	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.
1124	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.
1125	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Motors)
1126	External disturbances	Organic growth	Organic growth (e.g., mold) might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.
1127	External disturbances	Physical interference (e.g., chafing)	Physical interference might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.
1128	External disturbances	Magnetic interference	Magnetic interference might affect the rear road wheel motors and cause it to incorrectly change the rear road wheel position.
1129	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of 12-volt power might affect the rear road wheel motors. This may prevent the motor from adjusting the rear wheel position.
1130	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1131	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	A power supply that is faulty (high, low, disturbance) might affect the rear road wheel motors. This may cause the motor to incorrectly adjust the rear wheel position.
1132	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1133	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1134	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1135	Hazardous interaction with other components in the rest of the vehicle	Magnetic interference	Magnetic interference from components within the vehicle might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Motors)
1136	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1137	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components could affect the rear road wheel motors and cause the motors to incorrectly position the rear road wheels.
1138	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle contains a high voltage power system, corona effects from high voltage components may affect the rear road wheel motors. This may cause the motors to incorrectly position the rear road wheels.
1620	Actuator inadequate operation, change over time	Relay failure modes, including: 1) does not energize, 2) does not de-energize, and 3) welded contacts	If the rear road wheel motor allows for two way direction operation, a relay failure might cause the rear road wheel motor to send incorrect response to the rear road wheels.

Table I- 5: Rear Road Wheel Position Sensor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor)
894	Sensor inadequate operation, change over time	Internal hardware failure	An internal hardware failure might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
895	Sensor inadequate operation, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
896	Sensor inadequate operation, change over time	Degradation over time	Degradation over time might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
897	Sensor inadequate operation, change over time	Reporting frequency too low	A reporting frequency that is too low might affect the rear road wheel position sensor and cause a delay in reporting the rear road wheel steering angle to the SbW control module. This might delay the SbW control module's adjustment of the rear road wheel steering angle.
898	External disturbances	EMI or ESD	EMI or ESD might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
899	External disturbances	Single event effects (e.g., cosmic rays, protons)	Single event effects (e.g., cosmic rays, protons) might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
900	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
901	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor)
902	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
903	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
904	External disturbances	Organic growth	Organic growth (e.g., mold) might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
905	External disturbances	Physical interference (e.g., chafing)	Physical interference from the external environment (e.g., road debris) might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
906	External disturbances	Magnetic interference	Magnetic interference might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
907	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of 12-volt power might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel position to the SbW control module. This might affect control of the rear road wheel position.
908	Power supply faulty (high, low, disturbance)	Reference voltage incorrect (e.g., too low, too high)	Reference voltage that is incorrect (e.g., too low, too high) might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel position to the SbW control module. This might affect control of the rear road wheel position.
910	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	Power supply that is faulty (high, low, disturbance) might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel position to the SbW control module. This might affect control of the rear road wheel position.
911	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor)
912	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
913	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
914	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
915	Hazardous interaction with other components in the rest of the vehicle	Magnetic interference	Magnetic interference from components within the vehicle might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
916	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
1189	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle contains a high voltage power system, corona effects from high voltage components may affect the rear road wheel position sensors. This may cause the rear road wheel position sensors to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
1612	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other components within the vehicle might affect the rear road wheel position sensor and cause it to output an incorrect rear road wheel steering angle measurement to the SbW control module. This might affect the SbW control module's adjustment of the rear road wheel steering angle.

Table I- 6: Rack and Pinion

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rack and Pinion)
1058	Controlled component failure, change over time	Internal hardware failure	An internal hardware failure might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1059	Actuator inadequate operation, change over time	Degradation over time	Degradation over time might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1059	Controlled component failure, change over time	Degradation over time	Degradation over time might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1060	Actuator inadequate operation, change over time	Incorrectly sized actuator	An incorrectly sized rack and pinion (e.g., incorrect torsion bar diameter) might affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1061	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the rack and pinion. This could affect the feedback the SbW control module or affect the transmission of torque from the steering motors.
1062	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1063	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1064	External disturbances	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1066	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1067	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the rack and pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rack and Pinion)
1068	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the rack pinion. This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1069	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components could affect the rack and pinion (e.g., thermal expansion causing binding). This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
1069	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Excessive heat from other vehicle components could affect the rack and pinion (e.g., thermal expansion causing binding). This could affect the feedback to the SbW control module or affect the transmission of torque from the steering motors.
If the SbW system has a mechanical backup and the backup is engaged, these causal factors may also directly affect feedback to the driver via the steering column, as well as mechanical transmission of forces from the driver.			

Table I- 7: Steering Wheel

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel)
12	Actuator inadequate operation, change over time	Degradation over time	Degradation over time can affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
14	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from the driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
15	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from the driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
16	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
17	External disturbances	Physical interference (e.g., chafing)	Physical interference from everyday objects in the vehicle cabin might affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel)
18	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
19	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
20	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
630	Actuator inadequate operation, change over time	Internal hardware failure	An internal hardware failure might affect the motion of the steering wheel. This could affect the feedback to the driver and affect the transmission of torque from driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.
1054	External disturbances	Extreme external temperature or thermal cycling	Excessive heat in the vehicle cabin may affect the motion of the steering wheel (e.g., thermal expansion causing binding or increased friction). This could affect the feedback to the driver and affect the transmission of torque from the driver (both mechanical and electronic transmission). Affecting the feedback to the driver may cause the driver to incorrectly issue a steering adjustment. Incorrectly transmitting the driver's torque may cause the vehicle to respond differently from the driver's intent.

Table I- 8: Steering Wheel Angle Sensor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor)
686	Sensor inadequate operation, change over time	Internal hardware failure	An internal hardware failure might affect the steering wheel angle sensor and cause it to output an incorrect steering wheel angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
687	Sensor inadequate operation, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting might affect the steering wheel angle sensor and cause it to output an incorrect steering wheel angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
688	Sensor inadequate operation, change over time	Degradation over time	Degradation over time might affect the steering wheel angle sensor and cause it to output an incorrect steering wheel angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
689	Sensor inadequate operation, change over time	Reporting frequency too low	A reporting frequency that is too low might affect the steering wheel angle sensor and prevent or delay reporting the steering wheel angle measurement to the SbW control module. This might affect the SbW control module's timing for providing steering assist.
690	External disturbances	EMI or ESD	EMI or ESD might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
691	External disturbances	Single event effects (e.g., cosmic rays, protons)	Single event effects (e.g., cosmic rays, protons) might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
692	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
693	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor)
694	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
695	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
696	External disturbances	Organic growth	Organic growth might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
697	External disturbances	Physical interference (e.g., chafing)	Physical interference might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
698	External disturbances	Magnetic interference	Magnetic interference might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction or level of steering assist required.
699	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of 12-volt power might affect the steering wheel angle sensor and cause it not to output a steering angle measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
700	Power supply faulty (high, low, disturbance)	Reference voltage incorrect (e.g., too low, too high)	A reference voltage that is incorrect (e.g., too low, too high) might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
701	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	Power supply that is faulty (high, low, disturbance) might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
827	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor)
828	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
829	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
830	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
831	Hazardous interaction with other components in the rest of the vehicle	Magnetic interference	Magnetic interference from components within the vehicle might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
832	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
833	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
1190	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components might affect the steering wheel angle sensor and cause it to output an incorrect steering angle measurement to the SbW control module. This might affect how the SbW control module determines the direction and level of steering assist required.
1191	Sensor inadequate operation, change over time	Other	The steering wheel angle sensor may not correctly measure steering inputs greater than 360 degrees (e.g., the steering wheel may be able to rotate 720 degrees, but the steering wheel angle sensor may only detect rotation up to 360 degrees). This might affect how the SbW control module determines the direction and level of steering assist required.

Table I- 9: Steering Wheel Torque Sensor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor)
702	Sensor inadequate operation, change over time	Internal hardware failure	An internal hardware failure might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
703	Sensor inadequate operation, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
704	Sensor inadequate operation, change over time	Degradation over time	Degradation over time might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
705	Sensor inadequate operation, change over time	Reporting frequency too low	A reporting frequency that is too low might affect the steering wheel torque sensor and delay or prevent it from reporting the steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
706	External disturbances	EMI or ESD	EMI or ESD might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
707	External disturbances	Single event effects (e.g., cosmic rays, protons)	Single event effects (e.g., cosmic rays, protons) might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
708	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
709	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
710	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor)
711	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
712	External disturbances	Organic growth	Organic growth might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
713	External disturbances	Physical interference (e.g., chafing)	Physical interference might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
714	External disturbances	Magnetic interference	Magnetic interference might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might how affect how the SbW control module determines the level of steering assist required.
715	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of 12-volt power might affect the steering wheel torque sensor and cause it not to output a steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
716	Power supply faulty (high, low, disturbance)	Reference voltage incorrect (e.g., too low, too high)	A reference voltage that is incorrect (e.g., too low, too high) might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
717	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	Power supply that is faulty (high, low, disturbance) might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
718	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
719	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor)
720	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
721	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
722	Hazardous interaction with other components in the rest of the vehicle	Magnetic interference	Magnetic interference from components within the vehicle might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
723	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the steering wheel torque sensor and cause it to output an incorrect steering wheel torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
724	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects might affect the steering wheel torque sensor and cause it to output an incorrect steering torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.
1192	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components might affect the steering wheel torque sensor and cause it to output an incorrect steering torque measurement to the SbW control module. This might affect how the SbW control module determines the level of steering assist required.

Table I- 10: Driver Feedback Motor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Driver Feedback Motor)
1374	Actuator inadequate operation, change over time	Internal hardware failure	Internal hardware failure of the driver feedback motor might cause the motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1375	Actuator inadequate operation, change over time	Degradation over time	Degradation of the driver feedback motor might cause the motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1376	Actuator inadequate operation, change over time	Over temperature due to faulty cooling system	Over temperature due to faulty cooling system might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1377	Actuator inadequate operation, change over time	Incorrectly sized actuator	Incorrectly sized driver feedback motor might incorrectly (delayed, missing, counterintuitive, etc.) send feedback to the driver resulting an in incorrect driver reaction.
1378	Actuator inadequate operation, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting of the driver feedback motor might cause the motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1379	External disturbances	EMI or ESD	EMI or ESD might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1380	External disturbances	Vibration or shock impact	Vibration or shock impact might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1381	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1382	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1383	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Driver Feedback Motor)
1384	External disturbances	Organic growth	Organic growth might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1385	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with external components might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1386	External disturbances	Magnetic interference	Magnetic interference might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in incorrect driver reaction.
1387	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of power might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in incorrect driver reaction.
1388	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	A power supply that is faulty (high, low, disturbance) might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1389	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from other components within the vehicle might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1390	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other components within the vehicle might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1391	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with other components within the vehicle might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1392	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from other components within the vehicle might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Driver Feedback Motor)
1393	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other components within the vehicle might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1394	Hazardous interaction with other components in the rest of the vehicle	Magnetic interference	Magnetic interference from other components within the vehicle might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1395	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1396	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	Corona effects from high voltage components might cause the driver feedback motor to send incorrect (delayed, missing, counterintuitive, etc.) feedback to the driver resulting in an incorrect driver reaction.
1619	Actuator inadequate operation, change over time	Relay failure modes, including: 1) does not energize, 2) does not de-energize, and 3) welded contacts	If the feedback motor allows for two way direction operation, a relay failure might cause the feedback motor to send incorrect feedback to the driver resulting in an incorrect driver reaction.

Table I- 11: Mechanical Backup System Clutch

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Mechanical Backup System Clutch)
1676	Actuator inadequate operation, change over time	Internal hardware failure	The mechanical clutch may have a hardware failure that affects the function of the mechanical backup system.
1677	Actuator inadequate operation, change over time	Degradation over time	The mechanical clutch may degrade, affecting the function of the mechanical backup system.
1678	Actuator inadequate operation, change over time	Incorrectly sized actuator	The mechanical clutch may not be sufficient to handle the steering forces transmitted via the mechanical backup system.
1679	External disturbances	Vibration or shock impact	Vibration or shock impact from the external environment may affect the mechanical clutch.
1680	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects or assembly problems may affect the mechanical clutch.
1681	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling may affect operation of the mechanical clutch.
1682	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from the external environment may affect operation of the mechanical clutch.
1683	External disturbances	Physical interference (e.g., chafing)	Physical interference from the external environment (e.g., debris) may affect operation of the mechanical clutch.
1684	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	If the mechanical clutch requires power to operate (e.g., the clutch is normally open), loss of low voltage power may prevent the clutch from engaging.
1685	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	If the mechanical clutch is normally closed, a power spike or other disturbance may cause the clutch to disengage when the mechanical backup is needed.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Mechanical Backup System Clutch)
1686	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other vehicle components could affect the mechanical clutch.
1687	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference from other vehicle components could affect the mechanical clutch.
1688	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from other vehicle components could affect the mechanical clutch.
1689	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components could affect the mechanical clutch.
1690	Hazardous interaction with other components in the rest of the vehicle	Magnetic interference	Magnetic interference from other vehicle components could affect the mechanical clutch.
These causal factors only apply to SbW systems with a mechanical backup (i.e., intermediate SbW systems).			

Table I- 12: Yaw Rate/Lateral Acceleration Sensor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor)
663	Sensor inadequate operation, change over time	Internal hardware failure	An internal hardware failure might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
664	Sensor inadequate operation, change over time	Overheating due to increased resistance in a subcomponent or internal shorting	Overheating due to increased resistance in a subcomponent or internal shorting might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
665	Sensor inadequate operation, change over time	Degradation over time	Degradation over time might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
666	Sensor inadequate operation, change over time	Reporting frequency too low	Reporting frequency that is too low might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
667	External disturbances	EMI or ESD	EMI or ESD might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
668	External disturbances	Single event effects (e.g., cosmic rays, protons)	Single event effects (e.g., cosmic rays, protons) might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
669	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
670	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
671	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor)
672	External disturbances	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
673	External disturbances	Organic growth	Organic growth might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
674	External disturbances	Physical interference (e.g., chafing)	Physical interference might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
676	Power supply faulty (high, low, disturbance)	Loss of 12-volt power	Loss of 12-volt power might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
677	Power supply faulty (high, low, disturbance)	Reference voltage incorrect (e.g., too low, too high)	Reference voltage that is incorrect (e.g., too low, too high) might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
678	Power supply faulty (high, low, disturbance)	Power supply faulty (high, low, disturbance)	Power supply that is faulty (high, low, disturbance) might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
679	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
680	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
681	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor)
682	Hazardous interaction with other components in the rest of the vehicle	Moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
684	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to driver feedback.
685	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW yaw rate stabilization or adjustments to driver feedback.
1161	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from components within the vehicle might affect the yaw rate/lateral acceleration sensor and cause it to output an incorrect yaw rate or lateral acceleration measurement to the SbW control module. This might affect the SbW yaw rate stabilization or adjustments to the driver feedback.
1249	Sensor inadequate operation, change over time	Other	Yaw rate sensor has faulty signal conditioning or converting (e.g., signal filters, signal amplification).
1250	Sensor inadequate operation, change over time	Other	Steering wheel angle sensor incorrectly indexes rotations above 360 degrees. This may cause the steering wheel angle sensor to report too small of a steering angle or develop an offset from the actual steering wheel position.

Table I- 13: Brake System (with ESC/ABS) to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Brake System (with ESC/ABS) to SbW Control Module)
1314	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	Intermittent connection between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1315	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	Connection that is open, short to ground, short to battery, or short to other wires in harness between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1316	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1317	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	Contact resistance that is too high between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Brake System (with ESC/ABS) to SbW Control Module)
1318	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Short circuit on the connector neighboring pins between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1319	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Resistive drift on the connector neighboring pins between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1320	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Bus overload or bus error	Bus overload or bus error between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1321	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Signal priority too low	Signal priority that is too low between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1322	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	Failure of the message generator, transmitter, or receiver between the brake system and SbW control module might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Brake System (with ESC/ABS) to SbW Control Module)
1323	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	Malicious intruder on the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1324	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect wiring connection	Incorrect brake system and SbW control module wiring connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1325	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect pin assignment	Incorrect pin assignment on the brake system and SbW control module brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1326	External disturbances	EMI or ESD	EMI or ESD on the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1327	External disturbances	Vibration or shock impact	Vibration or shock impact disrupting the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1328	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems of the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1329	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling affecting the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1330	External disturbances	Organic growth	Organic growth on the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Brake System (with ESC/ABS) to SbW Control Module)
1331	External disturbances	Physical interference (e.g., chafing)	External physical interference (e.g., shafting) with brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1332	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination on the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1333	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle dispersed on the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1334	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle disrupting the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1335	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle and the brake system and SbW control module connection might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1336	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals could affect the brake system and SbW control module connection and might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1337	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects from high voltage components could affect the brake system and SbW control module connection and might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.
1338	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the brake system or SbW control module may be affected by moisture, corrosion, or contamination from components within the vehicle and might affect the vehicle speed and/or friction coefficient and/or brake pedal position feedback to the SbW control module.

Table I- 14: Driver to Steering Wheel

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Driver to Steering Wheel)
224	External disturbances	Extreme external temperature or thermal cycling	Extreme temperatures in the vehicle cabin might affect the driver's ability to operate the steering wheel (e.g., the driver might maintain a light grip on the steering wheel).
230	External disturbances	Vibration or shock impact	Vibration or shock impact (e.g., excessive vibrations due to poor road conditions) might affect the driver's handling of the steering wheel.
232	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle (e.g., a deflated tire on one side of the vehicle causing extreme vibrations) might affect the driver's ability to operate the steering wheel.
233	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with components within the vehicle (e.g., the seat belt locking mechanism) might affect the driver's ability to operate the steering wheel.
1193	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	If the steering wheel has a steering wheel cover, moisture, corrosion, or contamination from other vehicle components may cause deterioration or degradation of the steering wheel cover, affecting the driver's ability to operate the steering wheel.
1194	External disturbances	Other	If the steering wheel has a steering wheel cover, moisture, corrosion, or contamination may cause deterioration or degradation of the steering wheel cover, affecting the driver's ability to operate the steering wheel.

Table I- 15: Steer-by-Wire Control Module to Instrument Panel Display

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Module to Instrument Panel Display)
200	External disturbances	EMI or ESD	EMI or ESD might disrupt the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
202	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
203	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
204	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
206	External disturbances	Organic growth	Organic growth (e.g. mold on a printed circuit board) might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
207	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
1261	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the SbW control module or instrument panel display may be affected by moisture, corrosion, or contamination. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Module to Instrument Panel Display)
1263	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the SbW control module and instrument panel display may be affected by moisture, corrosion, or contamination. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
209	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
210	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
211	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
212	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other components might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
213	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Module to Instrument Panel Display)
214	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects from high voltage components might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
1262	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the SbW control module or instrument panel display may be affected by moisture, corrosion, or contamination from other components within the vehicle. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
1264	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the SbW control module and instrument panel display may be affected by moisture, corrosion, or contamination from components within the vehicle. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
188	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	The connection between the SbW Control Module and instrument panel display may become intermittent. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
189	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	Connection that is open, short to ground, short to battery, or short to other wires in harness might disrupt the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Module to Instrument Panel Display)
190	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD might disrupt the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
191	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	Contact resistance in the connectors of the SbW control module and instrument panel display may be too high. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
192	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Shorting between neighboring pins in the connectors might disrupt the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
193	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Connector resistive drift between neighboring pins might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
194	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error might disrupt communication between the SbW control module and instrument panel display. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Module to Instrument Panel Display)
195	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Signal priority too low	A signal priority that is too low might delay or prevent communication between the SbW control module and instrument panel display. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
196	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	Failure of the message generator, transmitter, or receiver might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
197	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder or aftermarket component might disrupt communication between the SbW control module and instrument panel display. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
198	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect wiring connection	Incorrect wiring might affect the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).
199	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment might disrupt the SbW control module and instrument panel display connection. This might cause the steering system malfunction indicator light to turn on or off regardless of the actual command from the SbW control module. This could affect the driver's understanding of the status of the steering system (e.g., whether or not power assist is available).

Table I- 16: Steer-by-Wire Control Module to Steering Motor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Control Module to Steering Assist Motor)
1660	External disturbances	EMI or ESD	EMI or ESD from the external environment could affect the connection between the SbW control module and steering motor.
1661	External disturbances	Vibration or shock impact	Vibration or shock impact from the external environment could affect the connection between the SbW control module and steering motor.
1662	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects or assembly problems could affect the connection between the SbW control module and steering motor.
1663	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling could affect the connection between the SbW control module and steering motor.
1664	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the SbW control module and steering motor could be affected by moisture, corrosion, or contamination from the external environment.
1665	External disturbances	Organic growth	Organic growth (e.g., mold) could affect the connection terminals of the SbW control module or steering motor (e.g., causing shorting).
1666	External disturbances	Physical interference (e.g., chafing)	Physical interference from the external environment (e.g., road debris) could affect the connection between the SbW control module and steering motor.
1667	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination from the external environment could affect the connection terminals of the SbW control module or steering motor.
1668	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from other vehicle components could affect the connection between the SbW control module and steering motor.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Control Module to Steering Assist Motor)
1669	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other vehicle components could affect the connection between the SbW control module and steering motor.
1670	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference from other vehicle components could affect the connection between the SbW control module and steering motor.
1671	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the SbW control module and steering motor could be affected by moisture, corrosion, or contamination from other vehicle components.
1672	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination from other vehicle components could affect the connection terminals of the SbW control module or steering motor.
1673	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components could affect the connection between the SbW control module and steering motor.
1674	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components could affect the connection terminals of the SbW control module or steering motor.
1675	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	Corona effects from high voltage components could affect the connection terminals of the SbW control module or steering motor.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Control Module to Steering Assist Motor)
1651	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	The connection between the SbW control module and steering motor may become intermittent.
1652	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	The connection between the SbW control module and steering motor may become open or shorted (e.g., to battery, ground, or other wires).
1653	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD could affect the signal from the SbW control module to the steering motor.
1655	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	The contact resistance in the connectors for the SbW control module or steering motor may be too high.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (SbW Control Module to Steering Assist Motor)
1656	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Shorting may occur between neighboring pins in the connector for the SbW control module or steering motor.
1657	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Resistive drift may occur between neighboring pins in the connectors for the SbW control module or steering motor.
1658	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect wiring connection	The SbW control module and steering motor may be incorrectly wired (e.g., reversed wires).
1659	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect pin assignment	The SbW control module may have an incorrect pin assignment for the connection with the steering motor.

Table I- 17: Steer-by-Wire Control Module to Rear Road Wheel Motors

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Rear Road Wheel Motors)
917	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	An intermittent connection between the SbW control module and rear road wheel motors might affect the SbW control module's adjustment of the rear road wheel steering angle.
918	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	Connection that is open, short to ground, short to battery, or short to other wires in harness between the SbW control module and rear road wheel motors might affect the SbW control module's adjustment of the rear road wheel steering angle.
919	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD might affect the connection between the SbW control module and rear road wheel motors. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
920	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	Contact resistance that is too high in the connector of the SbW control module or the rear road wheel motors might affect the SbW control module's adjustment of the rear road wheel steering angle.
921	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Connector shorting between neighboring pins on the SbW control module and rear road wheel motors might affect the SbW control module's adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Rear Road Wheel Motors)
925	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	A failure of the message generator, transmitter, or receiver can affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
926	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder or aftermarket component might issue a command to the communication bus that affects communication between the SbW control module and the rear road wheel motors. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
927	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Signal priority too low	A signal priority that is too low might delay or prevent communication between the SbW control module and rear road wheel motors. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
928	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error can affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
929	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Connector resistive drift between neighboring pins on the SbW control module and rear road wheel motors might affect the SbW control module's adjustment of the rear road wheel steering angle.
930	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect wiring connection	An incorrect wiring connection between the SbW control module and rear road wheel motors might affect the SbW control module's adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Rear Road Wheel Motors)
931	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment between the SbW control module and rear road wheel motors connection might affect the SbW control module's adjustment of the rear road wheel steering angle.
932	External disturbances	EMI or ESD	EMI or ESD might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
934	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
935	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
936	External disturbances	Organic growth	Organic growth (e.g., mold) might create a short circuit in the connection between the SbW control module and rear road wheel motors. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
937	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
938	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the SbW control module or the rear road wheel motors might be affected by moisture, corrosion, or contamination from other vehicle components (e.g., shorting). This might affect the SbW control module's adjustment of the rear road wheel steering angle.
939	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
940	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Rear Road Wheel Motors)
941	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
942	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
943	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects from high voltage components might affect the SbW control module and rear road wheel motors connection. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
1197	External disturbances	Extreme external temperature or thermal cycling	Extreme ambient temperatures or thermal cycling may affect the connection between the SbW control module and the rear road wheel motors. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
1198	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the SbW control module and the rear road wheel motors might be affected by moisure, corrosion, or contamination from the external environment. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
1199	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components might affect the connection between the SbW control module and the rear road wheel motors. This might affect the SbW control module's adjustment of the rear road wheel steering angle.
1200	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the SbW control module and the rear road wheel motors might be affected by moisure, corrosion, or contamination from other vehicle components. This might affect the SbW control module's adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Rear Road Wheel Motors)
1372	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the SbW control module or the rear road wheel motors might be affected by moisture, corrosion, or contamination from the external environment (e.g., shorting). This might affect the SbW control module's adjustment of the rear road wheel steering angle.

Table I- 18: Steer-by-Wire Control Module to Driver Feedback Motor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Driver Feedback Motor)
1473	External disturbances	EMI or ESD	EMI or ESD might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1475	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1476	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1477	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1479	External disturbances	Organic growth	Organic growth might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1480	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1481	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to provide an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1636	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals affected by moisture, corrosion, or contamination from external environment might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Driver Feedback Motor)
1478	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from other components within the vehicle might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1481	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to provide an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1482	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact due to other components within the vehicle might affect the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1483	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with other components within the vehicle might affect the signal from the steer-by-wire control module - driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1484	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other components might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedbback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1485	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1486	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	Corona effects from high voltage components might affect the signal from the steer-by-wire control module to the driver feedback motor. This may cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Driver Feedback Motor)
1637	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals affected by moisture, corrosion, or contamination from other components within the vehicle might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1461	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	An intermittent connection might cause the signal from the steer-by-wire control module to the driver feedback motor to be incorrect (delayed, missing, etc.).
1462	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	The connection between the steer-by-wire control module and driver feedback motor may be open, short to ground, short to battery, or short to other wires in harness. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1463	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1464	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	A connector contact resistance that is too high might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Driver Feedback Motor)
1465	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Shorting between neighboring pins in the connectors of the steer-by-wire control module or driver feedback motor could result in an incorrect (delayed, missing, etc.) torque command to the driver feedback motor.
1466	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Resistive drift between neighboring pins in the connectors of the steer-by-wire control module or driver feedback motor could result in an incorrect (delayed, missing, etc.) torque command to the driver feedback motor.
1467	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1468	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Signal priority too low	A signal priority that is too low might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1469	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	A failure of the message generator, transmitter, or receiver might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.
1470	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder (virus) might affect the signal from the steer-by-wire control module to the driver feedback motor. This might cause the driver feedback motor to receive an incorrect (delayed, missing, etc.) torque command resulting in incorrect feedback to the driver.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Driver Feedback Motor)
1471	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect wiring connection	An incorrect wiring connection might cause the signal from the steer-by-wire control module to the driver feedback motor connection to be incorrect.
1472	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment might cause the signal from the steer-by-wire control module to the driver feedback motor connection to be incorrect.

Table I- 19: Steer-by-Wire Control Module to Mechanical Backup Clutch

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Mechanical Backup Clutch)
1605	External disturbances	EMI or ESD	EMI or ESD might affect the signal from the steer-by-wire control module to the clutch, causing the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1606	External disturbances	Single event effects (e.g., cosmic rays, protons)	Single event effects (e.g., cosmic rays, protons) might affect the signal from the steer-by-wire control module to the clutch, causing the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1607	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1608	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1609	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1610	External disturbances	Organic growth	Organic growth might affect the connection terminals of the steer-by-wire control module or the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1611	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1612	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination might affect the signal from the steer-by-wire control module to the clutch. This might cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1638	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals affected by moisture, corrosion, or contamination from external environment might affect the signal from the steer-by-wire control module to the clutch, causing the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Mechanical Backup Clutch)
1612	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination might affect the signal from the steer-by-wire control module to the clutch. This might cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1613	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the signal from the steer-by-wire control module to the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1614	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other components within the vehicle might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1615	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with other components within the vehicle might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1616	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other components within the vehicle might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1617	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1618	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	Corona effects from other components within the vehicle might affect the connection between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Mechanical Backup Clutch)
1639	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals affected by moisture, corrosion, or contamination from components within the vehicle might affect the signal from the steer-by-wire control module to the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1587	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	In systems with a mechanical backup, an intermittent connection may affect the signal between the steer-by-wire control module and the clutch. This may cause the mechanical clutch to incorrectly engage (delayed, intermittently, too short a period, too little force, etc.).
1594	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	In systems with a mechanical backup, resistive drift between neighboring pins in the connectors for the steer-by-wire control module or the clutch may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1595	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	In systems with a mechanical backup, shorting between neighboring pins in the connectors for the steer-by-wire control module or the clutch may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1596	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	In systems with a mechanical backup, contact resistance in the connectors for the steer-by-wire control module or clutch that is too high might cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Mechanical Backup Clutch)
1597	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	In systems with a mechanical backup, electrical noise other than EMI or ESD might affect the signal from the steer-by-wire control module to the clutch, causing the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1599	Controller to actuator signal ineffective, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	In systems with a mechanical backup, if the connection between the steer-by-wire control module and clutch is open, short to ground, short to battery, or short to other wires in harness, this may cause the mechanical clutch to incorrectly engage (delayed, intermittently, too short a period, too little force, etc.).
1593	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Bus overload or bus error	In systems with a mechanical backup, a bus overload or bus error might affect the signal from the steer-by-wire control module to the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1600	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Signal priority too low	In systems with a mechanical backup, a signal priority that is too low might affect the signal from the steer-by-wire control module to the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1601	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	In systems with a mechanical backup, a failure of the message generator, transmitter, or receiver might affect the signal from the steer-by-wire control module to the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1602	Controller to actuator signal ineffective, missing, or delayed: Communication bus error	Malicious intruder	In systems with a mechanical backup, a malicious intruder might affect the signal from the steer-by-wire control module to the clutch. This may cause the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steer-by-Wire Control Module to Mechanical Backup Clutch)
1603	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect wiring connection	An incorrect wiring connection might affect the signal from the steer-by-wire control module -to the clutch, causing the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
1604	Controller to actuator signal ineffective, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment might affect the signal from the steer-by-wire control module -to the clutch, causing the mechanical clutch to engage incorrectly (delayed, intermittently, too short a period, too little force, etc.).
These causal factors only apply to SbW systems with a mechanical backup subsystem (i.e., intermediate SbW systems).			

Table I- 20: Ignition Key to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Ignition Key to SbW Control Module)
1339	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	Intermittent connection between the ignition key and SbW control module might affect the steering adjustment of the driver. A proximity key with a push button for engine start might fail (RFID tag might stop working) causing the steering wheel to lock.
1341	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	Connection that is open, short to ground, short to battery, or short to other wires in harness between the ignition key and SbW control module might affect the steering adjustment of the driver. This might cause the steering wheel to lock. This will most likely be possible with vehicles that use transponder keys.
1342	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD between the ignition key and SbW control module might affect the steering adjustment of the driver (e.g., electrical noise affecting the RFID tag possibly causing the engine to turn off). This might cause the steering wheel to lock.
1343	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	Failure of the message generator, transmitter, or receiver between the ignition key and SbW control module might affect the steering adjustment of the driver (e.g., RFID tag and the vehicle communicating an incorrect message and possibly causing the engine to turn off). This might cause the steering wheel to lock.
1344	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	Malicious intruder might disrupt the communication between the RFID keyless ignition and the vehicle communicating an incorrect message and possibly causing the engine to turn off. This might cause the steering wheel to lock.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Ignition Key to SbW Control Module)
1345	External disturbances	EMI or ESD	EMI or ESD might disrupt the communication between the RFID keyless ignition and the vehicle communicating an incorrect message and possibly causing the engine to turn off. This might cause the steering wheel to lock.
1346	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems of the ignition key and SbW control module might affect the steering adjustment of the driver. This might cause the steering wheel to lock.
1347	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the ignition key and SbW control module connection. This might cause the steering wheel to lock and affect the driver steering.
1348	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the ignition key and SbW control module connection. This might cause the steering wheel to lock and affect the driver steering. This might apply to transponder keys only.
1349	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might disrupt the communication between the RFID keyless ignition and the vehicle communicating an incorrect message and possibly causing the engine to turn off. This might cause the steering wheel to lock.
1350	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) within the vehicle might affect the ignition key and SbW control module connection. This might cause the steering wheel to lock and affect the driver steering. This might apply to transponder keys only.

Table I- 21: Instrument Panel Display to Driver

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Instrument Panel Display to Driver)
217	Hazardous interaction with other components in the rest of the vehicle	Other	A confusing telematics interface that makes it hard to differentiate warnings from other things might cause the driver to make incorrect steering adjustment or no steering adjustment when needed.
234	External disturbances	Other	External factors might affect the visual feedback from instrument panel display to the driver. For example, the display may not have a non-glare coating. If there's glare, the driver may not see the notification in the first place. This might cause the driver to make incorrect steering adjustment or no steering adjustment when needed.
1204	Hazardous interaction with other components in the rest of the vehicle	Other	Interaction with components within the vehicle might affect the visual feedback from instrument panel display to the driver. Visually obscured notifications (e.g., steering wheel design might limit what the driver can see on the dashboard) might cause the driver to make incorrect steering adjustment or no steering adjustment when needed.
1205	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	Environmental conditions in the vehicle cabin (e.g., moisture/humidity or icing) may affect the visibility of critical steering notifications on the instrument panel display (e.g., SbW availability or lateral automation system status).
1259	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Other	Warning notifications do not provide enough information to the driver to take appropriate action. For example, the driver may see a notification without an explanation of what it means (some vehicles have an LCD on the side to explain what the warning means).
1260	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Other	A single LCD screen might be used to show multiple system failures. If two failures occur at the same time or in rapid succession, the LCD screen might not show all system failures or might not display a system failure long enough for the driver to notice. This might cause the driver to issue an incorrect steering command.

Table I- 22: Rear Road Wheel Motors to Rear Road Wheels

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Motors to Rear Road Wheels)
945	Actuation delivered incorrectly or inadequately: Hardware faulty	Actuation delivered incorrectly or inadequately: Hardware faulty	Faulty hardware in the connection between rear road wheel motors and rear road wheels might affect the transmission of torque to adjust the rear road wheel steering angle.
946	Actuation delivered incorrectly or inadequately: Actuation delayed	Actuation delivered incorrectly or inadequately: Actuation delayed	The connection between rear road wheel motors and rear road wheels might cause a delay when transmitting torque to adjust the rear road wheel steering angle.
947	Actuation delivered incorrectly or inadequately: Incorrect connection	Actuation delivered incorrectly or inadequately: Incorrect connection	The rear road wheel motors might be incorrectly connected to the rear road wheels, affecting the transmission of torque to adjust the rear road wheel steering angle.
948	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the rear road wheel motors and rear road wheels connection. This might affect the transmission of torque to change the rear road wheel steering angle.
949	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the rear road wheel motors and rear road wheels connection. This might affect the feedback transmission of torque to change the rear road wheel steering angle.
950	External disturbances	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the rear road wheel motors and rear road wheels connection. This might affect the transmission of torque to change the rear road wheel steering angle.
952	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the rear road wheel motors and rear road wheels connection. This might affect the transmission of torque to change the rear road wheel steering angle.
953	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle might might affect the rear road wheel motors and rear road wheels connection. This might affect the transmission of torque to change the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Motors to Rear Road Wheels)
954	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the rear road wheel motors and rear road wheels connection. This might affect the transmission of torque to change the rear road wheel steering angle.
1212	External disturbances	Physical interference (e.g., chafing)	Physical interference from the external environment (e.g., road debris) may affect the connection between the rear road wheel motors and rear road wheels. This might affect the transmission of torque to change the rear road wheel steering angle.
1213	External disturbances	Extreme external temperature or thermal cycling	Extreme ambient temperatures or thermal cycling might affect the connection between the rear road wheel motors and rear road wheels (e.g., premature wear of seals). This might affect the transmission of torque to change the rear road wheel steering angle.
1214	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components might affect the connection between the rear road wheel motors and rear road wheels. This might affect the transmission of torque to change the rear road wheel steering angle.

Table I- 23: Rear Road Wheel Position Sensor to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor to Steer-by-Wire Control Module)
1004	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	An intermittent connection between the rear road wheel position sensor and electric power steering control module might affect the SbW control module's ability to control the rear road wheel steering angle.
1005	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	The connection between the rear road wheel position sensor and SbW control module might be open, short to ground, short to battery, or short to other wires in harness. This might affect the rear road wheel position measurement received by the SbW control module.
1006	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD might affect the connection between the rear road wheel position sensor and electric power steering control module. This might affect the rear road wheel position measurement received by the SbW control module.
1007	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	Contact resistance that is too high in the connection terminals of the rear road wheel position sensor or electric power steering control module might affect the rear road wheel position measurement received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor to Steer-by-Wire Control Module)
1008	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Connector shorting between neighboring pins in the connection terminals of the rear road wheel position sensor or electric power steering control module might affect the rear road wheel position measurement received by the SbW control module.
1009	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Connector resistive drift between neighboring pins in the connection terminals of the rear road wheel position sensor or electric power steering control module might affect the rear road wheel position measurement received by the SbW control module.
1014	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error might affect the rear road wheel position sensor and electric power steering control module connection (e.g., prevent data transmission). This might affect the SbW control module's ability to control the rear road wheel steering angle.
1017	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder or aftermarket component might disrupt or corrupt data transmission from the rear road wheel position sensor to the electric power steering control module. This might affect the SbW control module's ability to control the rear road wheel steering angle.
1018	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	A failure of the message generator, transmitter, or receiver might affect the rear road wheel position sensor and electric power steering control module connection (e.g., prevent data transmission). This might affect the SbW control module's ability to control the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor to Steer-by-Wire Control Module)
1019	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Signal priority too low	A signal priority that is too low might delay transmission of disrupt the rear road wheel position measurement to the electric power steering control module. This might affect the SbW control module's ability to control the rear wheel position.
1020	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect wiring connection	Incorrect wiring in the connection between the rear road wheel position sensor and electric power steering control module might affect the rear road wheel position measurement received by the SbW control module.
1021	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment for the connection between the rear road wheel position sensor and electric power steering control module might affect the rear road wheel position measurement received by the SbW control module.
1024	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the rear road wheel position sensor and electric power steering control module connection. This might affect the rear road wheel position measurement received by the SbW control module.
1026	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the rear road wheel position sensor and electric power steering control module connection. This might affect the rear road wheel position measurement received by the SbW control module.
1027	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the rear road wheel position sensor and electric power steering control module connection. This might affect the rear road wheel position measurement received by the SbW control module.
1028	External disturbances	Organic growth	Organic growth (e.g., mold) in the connection terminals of the rear road wheel position sensor or SbW control module might affect the rear road wheel position sensor and electric power steering control module connection (e.g., causing shorting). This might affect the rear road wheel position measurement received by the SbW control module.
1029	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the rear road wheel position sensor and electric power steering control module connection. This might affect the rear road wheel position measurement received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor to Steer-by-Wire Control Module)
1030	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination in the connection terminals of the rear road wheel position sensor or SbW control module might affect the rear road wheel position sensor and electric power steering control module connection (e.g., causing shorting). This might affect the rear road wheel position measurement received by the SbW control module.
1032	External disturbances	EMI or ESD	EMI or ESD might affect the rear road wheel position sensor and electric power steering control module connection. This might affect the rear road wheel position measurement received by the SbW control module.
1033	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the rear road wheel position sensor and electric power steering control module connection. This could affect the rear road wheel position measurement received by the SbW control module.
1034	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the rear road wheel position sensor and electric power steering control module connection. This could affect the rear road wheel position measurement received by the SbW control module.
1035	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle might affect the rear road wheel position sensor and electric power steering control module connection. This could affect the rear road wheel position measurement received by the SbW control module.
1036	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the rear road wheel position sensor and electric power steering control module connection. This could affect the rear road wheel position measurement received by the SbW control module.
1037	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrains), corona effects from high voltage components might affect the rear road wheel position sensor and electric power steering control module connection. This could affect the rear road wheel position measurement received by the SbW control module.
1038	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the rear road wheel position sensor or SbW control module might be affected by moisture, corrosion, or contamination from other vehicle components. This could affect the rear road wheel position measurement received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheel Position Sensor to Steer-by-Wire Control Module)
1215	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect unused connection terminals in the wiring harness connecting the rear road wheel position sensor and the SbW control module. This may affect the rear road wheel position measurement received by the SbW control module.
1216	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the rear road wheel position sensor and SbW control module might be affected by moisture, corrosion, or contamination from other vehicle components. This could affect the rear road wheel position measurement received by the SbW control module.
1217	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components might affect the connection between the rear road wheel position sensor and SbW control module (e.g., melting the wiring). This could affect the rear road wheel position measurement received by the SbW control module.

Table I- 24: Rear Road Wheels to Rear Road Wheel Position Sensor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheels to Rear Road Wheel Position Sensor)
955	Sensor measurement incorrect or missing	Sensor incorrectly aligned or positioned	If the connection between the rear road wheels and rear road wheel position sensor is missing (e.g., the sensor is incorrectly positioned), the SbW control module may not receive a rear road wheel position measurement.
956	Sensor measurement inaccurate	Sensor incorrectly aligned or positioned	If the connection between the rear road wheels and rear road wheel position sensor is inaccurate (e.g., the sensor is incorrectly aligned), the SbW control module may receive an incorrect rear road wheel position measurement.
960	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
961	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
962	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
963	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
964	External disturbances	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
965	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
966	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rear Road Wheels to Rear Road Wheel Position Sensor)
967	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
968	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
969	Sensor measurement delay	Sensor incorrectly aligned or positioned	If the rear road wheel position sensor is incorrectly aligned or positioned relative to the rear road wheels, this may delay the measurement of the rear road wheel position.
1218	External disturbances	EMI or ESD	EMI or ESD might affect the rear road wheels and rear road wheel position sensor connection. This might affect the measurement of the rear road wheel position.
1219	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components could affect the connection between the rear road wheels and rear road wheel position sensor. This might affect the measurement of the rear road wheel position.

Table I- 25: Rack and Pinion to Front Road Wheels

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rack and Pinion to Front Road Wheels)
161	Actuation delivered incorrectly or inadequately: Hardware faulty	Actuation delivered incorrectly or inadequately: Hardware faulty	Faulty hardware might affect torque transmission from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motor to the road wheels. Incorrectly transmitting the driver's torque or the steering motor torque may cause the system to respond differently than expected.
162	Actuation delivered incorrectly or inadequately: Actuation delayed	Actuation delivered incorrectly or inadequately: Actuation delayed	A delayed torque transmission from the rack and pinion to the front road wheels might delay transmission of torque from the driver or from the steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
163	Actuation delivered incorrectly or inadequately: Incorrect connection	Actuation delivered incorrectly or inadequately: Incorrect connection	An incorrect connection between the rack and pinion and front road wheels might affect the transmission of torque from driver or from steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
164	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
165	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
166	External disturbances	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
167	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other components within the vehicle might affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motors. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rack and Pinion to Front Road Wheels)
168	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference with other components within the vehicle might affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
169	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motors. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
1220	External disturbances	Extreme external temperature or thermal cycling	Extreme ambient temperatures or thermal cycling may affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect transmission of torque from the driver or steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
1221	External disturbances	Physical interference (e.g., chafing)	Physical interference from foreign objects may affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect transmission of trorque from the driver or steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
1222	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Excessive heat from other vehicle components might affect the transmission of steering torque from the rack and pinion to the front road wheels. This could affect the transmission of torque from the driver or from the steering motors to the road wheels. Incorrectly transmitting the driver's torque or the steering motors torque may cause the system to respond differently than expected.
1513	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the connection between the rack and pinion and steering motor, causing incorrect (delayed, missing, counterintuitive, etc.) feedback to the SbW control module.
1514	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the connection between the rack and pinion and steering motor, causing incorrect (delayed, missing, counterintuitive, etc.) feedback to the SbW control module.
1515	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the connection between the rack and pinion and steering motor, causing incorrect (delayed, missing, counterintuitive, etc.) feedback to the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Rack and Pinion to Front Road Wheels)
1516	External disturbances	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the connection between the rack and pinion and the steering motor. This may result in transmitting the incorrect (delayed, missing, counterintuitive, etc.) roadway feedback to the SbW control module.
1516	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the connection between the rack and pinion and the steering motor. This may result in transmitting the incorrect (delayed, missing, counterintuitive, etc.) roadway feedback to the SbW control module.
1517	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other components within the vehicle might affect the connection between the rack and pinion and the steering motor. This may result in transmitting the incorrect (delayed, missing, counterintuitive, etc.) roadway feedback to the SbW control module.
1518	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with other components within the vehicle might affect the connection between the rack and pinion and the steering motor. This may result in transmitting the incorrect (delayed, missing, counterintuitive, etc.) roadway feedback to the SbW control module.
1634	Actuation delivered incorrectly or inadequately: Hardware faulty	Actuation delivered incorrectly or inadequately: Hardware faulty	A faulty hardware might affect the connection between the rack and pinion and steering motor, causing incorrect feedback to the SbW control module.
1635	Actuation delivered incorrectly or inadequately: Actuation delayed	Actuation delivered incorrectly or inadequately: Actuation delayed	A delayed actuation might affect the connection between the rack and pinion and steering motor, causing incorrect feedback to the SbW control module.

Table I- 26: Steering Wheel to Driver

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel to Driver)
222	External disturbances	Vibration or shock impact	Vibration or shock impact from the external environment (e.g., vibrations due to poor road conditions) might mask the feedback from the steering wheel to the driver. This might affect the torque feedback to the driver and can affect the driver's steering command.
227	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might mas the feedback from the steering wheel to the driver. For example, deflated tire on one side of the vehicle causing vibrations might affect the steering wheel torque feedback to the driver.
1227	External disturbances	Extreme external temperature or thermal cycling	An extreme temperature in the vehicle cabin may cause the driver to grip the steering wheel lightly (e.g., steering wheel is too hot). The driver's reduced grip may limit the amount of feedback that can be transmitted to the driver.
1228	External disturbances	Mechanical connections affected by moisture, corrosion, or contamination	If the steering wheel has a steering wheel cover, moisture, corrosion, or contamination from the external environment may cause deterioration or degradation of the steering wheel cover. If the cover becomes loose, this may affect the feedback transmitted from the steering wheel to the driver.
1229	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	If the steering wheel has a steering wheel cover, moisture, corrosion, or contamination from other vehicle components may cause deterioration or degradation of the steering wheel cover. If the cover becomes loose, this may affect the feedback transmitted from the steering wheel to the driver.

Table I- 27: Steering Wheel to Steering Wheel Angle Sensor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel to Steering Wheel Angle Sensor)
516	Sensor measurement inaccurate	Sensor incorrectly aligned or positioned	If the steering wheel and steering wheel angle sensor are incorrectly aligned or positioned (e.g., offset), the steering wheel angle measurement may be inaccurate (e.g., wrong value but within range). This might affect the steering wheel angle measurement, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
517	Sensor measurement incorrect or missing	Sensor incorrectly aligned or positioned	If the steering wheel and steering wheel angle sensor are incorrectly aligned or positioned (e.g., offset), the steering wheel angle measurement may be incorrect or missing (e.g., no value or value outside of range). This might affect the steering wheel angle measurement, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
518	Sensor measurement delay	Sensor incorrectly aligned or positioned	If the steering wheel and steering wheel angle sensor are incorrectly aligned or positioned, the steering wheel angle measurement may be delayed. This could delay the steering assist provided by the SbW control module or delay adjustment of the rear road wheel steering angle.
813	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the steering wheel and steering wheel angle sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
814	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the steering wheel and steering wheel angle sensor connection and might affect the feedback to the SbW control module. This might affect the SbW control module torque command.
815	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature might affect the steering wheel and steering wheel angle sensor connection and might affect the feedback to the SbW control module. This might affect the SbW control module torque command.
817	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the steering wheel and steering wheel angle sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
818	External disturbances	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination may affect the connection between the steering wheel and steering wheel angle sensor. This might affect the measurement of the driver's steering input, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel to Steering Wheel Angle Sensor)
820	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the steering wheel and steering wheel angle sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
821	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle might affect the steering wheel and steering wheel angle sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
1230	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination from other vehicle components may affect the connection between the steering wheel and steering wheel angle sensor. This might affect the measurement of the driver's steering input, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
1231	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components might affect the connection between the steering wheel and steering wheel angle sensor. This might affect the measurement of the driver's steering input, which could affect the amount of steering assist provided by the SbW control module or adjustment of the rear road wheel steering angle.

Table I- 28: Steering Wheel to Steering Wheel Torque Sensor

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel to Steering Wheel Torque Sensor)
534	Sensor measurement inaccurate	Sensor incorrectly aligned or positioned	The steering wheel torque sensor may be incorrectly aligned or positioned relative to the steering wheel, resulting in an inaccurate measurement (e.g., within range, but incorrect value). This might affect the measurement of the driver's steering input, which could affect amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
535	Sensor measurement delay	Sensor incorrectly aligned or positioned	The steering wheel torque sensor may be incorrectly aligned or positioned relative to the steering wheel, resulting in a delayed measurement (e.g., within range, but incorrect value). This might affect the measurement of the driver's steering input, which could affect amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
536	Sensor measurement incorrect or missing	Sensor incorrectly aligned or positioned	The steering wheel torque sensor may be incorrectly aligned or positioned relative to the steering wheel, resulting in an incorrect measurement (e.g., out of range or missing). This might affect the measurement of the driver's steering input, which could affect amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
539	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the steering wheel and steering wheel torque sensor connection. This might affect the measurement of the driver's steering input, which could affect amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
540	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the steering wheel and steering wheel torque sensor connection. This might affect the measurement of the driver's steering input, which could affect amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
542	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the steering wheel and steering wheel torque sensor connection. This might affect the SbW control module torque command.
548	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle might affect the steering wheel and steering wheel torque sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
549	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle might affect the steering wheel and steering wheel torque sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel to Steering Wheel Torque Sensor)
1232	External disturbances	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination might affect the steering wheel and steering wheel torque sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
1233	Hazardous interaction with other components in the rest of the vehicle	Mechanical connections affected by moisture, corrosion, or contamination	Moisture, corrosion, or contamination from components within the vehicle might affect the steering wheel and steering wheel torque sensor connection. This might affect the measurement of the driver's steering input, which could affect the amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
1234	External disturbances	Extreme external temperature or thermal cycling	Extreme ambient temperatures or thermal cycling may affect the connection between the steering wheel and steering wheel torque sensor. This might affect the measurement of the driver's steering input, which could affect the amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.
1235	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components may affect the connection between the steering wheel and steering wheel torque sensor. This might affect the measurement of the driver's steering input, which could affect the amount of power assist provided by the SbW control module or adjustment of the rear road wheel steering angle.

Table I- 29: Steering Wheel Angle Sensor to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor to SbW Control Module)
579	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	An intermittent connection between the steering wheel angle sensor and SbW control module could affect the measurement of the driver's steering input received by the SbW control module.
580	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	The connection between the steering wheel angle sensor and SbW control module could become open, short to ground, short to battery, or short to other wires in harness. This could affect the measurement of the driver's steering input received by the SbW control module.
581	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD could affect the connection between the steering wheel angle sensor and SbW control module. This could affect the measurement of the driver's steering input received by the SbW control module.
582	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	The contact resistance in the connection terminal of the steering wheel angle sensor or SbW control module may be too high. This could affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor to SbW Control Module)
583	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	The connector shorting between neighboring pins in the connection terminal of the steering wheel angle sensor or SbW control module may affect the measurement of the driver's steering input received by the SbW control module.
584	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Connector resistive drift between neighboring pins in the connection terminal of the steering wheel angle sensor or SbW control module may affect the measurement of the driver's steering input received by the SbW control module.
585	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error could affect the steering wheel angle sensor and SbW control module connection (e.g., prevent transmission of the steering angle). This could affect the measurement of the driver's steering input received by the SbW control module.
586	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Signal priority too low	Signal priority that is too low could affect the steering wheel angle sensor and SbW control module connection (e.g., prevent transmission of the steering angle). This could affect the measurement of the driver's steering input received by the SbW control module.
587	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	Failure of the message generator, transmitter, or receiver could affect the steering wheel angle sensor and SbW control module connection (e.g., prevent transmission of the steering angle). This could affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor to SbW Control Module)
588	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder or aftermarket component could affect the steering wheel angle sensor and SbW control module connection (e.g., transmit incorrect information). This could affect the measurement of the driver's steering input received by the SbW control module.
590	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect wiring connection	Incorrect wiring of the steering wheel angle sensor and SbW control module connection could affect the measurement of the driver's steering input received by the SbW control module.
591	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment in the steering wheel angle sensor or SbW control module could affect the measurement of the driver's steering input received by the SbW control module.
592	External disturbances	EMI or ESD	EMI or ESD might affect the steering wheel angle sensor and SbW control module connection. This could affect the measurement of the driver's steering input received by the SbW control module.
594	External disturbances	Vibration or shock impact	Vibration or shock impact could result in disturbances to the steering wheel angle sensor and SbW control module connection (e.g., fretting at the connection terminals). This could affect the measurement of the driver's steering input received by the SbW control module.
595	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
596	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
597	External disturbances	Organic growth	Organic growth could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor to SbW Control Module)
598	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
600	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
601	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
602	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
603	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
604	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects from high voltage components could affect the steering wheel angle sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
1236	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals in the steering wheel angle sensor and SbW control module connection may be affected by moisture, corrosion, or contamination. This might affect the measurement of the driver's steering input received by the SbW control module.
1237	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the steering wheel angle sensor and SbW control module may be affected by moisture, corrosion, or contamination. This might affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Angle Sensor to SbW Control Module)
1238	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the steering wheel angle sensor and SbW control module may be affected by moisture, corrosion, or contamination. This might affect the measurement of the driver's steering input received by the SbW control module.
1239	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components could affect the connection between the steering wheel angle sensor and SbW control module (e.g., melting the wiring). This might affect the measurement of the driver's steering input received by the SbW control module.
1240	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the steering wheel angle sensor and SbW control module may be affected by moisture, corrosion, or contamination from other vehicle components. This might affect the measurement of the driver's steering input received by the SbW control module.

Table I- 30: Steering Wheel Torque Sensor to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor to SbW Control Module)
605	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	An intermittent connection between the steering wheel torque sensor and SbW control module could affect the measurement of the driver's steering input received by the SbW control module.
606	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	The connection between the steering wheel torque sensor and SbW control module could become open, short to ground, short to battery, or short to other wires in harness. This could affect the measurement of the driver's steering input received by the SbW control module.
607	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD could affect the connection between the steering wheel torque sensor and SbW control module. This could affect the measurement of the driver's steering input received by the SbW control module.
608	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	The contact resistance in the connection terminal of the steering wheel torque sensor or SbW control module may be too high. This could affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor to SbW Control Module)
609	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	The connector shorting between neighboring pins in the connection terminal of the steering wheel torque sensor or SbW control module may affect the measurement of the driver's steering input received by the SbW control module.
610	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Connector resistive drift between neighboring pins in the connection terminal of the steering wheel torque sensor or SbW control module may affect the measurement of the driver's steering input received by the SbW control module.
611	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error could affect the steering wheel torque sensor and SbW control module connection (e.g., prevent transmission of the steering angle). This could affect the measurement of the driver's steering input received by the SbW control module.
612	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Signal priority too low	Signal priority that is too low could affect the steering wheel torque sensor and SbW control module connection (e.g., prevent transmission of the steering angle). This could affect the measurement of the driver's steering input received by the SbW control module.
613	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	Failure of the message generator, transmitter, or receiver could affect the steering wheel torque sensor and SbW control module connection (e.g., prevent transmission of the steering angle). This could affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor to SbW Control Module)
614	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder or aftermarket component could affect the steering wheel torque sensor and SbW control module connection (e.g., transmit incorrect information). This could affect the measurement of the driver's steering input received by the SbW control module.
615	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect wiring connection	Incorrect wiring of the steering wheel torque sensor and SbW control module connection could affect the measurement of the driver's steering input received by the SbW control module.
616	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment in the steering wheel torque sensor or SbW control module could affect the measurement of the driver's steering input received by the SbW control module.
617	External disturbances	EMI or ESD	EMI or ESD might affect the steering wheel torque sensor and SbW control module connection. This could affect the measurement of the driver's steering input received by the SbW control module.
619	External disturbances	Vibration or shock impact	Vibration or shock impact could result in disturbances to the steering wheel torque sensor and SbW control module connection (e.g., fretting at the connection terminals). This could affect the measurement of the driver's steering input received by the SbW control module.
620	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
621	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
622	External disturbances	Organic growth	Organic growth could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor to SbW Control Module)
623	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
625	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
626	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
627	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
628	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
629	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects from high voltage components could affect the steering wheel torque sensor and SbW control module connection. This might affect the measurement of the driver's steering input received by the SbW control module.
1241	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals in the steering wheel torque sensor and SbW control module connection may be affected by moisture, corrosion, or contamination. This might affect the measurement of the driver's steering input received by the SbW control module.
1242	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the steering wheel torque sensor and SbW control module may be affected by moisture, corrosion, or contamination. This might affect the measurement of the driver's steering input received by the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Wheel Torque Sensor to SbW Control Module)
1243	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the steering wheel torque sensor and SbW control module may be affected by moisture, corrosion, or contamination. This might affect the measurement of the driver's steering input received by the SbW control module.

Table I- 31: Steering Motor to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor to SbW Control Module)
1487	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	A connection that is intermittent might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1488	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	The connection between the steering motor and steer-by-wire control module may be open, short to ground, short to battery, or short to other wires in harness. This might cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1489	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD might affect the signal from the steering motor to the steer-by-wire control module. This might cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1490	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	Connector contact resistance that is too high might affect the signal from the steering motor to the steer-by-wire control module. This might cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor to SbW Control Module)
1491	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Shorting between neighboring pins in the connectors of the steering motor or steer-by-wire control module might result in the steer-by-wire control module receiving incorrect (delayed, missing, counterintuitive, etc.) roadway feedback or an incorrect motor position.
1492	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Resistive drift between neighboring pins in the connectors the steering motor or steer-by-wire control module might result in the steer-by-wire control module receiving incorrect (delayed, missing, counterintuitive, etc.) roadway feedback or an incorrect motor position.
1493	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1494	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Signal priority too low	A signal priority that is too low might delay the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1495	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	A failure of the message generator, transmitter, or receiver affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor to SbW Control Module)
1496	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder (e.g., virus) might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1497	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect wiring connection	An incorrect wiring connection might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive an incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1498	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect pin assignment	An incorrect pin assignment might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive an incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1499	External disturbances	EMI or ESD	EMI or ESD might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1501	External disturbances	Vibration or shock impact	Vibration or shock impact might affect the connection between the steering motor and the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1502	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems might affect the connection between the steering motor and the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1503	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling might affect the connection between the steering motor and the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1504	External disturbances	Organic growth	Organic growth might affect the connection between the steering motor and the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor to SbW Control Module)
1505	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) might affect the connection between the steering motor and the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1506	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1506	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1507	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle might affect the signal from the steering motor to the steer-by-wire control module. This could result in the steer-by-wire control module receiving incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1508	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from other components within the vehicle might affect the connection between the steering motor and the steer-by-wire control module. This could result in the steer-by-wire control module receiving incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1509	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with other components within the vehicle might affect the connection between the steering motor and the steer-by-wire control module. This could result in the steer-by-wire control module receiving incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1510	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other components within the vehicle might affect the connection between the steering motor and the steer-by-wire control module. This could result in the steer-by-wire control module receiving incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Steering Motor to SbW Control Module)
1511	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals might affect the connection between the steering motor and the steer-by-wire control module. This could result in the steer-by-wire control module receiving incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1512	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	Corona effects from high voltage components might affect the connection between the steering motor and the steer-by-wire control module. This could result in the steer-by-wire control module receiving incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1628	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals affected by moisture, corrosion, or contamination from the external environment might affect the connection between the steering motor and the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.
1629	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals affected by moisture, corrosion, or contamination from components within the vehicle might affect the signal from the steering motor to the steer-by-wire control module. This may cause the steer-by-wire control module to receive incorrect (delayed, missing, etc.) roadway feedback or an incorrect motor position.

Table I- 32: Wheel Speed Sensor to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Wheel Speed Sensor to Steer-by-Wire Control Module)
1280	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling affecting the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1290	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	Intermittent connection between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.
1291	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	Connection that is open, short to ground, short to battery, or short to other wires in harness between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.
1292	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.
1293	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	Contact resistance that is too high between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Wheel Speed Sensor to Steer-by-Wire Control Module)
1294	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Short circuit on the connector neighboring pins between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.
1295	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Resistive drift on the connector neighboring pins between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.
1296	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Bus overload or bus error	Bus overload or bus error between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.
1297	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Signal priority too low	Signal priority that is too low between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.
1298	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	Failure of the message generator, transmitter, or receiver between the wheel speed sensor and SbW control module might affect the individual wheel speed feedback to the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Wheel Speed Sensor to Steer-by-Wire Control Module)
1299	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	Malicious intruder on the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1300	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect wiring connection	Incorrect wheel speed sensor and SbW control module wiring connection might affect the individual wheel speed feedback to the SbW control module.
1301	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect pin assignment	Incorrect pin assignment on the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1302	External disturbances	EMI or ESD	EMI or ESD on the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1303	External disturbances	Vibration or shock impact	Vibration or shock impact disrupting the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1304	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems of the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1305	External disturbances	Organic growth	Organic growth on the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1306	External disturbances	Physical interference (e.g., chafing)	External physical interference (e.g., shafting with dry snow or extreme rain) with wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1307	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals affected by moisture, corrosion, or contamination on the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Wheel Speed Sensor to Steer-by-Wire Control Module)
1308	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle dispersed on the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1309	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle disrupting the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1310	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle and the wheel speed sensor and SbW control module connection might affect the individual wheel speed feedback to the SbW control module.
1311	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals could affect the wheel speed sensor and SbW control module connection and might affect the individual wheel speed feedback to the SbW control module.
1312	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects from high voltage components could affect the wheel speed sensor and SbW control module connection and might affect the individual wheel speed feedback to the SbW control module.
1313	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the wheel speed sensor or SbW control module may be affected by moisture, corrosion, or contamination from components within the vehicle and might affect the individual wheel speed feedback to the SbW control module.

Table I- 33: Yaw Rate/Lateral Acceleration Sensor to Steer-by-Wire Control Module

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor to SbW Control Module)
552	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is intermittent	The connection between the yaw rate/lateral acceleration sensor and SbW control module could become intermittent. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
553	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connection is open, short to ground, short to battery, or short to other wires in harness	The connection between the yaw rate/lateral acceleration sensor and SbW control module could become open, short to ground, short to battery, or short to other wires harness. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
554	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Electrical noise other than EMI or ESD	Electrical noise other than EMI or ESD could affect the connection between the yaw rate/lateral acceleration sensor and SbW control module. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
555	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector contact resistance is too high	Contact resistance in the connectors for the yaw rate/lateral acceleration sensor or SbW control module could be too high. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor to SbW Control Module)
557	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector shorting between neighboring pins	Connector shorting between neighboring pins on the yaw rate/lateral acceleration sensor and SbW control module connection could affect the feedback to the SbW control module torque command. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
558	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	Connector resistive drift between neighboring pins	Connector resistive drift between neighboring pins on the yaw rate/lateral acceleration sensor and SbW control module connection could affect the SbW control module torque command. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
559	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Bus overload or bus error	A bus overload or bus error could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
560	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Signal priority too low	A signal priority that is too low could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might cause a delay when implementing these active feedback features.
561	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Failure of the message generator, transmitter, or receiver	A failure of the message generator, transmitter, or receiver could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor to SbW Control Module)
563	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect wiring connection	The connection between the yaw rate/lateral acceleration sensor and SbW control module might be incorrectly wired. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
564	Sensor to controller signal inadequate, missing, or delayed: Incorrect connection	Incorrect pin assignment	The pin assignment for the yaw rate/lateral acceleration sensor or SbW control module might be incorrect. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
565	External disturbances	EMI or ESD	EMI or ESD could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
567	External disturbances	Vibration or shock impact	Vibration or shock impact could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
568	External disturbances	Manufacturing defects and assembly problems	Manufacturing defects and assembly problems could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
569	External disturbances	Extreme external temperature or thermal cycling	Extreme external temperature or thermal cycling could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
570	External disturbances	Organic growth	Organic growth could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor to SbW Control Module)
571	External disturbances	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
573	Hazardous interaction with other components in the rest of the vehicle	EMI or ESD	EMI or ESD from components within the vehicle could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
574	Hazardous interaction with other components in the rest of the vehicle	Vibration or shock impact	Vibration or shock impact from components within the vehicle could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
576	Hazardous interaction with other components in the rest of the vehicle	Physical interference (e.g., chafing)	Physical interference (e.g., chafing) with components within the vehicle could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
577	Hazardous interaction with other components in the rest of the vehicle	Electrical arcing from neighboring components or exposed terminals	Electrical arcing from neighboring components or exposed terminals could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
578	Hazardous interaction with other components in the rest of the vehicle	Corona effects from high voltage components	If the vehicle has high voltage components (e.g., electric or hybrid electric powertrain), corona effects from high voltage components could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
589	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	Malicious intruder	A malicious intruder or aftermarket component could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.

Causal Factor ID Number	Causal Factor Guide Phrase	Causal Factor Subcategory	Causal Factor (Yaw Rate/Lateral Acceleration Sensor to SbW Control Module)
1244	External disturbances	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the yaw rate/lateral acceleration sensor or SbW control module might be affected by moisture, corrosion, or contamination. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
1245	Hazardous interaction with other components in the rest of the vehicle	Active connection terminals affected by moisture, corrosion, or contamination	Active connection terminals of the yaw rate/lateral acceleration sensor or SbW control module may be affected by moisture, corrosion, or contamination from components within the vehicle. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
1246	External disturbances	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the yaw rate/lateral acceleration sensor and SbW control module might be affected by moisture, corrosion, or contamination. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
1247	Hazardous interaction with other components in the rest of the vehicle	Excessive heat from other components	Excessive heat from other vehicle components could affect the yaw rate/lateral acceleration sensor and SbW control module connection. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.
1248	Hazardous interaction with other components in the rest of the vehicle	Unused connection terminals affected by moisture, corrosion, or contamination	Unused connection terminals in the wiring harness connecting the yaw rate/lateral acceleration sensor and the SbW control module may be affected by moisture, corrosion, or contamination from other components in the vehicle. If the yaw rate/lateral acceleration sensor is used by the SbW control module for yaw rate stabilization or to compensate for pull or drift independent of the driver's input, this might affect implementation of these active feedback features.

APPENDIX J: THREE-LEVEL MONITORING STRATEGY

The three-level monitoring strategy is a redundant design strategy that is employed to meet requirements for components that address high ASIL (C or D) hazards. To employ a three-level monitoring strategy, the control module will include two microcontrollers: a main controller and an auxiliary controller. The main controller is the one that runs the system. It receives the inputs, runs the algorithms, makes the decisions, and sends out the output. It is also the one that communicates with the rest of the vehicle systems, and takes the vehicle to a safe state in the case of a sufficiently severe hazard.

The sole purpose of the auxiliary controller is to ensure the health and "sanity" of the main controller. It cannot run any system controls. However, it is capable of shutting down the main controller and taking the vehicle into a safe state. in the context of a "true" SbW system, the three-level monitoring strategy may be a suitable monitoring strategy for detecting faults in an individual controller. However, three-level monitoring alone may not be sufficient to meet the fail-operational architecture.

The three levels of the strategy can be described as follows:

Level 1: The main controller runs its calculations or algorithms. It re-runs them again using different calculation methods or algorithms. If the two results don't match, a fault is set, and a fault mitigation strategy is enacted.

Level 2: The auxiliary controller collects the inputs independently, and runs the calculations or algorithms that the main controller ran, although it uses different methods and algorithms. The auxiliary controller then compares its results to those of the main controller. If the results don't match, a fault is set, and a fault mitigation strategy is enacted.

Level 3: This level has different names in industry: "Seed & Key," "Quizzer," "Questions & Answers," etc. It employs a set of scenarios or questions with pre-determined answers. The auxiliary controller poses these questions or scenarios to the main controller randomly. If the main controller does not respond correctly, then a fault is set, and a fault mitigation strategy is enacted.

APPENDIX K: DIAGNOSTIC TROUBLE CODES RELEVANT TO THE EPS SYSTEM

Table K-1. Identification of Selected SAE J2012 DTCs for the SbW System

SAE J2012 Code	Phenomenon	System or Component
C0051	Steering Wheel Position Sensor (Subfault)	Steering Wheel Angle Sensor
C0052	Steering Wheel Position Sensor "Signal A" (Subfault)	Steering Wheel Angle Sensor
C0053	Steering Wheel Position Sensor "Signal B" (Subfault)	Steering Wheel Angle Sensor
C0054	Steering Wheel Position Sensor "Signal C" (Subfault)	Steering Wheel Angle Sensor
C0055	Steering Wheel Position Sensor "Signal D" (Subfault)	Steering Wheel Angle Sensor
C0079	Variable Effort Steering (Subfault)	Variable Effort Steering
U0126	Lost Communication With Steering Angle Sensor Module	Steering Wheel Angle Sensor
U0130	Lost Communication With Steering Effort Control Module	Steering Wheel Torque Sensor
U0319	Software Incompatibility With Steering Effort Control Module	Steering Wheel Torque Sensor
U0328	Software Incompatibility With Steering Angle Sensor Module	Steering Wheel Angle Sensor
U0428	Invalid Data Received From Steering Angle Sensor Module	Steering Wheel Angle Sensor

Table K-2. Identification of Selected SAE J2012 DTCs for Critical SbW System Interfaces

SAE J2012 Code	Phenomenon	System or Component
C0030	Left Front Tone Wheel (Subfault)	Wheel Speed Sensor
C0031	Left Front-Wheel Speed Sensor (Subfault)	Wheel Speed Sensor
C0032	Left Front-Wheel Speed Sensor Supply (Subfault)	Wheel Speed Sensor
C0033	Right Front Tone Wheel (Subfault)	Wheel Speed Sensor
C0034	Right Front-Wheel Speed Sensor (Subfault)	Wheel Speed Sensor
C0035	Right Front-Wheel Speed Sensor Supply (Subfault)	Wheel Speed Sensor
C0036	Left Rear Tone Wheel (Subfault)	Wheel Speed Sensor
C0037	Left Rear-Wheel Speed Sensor (Subfault)	Wheel Speed Sensor
C0038	Left Rear-Wheel Speed Sensor Supply (Subfault)	Wheel Speed Sensor
C0039	Right Rear Tone Wheel (Subfault)	Wheel Speed Sensor
C003A	Right Rear-Wheel Speed Sensor (Subfault)	Wheel Speed Sensor
C003B	Right Rear-Wheel Speed Sensor Supply (Subfault)	Wheel Speed Sensor
C003C	Rear Tone Wheel (Subfault)	Wheel Speed Sensor
C003D	Rear-Wheel Speed Sensor (Subfault)	Wheel Speed Sensor
C003E	Rear-Wheel Speed Sensor Supply (Subfault)	Wheel Speed Sensor
C0040	Brake Pedal Switch "A" (Subfault)	Brake Pedal Switch
C0041	Brake Pedal Switch "B" (Subfault)	Brake Pedal Switch
C0042	Brake Pedal Position Sensor "Circuit A" (Subfault)	Brake Pedal Position Sensor
C0043	Brake Pedal Position Sensor "Circuit B" (Subfault)	Brake Pedal Position Sensor
C0044	Brake Pressure Sensor "A" (Subfault)	Brake Pressure Sensor
C0045	Brake Pressure Sensor "B" (Subfault)	Brake Pressure Sensor
C0046	Brake Pressure Sensor "A"/"B" (Subfault)	Brake Pressure Sensor
C0086	Vehicle Dynamics Indicator (Subfault)	Brake/Stability Control System
P0500	Vehicle Speed Sensor "A"	Vehicle Speed Sensor
P0501	Vehicle Speed Sensor "A" Range/Performance	Vehicle Speed Sensor
P0502	Vehicle Speed Sensor "A" Circuit Low	Vehicle Speed Sensor
P0503	Vehicle Speed Sensor "A" Intermittent/Erratic/High	Vehicle Speed Sensor
P0644	Driver Display Serial Communication Circuit	Instrument Panel System
P0650	Malfunction Indicator Lamp (MIL) Control Circuit	Instrument Panel System
P2158	Vehicle Speed Sensor "B"	Vehicle Speed Sensor
P2159	Vehicle Speed Sensor "B" Range/Performance	Vehicle Speed Sensor
P215A	Vehicle Speed - Wheel Speed Correlation	Vehicle Speed Sensor
P215B	Vehicle Speed - Output Shaft Speed Correlation	Vehicle Speed Sensor
P2160	Vehicle Speed Sensor "B" Circuit Low	Vehicle Speed Sensor
P2161	Vehicle Speed Sensor "B" Intermittent/Erratic/High	Vehicle Speed Sensor

SAE J2012 Code	Phenomenon	System or Component
P2162	Vehicle Speed Sensor "A"/"B" Correlation	Vehicle Speed Sensor
U0001	High Speed CAN Communication Bus	Communication Bus
U0002	High Speed CAN Communication Bus Performance	Communication Bus
U0003	High Speed CAN Communication Bus (+) Open	Communication Bus
U0004	High Speed CAN Communication Bus (+) Low	Communication Bus
U0005	High Speed CAN Communication Bus (+) High	Communication Bus
U0006	High Speed CAN Communication Bus (-) Open	Communication Bus
U0007	High Speed CAN Communication Bus (-) Low	Communication Bus
U0008	High Speed CAN Communication Bus (-) High	Communication Bus
U0009	High Speed CAN Communication Bus (-) shorted to Bus (+)	Communication Bus
U0010	Medium Speed CAN Communication Bus	Communication Bus
U0011	Medium Speed CAN Communication Bus Performance	Communication Bus
U0012	Medium Speed CAN Communication Bus (+) Open	Communication Bus
U0013	Medium Speed CAN Communication Bus (+) Low	Communication Bus
U0014	Medium Speed CAN Communication Bus (+) High	Communication Bus
U0015	Medium Speed CAN Communication Bus (-) Open	Communication Bus
U0016	Medium Speed CAN Communication Bus (-) Low	Communication Bus
U0017	Medium Speed CAN Communication Bus (-) High	Communication Bus
U0018	Medium Speed CAN Communication Bus (-) shorted to Bus (+)	Communication Bus
U0019	Low Speed CAN Communication Bus	Communication Bus
U0020	Low Speed CAN Communication Bus Performance	Communication Bus
U0021	Low Speed CAN Communication Bus (+) Open	Communication Bus
U0022	Low Speed CAN Communication Bus (+) Low	Communication Bus
U0023	Low Speed CAN Communication Bus (+) High	Communication Bus
U0024	Low Speed CAN Communication Bus (-) Open	Communication Bus
U0025	Low Speed CAN Communication Bus (-) Low	Communication Bus
U0026	Low Speed CAN Communication Bus (-) High	Communication Bus
U0027	Low Speed CAN Communication Bus (-) shorted to Bus (+)	Communication Bus
U0028	Vehicle Communication Bus A	Communication Bus
U0029	Vehicle Communication Bus A Performance	Communication Bus
U0030	Vehicle Communication Bus A (+) Open	Communication Bus
U0031	Vehicle Communication Bus A (+) Low	Communication Bus
U0032	Vehicle Communication Bus A (+) High	Communication Bus
U0033	Vehicle Communication Bus A (-) Open	Communication Bus
U0034	Vehicle Communication Bus A (-) Low	Communication Bus
U0035	Vehicle Communication Bus A (-) High	Communication Bus

SAE J2012 Code	Phenomenon	System or Component
U0036	Vehicle Communication Bus A (-) shorted to Bus A (+)	Communication Bus
U0037	Vehicle Communication Bus B	Communication Bus
U0038	Vehicle Communication Bus B Performance	Communication Bus
U0039	Vehicle Communication Bus B (+) Open	Communication Bus
U0040	Vehicle Communication Bus B (+) Low	Communication Bus
U0041	Vehicle Communication Bus B (+) High	Communication Bus
U0042	Vehicle Communication Bus B (-) Open	Communication Bus
U0043	Vehicle Communication Bus B (-) Low	Communication Bus
U0044	Vehicle Communication Bus B (-) High	Communication Bus
U0045	Vehicle Communication Bus B (-) shorted to Bus B (+)	Communication Bus
U0046	Vehicle Communication Bus C	Communication Bus
U0047	Vehicle Communication Bus C Performance	Communication Bus
U0048	Vehicle Communication Bus C (+) Open	Communication Bus
U0049	Vehicle Communication Bus C (+) Low	Communication Bus
U0050	Vehicle Communication Bus C (+) High	Communication Bus
U0051	Vehicle Communication Bus C (-) Open	Communication Bus
U0052	Vehicle Communication Bus C (-) Low	Communication Bus
U0053	Vehicle Communication Bus C (-) High	Communication Bus
U0054	Vehicle Communication Bus C (-) shorted to Bus C (+)	Communication Bus
U0055	Vehicle Communication Bus D	Communication Bus
U0056	Vehicle Communication Bus D Performance	Communication Bus
U0057	Vehicle Communication Bus D (+) Open	Communication Bus
U0058	Vehicle Communication Bus D (+) Low	Communication Bus
U0059	Vehicle Communication Bus D (+) High	Communication Bus
U0060	Vehicle Communication Bus D (-) Open	Communication Bus
U0061	Vehicle Communication Bus D (-) Low	Communication Bus
U0062	Vehicle Communication Bus D (-) High	Communication Bus
U0063	Vehicle Communication Bus D (-) shorted to Bus D (+)	Communication Bus
U0064	Vehicle Communication Bus E	Communication Bus
U0065	Vehicle Communication Bus E Performance	Communication Bus
U0066	Vehicle Communication Bus E (+) Open	Communication Bus
U0067	Vehicle Communication Bus E (+) Low	Communication Bus
U0068	Vehicle Communication Bus E (+) High	Communication Bus
U0069	Vehicle Communication Bus E (-) Open	Communication Bus
U0070	Vehicle Communication Bus E (-) Low	Communication Bus
U0071	Vehicle Communication Bus E (-) High	Communication Bus
U0072	Vehicle Communication Bus E (-) shorted to Bus E (+)	Communication Bus
U0122	Lost Communication With Vehicle Dynamics Control Module	Brake/Stability Control System

SAE J2012 Code	Phenomenon	System or Component
U0123	Lost Communication With Yaw Rate Sensor Module	Yaw Rate Sensor
U0124	Lost Communication With Lateral Acceleration Sensor Module	Lateral Acceleration Sensor
U0129	Lost Communication With Brake System Control Module	Brake/Stability Control System
U0135	Lost Communication With Differential Control Module	Differential Control Module
U0136	Lost Communication With Differential Control Module	Differential Control Module
U0155	Lost Communication With Instrument Panel Cluster (IPC) Control Module	Instrument Panel System
U0316	Software Incompatibility With Vehicle Dynamics Control Module	Brake/Stability Control System
U0318	Software Incompatibility With Brake System Control Module	Brake/Stability Control System
U0323	Software Incompatibility With Instrument Panel Control Module	Instrument Panel System
U0416	Invalid Data Received From Vehicle Dynamics Control Module	Brake/Stability Control System
U0418	Invalid Data Received from Brake System Control Module	Brake/Stability Control System
U0423	Invalid Data Received From Instrument Panel Cluster Control	Instrument Panel System
U0436	Invalid Data Received From Differential Control Module	Differential Control Module
U0437	Invalid Data Received From Differential Control Module	Differential Control Module
U0513	Invalid Data Received From Yaw Rate Sensor Module	Yaw Rate Sensor
U0536	Invalid Data Received From Lateral Acceleration Sensor Module	Lateral Acceleration Sensor
U3003	Battery Voltage	Battery
U300A	Ignition Switch	Ignition Switch
U300B	Ignition Input Accessory/On/Start	Ignition Switch
U300C	Ignition Input Off/On/Start	Ignition Switch
U300D	Ignition Input On/Start	Ignition Switch
U300E	Ignition Input On	Ignition Switch
U300F	Ignition Input Accessory	Ignition Switch
U3010	Ignition Input Start	Ignition Switch
U3011	Ignition Input Off	Ignition Switch

DOT HS 812 576
August 2018

U.S. Department
of Transportation

National Highway
Traffic Safety
Administration

NHTSA

13502-080318-v3