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COST, WEIGHT, AND LEAD TIME ANALYSIS OF BLIND SPOT INTERVENTION

from:

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Abstract

Blind spot intervention (BSI) is, technologically, a combination of two existing systems, namely Blind Spot Detection (BSD) and Lane Keeping Assist (LKA). Vehicles were reviewed for the presence of BSD, LKA, and BSI features and it was found that the 2016 – 2020 model year platform of the Jaguar F-Pace was uniquely qualified for this study by the addition of BSI functionality between model years on the same vehicle. The F-Pace control system hardware for steering, braking, blind spot monitoring, and lane keeping was evaluated and found to exhibit no evidence of changes that were necessary to enable BSI.

The software development effort to enable BSI was also evaluated and was found to potentially require the inter-linking of the BSD and LKA algorithms along with functional safety validation, depending on the generation of software architecture, as shown in **Table 1**. Gen 1 vehicles have BSD and LKA existent but performing as stand-alone systems; Gen 2 vehicles likewise have BSD and LKA and are capable of communicating with each but do not do so; Gen 3 vehicles have fully-integrated ADAS systems including at least BSD and LKA but may not have enabled BSI functionality.

Table 1 Software development effort and cost required for BSI enablement

	Gen 1	Gen 2	Gen 3+
Software design	BSD zone parameters LKA steering parameters BSI linkage parameters	BSI linkage parameters	n/a
Validation testing	BSD zone parameters LKA steering parameters BSI linkage parameters	BSD zone parameters LKA steering parameters BSI linkage parameters	BSI linkage parameters
Development hours	800 - 1000	600 - 800	500 - 700
Development costs	\$80k - \$100k	\$60k - \$80k	\$50 k- \$70k
Overhead (SG&A + Profit)	24%		
Dealer markup	11%		
Amortization volume	1M units		
Per vehicle end-user price increase	\$0.11 - \$0.14	\$0.08 - \$0.11	\$0.07 - \$0.10

Using these software development efforts, the total aggregated engineering costs, from the supply base to the OEM, was found to be on the order of \$100,000. When calculated on a per-vehicle basis, amortizing over a 1M unit production run the costs are seen to be very small.

It would appear that reluctance on the part of OEMs to advertise or offer the feature is due more so to the industry's concern for keeping the driver engaged with the dynamic driving task for safety reasons than it is to cost pressures. Effective driver monitoring systems are crucial to ensuring a safe rollout of advanced driver assistance technologies.

Summary of Findings

Blind spot intervention (BSI) is, technologically, a combination of two existing systems, namely Blind Spot Detection (BSD) and Lane Keeping Assist (LKA). The Jaguar F-Pace was uniquely qualified for this study by the addition of BSI functionality between model years on the same vehicle. The F-Pace control system hardware for steering, braking, blind spot monitoring, and lane keeping was evaluated and found to exhibit no evidence of changes that were necessary to enable BSI.

The software development effort to enable BSI was also evaluated and was found to potentially require the inter-linking of the BSD and LKA algorithms along with functional safety validation, depending on the generation of software architecture, as shown in **Table 2**. Gen 1 vehicles have BSD and LKA existent but performing as stand-alone systems; Gen 2 vehicles likewise have BSD and LKA and are capable of communicating with each but do not do so; Gen 3 vehicles have fully-integrated ADAS systems including at least BSD and LKA but may not have enabled BSI functionality.

Table 2 Software development effort required for BSI enablement

	Gen 1	Gen 2	Gen 3+
Software design	BSD zone parameters LKA steering parameters BSI linkage parameters	BSI linkage parameters	n/a
Validation testing	BSD zone parameters LKA steering parameters BSI linkage parameters	BSD zone parameters LKA steering parameters BSI linkage parameters	BSI linkage parameters

Using these software development efforts, the total aggregated engineering costs, from the supply base to the OEM, was found to be on the order of $100,000 and the cost to add it is very small (pennies) on a per-vehicle basis when amortized over a 1M unit production run, as shown in **Table 3**.

Table 3 Software development levels of effort and costs for BSI system addition

	Gen 1	Gen 2	Gen 3+
Development hours	800 - 1000	600 - 800	500 - 700
Development costs	$80k - $100k	$60k - $80k	$50 k- $70k
Overhead (SG&A + Profit)	24%		
Dealer markup	11%		
Amortization volume	1M units		
Per vehicle end-user price increase	$0.11 - $0.14	$0.08 - $0.11	$0.07 - $0.10

Engineering Analysis

Blind Spot Intervention Technology Overview

Blind Spot Intervention[1] (BSI) is used here to describe a vehicle technology which automatically intervenes to guide a vehicle back to its lane center when it is approaching lane markers and another vehicle is identified in its blind spot. BSI is a combination of the functions provided by BSD and LKA systems as illustrated in Figure 1. BSI produces the same physical effect as an LKA system in which either steering system or individual wheel braking corrections are applied to prevent a vehicle from approaching and potentially crossing a lane marker by using, typically, a windshield mounted camera along with software algorithms to monitor the vehicle position relative to lane markers. Unlike LKA however, BSI is also informed of an event requiring intervention via signals generated by the BSD system and it functions intermittently as opposed to the continuous action of lane centering. As such, in a situation that would generate an alert to the driver of blind spot activity (a BSD alert) combined with lane deviation towards that blind spot activity, the BSI system will take action to steer the vehicle back towards the center of its lane, which the LKA system may not have done on it's own; for example, if the turn signal were used to signal a lane change. In addition, BSI alerts may be used to attempt to solicit driver action prior intervening.

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[1] BLIND SPOT INTERVENTION® is a registered trademark of Nissan North America, Inc.; see also USPTO Trademark Electronic Search System (TESS) and search for “blind spot intervention.” In this report, “blind spot intervention” or “BSI” is used as a generic technology or system name that can be applied to any vehicle.

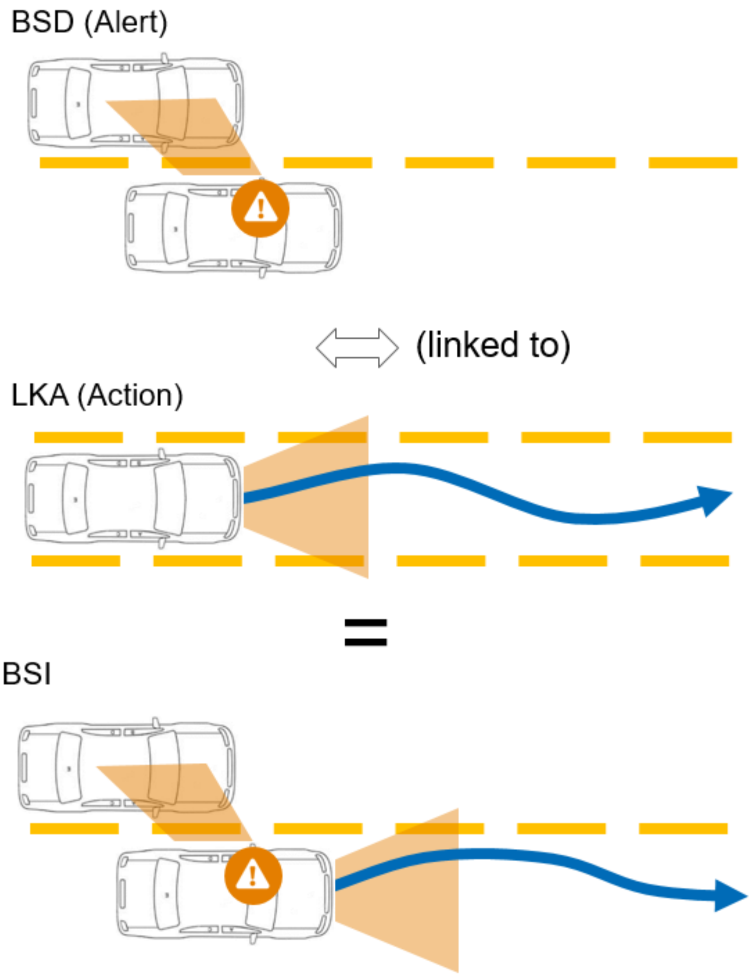

Figure 1 Graphical explanation of Blind Spot Detection linked to Lane Keep Assist to create Blind Spot Intervention functionality

ADAS and Other Key Terminology

The implementation of Advanced Driver Assist System (ADAS) features in vehicles requires complex architectures to support both existing and emerging technologies. Figure 2 shows a simplification of a potential ADAS architecture with what is considered an embedded machine.

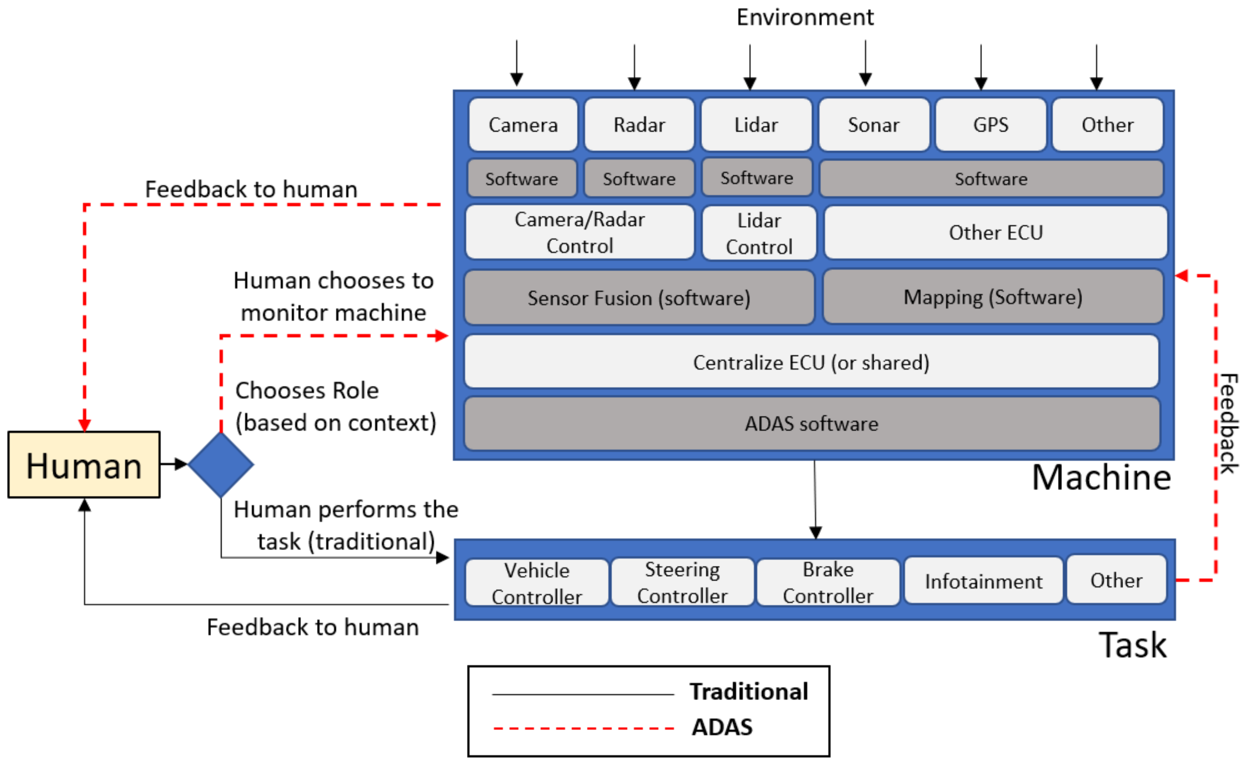

Figure 2 ADAS system overview[2]

A number of stakeholders have collaborated to produce and promote a common naming convention for ADAS technologies given the lack of commonality of naming the basic features by the automakers due to sometimes subtle differences in implementation for marketing distinctiveness and brand awareness; a snapshot of the first page is shown in Figure 3.[3,4]

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[2] Ricardo Analysis with input from Industry Experts

[3] AAA, Consumer Reports, J.D. Power, et. al., "Clearing the Confusion: Recommended Common Naming for Advanced Driver Assistance Technologies," last modified 08/03/20, taken from https://advocacy.consumerreports.org/wp-content/uploads/2018/10/Clearing-the-Confusion-ADAS-Nomenclature-one-pager-8-3-20-FINAL.pdf, last visited on 03/19/2021.

[4] The purpose of the list is to reduce confusion and to describe the basic technologies in a consistent manner while also emphasizing the criticality of "ensur[ing] that drivers are aware these systems are designed to assist, not replace an engaged driver."

CLEARING THE CONFUSION:
Recommended Common Naming for
Advanced Driver Assistance Technologies

Advanced Driver Assistance Systems (ADAS) have become increasingly prevalent on new vehicles, but the terminology used by automakers to describe them varies widely and so far has focused on marketing strategies.

The common naming outlined is simple, specific and based on system functionality. The list is meant to aid in reducing driver confusion and define the functions of ADAS in a consistent manner. **This is critical to ensure that drivers are aware these systems are designed to assist, not replace an engaged driver.**

The list is not meant to replace automaker proprietary system or package names, but rather help identify key functions within those packages and provide clarity to consumers. *The list will be continually refined as we work with other stakeholders and as new systems are developed.*

COLLISION WARNING	
Blind Spot Warning	Detects vehicles in the blind spot while driving and notifies the driver to their presence. Some systems provide an additional warning if the driver activates the turn signal.
Forward Collision Warning	Detects a potential collision with a vehicle ahead and alerts the driver. Some systems also provide alerts for pedestrians or other objects.
Lane Departure Warning	Monitors vehicle's position within the driving lane and alerts driver as the vehicle approaches or crosses lane markers.
Parking Collision Warning	Detects objects close to the vehicle during parking maneuvers and notifies the driver.
Rear Cross Traffic Warning	Detects vehicles approaching from the side at the rear of the vehicle while in reverse gear and alerts the driver. Some systems also warn for pedestrians or other objects.

COLLISION INTERVENTION	
Automatic Emergency Braking	Detects potential collisions with a vehicle ahead, provides forward collision warning, and automatically brakes to avoid a collision or lessen the severity of impact. Some systems also detect pedestrians or other objects.
Automatic Emergency Steering	Detects potential collisions with a vehicle ahead and automatically steers to avoid or lessen the severity of impact. Some systems also detect pedestrians or other objects.
Reverse Automatic Emergency Braking	Detects potential collisions while in reverse gear and automatically brakes to avoid or lessen the severity of impact. Some systems also detect pedestrians or other objects.

[1] Classified as Level 2 Driving Automation by SAE J3016

Last Modified 08/03/20

Figure 3 "Clearing the Confusion: Recommended Common Naming for Advanced Driver Assistance Technologies"

The following definitions that are relevant to ADAS in general and BSI are taken from the list:

Collision Warning

- Blind Spot Warning (BSW): Detects vehicles in the blind spot while driving and notifies the driver to their presence. Some systems provide an additional warning if the driver activates the turn signal.
- Lane Departure Warning (LDW): Monitors vehicle's position within the driving lane and alerts driver as the vehicle approaches or crosses lane markers.

Collision Intervention

- Automatic Emergency Braking (AEB): Detects potential collisions with a vehicle ahead, provides forward collision warning, and automatically brakes to avoid a collision or lessen the severity of impact. Some systems also detect pedestrians or other objects.
- Automatic Emergency Steering (AES): Detects potential collisions with a vehicle ahead and automatically steers to avoid or lessen the severity of impact. Some systems also detect pedestrians or other objects.

Driving Control Assistance

- Adaptive Cruise Control (ACC): Cruise control that also assists with acceleration and/or braking to maintain a driver-selected gap to the vehicle in front
- Lane Keeping Assistance: Provides steering support to assist the driver in preventing the vehicle from departing the lane. Some systems also assist to keep the vehicle centered in the lane.
- Active Driving Assistance[5]: Provides steering and brake/acceleration support to the driver at the same time. The driver must constantly supervise this support feature and maintain responsibility for driving.

ADAS and Blind Spot Intervention Development

The growing expansion of electronic capabilities, particularly the incorporation of advanced sensing capabilities, has fueled the growth of ADAS technologies in the automotive transportation world. ADAS features have evolved from stand-alone, single-function features to increasingly integrated features that share sensors and processors to create new functionality. The evolution of ADAS systems is described as being characterized by three generations of development and shown graphically in Figure 4 below.

- Gen 1: This type of system architecture is defined by discrete driver aid systems in terms of both hardware and software, i.e. “black box” systems; each of these systems do not interact with other ADAS to perform their intended function.
- Gen 2: These systems are similar in terms of dedicated modules for different functions but unlike Gen 1 they do make use of networking capability in order to allow an interlinking of functions thereby creating new functionality (e.g. BSI from separate BSD and LKA.)
- Gen 3+: This category covers integrated ADAS architectures where a centralized module with networked communications is used to process inputs from multiple smart sensors and commands various smart actuators and alerts; this architecture allows for the discrete driver aid functions of previous generation systems (e.g. BSD or LKA) as well as new functions from combined multiple inputs (e.g. BSI with BSD and LKA.) The 2019MY Audi A8 is an example of a Gen 3+ vehicle with a centralized ADAS module that combines visible and night vision cameras, long and short range radars, and LiDAR inputs to offer driver assist features ranging from AEB to Traffic Jam Pilot.

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[5] Classified as Level 2 Driving Automation by SAE J3016

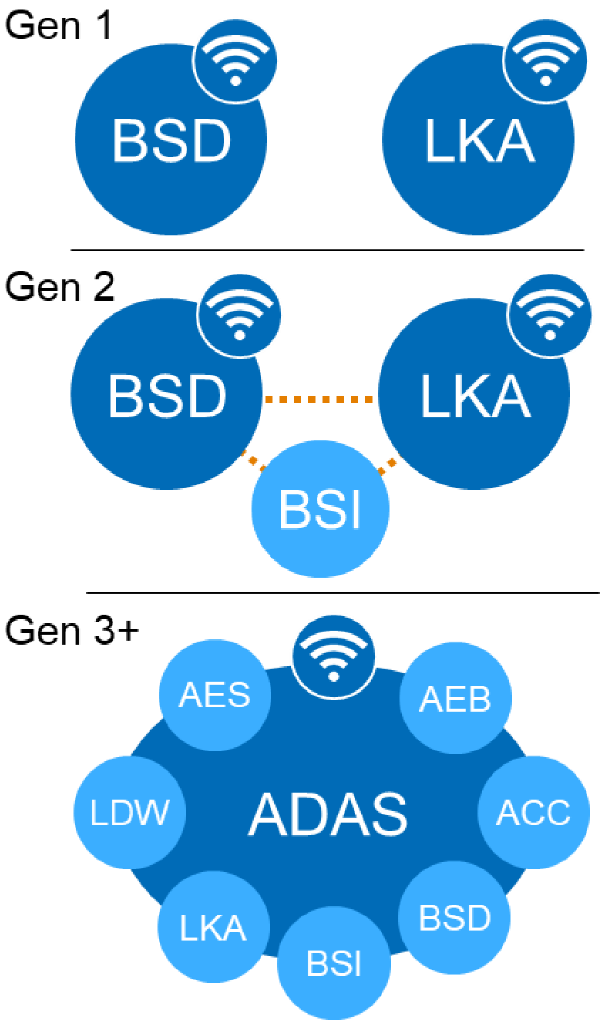


Figure 4 Visual representation of three generations of ADAS architectures

Third generation ADAS systems make use of increasingly integrated sensors as a means of improving vehicle awareness to improve active safety along with offering greater driver convenience.

Project Purpose

The objective of this investigation is to determine the incremental cost of adding BSI functionality to a vehicle. There are three possible baselines for determining this incremental cost:

- adding BSI to a vehicle with a **Gen 1** style of ADAS architecture;
- adding BSI to a vehicle with a **Gen 2** style of ADAS architecture;
- adding BSI to a vehicle with a **Gen 3+** style of ADAS architecture.

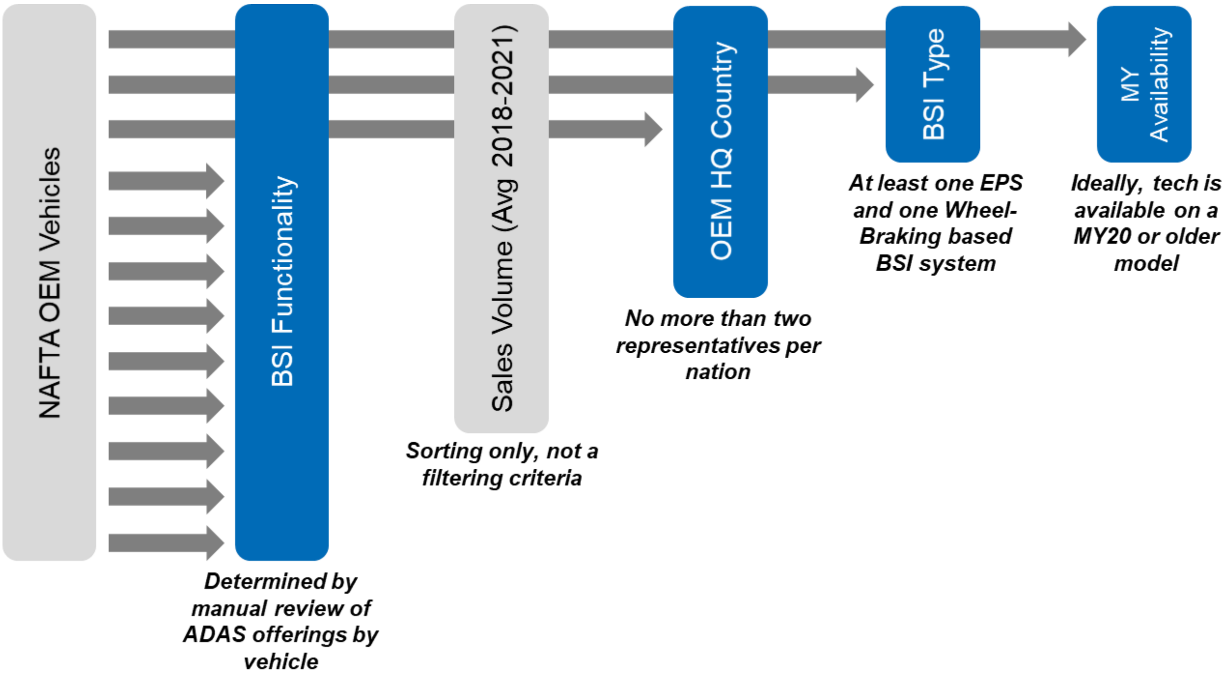
The rationale for choosing a second generation ADAS architecture and the final selection of the Jaguar F-Pace X761 platform for this study is discussed below.

Hardware Selection

As shown in Figure 5, the selection criteria for this study was multi-tiered. The preliminary sample pool was to contain at least six make-model vehicles that had:

- BSI availability as an advertised feature
- Manufacturers from North America, Europe, and Asia
- BSI types of Electric Power Steering (EPS) or wheel braking
- Model year availability, preferably MY20 or older (to make finding of used or new service parts easier.)

Though there were more than 100 make-models with both BSD and LKA, presence of BSI was critical for this project. The first stage of criteria, BSI as an advertised feature, eliminated a vast majority of vehicles sold in North America resulting in just over 20 make-models for further consideration as shown in **Table 4**.



Determined by manual review of ADAS offerings by vehicle

Sorting only, not a filtering criteria

No more than two representatives per nation

At least one EPS and one Wheel-Braking based BSI system

Ideally, tech is available on a MY20 or older model

Figure 5 Selection criteria utilized to generate viable, preliminary sample, and final selections

Table 4 Indicative, but non-exhaustive, list of vehicles sold in North America with available BSI functionality

Brand	Country	Nameplate	LKA Type	"BSI"	BSI Type	BSI offered before MY20?
Ford	US	Mustang Mach-E	EPS	Yes	EPS	No
Hyundai	KR	Palisade	EPS	Yes	Wheel	Yes
		Santa Fe	EPS	Yes	Wheel	Yes
Infiniti	JP	Q50	Wheel	Yes	Wheel	Yes
		QX50	Wheel	Yes	Wheel	Yes
		QX60	Wheel	Yes	Wheel	Yes
Jaguar	UK	E-Pace	EPS	Yes	EPS	Yes
		F-Pace	EPS	Yes	EPS	Yes

		I-Pace	EPS	Yes	EPS	Yes
Land Rover	UK	Discovery	EPS	Yes	EPS	Yes
		Range Rover	EPS	Yes	EPS	Yes
		Range Rover Sport	EPS	Yes	EPS	Yes
Mercedes-Benz	DE	C-Class	Wheel	Yes	Wheel	Yes
		GLB	Wheel	Yes	Wheel	Yes
		GLE	Wheel	Yes	Wheel	Yes
		GLE Coupe	Wheel	Yes	Wheel	Yes
		GLS	Wheel	Yes	Wheel	No
Nissan	JP	Leaf	Wheel	Yes	Wheel	Yes
Volkswagen	DE	Passat	EPS	Yes	EPS	Yes
		Tiguan	EPS	Yes	EPS	Yes
Volvo	SE	S60	EPS	Yes	EPS	Yes
		XC60	EPS	Yes	EPS	Yes
		XC90	EPS	Yes	EPS	Yes

Down Selection

From the list above of 23 viable vehicles, six were selected based on the following criteria; as shown in Figure 5**,** this included limiting selections to a maximum of two representatives per country, a minimum of one representative of each BSI actuation type (EPS or wheel braking [Wheel]), and availability of BSI as of MY20 vehicles to improve access to service componentry. In addition, considerations were made to avoid manufacturer and model redundancy (e.g. the Mercedes GLE coupe and Infiniti QX60 were omitted due to preference for higher volume Mercedes GLE and Infiniti QX50 models respectively). The resulting list of six vehicles is shown in Figure 6.

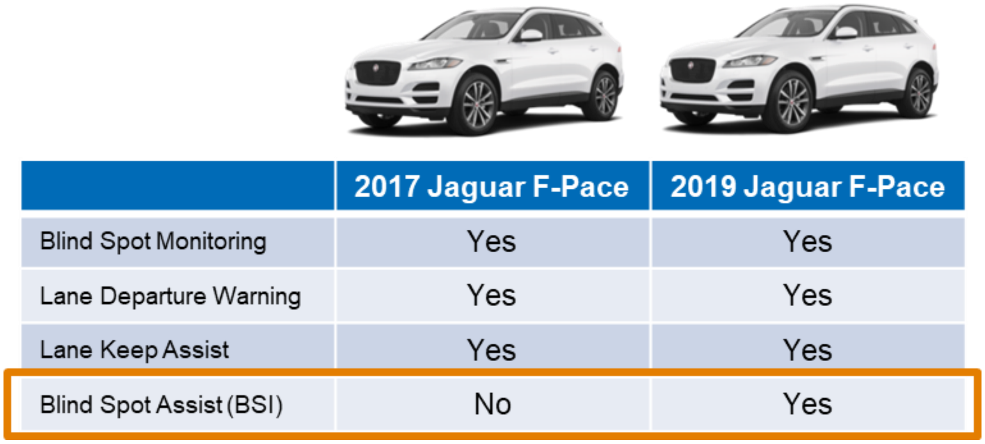
	VW Tiguan	Hyundai Santa Fe	Mercedes GLE	Volvo XC90	Infiniti QX50	Jaguar F-Pace
Vehicle Type	SUV	SUV	SUV	SUV	SUV	SUV
Sales Class	Mid	Mid	Premium	Premium	Premium	Premium
Sales Volume (CY18-21 avg *CY16-19 avg)	201,279	115,950	102,724	32,698*	28,718	14,801*
OEM Home Country	Germany	Korea	Germany	Sweden	Japan	United Kingdom
Intervention Style	EPS	Wheel-Braking	Wheel-Braking	EPS	Wheel-Braking	EPS
Alternative	VW Passat	Hyundai Palisade	Mercedes GLB	Volvo S60	Nissan LEAF	Multiple Jaguar or Land Rover Models

Figure 6 Down selection of six vehicle options

Final Selection

Each of the six models within the down-selected set were further investigated. Each was scrutinized primarily for availability of optional ADAS functionality to allow a "with / without" BSI juxtaposition as it pertained to other model trim levels, models sold by the same manufacturer, or older model years of the same platform. Attempting to contrast BSI feature sets between different models made by the same manufacturer (e.g. the Hyundai Santa Fe with BSI and the Hyundai Nexo with BSD and LKA but no BSI) would likely yield a variety of other confounding component differences convoluting the incremental differences to enable BSI. As such, BSI availability by model year was deemed the most attractive mechanism of comparison. Such a comparison between model years could introduce similar challenges if the vehicle line had undergone a platform redesign, so comparisons were limited to different model years built on the same platform. One model affords such a comparison opportunity: the Jaguar F-Pace.

The platform was released as a new model line in 2016 and sold through model year 2020 without a major refresh, the X761 generation Jaguar F-Pace uniquely has had a shift from no BSI availability to optional BSI availability within a product generation. As shown in Figure 7, model year 2017 F-Pace vehicles had the availability of BSD, LDW, and LKA systems but distinctly lacked BSI. The model gained this functionality part way through model year 2018 as a part of the optional "Drive Package".



	2017 Jaguar F-Pace	2019 Jaguar F-Pace
Blind Spot Monitoring	Yes	Yes
Lane Departure Warning	Yes	Yes
Lane Keep Assist	Yes	Yes
Blind Spot Assist (BSI)	No	Yes

Figure 7 Select ADAS comparison between 2017 Jaguar F-Pace and 2019 Jaguar F-Pace with Drive Package

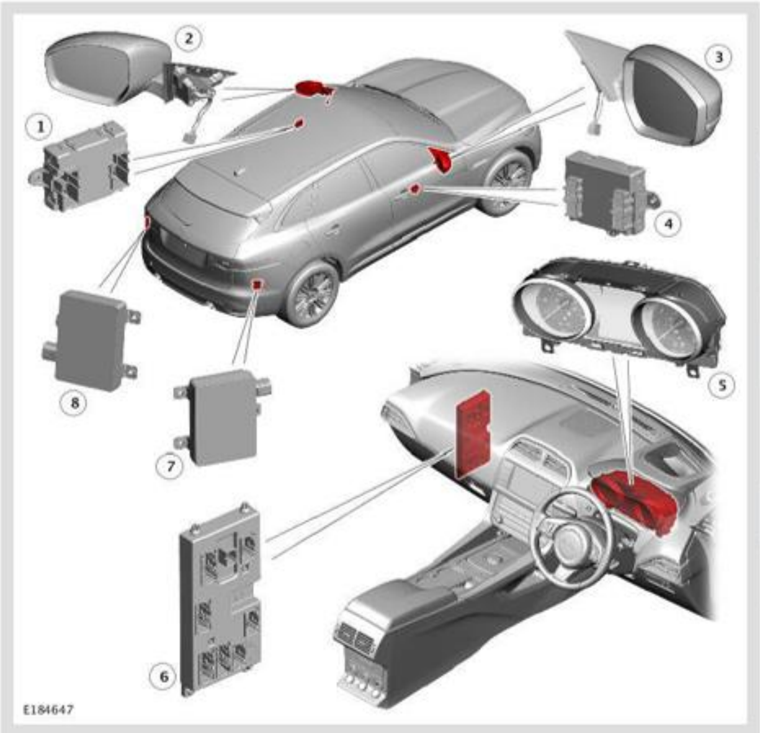
Considered in the context of the project objective, to determine the incremental cost for BSI, the 2016-2020 Jaguar F-Pace proved to be the ideal platform. The 2017-to-2019 model year comparison offers a rare ability to compare hardware sets on a Gen 2 architecture having BSD and LKA in common but having BSI functionality enabled only in the later model year. To confirm that the hardware sets had indeed not changed specifically *for the purpose of enabling BSI*, a hardware teardown analysis was performed on some of the relevant control modules.

Hardware Identification and Cost Analysis

As illustrated in our system map for a Gen 2 architecture (Figure 4), BSI function is a resultant of the interlinking of BSD and LKA. This section provides specific reference for the BSD and LKA systems as they exist in the Jaguar F-Pace. The BSI system (BSA, or Blind Spot Assist, for Jaguar) can be turned on and off through soft keys on the instrument panel menu for the F-Pace and does not add a hardware switch. An icon in the door mirrors is used to alert the driver of a vehicle in the blind spot when BSA is activated; the icon is partially or fully common with the blind spot monitoring system but differs in it's lighting color, intensity, and/or duration and was not costed in this study. Likewise, audible and/or tactical alerts were not costed for this study as they used common hardware to either BSD or LKA. Also, no steering intervention hardware was added for BSI as it used the same power steering and/or anti-lock braking hardware as the LKA system used.

BSD System

Figure 8 shows a schematic for the control modules, gateway module and warning lamps that are involved with the BSD system and Figure 9 shows the BSD system CAN communication networks in the Jaguar F-Pace.



Item	Description
1	Passenger Door Module (PDM)
2	Door mirror warning lamp – L
3	Door mirror warning lamp – R
4	Driver Door Module (DDM)
5	Instrument Cluster (IC) message center
6	Body Control Module/ GateWay Module (BCM/GWM) assembly
7	Blindspot Monitoring Control Module (BMCM) - R
8	Blindspot Monitoring Control Module (BMCM) - L

Figure 8 BSD system schematic for the Jaguar F-Pace[6]

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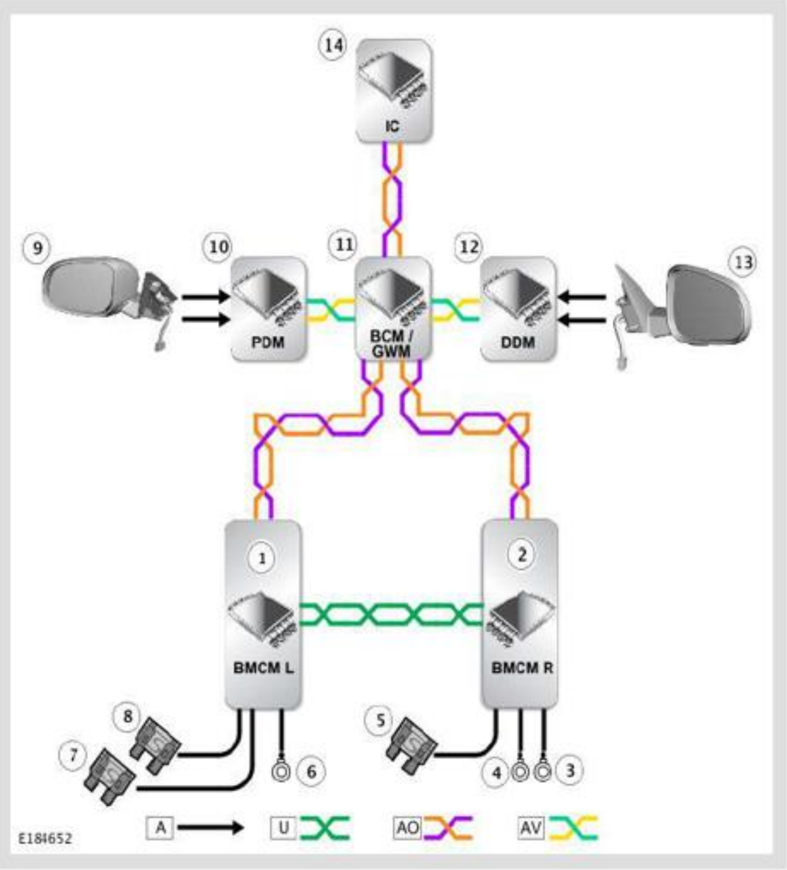
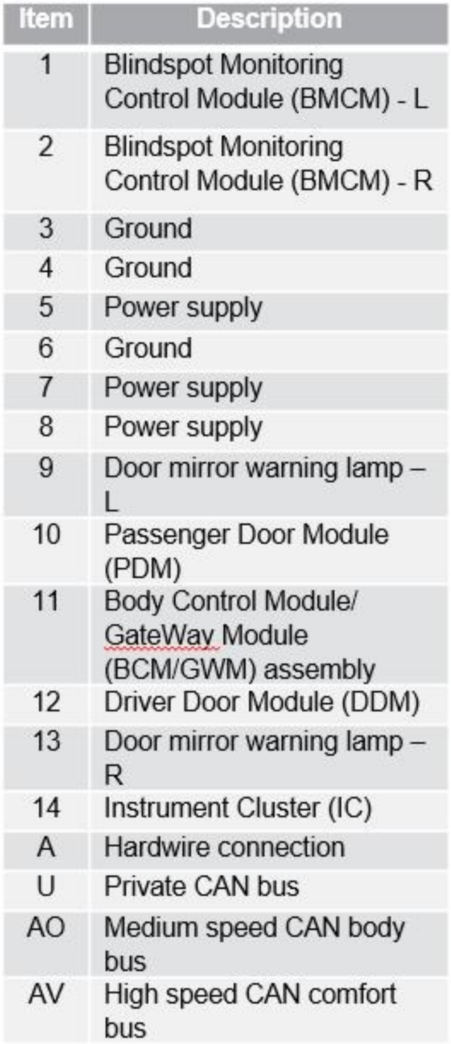
[6] Source: Jaguar F-Pace_X761_Workshop_Manual_All_Variations_2016-2019



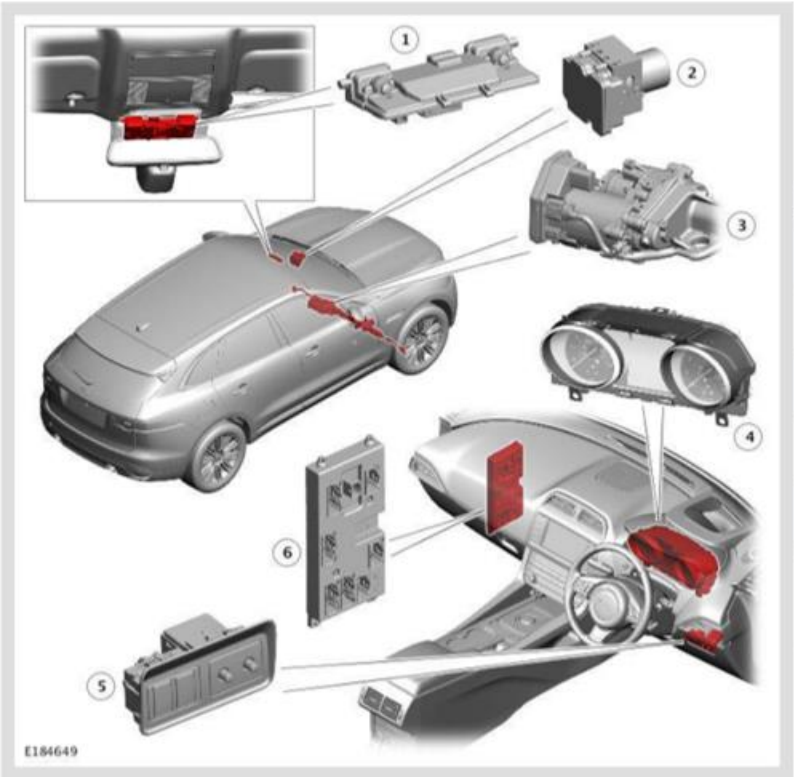


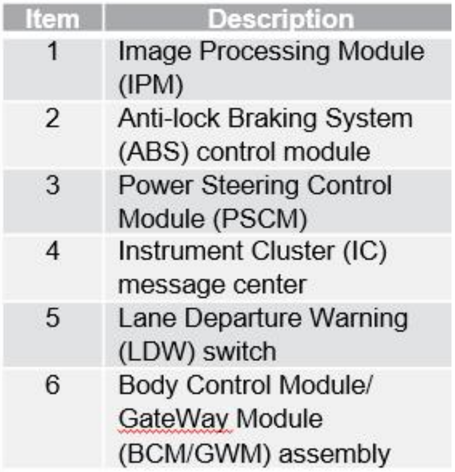
Item	Description
1	Blindspot Monitoring Control Module (BMCM) - L
2	Blindspot Monitoring Control Module (BMCM) - R
3	Ground
4	Ground
5	Power supply
6	Ground
7	Power supply
8	Power supply
9	Door mirror warning lamp – L
10	Passenger Door Module (PDM)
11	Body Control Module/ GateWay Module (BCM/GWM) assembly
12	Driver Door Module (DDM)
13	Door mirror warning lamp – R
14	Instrument Cluster (IC)
A	Hardwire connection
U	Private CAN bus
AO	Medium speed CAN body bus
AV	High speed CAN comfort bus

Figure 9 BSD system CAN network diagram for the Jaguar F-Pace [7]

LDW and LKA Systems

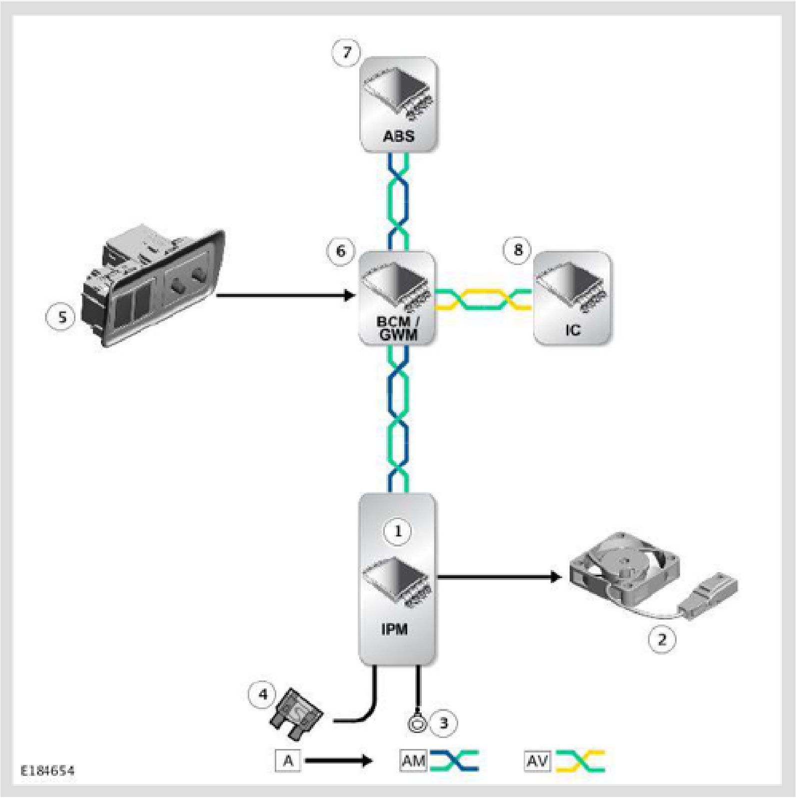
Figure 10 shows the LDW and LKA system schematic for the image processing, Anti-lock Braking System (ABS) control, power steering control, and body control/gateway modules along with the instrument cluster (IC) and LDW switch for the Jaguar F-Pace. All these modules are involved with the LDW and LKA functions and the Image Processing Module (IPM) hosts the algorithm that determines the steering torque to steer the vehicle away from crossing the lane markers and toward the center of the current lane. Figure 11 shows the LDW and LKA system Controller Area Network (CAN) communication networks.

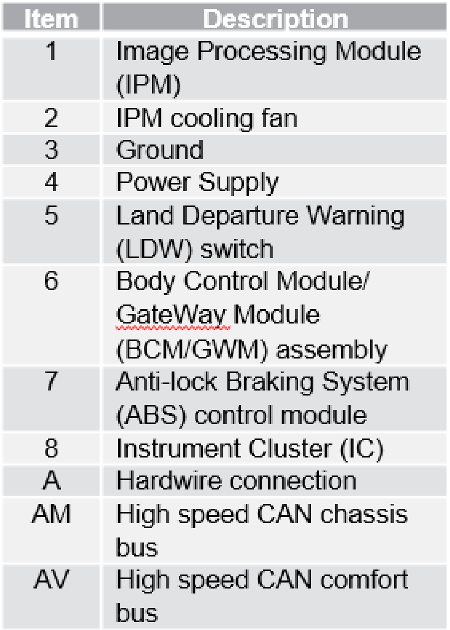




Item	Description
1	Image Processing Module (IPM)
2	Anti-lock Braking System (ABS) control module
3	Power Steering Control Module (PSCM)
4	Instrument Cluster (IC) message center
5	Lane Departure Warning (LDW) switch
6	Body Control Module/ GateWay Module (BCM/GWM) assembly

Figure 10 LDW and LKA system schematic for the Jaguar F-Pace[7]





Item	Description
1	Image Processing Module (IPM)
2	IPM cooling fan
3	Ground
4	Power Supply
5	Land Departure Warning (LDW) switch
6	Body Control Module/ GateWay Module (BCM/GWM) assembly
7	Anti-lock Braking System (ABS) control module
8	Instrument Cluster (IC)
A	Hardwire connection
AM	High speed CAN chassis bus
AV	High speed CAN comfort bus

Figure 11 LDW and LKA system CAN network diagram for the Jaguar F-Pace[7]

The Blind Spot Assist (BSA) feature is not called out in the F-Pace service manual; one may infer from this that the IPM also hosts the algorithm to how much intervening steering torque to apply in order to avoid a collision with a vehicle in the blind spot since it uses the same CAN bus structure and same controller schematics for LDW and LKA in both the 2017 and 2019 model years. This inference was confirmed by the subsequent hardware teardown analysis.

The above components for BSD, LDW and LKA were then assessed for relevance of function to our core objective of identifying incremental costs for BSI, resulting in a reducing the list of components. Components removed from further investigation performed functions common to the BSD or LKA systems, including switches, wiring, and explicit driver alert devices like the door mirror warning lamps. The power steering control module was eliminated due to high cost and limited availability of service parts that would have hindered timely execution of the project in addition to mounting evidence from expert interviews that BSI was enabled by software changes. From the remaining list of components, part numbers originating with our 2017 and 2019 vehicles were reviewed, looking specifically for variation. The resulting list is show below in **Table 5**.

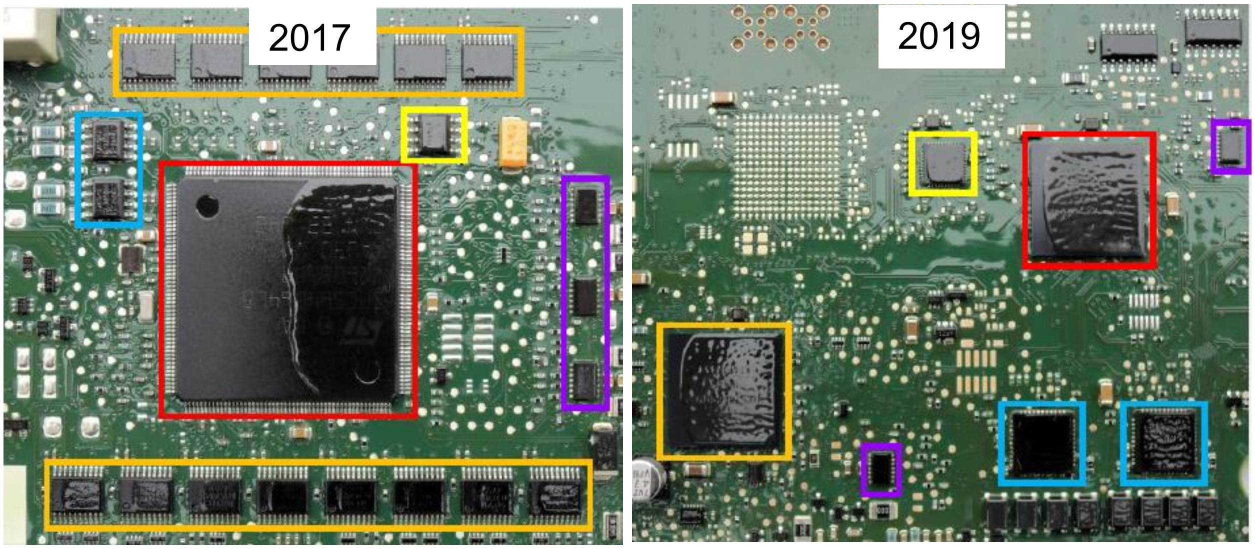
Table 5 The refined list of components that were considered for teardown analysis

Component	**2017 Jaguar F-Pace**	**2019 Jaguar F-Pace with Drive Package**
	Part Number	**Part Number**
Reference VIN	SADCM2BVXHA063719	SADCM2FV1KA396778
Blindspot Monitoring Control Module (BMCM; without bracket)	T2H1963	T4A28460
Driver's Door Control Module (DDM)	T4N6260	J9C9532
Passenger's Door Control Module (PDM)	T4N6274	T4A18083
Body Control Module (BCM) (Glovebox)	T2H21199	T4A34722
Instrument Cluster	T4A1887	T4N30869
Image Processing Module (IPM) (LDW/LKA Camera)	T4A2463	T4A18192
ABS Module and Controller	T2H38801	T4A37861

This list was refined once more to remove the Passenger Door Module (PDM), assumed to be largely redundant to the Driver Door Control Module (DDM); the left Blindspot Monitoring Control Module (BMCM), assumed to be redundant to the right-side module. The Instrument Cluster was assumed to be present for displaying set up information for the BSD and LDW/LKA features without material influence on the generation or execution of BSI related functions.

The remaining modules were scrutinized for differences that could be related to BSI functionality. It was observed that some differences did exist, for example around the radar antennae in the BMCMs, but these changes had a very small impact on the cost delta. The one module that did have significant changes that were introduced in the 2018 model year was the Body Control Module / Gateway Module as shown in Figure 12. The block diagram for the networking related to the BSD and LDW / LKA systems, Figure 13**Figure 20**, shows that the role of the BCM / GWM in the BSI feature is merely gating information between buses; the algorithms for BSI are hosted on the IPM just as they are for the LKW /

LKA features. The control modules and all other related hardware sets were found to be functionally equivalent between model years regarding the BSI system; for more detail on the other module hardware teardowns and the BCM / GWM see Appendix A.



Color	Name / Description
Red 🟥	MCU 32-Bit e200z4d Single Core RISC 1.5MB Flash 3V/5V 208-Pin LQFP
Orange 🟧	D-Type Transparent Latch 1 Channel 1:8 IC Tri-State 20-SSOP
Blue 🟦	1/1 Transceiver CAN 8-SO
Yellow 🟨	EEPROM Memory IC 128Kb (16K x 8) SPI 20MHz 8-SO
Purple 🟪	2/2 Transceiver LIN Bus 14-SO

Color	Name / Description
Red 🟥	MCU 32-bit e200z2/e200z4 RISC 3MB Flash 5V 256-Pin MAP-BGA
Orange 🟧	MCU 32-bit e200z2/e200z4 RISC 6MB Flash 5V 256-Pin MAP-BGA
Blue 🟦	FlexRay Transceiver 4TX 4RX 10Mbps 44-Pin HVQFN
Yellow 🟨	PHYTER, Single-Port10/100-Mbps Ethernet Transceiver, VQFN 40
Purple 🟪	2/2 Transceiver LIN Bus 14-SO

Figure 12 PCB layouts for the Body Control Module / Gateway Module from two model years show changes had occurred in 2018 MY

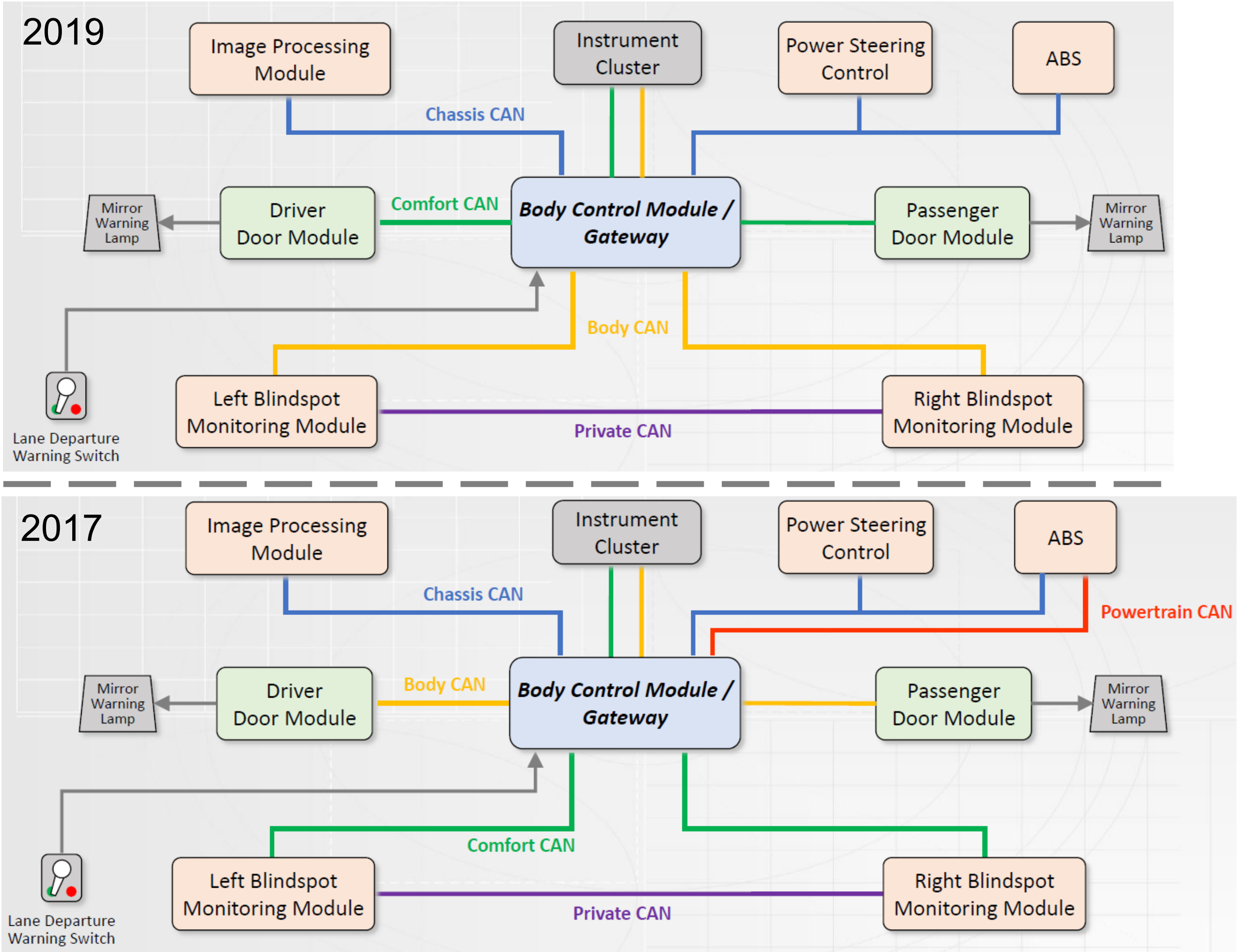


Figure 13 CAN structure related to the control modules for BSD and LDW / LKA systems in the Jaguar F-Pace

Software Development Cost Analysis

As in the Ricardo report to NHTSA describing the "Cost, Weight, and Lead Time Analysis of Components and Systems of Pedestrian Automatic Emergency Braking Systems (PAEB)," we have utilized the ISO 26262 functional safety model for road vehicles, illustrated in Figure 14, as a framework for establishing cost estimates for the software development of BSI systems and combined it with interview feedback from ADAS industry experts.

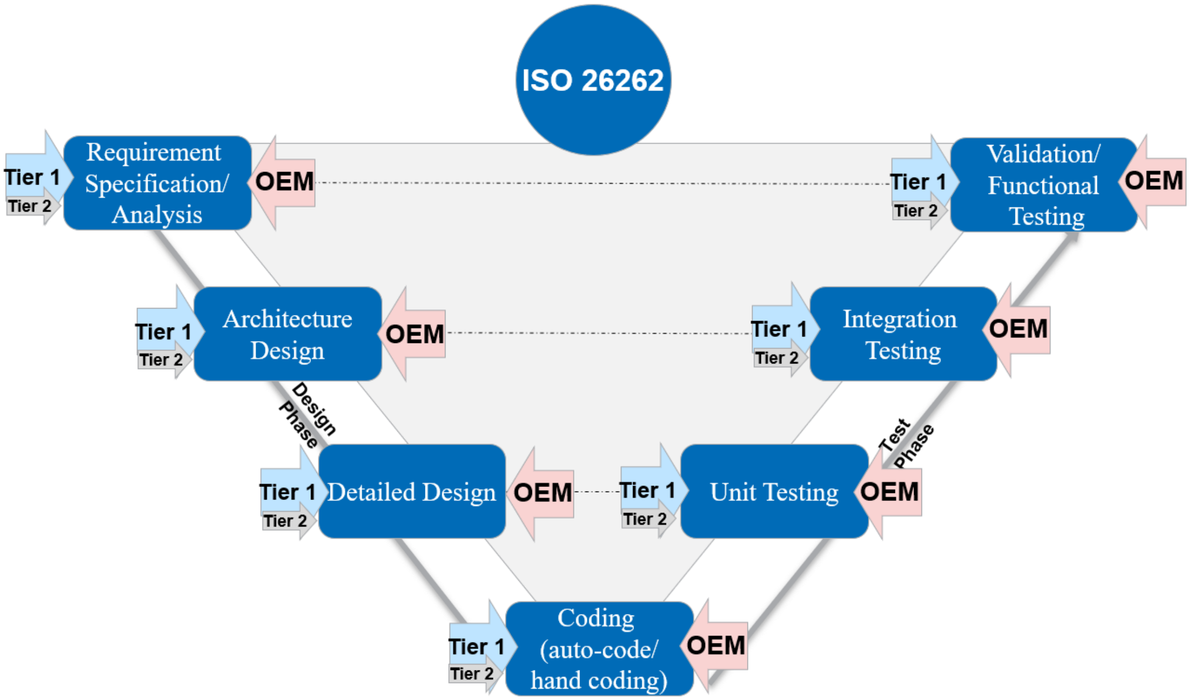


Figure 14 V-software development model

To help in determining software development costs, RSC interviewed three suppliers active in the ADAS field; two suppliers gave permission to use their names: Sense Photonics and Aptiv. In addition, we talked with three Ricardo employees who formerly worked at an OEM or within the supply base.

The experts agreed that BSD and LKA systems are often standalone systems with BSI being enabled through software interaction between the two as OEMs try to limit the addition of new hardware on a vehicle. Rather, new functions result from sensor fusion and improving sensor technology, such as adding a LiDAR system. Furthermore, sensor fusion is accelerating as suppliers seek to use common modules across multiple platforms with software tuning to enable differentiation between vehicles.

Secondly, BSD, LKA, and BSI systems are developed following the ISO 26262 V-software development model for functional safety as described above. The level of software development effort required to add BSI functionality to a vehicle platform depends on the starting point for the vehicle. Attempting to quantify the BSI development effort is complicated by the complex interactions of multiple OEMs and multiple Tier 1 and sub-tier suppliers as shown above**Figure 14**; based on feedback, we have simplified it down to the three generations or levels of software architecture for the ADAS systems on a vehicle, as shown in **Table 6**.

Table 6 Software development requirements for BSI enablement

	Gen 1	Gen 2	Gen 3+
Software design	Yes	Possible	No
Validation testing	Yes	Yes	Possible

For a Gen 1 architecture with unlinked BSD and LKA systems, both software algorithm development and validation development of the BSI system are required. With BSD and LKA existing as standalone features, it was assumed they would have to have additional parameters added to calibrate the size of the BSD zones differently. In addition, the steering intervention efforts in the LKA system may have to be changed to enable BSI functionality; and finally, the BSI functionality would need to be validated.

For a Gen 2 architecture the BSD and LKA systems are also unlinked, but the software may have already been developed with the linkage in mind as a future add-on; for this study it was assumed that "BSI linkage" parameters would have to be added to the software. BSI linkage could range from a simple switch to BSD zone settings and LKA steering intervention settings that also need to be validated; the latter was assumed for this study.

For a Gen 3 architecture, where an integrated ADAS was assumed to incorporate BSI functionality, it is still possible that development effort would need to be expended to calibrate and validate the BSI system if an OEM were to add BSI at a later date. This was expressed as "first mover" reluctance as OEMs and suppliers do not want to risk being liable for malfunction of a system only they have released to the market. The validation effort for a Gen 3 BSI system could range from validating just the linkage parameters to full validation of BDS zones, LKA steering efforts, and BSI linkage parameters; for this study it was assumed to involve validation of just the linkage parameters.

The levels of BSI development effort assumed for software algorithm design and validation testing for three generations of architecture as described above are summarized in **Table 7**.

Table 7 Software development effort required for BSI enablement

	Gen 1	Gen 2	Gen 3+
Software design	BSD zone parameters LKA steering parameters BSI linkage parameters	BSI linkage parameters	n/a
Validation testing	BSD zone parameters LKA steering parameters BSI linkage parameters	BSD zone parameters LKA steering parameters BSI linkage parameters	BSI linkage parameters

Discussions with experts also provided insight into the software development levels of effort. Feedback was also consistent with the PAEB study suggesting a 5:1 ratio of supply-base effort to OEM effort. The total software development effort, aggregated for suppliers and an OEM, required to enable BSI are summarized in **Table 8** below**Table 6Error! Reference source not found.**. For developing BSI on a vehicle with stand-alone BSD and LKA systems would require 800 – 1000 hours to implement the code, calibrate and validate the BSI system functionality, as the Gen 1 system indicates. It was assumed that development testing would be using the same vehicles and lab equipment that were used for the BSD and LKA functions, and therefore would not be as time-consuming nor as expense as developing either one of those features alone; this assumption appears to be justified by the list of vehicles with advanced safety systems from Consumer Reports.[7] There is significant variation in the range which is representative of the number of iterative loops that must be cycled through to achieve a well-tuned system that will neither be too sensitive resulting in driver annoyance and potentially switching it off nor

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[7] https://www.consumerreports.org/car-safety/cars-with-advanced-safety-systems/, last accessed 03/31/2021

not sensitive enough to the driver drifting towards the lane markers and the blind-spot-vehicle. Feedback also indicated the development effort could go even higher if the number of operational design domain (ODD) cases was increased.

With a Gen 2 system architecture the effort for implementing new code would only be required to create the linkage between the BSD and LKA systems and there could still be significant effort in validating the BSI system. This could save 200 hours off the approach needed for a stand-alone Gen 1 architecture. And for a Gen 3 architecture where it was assumed all the coding was in place and the BSI system was ready for functional validation, a further 100 hours could be saved from a Gen 1 system resulting in a 500 – 700 hour estimate.

Assuming annual salaries of $200,000 including overhead, as was done in the PAEB report, we arrived at the following cost estimates for enabling BSI functionality as shown in **Table 8**. In comparing with the costs for implementing one new ADAS feature in a Gen 3 architecture, as assumed in the PAEB study, these values at first appear to be low. However, the PAEB study was for a totally new feature including integration of a new sensor system into the vehicle whereas enabling BSI makes use of two already existing systems, BSD and LKA, and merely switches on the interlinking of those systems along with re-calibration of the sensitivities and validation of functional system safety, using the same test equipment. When viewed in that light, the cost for BSI validation at 1/10 the cost of validation for a new ADAS feature seems reasonable. The experts also concurred with this level of effort for BSI in comparison with developing a new feature from the ground up.

Table 8 Software development level of effort and costs for BSI system

	Gen 1	Gen 2	Gen 3+
Development hours	800 - 1000	600 - 800	500 - 700
Development costs	$80k - $100k	$60k - $80k	$50 k- $70k

Total Overall Costs

The total overall cost for a BSI system to be implemented on a vehicle was derived from the hardware costs plus the software costs. It was found that for vehicles with existing BSD and LKA systems, there was no need to add any new hardware for BSI enablement, so the hardware cost is zero. The software development cost, however, depends on the initial software architecture of the vehicle as described above. The software development costs estimated above were amortized over an assumed product lifespan of 5 years at a production rate of 200,000 units per year, as has been done in previous NHTSA automotive costing analyses. There are several possible scenarios that could add up to a 1M volume assumption from the numbers stated above for a single program to shared development over a few vehicles with shorter lifespans. With other assumptions the same as were used in the PAEB study, namely 24% overhead burden weighted from the Tier 1 supplier (24%) and the OEM (10%) at a 5:1 ratio and a dealer markup of 11%, an end-user price increase for BSI addition per vehicle was calculated, **Table *9***.

Table 9 Incremental cost to add BSI to existing vehicles, with first, second and third generation software architectures, are shown on a per vehicle basis

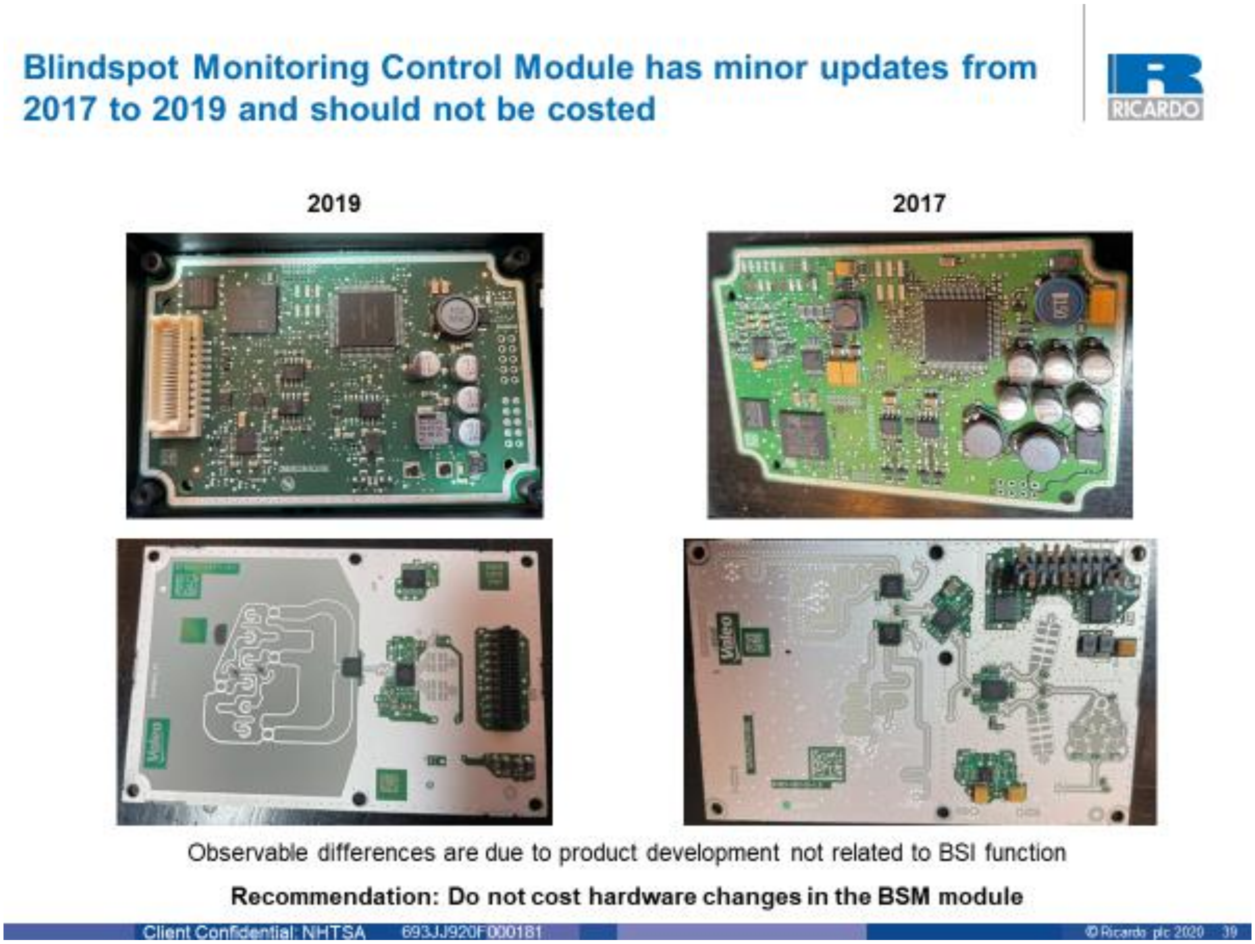
	Gen 1	Gen 2	Gen 3+
Overhead (SG&A + Profit)	24%		
Dealer markup	11%		
Amortization volume	1M units		
Per vehicle end-user price increase	$0.11 - $0.14	$0.08 - $0.11	$0.07 - $0.10

To add BSI to vehicles which have BSD and LKA features already existing, no additional hardware is required, and the development effort is largely spent on functional safety validation so the cost to add it is very small on a per-vehicle basis.

Appendix A: Hardware teardown analysis

Blindspot Monitoring Control Module

The BMCM, Figure 15, has minor updates such as shielding the ICs from the radar waves as can be seen on the bottom of the board below. These differences, including any changes to the antenna configuration itself that would have impacted the detectable range, were regarded as having a minor impact to cost. The microprocessor and the ICs were functionally equivalent.



Blindspot Monitoring Control Module has minor updates from 2017 to 2019 and should not be costed

2019

2017

Observable differences are due to product development not related to BSI function

Recommendation: Do not cost hardware changes in the BSM module

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Figure 15 BMCM circuit board layout

Image Processing Module

The IPM, Figure 16, has minor changes which did not impact the cost delta for the LDW / LKA and BSA systems. The microprocessor and the ICs were functionally equivalent.

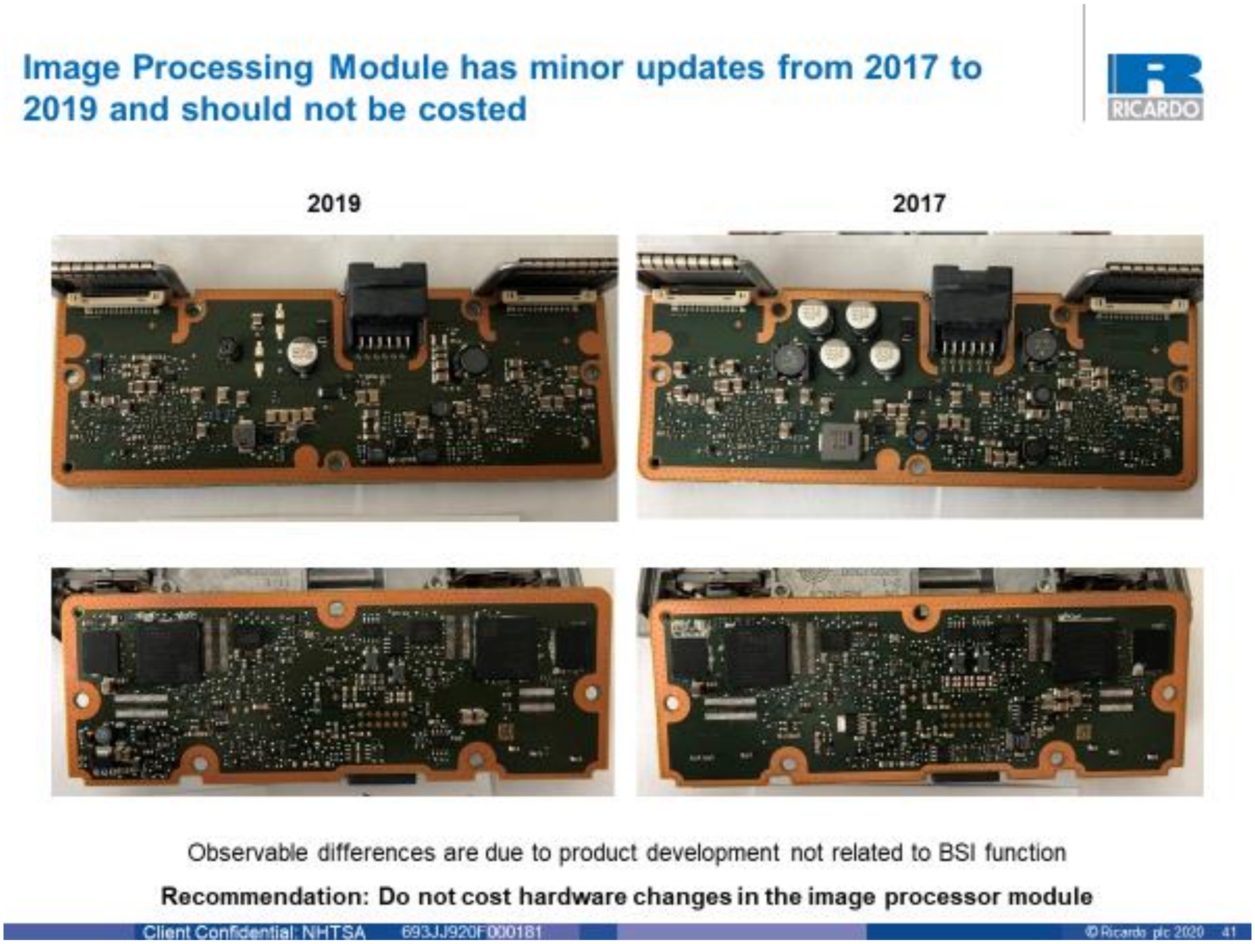

Image Processing Module has minor updates from 2017 to 2019 and should not be costed

Observable differences are due to product development not related to BSI function

Recommendation: Do not cost hardware changes in the image processor module

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Figure 16 IPM circuit board layout

Driver Door Module

The DDM, Figure 17, has minor changes such as adding 3 more pins to the 2019 bus connector which was necessary for 4-wire Flexray networking. The microprocessor and the ICs were functionally equivalent. These changes did not materially impact the cost delta for the BSD, LDW / LKA, and BSA systems.

Driver Door Module has minor updates from 2017 to 2019 and should not be costed

2019

2017

Observable differences are due to product development not related to BSI function

Recommendation: Do not cost hardware changes in the driver door module

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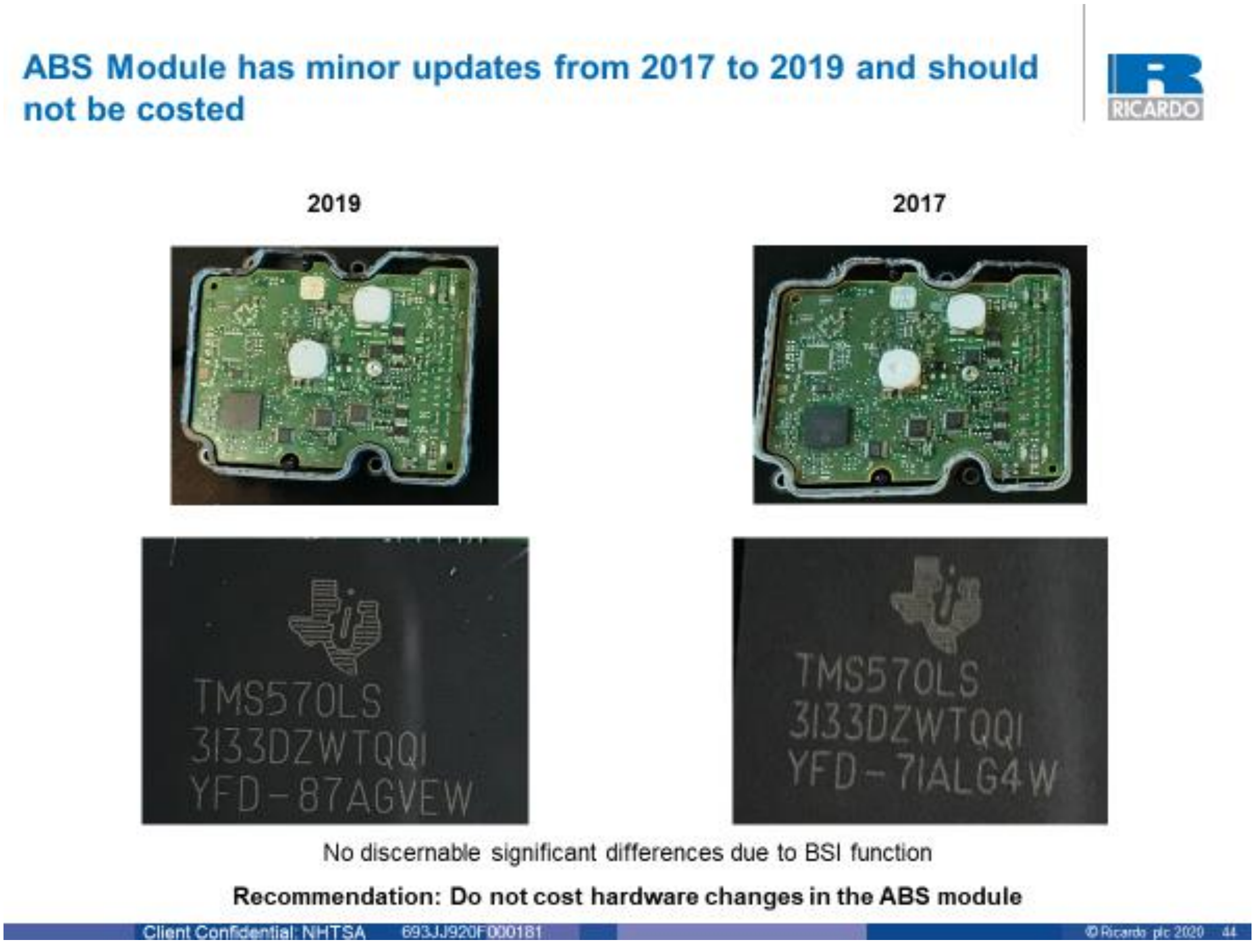
Figure 17 DDM circuit board layout

ABS Module

The ABS module, Figure 18, has minor observable differences and the microprocessor and ICs were functionally equivalent relative to the BSI system.



ABS Module has minor updates from 2017 to 2019 and should not be costed

No discernable significant differences due to BSI function

Recommendation: Do not cost hardware changes in the ABS module

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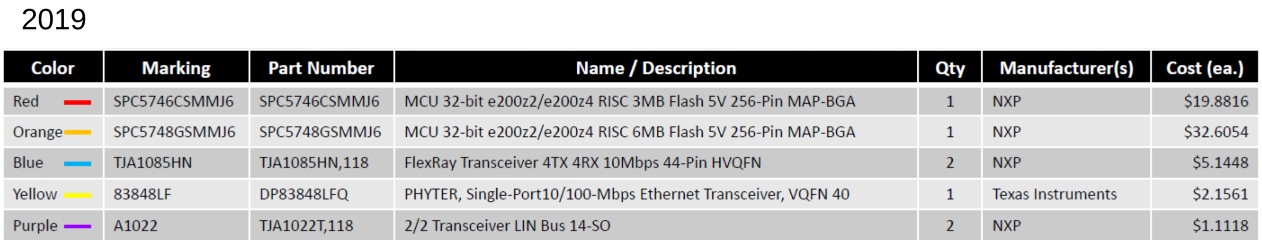
Figure 18 ABS module circuit board layout

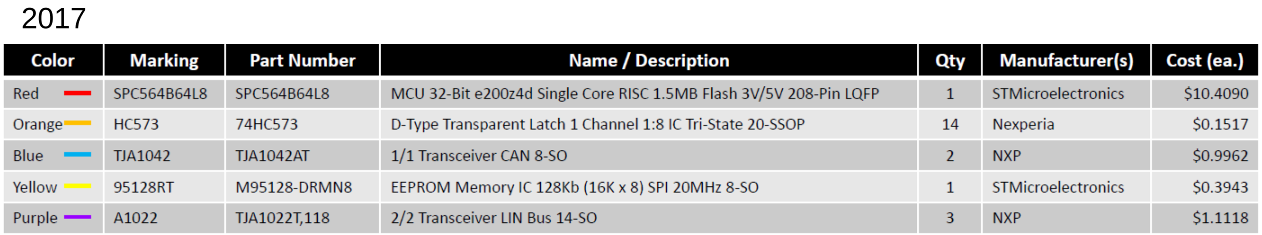
Body Control Module / Gateway Module

The cost breakdown of the major chip sets for the 2017 and 2019 MYs are shown in Figure 19.



2019

Color	Marking	Part Number	Name / Description	Qty	Manufacturer(s)	Cost (ea.)
Red —	SPC5746CSMMJ6	SPC5746CSMMJ6	MCU 32-bit e200z2/e200z4 RISC 3MB Flash 5V 256-Pin MAP-BGA	1	NXP	$19.8816
Orange —	SPC5748GSMMJ6	SPC5748GSMMJ6	MCU 32-bit e200z2/e200z4 RISC 6MB Flash 5V 256-Pin MAP-BGA	1	NXP	$32.6054
Blue —	TJA1085HN	TJA1085HN,118	FlexRay Transceiver 4TX 4RX 10Mbps 44-Pin HVQFN	2	NXP	$5.1448
Yellow —	83848LF	DP83848LFQ	PHYTER, Single-Port10/100-Mbps Ethernet Transceiver, VQFN 40	1	Texas Instruments	$2.1561
Purple —	A1022	TJA1022T,118	2/2 Transceiver LIN Bus 14-SO	2	NXP	$1.1118



2017

Color	Marking	Part Number	Name / Description	Qty	Manufacturer(s)	Cost (ea.)
Red —	SPC564B64L8	SPC564B64L8	MCU 32-Bit e200z4d Single Core RISC 1.5MB Flash 3V/5V 208-Pin LQFP	1	STMicroelectronics	$10.4090
Orange —	HC573	74HC573	D-Type Transparent Latch 1 Channel 1:8 IC Tri-State 20-SSOP	14	Nexperia	$0.1517
Blue —	TJA1042	TJA1042AT	1/1 Transceiver CAN 8-SO	2	NXP	$0.9962
Yellow —	95128RT	M95128-DRMN8	EEPROM Memory IC 128Kb (16K x 8) SPI 20MHz 8-SO	1	STMicroelectronics	$0.3943
Purple —	A1022	TJA1022T,118	2/2 Transceiver LIN Bus 14-SO	3	NXP	$1.1118

Figure 19 *Description and further detail of the key chip sets in the BCM / GWM*

The architecture of the BCM / GWM network in the Jaguar F-Pace is shown in Figure 20. The primary difference between the 2017 and 2019 BCM was for cyber security to help protect the vehicle from being hacked into and causing unintended consequences. The updated module also isolated the J-1962 diagnostic connector from the vehicle communication buses (to enhance security) and increased bus bandwidth capability with Flexray capability between modules and Ethernet for downloading software updates through the J1962 diagnostic connector. The telematics module was also isolated from the other controllers, for security hardening, in the 2019 version.

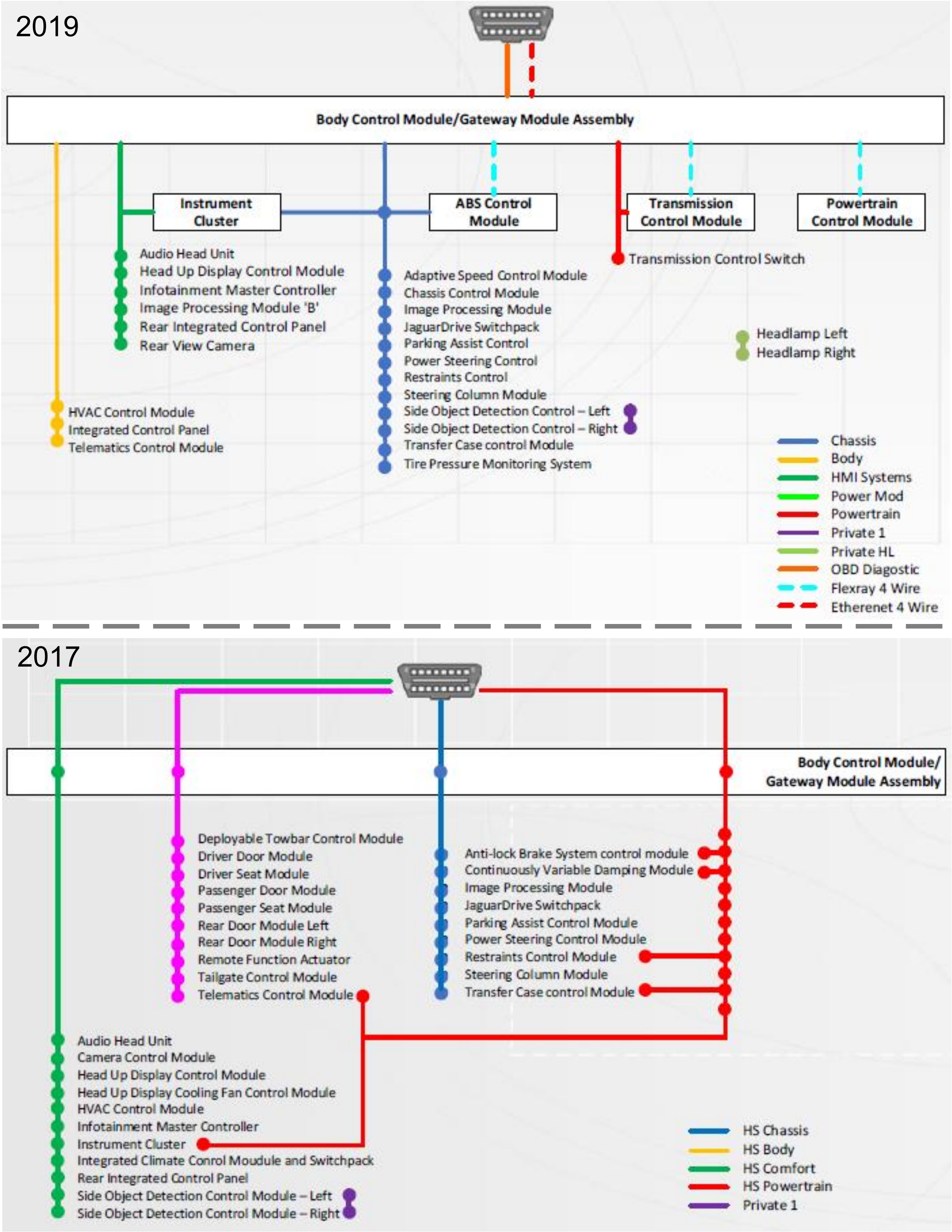
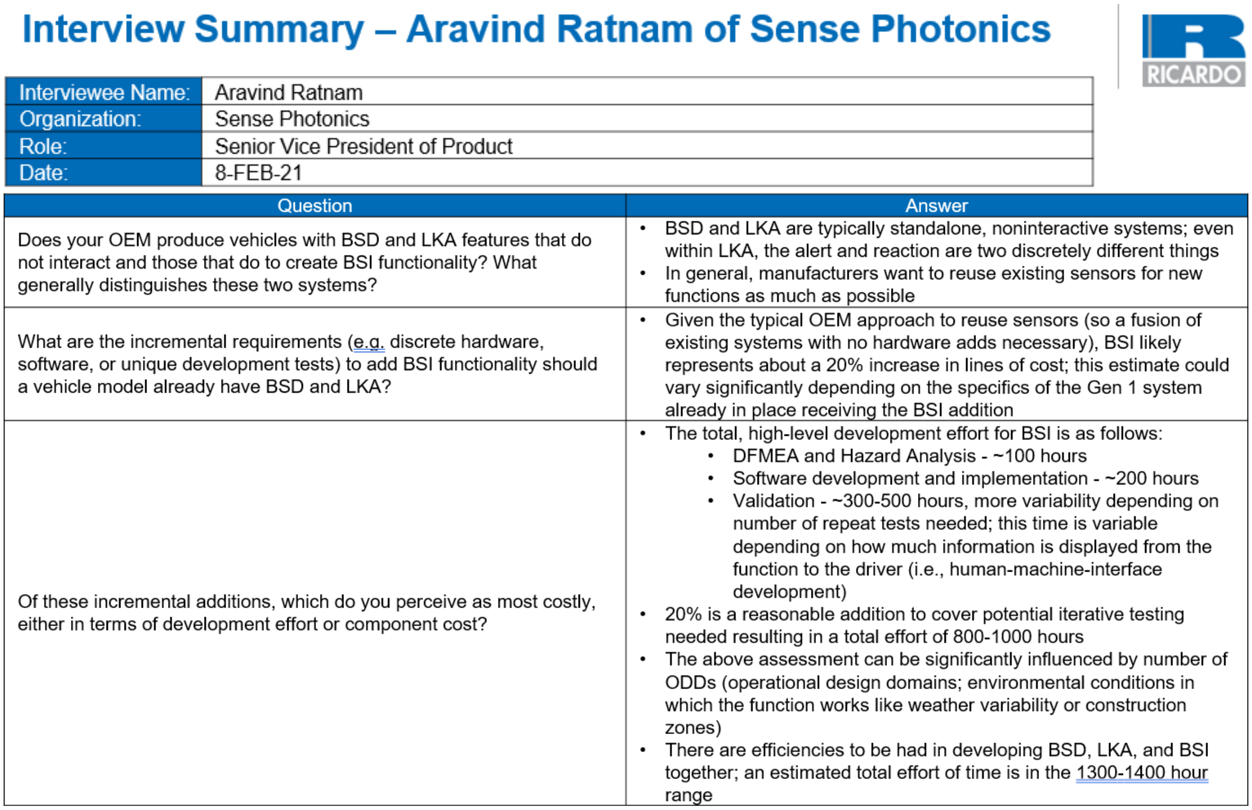


Figure 20 CAN architecture showing the centrality and the gating function of the Body Control Module / Gateway Module

Appendix B: Interview Responses

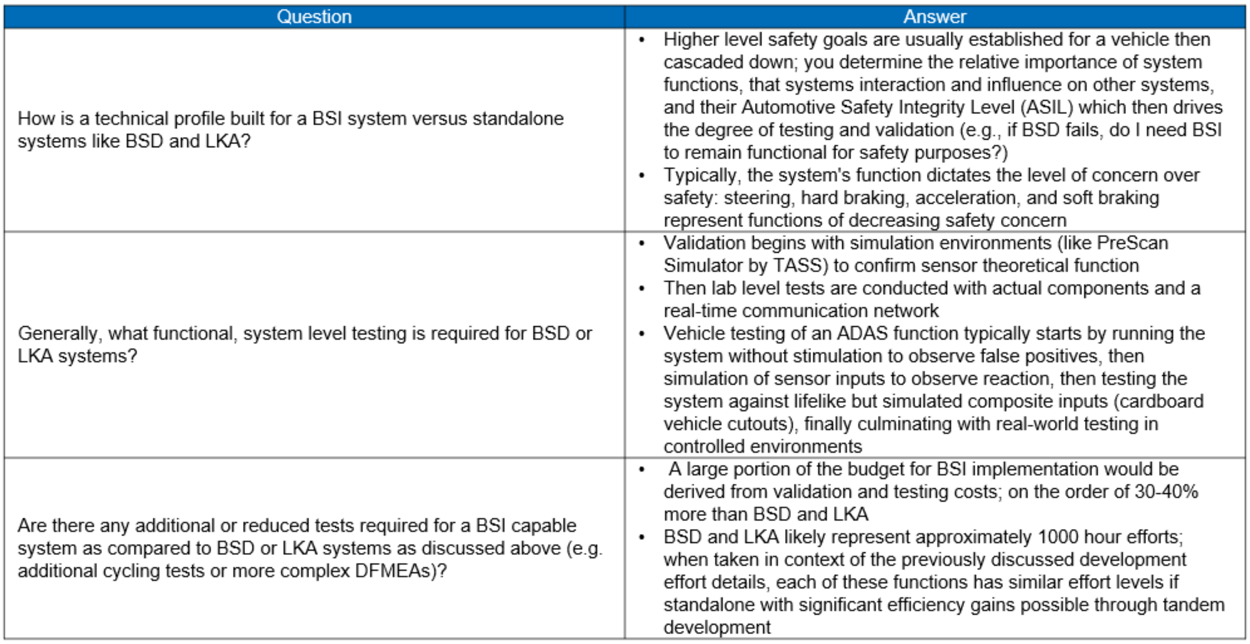


Interview Summary – Aravind Ratnam of Sense Photonics

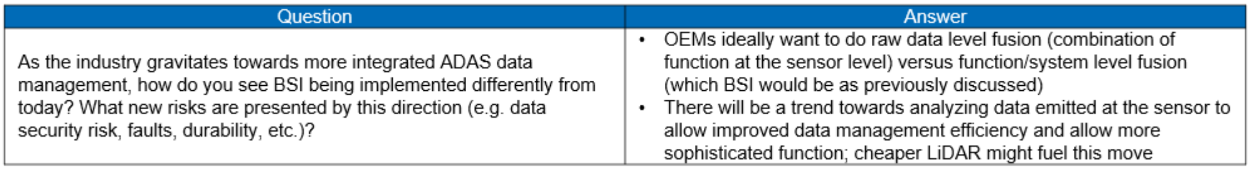
Interviewee Name:	Aravind Ratnam
Organization:	Sense Photonics
Role:	Senior Vice President of Product
Date:	8-FEB-21

Question	Answer
Does your OEM produce vehicles with BSD and LKA features that do not interact and those that do to create BSI functionality? What generally distinguishes these two systems?	• BSD and LKA are typically standalone, noninteractive systems; even within LKA, the alert and reaction are two discretely different things • In general, manufacturers want to reuse existing sensors for new functions as much as possible
What are the incremental requirements (e.g. discrete hardware, software, or unique development tests) to add BSI functionality should a vehicle model already have BSD and LKA?	• Given the typical OEM approach to reuse sensors (so a fusion of existing systems with no hardware adds necessary), BSI likely represents about a 20% increase in lines of cost; this estimate could vary significantly depending on the specifics of the Gen 1 system already in place receiving the BSI addition

Of these incremental additions, which do you perceive as most costly, either in terms of development effort or component cost?	• The total, high-level development effort for BSI is as follows:
	  • DFMEA and Hazard Analysis - ~100 hours
	  • Software development and implementation - ~200 hours
	  • Validation - ~300-500 hours, more variability depending on number of repeat tests needed; this time is variable depending on how much information is displayed from the function to the driver (i.e., human-machine-interface development)
	• 20% is a reasonable addition to cover potential iterative testing needed resulting in a total effort of 800-1000 hours
	• The above assessment can be significantly influenced by number of ODDs (operational design domains; environmental conditions in which the function works like weather variability or construction zones)
	• There are efficiencies to be had in developing BSD, LKA, and BSI together; an estimated total effort of time is in the 1300-1400 hour range



Question	Answer
How is a technical profile built for a BSI system versus standalone systems like BSD and LKA?	• Higher level safety goals are usually established for a vehicle then cascaded down; you determine the relative importance of system functions, that systems interaction and influence on other systems, and their Automotive Safety Integrity Level (ASIL) which then drives the degree of testing and validation (e.g., if BSD fails, do I need BSI to remain functional for safety purposes?) • Typically, the system's function dictates the level of concern over safety: steering, hard braking, acceleration, and soft braking represent functions of decreasing safety concern
Generally, what functional, system level testing is required for BSD or LKA systems?	• Validation begins with simulation environments (like PreScan Simulator by TASS) to confirm sensor theoretical function • Then lab level tests are conducted with actual components and a real-time communication network • Vehicle testing of an ADAS function typically starts by running the system without stimulation to observe false positives, then simulation of sensor inputs to observe reaction, then testing the system against lifelike but simulated composite inputs (cardboard vehicle cutouts), finally culminating with real-world testing in controlled environments
Are there any additional or reduced tests required for a BSI capable system as compared to BSD or LKA systems as discussed above (e.g. additional cycling tests or more complex DFMEAs)?	• A large portion of the budget for BSI implementation would be derived from validation and testing costs; on the order of 30-40% more than BSD and LKA • BSD and LKA likely represent approximately 1000 hour efforts; when taken in context of the previously discussed development effort details, each of these functions has similar effort levels if standalone with significant efficiency gains possible through tandem development



Question	Answer
As the industry gravitates towards more integrated ADAS data management, how do you see BSI being implemented differently from today? What new risks are presented by this direction (e.g. data security risk, faults, durability, etc.)?	• OEMs ideally want to do raw data level fusion (combination of function at the sensor level) versus function/system level fusion (which BSI would be as previously discussed) • There will be a trend towards analyzing data emitted at the sensor to allow improved data management efficiency and allow more sophisticated function; cheaper LiDAR might fuel this move

Interview Summary – Tier 1 ADAS Supplier

Interviewee Name:	*Anonymous*
Organization:	*Tier 1 ADAS Supplier*
Role:	ADAS and Autonomy Engineering Supervisor
Date:	4-FEB-21

Question	Answer
Does your OEM produce vehicles with BSD and LKA features that do not interact and those that do to create BSI functionality? What generally distinguishes these two systems?	• If a vehicle has BSD and LKA, BSI would typically be implemented via a software application • There are some implications on the processing capacity of the system ECU though this is more a comment on system architecture than outright ECU speed
Do some BSD and LKA systems have BSI functionality without advertisement of the feature?	• Yes, some vehicles have a partial step towards full BSI functionality (thought to be most common with Japanese OEMs) • Analogous example would be the relationship between AEB and active collision avoidance where the former function contains an element of the latter function, though in the case of the incomplete BSI function, it has not discrete name nor advertisement of capability • Such function is thought to not be advertised because of safety, liability, or driver behavior implications
Would a BSI system have different constituent parts if designed with that function from the outset rather than through the linkage of BSD and LKA?	• The add for BSI is not likely significant relative to the discrete costs for a BSD or LKA system (BSD and LKA are far more expensive) • Total added cost is likely well below 10% of the cost of BSD an LKA where the software itself is almost insignificant and validation costs are the primary driver
For vehicles with BSI as an optional feature, how is the upgrade between option levels typically made (e.g., hardware adds or software enabling)?	• If the feature is developed with the other systems from the start, the upgrade should have no significant imposition and be a software switch only • If a vehicle does not have it, a retrofit is dependent on the existing capability of the BSD and LKA systems and their control structure; in certain circumstances it would be possible to push an over-the-air update to enable BSI but this is likely a very rare scenario
How is a technical profile built for a BSI system versus standalone systems like BSD and LKA?	• If developed with BSD and LKA, BSI is likely to be a child system of the other two primary functions; it is generally not sufficiently complex for its own technical profile
Are there any unique or atypical requirements (e.g., GD&T, manufacturing, inspection, safety tests, etc.) for any BSI hardware not required for standalone BSD or LKA systems?	• Validation of the system becomes more complex because of the added application complexity, but not substantially more so than just a BSD and LKA system • The software management of the more complex system and its validation are the effort/cost drivers
Why don’t most cars with BSD and LKA have BSI?	• If a vehicle has BSD and LKA, generally, it should have BSI; however, speculation is that most OEMs are conservative and reluctant to be a first mover adding too many features too quickly • Regulation from NHTSA could help to make something like BSI more commonplace overcoming the first mover reluctance as the function itself has relatively modest associated cost
Generally, what functional, system level testing is required for BSD or LKA systems?	• Simulation; software can be largely validated this way • Bench tests • Vehicle testing (off public roads)
Are there any additional or reduced tests required for a BSI capable system as compared to BSD or LKA systems as discussed above (e.g., additional cycling tests or more complex DFMEAs)?	• Yes, because it is a specific function for a specific scenario, you need another set of tests and validation to specifically target BSI like any other unique capability
As the industry gravitates towards more integrated ADAS data management, how do you see BSI being implemented differently from today? What new risks are presented by this direction (e.g., data security risk, faults, durability, etc.)?	• The primary issue today is that BSI has not been implemented enough though it should become easier as there are more parent systems present • Difficult to assess how BSI specifically will be implemented differently as we are largely seeing the first series of implementations now • Ignoring practical issues of increasing electronics complexity like data security, the major risk of ADAS is people over-trusting their vehicle's capabilities causing increased levels of distractions • A driver monitoring system is the logical gap-filler to cover the increasing risk of greater ADAS prior to full autonomy being realized; this is another area where NHTSA regulation could overcome the first mover apprehension of including such a system

Interview Summary – Paul Martindale of Aptiv

Interviewee Name:	Paul Martindale
Organization:	Aptiv
Role:	Global Technical Marketing Manager
Date:	19-FEB-21

Question	Answer
Does your company produce vehicles with BSD and LKA features that do not interact (i.e. standalone BSD and LKA function) and those that do to create BSI functionality? What generally distinguishes these two types of systems?	• For LDW/LKA, the camera's primary function is watching lane markings: how close to lane markers, when are you going to cross, if you are about to cross (based on OEM desire for sensitivity); once conditions are met, a flag is set to do something (steering or braking; steering seems much more commonplace); next gen of this function is Lane Centering • BSD is typically a radar module in the rear quarter panel radar looking at a ~3 meter (lane width) x 6 meter box to the side and behind the vehicle; some are opening that viewing range backward to track vehicles based on closing speed and provide warning of an incoming vehicle; typically alert with a light or haptics, sometimes there is extra flashing when you engage a turn signal • BSI is the communication between the two prior standalone systems; so in general, it is just a software add with input from the OEM for how to react to a given condition
Are there systems with BSD and LKA where they can't communicate?	• Some OEMs only offer one or the other standalone systems (e.g., the radar or the camera, maybe not both); some less expensive vehicles might have a forward looking camera that only does AEB but relatively rare because once you have the camera you can do more things with relative ease
For systems with BSI functionality, what incremental additions over the BSD and LKA systems are necessary (e.g. hardware or software)? Is the BSI function developed as a standalone function or a feature subset of either BSD or LKA?	• If you have electric power steering and a camera, there should be nothing stopping you from having LKA; if you have BSD, then there is nothing stopping you from BSI function
For the incremental additions for BSI, can you approximate the cost associated with each item broken in terms of piece price and design/development effort (cost and headcount if possible)? How does this total incremental cost compare to the costs for designing and developing a BSD or LKA system?	• Much of the cost will be with the OEM so somewhat difficult to say • Software should be limited as you already control steering for LKA so adding a new flag for BSD seems like a small incremental cost • New dedicated testing and validation would be required but should be a small add in the context of other ADAS checks • The function is in the realm of a Level 1 autonomy feature so relatively low on the safety scale limiting added testing complexity
Are there any unique or atypical requirements (e.g., GD&T, manufacturing, inspection, safety tests, etc.) for any BSI functional elements not required for standalone BSD or LKA systems?	• No, there should be nothing unique to BSI; you will do the same types of things for BSD and LKA whether they are communicating or not • As a general comment, higher performance sensors will allow for more Operational Design Domains which will drive more validation testing, though this is true of all ADAS, not specifically BSI
As the industry gravitates towards more integrated ADAS data management, how do you see BSI being implemented differently from today? What new risks are presented by this direction (e.g. data security risk, faults, durability, etc.)?	• Aptiv is moving to a "satellite" architecture where there is a central processing unit, allows you to make the sensors as dumb or simple as possible, doing limited or no pre-processing at the sensor, and only performing those calculations at the centralized control unit • In most cases, data should be available on the CAN network to allow sensor data utilization by other systems