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COST, WEIGHT, AND LEAD TIME ANALYSIS OF COMPONENTS AND SYSTEMS OF PEDESTRIAN AUTOMATIC EMERGENCY BRAKING SYSTEMS (PAEB)

from:

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Table of Contents

1. ABSTRACT

Ricardo has combined existing hardware teardown studies with a study of the software development costs to develop incremental cost and weight impacts of Pedestrian Automatic Emergency Braking systems (PAEB) for passenger vehicle with a gross vehicle weight rating (GVWR) of 10,000 lbs. or less. Ricardo evaluated three different systems: Toyota Camry Safety Sense™ PAEB system, Subaru Outback EyeSight® PAEB system and Audi A8 PAEB.

Through research into system specifications and interviews with industry experts, Ricardo concluded that the PAEB system (Hardware and Software) could not be differentiated from all the rest of the Automatic Emergency Braking system (AEB) vehicle features. Specifically, AEB functionality relies on object detection capabilities in both the system hardware and software. PAEB functionality is achieved by improving the system object detection where pedestrians are concerned, primarily through software improvement. Additionally, Ricardo found out that the burden for software highly depends on how disruptive the ADAS is; the development of new and novel functionality requires greater development effort than the adaptation and modification of existing systems. Systems that were likely adapted from existing ADAS software functionality are referred to as "follower" while systems where much of the functionality required novel development are referred to as "disruptive". ADAS software cost is driven by system functionality, performance and confidence level requirements, as required by OEMs and their suppliers to comply with existing standards, regulations, and perceived customer requirements.

The Toyota Camry AEB system is part of Toyota Safety Sense™ P which has a Pre-Collision System (PCS) and uses a combination of radar and camera with sensor fusion. Ricardo consider this system as a "follower". The end user incremental costs and weights for the Toyota Camry camera system estimated to be $237.33. The Toyota Camry system weighed 883g.

The Subaru Outback, equipped with EyeSight®, uses a stereo camera system only for AEB. The system has a unique stereo camera module that can detect distance and speed of objects in front of the vehicle without the need for a radar sensor. Ricardo consider this system to be a "follower". The incremental cost of the Subaru camera system is estimated to be $288.36. The weight of the Subaru Outback AEB system is estimated to be 2478g but more than half of that total was for incremental wiring; the stereo camera module itself weighed 785g.

Toyota Camry and Subaru Outback AEB systems relied upon a processor that was shared with the vehicle and therefore was not included in the incremental analysis however the image detection System on a Chip (SoC) cost was added.

The Audi AEB system employs a forward-looking visible camera, an infrared (IR) night vision camera, a long-range radar, two forward-side looking short range radars and a first-to-market automotive grade laser scanner (LiDAR.) In addition, a central Driver Assistance Systems (DAS) controller coordinates the sensor inputs and incorporates AEB functionality. The European version of the A8 offers level 3 autonomous driving capability that Audi calls 'Traffic Jam Pilot;' the US version of the A8 does not offer all the functionality due to varying local regulations. Ricardo consider this system to be a "disruptive" system. The incremental costs and weights for the AUDI PAEB system estimated to be $1,826. The AUDI system weighed 5,077g. Image detection System on a Chip (SoC) is included in the dedicated ADAS controller.

Table 1 illustrates a summary of the systems analyzed

		Toyota Camry with Toyota Safety Sense P	Subaru Outback with EyeSight	Audi A8 with Audi AI Traffic Jam Pilot
Features	Forward object recognition	Daylight pedestrian	Pedestrian / bicyclist	Enhanced object recognition
	Dynamic Brake Support	✓	✓	✓
	Crash Imminent Braking	✓	✓	✓
	Active steering assist	✓	✓	✓
	Front cross-traffic alert	-	-	✓
	Cross and Turn assist	-	-	✓
	Autonomous pilot	-	-	✓
Sensors	Camera	Front	Stereo	Front
	Camera, night vision	-	-	Night vision
	Radar, forward	✓	-	✓
	Radar, front-side	-	-	L & R
	LiDAR	-	-	✓
Central Processor		Shared ECU	Shared ECU	Dedicated driver controller
System Category		Follower	Follower	Disruptor
End User System Price (USD) at 200 upa		$237.33	$288.35	$1,826.59
System Weight (g)		883	2478	5077

*List non-exhaustive, OEMs continuously add features

Table 1 Relevant systems features final costs and system weights

This work was completed by Ricardo Strategic Consulting (RSC) a division of Ricardo, Inc. Ricardo performed interviews with more than 20 industry experts in the field of ADAS with experience as Executives, Managers and Engineers from OEMs, Tier 1 and Tier 2s.

2. SUMMARY OF FINDINGS

Ricardo's analysis is divided in two steps. The first step was to perform a bottom-up hardware analysis to estimate the should-cost of the PAEB components. The second step was to estimate the software burden.

To fulfill the first step Ricardo utilized data from two previous reports to NHTSA reviewing the cost and weight of hardware for passenger car AEB systems: Cost and Weight Analysis of Automatic Emergency Braking Systems for Passenger Vehicles (Task Order 693JJ918F000185) and Cost and Weight Analysis of Automatic Emergency Braking Systems for Passenger Vehicles Optional Task: LiDAR-based AEB System (Tark Order 693JJ918F000185). These studies were performed using an Asset Center Costing (ACC) method. Due to high annual volumes in the automotive industry, this method provides a good estimate of manufacturing cost and price, as a function of manufacturing, tooling, and process burden to yield. Additionally, the industry's highly competitive nature forces many hardware suppliers to operate as commodity producers where an ACC cost analysis provides an accurate estimate of the cost and price of hardware components.

Software cost is more complex, as software development is completed at Tier 2 and Tier 1 supplier as well as at the OEM. Some software development is outsourced, either as a custom effort or through the purchase of an off-the-shelf solution. Software intellectual property is often held in trade secret form as it may be difficult to identify and defend against patent infringement. Additionally, the software development process is different from the typical OEM and Tiered supplier hardware or system development processes. Instead of a linear development of a system with full functionality from blank page to in Production, Agile development techniques are use. Software product development follows an iterative process where basic functionality is developed and validated, then incremental features are added through further iterative development loops. Each of these factors contributes the difficulty of establishing the cost of software development for ADAS system.

The software for a "follower" ADAS system is likely to contain pre-existing elements that are licensed from a Tier1 or Tier 2 supplier, some customization costs from the Tier 1 / Tier 2 to address novel or different features desired by the OEM, costs for system and component integration from the Tier 1, and costs from vehicle integration from the OEM as well as validation costs from both the Tier 1 and the OEM. Many experts highlighted that the companies involved in this industry have more head-count-equivalent working on the software development of the system than the hardware itself. Additionally, the software burden goes beyond the effort to develop algorithms and capture training data, thus software burden cannot be reverse engineered through examination of the hardware.

Consequently, to capture what is the status quo of ADAS software market, RSC performed first public information research (technical papers, standards, financial statements, etc.) and then conducted a series of interviews with experts in multiple levels of the industry.

Figure 1 illustrates the Software Burden range by OEM and Tier 1 estimated from Interviewees and using the Ricardo Software Estimation Model. Ricardo model follows the V-model development process, a common automotive software development process used to define requirements, develop code, and validate system functionality, and utilizes ISO 26262, an international standard for safety equipment in automotive vehicles, as definition of each step goal. Model inputs considers overhead count, time to complete each step and general software direct overhead costs. Ranges are an indicator of interviewee best effort to estimate the minimum and maximum effort to achieve the goal of each step.

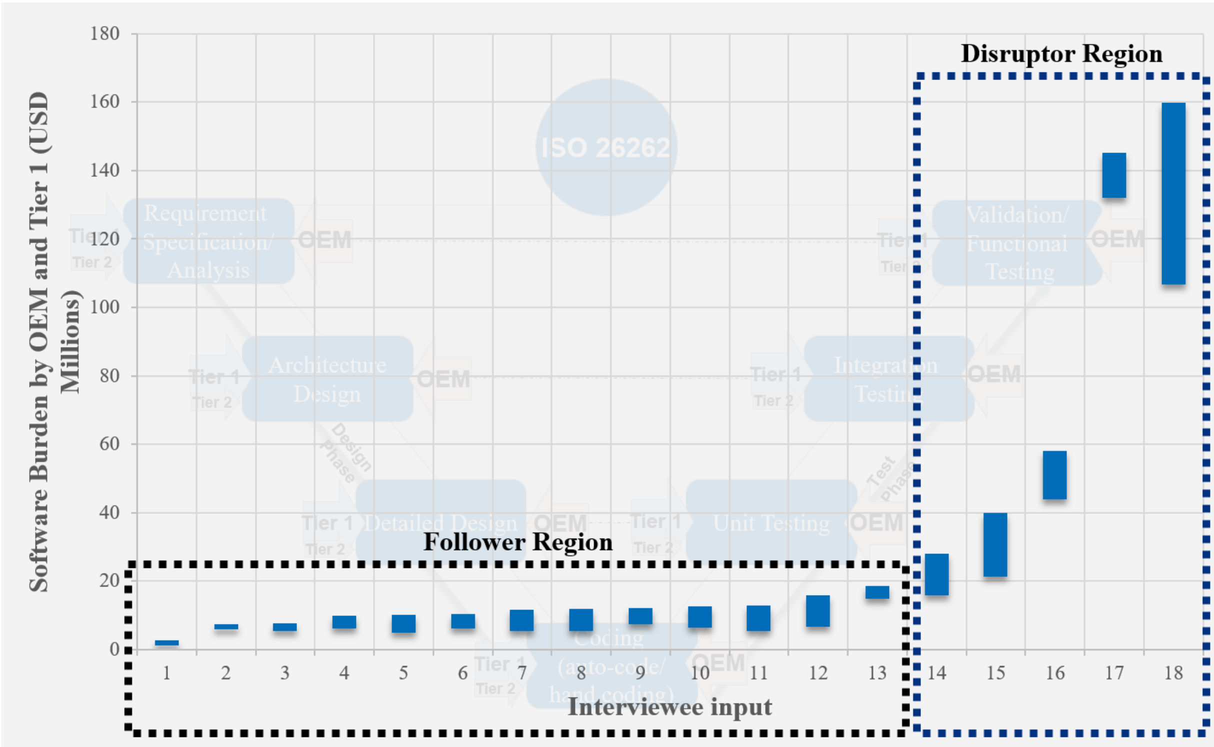


Figure 1 Results of V-Model for ADAS (Ranges)

Table 2 lists the PAEB system incremental end user costs, manufacturing costs along with assumed production rates for the selected systems. As it is expected the software burden of a disruptive system such as Audi is significant when contrasted against a follower system. The system burden includes object detection costs (Tier 2), Tier 1 software development costs and OEM costs. These costs are amortized per assumed production rate (200,000 units per annum) except in the disruptor where volumes are not expected to reach those levels.

Software Tier 1 expenses are traditionally higher than OEMs. Tier 1 burden becomes more significant in the coding step whilst OEMs expenses are higher during requirements definition and system validation phases of the program. However, due to the transition of ADAS to higher autonomy features, experts concluded that as more ADAS content is added to vehicles, as this content becomes more integral to overall vehicle operations, and as more raw vehicle data is collected, it is expected that OEMs will be taking a more active role in the development and integration of ADAS systems.

Item #	Description	Yearly Production volume assumption	Manufacturing Cost	End User Price Increase	Weight (g)
1.0	**Subaru Outback PAEB System**		**$ 213.52**	**$ 288.35**	**2478**
1.1	System Integration Costs (software)	200,000	$ 53.66	$ 81.14	**0**
1.2	Stereo Camera	200,000	$ 136.80	$ 177.32	**785**
1.3	Other	200,000	$ 23.06	$ 29.89	**1693**
2.0	**Toyota Camry PAEB System**		**$ 174.02**	**$ 237.33**	**883**
2.1	System Integration Costs (software)	200,000	$ 53.66	$ 81.15	0
2.2	Camera	200,000	$ 50.68	$ 65.77	553
2.3	Radar	200,000	$ 69.68	$ 90.42	330
3.0	**Audi A8 PAEB System**		**$ 1,163.38**	**$ 1,826.59**	**5077**
3.1	System Integration Costs (software)	200,000	$ 137.56	$ 202.78	0
3.2	Laser scanner system	200,000	$ 158.96	$ 283.18	947
3.3	DAS Control unit system	200,000	$ 353.59	$ 566.55	1308
3.4	Camera, lane assist system	200,000	$ 34.56	$ 54.90	132
3.5	Radar, distance control	200,000	$ 41.11	$ 72.84	324
3.6	Radar, object detection	200,000	$ 73.48	$ 117.67	281
3.7	Night vision camera system	200,000	$ 334.83	$ 490.55	887
3.8	Wiring harnesses	200,000	$ 29.29	$ 38.12	1198

Table 2 Cost and weight estimates for Pedestrian Automatic Emergency Braking systems (PAEB) for passenger vehicle

The end-user price increase is the retail price an end-user would pay for the incremental PAEB system as if it were offered as an option on the vehicle when manufactured at high production rates.

The end-user price increase includes manufacturing costs plus SG&A, Profit, Warranty, Transportation and Dealer markup. Financial statements for the specific components were utilized in determining the SG&A and profit. Dealer cost and markup are applied to the Ricardo wholesale price to arrive at the end-user price increase.

3. ENGINEERING ANALYSIS

3.1. Background

Advanced Driver Assistance Systems (ADAS) Definitions

Most of the new vehicles sold in the US possess at least one feature of Advanced Driver Assistance Systems (ADAS)[1]. ADAS is a conjunction of many emerging or evolving functions. To set a common understanding of the technology, AAA, JD Power, National Safety Council, and SAE classifies ADAS into functional groups[2]: Automated Driving Tasks, Collision Alerts, Collision Mitigation, Parking Assistance, and other Miscellaneous Driving Aids. Table 3 indicates the definitions.

[1] The American Automobile Association, ADVANCED DRIVER ASSISTANCE TECHNOLOGY NAMES, AAA's: recommendation for common naming of advanced safety systems. Retrieved from https://www.aaa.com/AAA/common/AAR/files/ADAS-Technology-Names-Research-Report.pdf

[2] The American Automobile Association et al, CLEARING THE CONFUSION: Recommended Common Naming for Advanced Driver Assistance Technologies, AAA, J.D. Power, National Safety Council, SAE International. Retrieved from https://www.sae.org/binaries/content/assets/cm/content/miscellaneous/adas-nomenclature.pdf

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
Driving Control Assistance	Adaptive Cruise Control	Controls acceleration and/or braking to maintain a prescribed distance between it and a vehicle in front. May be able to come to a stop and continue
	Lane Keeping Assistance	Controls vehicle acceleration, braking, and steering. SAE standard definition of L2 Autonomous systems outlines this functionality
	Dynamic Driving Assistance	Controls vehicle acceleration, braking, and steering. SAE standard definition of L2 Autonomous systems outlines this functionality
Parking Assistance	Backup Camera	Displays the area behind the vehicle when in reverse gear
	Surround View Camera	Displays the immediate surroundings of some or all sides of the vehicle while stopped or during low speed maneuvers
	Active Parking Assistance	Assists with steering and potentially other functions during parking maneuvers. Driver may be required to accelerate, brake, and/or select gear position. Some systems are capable of parallel and/or perpendicular parking. The driver must constantly supervise this support feature and maintain responsibility for parking
	Remote Parking Assistance	Without the driver being physically present inside the vehicle, provides steering, braking, accelerating and/or gear selection while moving a vehicle into or out of a parking space. The driver must constantly supervise this support feature and maintain responsibility for parking
	Trailer Assistance	Assists the driver with visual guidance while backing towards a trailer or backing maneuvers with a trailer attached. Some systems may provide additional images while driving or backing with a trailer. Some systems may provide steering assistance during backing maneuvers
Other Driver Systems	Auto High Beams	Switches between high and low beam headlamps automatically based on lighting and traffic.
	Driver Monitoring	Observes driver actions to estimate if they are not engaged in the task of driving. Some systems may monitor eye movement and/or head position.
	Head-Up Display	Projects information relevant to driving into the driver's forward line of sight.
	Night Vision	Improves forward visibility at night by projecting enhanced images on instrument cluster or head-up display.

Table 3 Advanced Driver Assistance Technologies Recommended Naming

Systems

The implementation of ADAS features in vehicles requires complex architectures to support all existing and emerging tasks. As OEMs continue to add optional ADAS functionality to vehicles, a variety of configurations of features and functionality are available in the marketplace.
Instead, the individual vehicle or platform architecture strategy is driven by the business or technological strategy at the OEM. Furthermore, the nature of this technology makes it difficult to isolate the functionality of a specific feature and correlate it to a particular sensor. Functional task outputs are co-dependent to multiple inputs at different conditions. The technology is evolving from a discrete sensor/ECU architecture towards an OEM's dominant centralized architecture. Control of sensor raw data accelerates the transition towards L2+, L3 or L4 vehicles. Figure 2 shows a simplification of a potential ADAS architecture with what is considered an embedded machine.

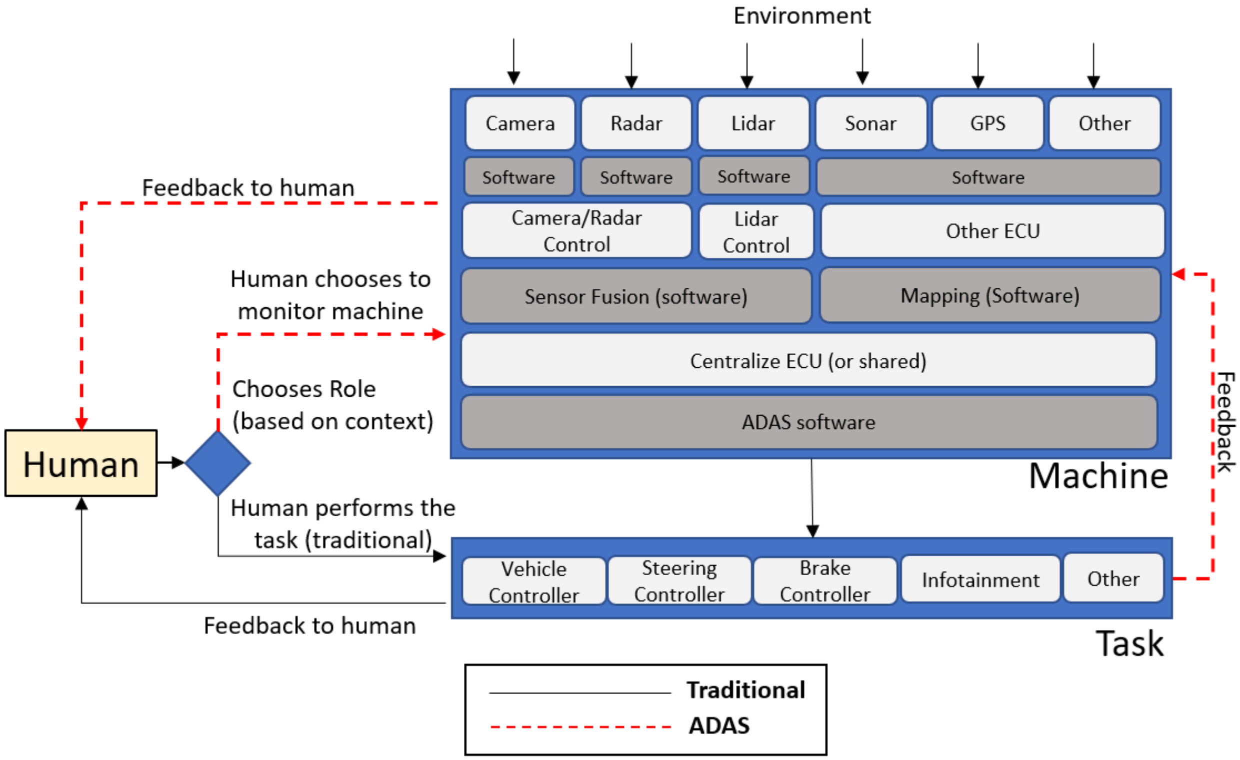


Figure 2 ADAS system overview[3]

Current ADAS perform automated Dynamic Driving Tasks (DDT) selected and monitored by the Human vehicle operator. ADAS disengages immediately upon requests. Most modern ADAS correspond to a SAE Level 2 autonomy[4] . Figure 3 illustrates SAE definition of autonomous capabilities

[3] Ricardo Analysis with analysis of Industry Experts papers. Lex Fridman, Massachusets Institute of Technology (MIT), Classical Vigilance Framework vs Functional Vigilance Framework. Retrieved from https://hcai.mit.edu/
[4] SAE J3016_201806 Surface Vehicle Recommended Practice, (R) Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. Retrieved from https://saemobilus.sae.org/content/j3016_201806

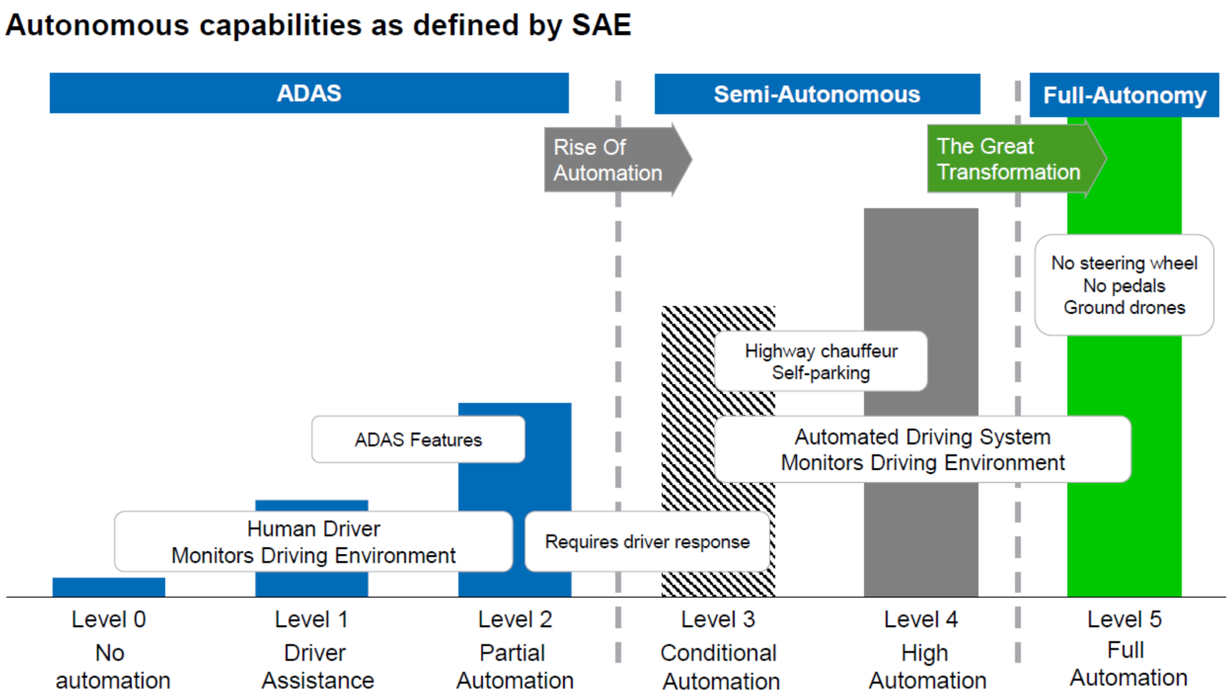


Figure 3 Autonomous capabilities as defined by SAE[5]

Traditional inputs for a vehicle ADAS include sensors such as cameras (day and night vision), Light Detection and Ranging (LiDAR), Radio Detection and Ranging (RADAR), Sound Navigation and Ranging (SONAR), as well as additional information such as maps, Global Positioning System (GPS), driver inputs and others. The machine subsequently processes the input information, allows some fusion of data, classifies the data, and processes the corresponding algorithm to generate the desired output signals. The ADAS outputs then actuate tasks through other sub-systems in the vehicle, such as steering, brakes, and driver warnings.

The Advanced Emergency Braking System (AEB) is part of the collision intervention function of many ADAS implementations. 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. Pedestrian and cyclist detection are considered within the industry to be a sub-set of AEB object detection functionality. Additional functionality includes the detection of sign, large animals, pets and stationary objects in the roadways.

AEB systems take into account situational features such as object movement, vehicle speed, pedestrian positioning, day or night condition, full or partial portion of the object, etc. The system requirements will frequently be defined by the suite of situational features defined by the OEM. AEB assigns a likelihood of the situation presented by an object, given training to the algorithm.

NHTSA defines Automatic Emergency Braking Systems (AEB)[6] as follow:

> *Automatic Emergency Braking Systems (AEB)help prevent rear-end crashes or reduce their severity by applying the brakes for the driver. The systems used on-vehicle forward-looking*

[5] SAE J3016, SAE. Retrieved from https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic

[6] Cost and Weight Analysis of Automatic Emergency Braking Systems for Passenger Vehicles Optional Task: LiDAR-based AEB System, Task Order: 693JJ918F000185, NTHSA

sensors such as radar, cameras or lasers to detect an imminent crash, warn the driver and apply the brakes if the driver does not take sufficient action quickly enough to avoid or mitigate the crash. AEB systems work with or without driver intervention, by combining inputs from radar and/or camera sensors and driver inputs to determine if a rear-end crash is likely to happen. Specifically, AEB technology includes two systems--crash imminent braking (CIB), which applies the brakes in cases where a rear-end crash is imminent and the driver is not taking any action to avoid the crash, and dynamic brake support (DBS), which supplements the driver's braking input if the driver is not applying sufficient braking to avoid a rear-end crash

In the specific case of pedestrians, AEB systems work with or without driver intervention, by combining inputs from RADAR, LiDAR, camera sensors, vehicle speed sensors, driver inputs and others to determine if a pedestrian collision is likely to occur. The systems are essentially trained with specific scenarios and will likely perform as desired if they encounter those. The current industry trend appears to focus on cases that have the highest statistical likelihood of occurring (data acquired), but that leaves a statistical tail of rare but real-world scenarios where the system behavior is unknown. Systems currently available in the US are driver assistance and depend on the driver to react in situations that are not covered within the functional envelope of the AEB system. Many of these systems can also detect and respond to bicycle riders and other road objects defined during development of the project. In the vision-based sensing industry pedestrian detection is considered a particular case of object detection[7]. NHTSA defines Pedestrian Automatic Emergency Braking systems (PAEB)[8] as follow:

Pedestrian Automatic Emergency Braking systems (PAEB) help prevent pedestrian crashes or reduce their severity by warning of imminent crashes and applying the brakes if the driver does not respond appropriately. The systems use on-vehicle forward-looking sensors such as radar or cameras to detect pedestrians, predict if a crash is imminent, warn the driver and apply the brakes if the driver does not take sufficient action quickly enough. PAEB systems work with or without driver intervention, by combining inputs from radar and/or camera sensors and driver inputs to determine if a pedestrian crash is likely to happen. Many of these systems are capable of detecting and responding to bicycle riders in addition to pedestrians.

Sensors

The industry has three types of cameras available in the market: monocular cameras, stereo cameras, and Infrared cameras (IR cameras). To supplement the information provided by the cameras and reduce the false positive signals, many of the architectures use Radars for AEB features. Vipin Kumar Kukkala Et al. [9] provide a concise definition for these sensors:

- ***Monocular Cameras:*** *These camera systems have only one lens. As these systems have only one image output at any point of time, they have low image-processing requirements compared to those of other camera types. These cameras can be used for multiple applications, such as the detection of obstacles, pedestrians, lanes, and traffic signs. They can also be used for monitoring*

7 Real Time Pedestrian and Object Detection and Tracking-based Deep Learning. Application to Drone Visual Tracking, Redouane Khemmar, Matthias Gouveia, Benoit Decoux, Jean-Yves Ertaud. Real Time Pedestrian and Object Detection and Tracking-based Deep Learning. Application to Drone Visual Tracking. WSCG'2019 - 27. International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision. Retrieved from https://www.researchgate.net/publication/336307108_Real_Time_Pedestrian_and_Object_Detection_and_Tracking-based_Deep_Learning_Application_to_Drone_Visual_Tracking

8 Cost and Weight Analysis of Pedestrian Automatic Emergency Braking Systems for Passenger Vehicles SOLICITATION NUMBER 693JJ919R000100, NTHSA

9 Advanced Driver-Assistance Systems: A Path Toward Autonomous Vehicles, IEEE Consumer Electronics Magazine, Vipin Kumar Kukkala et al. Retrieved from https://ieeexplore.ieee.org/document/8429957/authors#authors

the driver inside a vehicle, e.g., for face- and eye detection and head-pose analysis. But monocular camera images lack depth information and are, therefore, not reliable sensors for distance estimation. Some techniques allow approximating distance by identifying key features in the captured image frame and tracking their position when the camera is in motion.

- ***Stereo Cameras:*** *These systems consist of two or more lenses, each with image sensors, separated by a certain distance (known as stereo base). Stereo cameras are useful in extracting three-dimensional (3-D) information from two or more two-dimensional images by matching stereo pairs (images from left and right sensors) and using a disparity map to estimate the relative depth of a scene. These cameras can be used for a variety of applications, such as traffic sign recognition, lane, pedestrian, and obstacle detection as well as distance estimation, with much greater accuracy compared to monocular cameras. Stereo systems can be relied upon for accurate distance (depth) estimation over short distances, up to 30 m. In most production vehicles with stereo cameras, the cameras are located inside the vehicle, behind the rear-view mirror, angled slightly downward, and facing the road.*
- ***IR Cameras:*** *There are two main types of IR cameras. Active IR cameras use a near-IR light source (with wavelengths from 750 to 1,400 nm) built in the vehicle to illuminate the scene (which cannot be seen by the human eye) and a standard digital camera sensor to capture the reflected light. Passive IR cameras use an IR sensor, where every pixel on the IR sensor can be considered as a temperature sensor that can capture the thermal radiation emitted by any material. Unlike active IR cameras, passive IR cameras do not require any special illumination of the scene. Still, popular night-vision solutions mainly use active IR cameras to assist the driver by displaying video data on a screen during low light conditions.*
- ***Radar:*** *Radar systems emit microwaves and estimate the speed and distance of an object by measuring the change in the frequency of the reflected wave as per the Doppler effect. Due to the longer wavelength of microwaves, they can travel much farther than optical light (e.g., with lidar) and can detect objects at a longer distance. Unlike lidar, radar is not affected by foggy or rainy weather conditions and is relatively inexpensive. Depending on their operating distance range, radar systems can be classified as short range (0.2–30 m), medium range (30–80 m), or long range (80–200 m). Cross-traffic alerts and blind-spot detection are some of the applications of short-/medium-range radars. These systems are often located at the corners of a vehicle. Adaptive cruise control is a long-range radar application, with the system located behind the front grill or under the bumper. Researchers have been developing algorithms to improve the performance of radar and reliability all the while attempting to reduce the cost and power of the system.*

Some ADAS are capable of providing more complex features such as Dynamic Driving Assistance, informally denominated in the industry as L2+, currently require more expensive sensors such a LiDAR or LiDAR Maps[10].

- ***Lidar***[11]*: Lidar works by firing a laser beam at an object and then measuring the time taken for the light to bounce back to the sensor, to calculate the distance of an object. These systems can achieve high-resolution 3-D images and operate at longer ranges than camera systems. Some of the lidar scanners support surround-view sensors (that fire laser beams continuously in all directions), which can generate a 360° 3-D image of the surroundings with extremely accurate depth information. Lidar is becoming very popular in autonomous vehicles. Several prototype*

[10] GM is working on a hands-off advanced driving system for city streets, Kirsten Korosec. Retrieved from https://techcrunch.com/2020/05/19/gm-is-working-on-a-hands-off-advanced-driving-system-for-city-streets/

[11] Advanced Driver-Assistance Systems: A Path Toward Autonomous Vehicles, IEEE Consumer Electronics Magazine, Vipin Kumar Kukkala et al. Retrieved from https://ieeexplore.ieee.org/document/8429957/authors#authors

vehicles have demonstrated the advantages of using lidar in autonomous driving. Lidar is useful for systems implementing automatic braking, object detection, collision avoidance, and more. Depending on the type of sensor, lidars for cars can have a range of up to 60 m. Despite the advantages, lidars are heavy, bulky in size, and expensive. Moreover, atmospheric conditions such as rain or fog can impact the coverage and accuracy of these systems. Emerging solid-state lidars have opened the possibility of powerful lidars that are significantly smaller and relatively inexpensive.

Recent industry trends are to reduce the cost of LiDAR technology either by the development of solid-state LiDARs or other laser-based systems [12]. However, there are industry leaders who believe vision based ADAS could achieve higher levels of autonomy without the requirement of a LiDAR sensor [13].

Vehicle manufacturers and Tier 1s have not settled on a single optimal architecture solution for current and future pedestrian detection needs. Systems in production today range from camera only to complex systems like the Audi A8. However, multiple industry experts agree that the current systems rely predominantly on camera technology for object detection due to its early and extremely fast development, low cost, and capacity to process Artificial Intelligence (AI). Radar sensors can be used to support object detection through sensor fusion but are more predominantly used to support features where relative speed and position to other vehicles is involved (blind spot detection, parking assist, and adaptive cruise control). LiDAR can be particularly useful for longer range detection and may be necessary for adaptive cruise control at European highway speeds.

Additionally, camera industry-specific experts highlight that Visual ADAS containing camera only sensors could achieve high scores in current testing protocols of EURO NCAP [14]. However, due to the increase of ADAS features offered by OEMs and an architecture migrating from a discrete structure to a more consolidating architecture, isolating a single sensor system for feature will most likely not be a long-term tendency by industry in general.

Object detection algorithms

Specific, to camera technology and object detection, a list of microcontrollers sequentially processes the data received from the sensor through algorithms to generate an image classification, with an assigned probability that the image is correctly classified. There are several challenges to assign an image a classification (define it as pedestrian, cyclist, car, sign, lane, or other). To isolate pedestrian detection from the convoluted algorithm is difficult since it shares the same channel of processing with other feature detections. Dr. Fei-Fei Li et al in her Introduction to Convolutional Neural Networks for Visual Recognition class lists the following as major challenges for image recognition[15]:

- ***Viewpoint variation.*** *A single instance of an object can be oriented in many ways with respect to the camera.*
- ***Scale variation.*** *Visual classes often exhibit variation in their size (size in the real world, not only in terms of their extent in the image).*

[12] Next generation Volvo cars to be powered by Luminar LiDAR technology for safe self-driving, Luminar, Retrieved from https://www.luminartech.com/vcc/
[13] 'Anyone relying on lidar is doomed,' Elon Musk says, Matt Burns. Retrieved from: https://techcrunch.com/2019/04/22/anyone-relying-on-lidar-is-doomed-elon-musk-says/#:~:text=%E2%80%9CLidar%20is%20a%20fool's%20errand,expensive%20sensors%20that%20are%20unnecessary.
[14] Industry leader in Vision-Based company
[15] CS231n: Convolutional Neural Networks for Visual Recognition. Stanford Class, Retrieved from: https://cs231n.github.io/classification/

- ***Deformation****. Many objects of interest are not rigid bodies and can be deformed in extreme ways.*
- ***Occlusion.*** *The objects of interest can be occluded. Sometimes only a small portion of an object (as little as few pixels) could be visible.*
- ***Illumination conditions.*** *The effects of illumination are drastic on the pixel level.*
- ***Background clutter.*** *The objects of interest may blend into their environment, making them hard to identify.*
- ***Intra-class variation****. The classes of interest can often be relatively broad, such as chair. There are many different types of these objects, each with their own appearance.*

Industry experts highlight Neural Networks as the state-of-art of the image recognition algorithm. There are an extensive list of patents and papers documenting the evolution of this algorithm from engineered feature recognition algorithms towards a more complex domain such as Convolutional Neural Network (CNN). CNN emerged as an engineering solution after obtaining very high performance in the 2012 ImageNet Challenge[16]. Krizhevsky et al[17][18] with AlexNet made CNN the dominant paradigm in generic object detection and pedestrian detection since then [19]. Figure 4 shows the architecture of model of AlexNet. Appendix E shows Tesla Motors CNN.

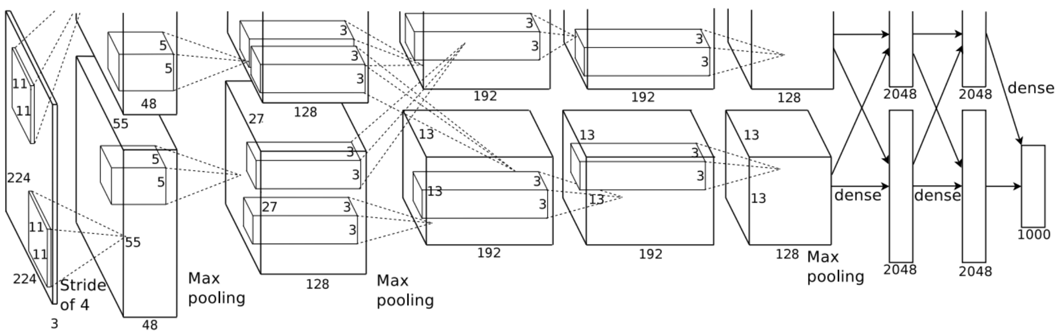


Figure 4 Architecture of AlexNET CNN[20]

CNN is a type Neural Network (NN) that takes in consideration the input as an image (instead of a vector) and arrange the data in 3 dimensions. Figure 5 shows the layers of a traditional CNN. Dr Fei-Fei Li[21] describes the layers as follow:

- ***Input.*** *It will hold the raw pixel values of the image, an image of width, height, and with three color channels R,G,B*

[16] The Pascal Visual Object Classes Challenge: A Retrospective, Everingham, M, Eslami, SMA, Van Gool, L, Williams, CKI, Winn, J & Zisserman, Retrieved from: https://www.research.ed.ac.uk/portal/files/20017166/ijcv_voc14.pdf
[17] ImageNet Classification with Deep Convolutional Neural Networks, Alex Krizhevsky University of Toronto, Retrieved from https://papers.nips.cc/paper/4824-imagenet-classification-with-deep-convolutional-neural-networks.pdf
[18] Lecture 1 | Introduction to Convolutional Neural Networks for Visual Recognition, Stanford University School of Engineering, Retrieved from: https://www.youtube.com/watch?v=vT1JzLTH4G4
[19] Pedestrian Detection: The Elephant In TheRoom. Irtiza Hasan, Shengcai Liao, Jinpeng Li, Saad Ullah Akram, and Ling Shao. Retrieved from: https://arxiv.org/abs/2003.08799
[20] ImageNet Classification with Deep Convolutional Neural Networks, Alex Krizhevsky University of Toronto. Retrieved from: https://papers.nips.cc/paper/4824-imagenet-classification-with-deep-convolutional-neural-networks.pdf
[21] CS231n: Convolutional Neural Networks for Visual Recognition. Stanford Class, Retrieved from: https://cs231n.github.io/convolutional-networks/#architectures

- ***CONV layer.*** *It will compute the output of neurons that are connected to local regions in the input, each computing a dot product between their weights and a small region they are connected to in the input volume*
- ***RELU layer*** *It will apply an elementwise activation function*
- ***POOL layer*** *It will perform a down sampling operation along the spatial dimensions (width, height)*
- ***FC (i.e. fully connected) layer*** *It will compute the class scores*

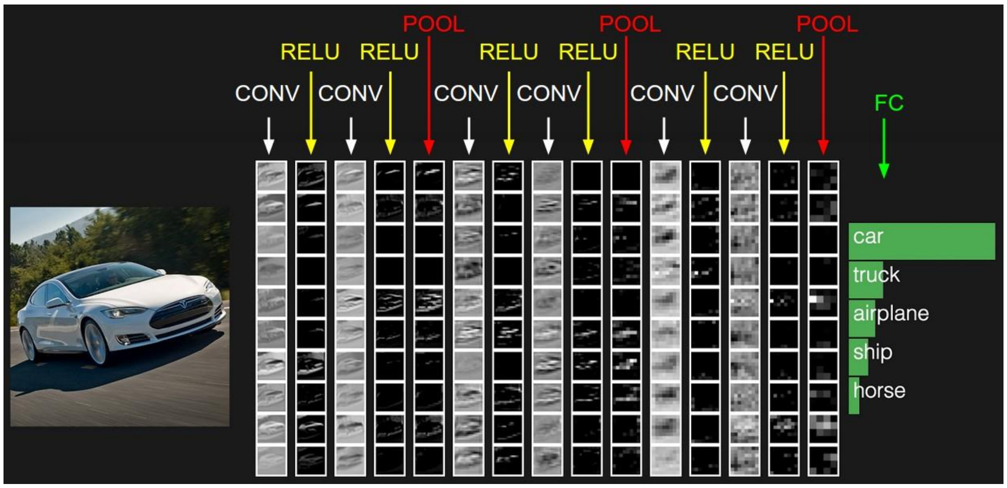


Figure 5 Layers of a CNN

Another example of how pedestrian detection is consolidated with other features is Tesla Motors Vision-based ADAS Autopilot™ system. Tesla claims it is progressively migrating to a self-denominated "Software 2.0" programming that relies heavily on Neural Networks[22,23]. Tesla ADAS HydraNET architecture possess a main backbone with "ResNET-50 like" Neural Network and "FPN/DeepLabV3/UNet like" head Neural Network for objects, traffic lights and markings. Figure 6 illustrates a simplification of Tesla ADAS algorithm.

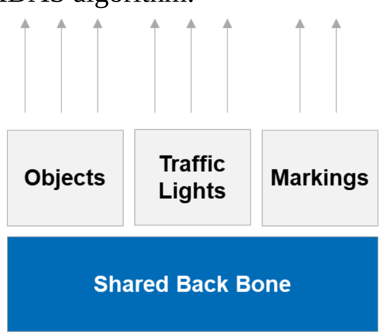


Figure 6 Vision Based Tesla Hydra Net Architecture[24]

Object detection data

[22] Tesla just bought an AI startup to improve Autopilot—here's what it does, Timothy B. Lee. Retrieved from: https://arstechnica.com/cars/2019/10/how-teslas-latest-acquisition-could-accelerate-autopilot-development/
[23] Building the Software 2 0 Stack (Andrej Karpathy), Databricks, Retrieved from: https://www.youtube.com/watch?v=y57wwucbXR8
[24] Building the Software 2 0 Stack (Andrej Karpathy), Databricks, Retrieved from: https://www.youtube.com/watch?v=y57wwucbXR8

Since the implementation of these new types of algorithms, the process to optimize relies heavily on data acquisition and labeling. Labeling is the process of assigning the data a specific classification. This process is non-trivial, must be highly reliable [25]and demands-resources. There are publicly available data source; however, OEMs and suppliers are pursuing this data acquisition with different strategies. Table 4 illustrates some public data sets for pedestrian applications.

		Training			Testing									
Datasets	Imaging Setup	# Pedestrians	# Neg. Images	# Pos. Images	# Pedestrians	# Neg. Images	# Pos. Images	Color Images	Occlusion Labels	Illumination	Video Seq.	View Labels	Pose Labels	Publication
MIT	photo	924	-	-	-	-	-	✓						2000
CVC	mobile	1,000	6,175	-	-	-	-	✓						2007
Daimler	mobile	1,506,000	-	6,700	56,600	21,800	-					✓		2009
INRIA	photo	1,208	614	1,218	556	288	453	✓						2005
Caltech	mobile	192,000	67,000	61,000	155,000	65,000	56,000	✓	✓			✓	✓	2009
PSU	photo	1,186	517	1,051	1,270	517	755	✓	✓	✓		✓	✓	2018

Table 4 Comparison of pedestrian datasets[26]

Figure 7 illustrates a data acquisition process using a data source, labeling and optimizing models used by some OEMs. RSC did not find the benchmark of acquired data by OEMs, Tier 1 or Tier 2 for pedestrian detection. The OEM could also enhance the performance of the PAEB system if more data is acquired to label peculiar pedestrian scenarios.

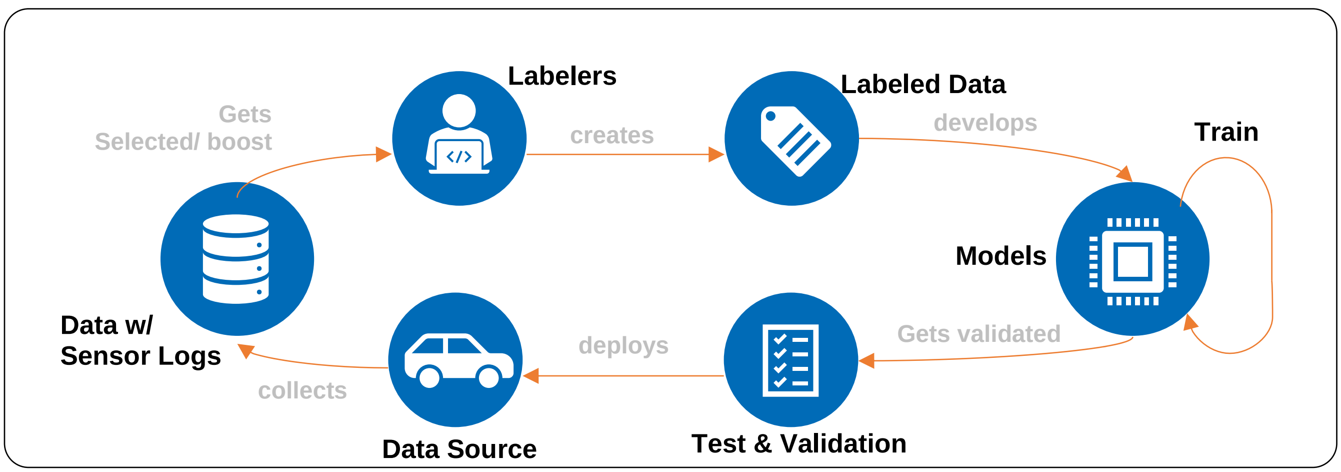


Figure 7 Data acquisition and Machine Learning (ML) processing (Various)[27,28]

[25] Please check your data: A self-driving car dataset failed to label hundreds of pedestrians, thousands of vehicles, Katyanna Quach, Retrieved from: https://www.theregister.com/2020/02/17/self_driving_car_dataset/

[26] A New Dataset Benchmark for Pedestrian Detection, May Thu et al. Retrieved from: https://dl.acm.org/doi/pdf/10.1145/3278229.3278243

[27] Drago Anguelov (Waymo) - MIT Self-Driving Cars, Lex Fridman. Retrieved from: https://www.youtube.com/watch?v=Q0nGo2-y0xY&t=3022s

[28] Andrej Karpathy - AI for Full-Self Driving, Matroid, Retrieved from: https://www.youtube.com/watch?v=hx7BXih7zx8&t=682s

3.2. Project Purpose

The purpose of this study is "to perform and establish reliable cost and weight estimates for PAEB for passenger vehicle with a gross vehicle weight rating (GVWR) of 10,000 lbs. or less". RSC identified several vehicles possessing some level of ADAS, each component is described in Figure 8

		Toyota Camry w/ Toyota Safety Sense 2.0	**Subaru Outback** w/ EyeSight	**Audi A8** w/ Audi pre sense	**Honda CR-V** w/ Collision Mitigation Braking System	**Chevrolet Equinox** w/ Front Pedestrian Braking	**Mitsubishi Outlander** w/ Forward Collision Mitigation System	**BMW X1** w/ Active Driving Assistant	**MB E-class** w/ Pre-Safe	**Cadillac Escalade** w/ Front Pedestrian Braking	**Volvo S90** w/ Collision Warning System
Features	Forward Collision Detection										
	Vehicle	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Pedestrian (daytime)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Pedestrian (low-light)	-	✓	✓	-	-	-	-	✓	tbd	-
	Bicyclist (daytime)	✓	✓	✓	-	-	✓	-	tbd	tbd	✓
	Dynamic Brake Support	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Crash Imminent Braking	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Pedestrian Protection	tbd	✓	tbd	tbd	tbd	tbd	tbd	✓	tbd	✓
Equipment	Visible camera	Mono	Stereo	Mono	Mono	Mono	Mono	Mono	Stereo	Mono	Mono
	IR camera	-	-	✓	-	-	-				-
	Radar	Far	-	Far & Mid range	Far	-	Far		Far, Mid & Short		Far
	LiDAR	-	-	✓	-	-	-	-			-
	Visual alert	MID[1]	MID[1]	MID[1], HUD	MID[1]	MID[1], HUD	MID[1]	MID[1]			MID[1], HUD
	Audible alert	✓	✓	✓	✓	✓	✓	✓			✓
	Haptic alert	-	-	✓	-	-	✓	-			✓
	Processor	Shared ECU	Shared ECU	Dedicated DAS computer	tbd	tbd	tbd	tbd	tbd	tbd	tbd
	OEM Headquarters	Asian	Asian	European	Asian	NA	Asian	European	European	NA	European
	Recommendation	included in AEB study	included in AEB study	included in AEB study	Consider including	Consider including	Consider including	Consider including	Consider including	Consider including	Consider including

1) MID - Multi-Information Display

Figure 8 Sample of ADAS offering Pedestrian AEB

To maximize the benefit of this study, RSC conducted this study utilizing primarily the Audi A8 as a system reference but kept camera only ADAS for software analysis to understand the incremental cost of the PAEB system over AEB. Table 5 shows the systems considered for this study.

NHTSA		1 Chevy Equinox	2 Ford Taurus	3 Lexus ES	4 Volvo S80	5 '19 Audi A8	6 Subaru Outback
	OEM / Tier 1	GM / tbd	Ford / DELPHI	Lexus / DENSO	Volvo / DELPHI	Audi / Valeo, BOSCH, DELPHI	Subaru / HITACHI
Features	Forward Collision Warning	Yes	Yes	Yes	Yes	Yes	Yes
Features	Dynamic Brake Support	Yes	Yes	Yes	Yes	Yes	Yes
Features	Crash Imminent Braking	Yes		Yes	Yes	Yes	Yes
Equipment	Camera	Yes		Yes	Yes	Yes	Yes (x2)
Equipment	Radar		Yes	Yes	Yes	Yes (x2)	
Equipment	Lidar					Yes – for 2019MY	
Equipment	Visual Indicator	HUD / DIC indicator*	HUD	Multi-information display*	HUD	DIC indicator*	DIC indicator*
Equipment	Haptic Indicator*	Seat optional*	-	-	Yes*	Yes*	-
				Base combined recommendation		Optional LIDAR recommendation	Base camera recommendation

Legend: Added features in new model | Existing features in old model | Additional selected system

Table 5 Selected systems for PAEB analysis

3.3. Hardware cost Methodology

RSC has submitted two previous reports to NHTSA reviewing the cost and weight of hardware for passenger car AEB systems: Cost and Weight Analysis of Automatic Emergency Braking Systems for Passenger Vehicles (Task Order 693JJ918F000185) and Cost and Weight Analysis of Automatic Emergency Braking Systems for Passenger Vehicles Optional Task: LiDAR-based AEB System (Task Order 693JJ918F000185). This section will provide a summary of the information presented in those reports but will not include full cost breakdown details. Please refer to those reports directly for further details on hardware cost. Below is a brief summary of each report

Ricardo has analyzed the cost and weight of Automatic Emergency Braking (AEB) systems, exclusive of forward collision warning hardware, which use radar and/or camera sensors. AEB systems can avoid or mitigate forward collisions by either assisting the driver if enough braking force is not being applied (called Dynamic Braking Support, DBS) or automatically applying the brakes if a forward collision is imminent (Crash Imminent Braking, CIB.). The Toyota Camry AEB system is part of Toyota Safety SenseTM P which has a Pre-Collision System (PCS) and uses a combination of radar and camera with sensor fusion. The Subaru Outback, equipped with EyeSight®, uses a stereo camera system only for AEB. The system has a unique stereo camera module that is capable of detecting distance and speed of objects in front of the vehicle without the need for a radar sensor.[29]

Ricardo has analyzed the cost and weight of a LiDAR-based Automatic Emergency Braking (AEB) system as implemented in the 2019 Audi A8. AEB systems can avoid or mitigate forward

[29] Department of Transportation National Highway Traffic Safety Administration Office of Acquisition Management (NPO-320) West Building 51-117 1200 New Jersey Avenue, SE Washington, DC 20590 Contract Number: DTNH2216D00037 Task Order: 693JJ918F000185 Cost and Weight Analysis of Automatic Emergency Braking Systems for Passenger Vehicles Ricardo Inc. Detroit Technical Center
Van Buren Twp., MI 48111 USA August 13, 2019

collisions by either assisting the driver if enough braking force is not being applied (called Dynamic Braking Support, DBS) or automatically applying the brakes if a forward collision is imminent (Crash Imminent Braking, CIB.)[30]

Ricardo was tasked with identifying the hardware cost and weight for PAEB functionality. Through research into system specifications, and interviews with industry experts, it was determined that common hardware is used for AEB and PAEB functionality. In the development of system software, pedestrians and cyclists are considered a specific category of object detection that is used for PAEB. As such, new hardware was not selected or torn down for this study, as AEB hardware has already been torn down and costed as part of the two previous studies. RSC will use the results of these reports to estimate the incremental costs for PAEB on a vehicle that has neither a PAEB or AEB system. The incremental cost of PAEB on a vehicle that is equipped with an AEB system would be dependent on the incremental and novel requirements for system performance associated with the PAEB functionality. Because with software the functional requirements of the system, and how many new features are required strongly influence the amount of effort required for system development, we have chosen to separate the systems into "disruptor" and "follower" systems. Two different hardware systems can be concluded from these reports, one very complex "disruptor" system such as the A8 and the "follower" systems such as the Toyota and Subaru. It is important to note that both systems can detect pedestrians (PAEB).

For the previous AEB studies, Ricardo acquired AEB system hardware, and parts were disassembled and evaluated. The total manufacturing cost was built up from the following elements: Direct labor cost per unit, Direct material costs including scrap allowance and inbound freight per unit, Variable burden/overhead costs, including indirect labor, energy, and other costs that vary with production volume, Fixed burden / overhead per unit, including capital depreciation and other fixed costs.

The following assumptions were taken:

- Annual vehicle production volume of 200,000 units was assumed.
- Burdened labor rate: labor rates were determined for specific manufacturing processes performed in the country of manufacture and applied to the cost analysis as noted for each of the key sensors/modules. For other components labor rates were assumed to be for associated process operations at a union production facility located in the Midwest USA.
- Capital equipment depreciation schedule of 12 years straight line with no residual value, for electronic sensor and controller modules a 20-year depreciation schedule
- Special tooling depreciation schedule of 5 years straight line with no residual value
- Scrap rate of 1% of direct material cost based on an average for the automotive industry was used for individual components/assemblies other than the key electronic modules; scrap rates are noted for certain manufacturing steps of electronic circuit boards.

[30] Department of Transportation National Highway Traffic Safety Administration Office of Acquisition Management (NPO-320) West Building 51-117 1200 New Jersey Avenue, SE Washington, DC 20590 Contract Number: DTNH2216D00037 Task Order: 693JJ918F000185 Cost and Weight Analysis of Automatic Emergency Braking Systems for Passenger Vehicles Optional Task: LiDAR-based AEB System Ricardo Inc. Detroit Technical Center Van Buren Twp., MI 48111 USA January 10, 2020

Additionally, due to the diverse companies analyzed, the following traditional automotive corporate overhead rates were used for insourced components and outsourced components. Assumptions are extracted from Spinney et al[31], Rogozhin et al[32], National Academy of Sciences (NAS)[33], and Vyas et al[34].

Overhead costs for in-house made components include:

- SG&A of 8% applied to total manufacturing costs, including: Sales, Research & Development, General administration, Human resources, Supplier quality, Senior plant management
- Profit of 5% applied to total manufacturing cost
- Transportation and warranty costs of 10% applied to total manufacturing cost.

Following corporate overhead rates for outsourced commodity components, at 75% of the OEM in-house component rates, were used:

- SG&A of 6% applied to total manufacturing costs (8% x 75% = 6%)
- Profit of 3.75% applied to total manufacturing cost
- Transportation and warranty costs of 7.5% applied to total manufacturing cost.

For components that are new to the automotive marketplace, the SG&A and profit margins were derived by firstly extracting the cost of sales, R&D expenditures, and SG&A, and profit margins from the suppliers' two most recent consolidated financial statements and secondly by shifting from the cost of sales into R&D expenditures on a case-by-case basis.

These overhead burdens applied to direct labor, variable and fixed manufacturing costs equate to a wholesale price from the manufacturer. Dealer costs and markup were estimated to be 11% of the wholesale price, consistent with Spinney et al, to arrive at a final cost to the end-user.

Additional details on the hardware estimations assumptions can be found in each individual report.

Historically, the cost of software development, integration, and validation has not been included in the hardware cost and weight analysis studies.

3.4. Software cost Methodology

Traditionally hardware cost studies are to establish the cost and weight impact of vehicle technologies in support of rulemaking, are performed by using Asset Center Costing (ACC). Due to the automotive industry's yearly volumes, the asset can provide a good indication of manufacturing, tooling, and process burden to yield an estimated price subsequently. Additionally, this industry's highly competitive nature

[31] Advanced Air Bag Systems Cost, Weight, and Lead Time analysis Summary Report, Contract NO. DTNH22-96-0-12003, Task Orders – 001, 003, and 005. Spinney, B.C., Faigin, B., Bowie, N., & Kratzke, S., 1999, Washington, D.C., U.S. Department of Transportation

[32] Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers. Report by RTI International to Office of Transportation Air Quality. Rogozhin, A., Gallaher, M., & McManus, W., 2009, U.S. Environmental Protection Agency, RTI Project Number 0211577.002.004, February, Research Triangle Park, N.C.

[33] National Academy of Sciences, Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, "Assessment of Fuel Economy Technologies for Light-Duty Vehicles," The National Academies Press, Washington D.C., 2011

[34] "Comparison of Indirect Cost Multipliers for Vehicle Manufacturing," Vyas, A., Santini, D., And Cuenca, R., Technical Memorandum of the Center for Transportation Research, Argonne National Laboratory, April 2000

forces most of the companies to operate as commodity producers where an ACC cost analysis provides an accurate estimate of the cost and price of hardware components. Software cost is more complex, as software development is completed at Tier 2 and Tier 1 suppliers as well as at the OEM. Some software development is outsourced, either as a custom effort or through the purchase of an off-the-shelf solution. The software for a “follower” ADAS system is likely to contain pre-existing elements that are licensed from a Tier1 or Tier 2 supplier, some customization costs from the Tier 1 / Tier 2 to address novel or different features desired by the OEM, costs for system and component integration from the Tier 1, and costs from vehicle integration from the OEM as well as validation costs from both the Tier 1 and the OEM.

On the other hand, ADAS rely heavily on software, and as more features emerge, so does the software burden (Mobileye R&D yearly growth is a good indicator[35]). Many experts highlighted that the companies involved in this industry have more head-count-equivalent working on the software development of the system than the hardware itself. Additionally, the software burden goes beyond the effort to develop algorithms and capture training data thus software burden cannot be reverse engineered through examination of the hardware. Some of the uncertainty and variance in software cost is attributed to:

- Algorithm developers experience and access to training data
- Organization implementation of process to comply and guarantee a safety, quality and reliability standards
- Diverse types of individual OEMs requirements and levels of targets
- Common sections of software between platforms such as the effort of AUTomotive Open System ARchitecture (AUTOSAR)
- ADAS integration software scope, centralized OEM driven ADAS vs discrete ADAS with multiple Tier 1 suppliers

Consequently, in an effort to capture what is the status quo of ADAS software market, RSC performed first public information research (technical papers, standards, financial statements, etc) and then conducted a series of interviews with experts in multiple levels of the industry. The discussion was around these four main cost drivers:

- Level of effort and personnel for each stage of development
- Process and system requirements to develop reliable automotive embedded system, such as ISO 26262, ISO 21434 (draft) or ISO 21448
- Publicly available system functional targets, such as ECE R152, ISO 19237, or EURO NCAP (these documents that describe the expected vehicle ADAS system behavior in response to specified situations)
- Raw material requirements (algorithms and training data) for state-of-the-art software and systems

This approach was recommended because publicly available information about ADAS software development costs is scarce. Information about software development requirements is a relatively minor effort in large OEMs and Tier 1s as compared to their other ventures. Subsequently there is not much financial data from ADAS software development companies that is not obscured by other activities. Additionally, software development teams are often spread across multiple programs and platforms, so identifying the effort to allocate to a single program or platform was non-trivial.

[35] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. Retrieved from: https://www.sec.gov/Archives/edgar/data/1607310/000157104915001638/t1500418-20f.htm

In order to create as realistic as possible a picture of the effort and overhead required for software development, we set out a list of criteria for interviewees and developed an interview guide. These documents can be found in Appendix B and Appendix C.

To normalize the discussion RSC utilized the V-development model (shown in Figure 9) and quantified the effort in the OEM and Tier 1 side the labor requirements (people and time) and overhead requirements (equipment, space and software) for software development and validation.

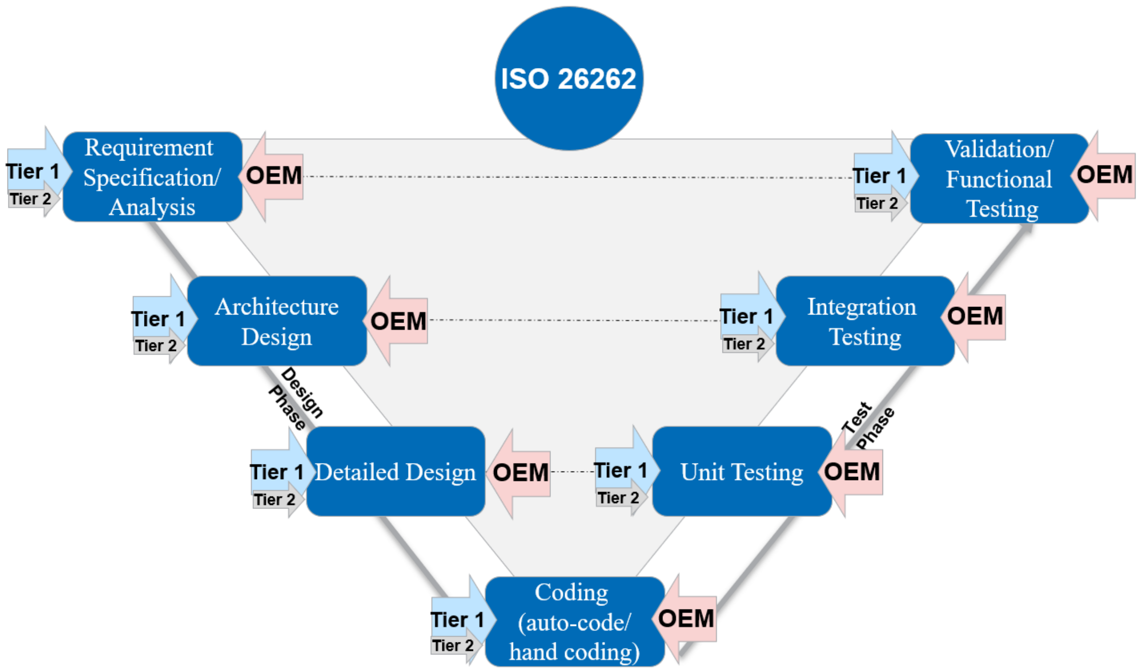


Figure 9 V Software development model

RSC requested the interviewees to not release any specific company information that is not publicly available and provide feedback purely based on their technical opinion. Questions were posed from the perspective of the industry standard, or industry average, not the perspective of a single company.

This approach does not allow an estimation to a specific architecture or vehicle (defined features, sensors, vehicle type, region, released year, etc.). However, the inputs from multiple experts creates a spectrum of a general cost and provides a good rough order-of-magnitude (ROM) cost.

RSC Software cost process

1. Research AEB and Pedestrian AEB Systems

- Research vehicles with different types of PAEB systems, understand its performance in existing testing
- Studied OEMs and suppliers from European, American, and Asian HQs
- Perform research on financial statements of publicly trade Tier ones and Tier two specialized in ADAS
- Performed research on technology trends, company leaders and key milestones

- Identified relevant conferences, working groups or lectures relevant to this industry and technology

2. Select PAEB Experts & Industry Leaders

- Identify experts and industry leaders with automotive OEMs and system suppliers
- Selected interviewees based on the potential contribution to the overall software development Figure 10 shows types of interviewees and their functions in the V-model process.

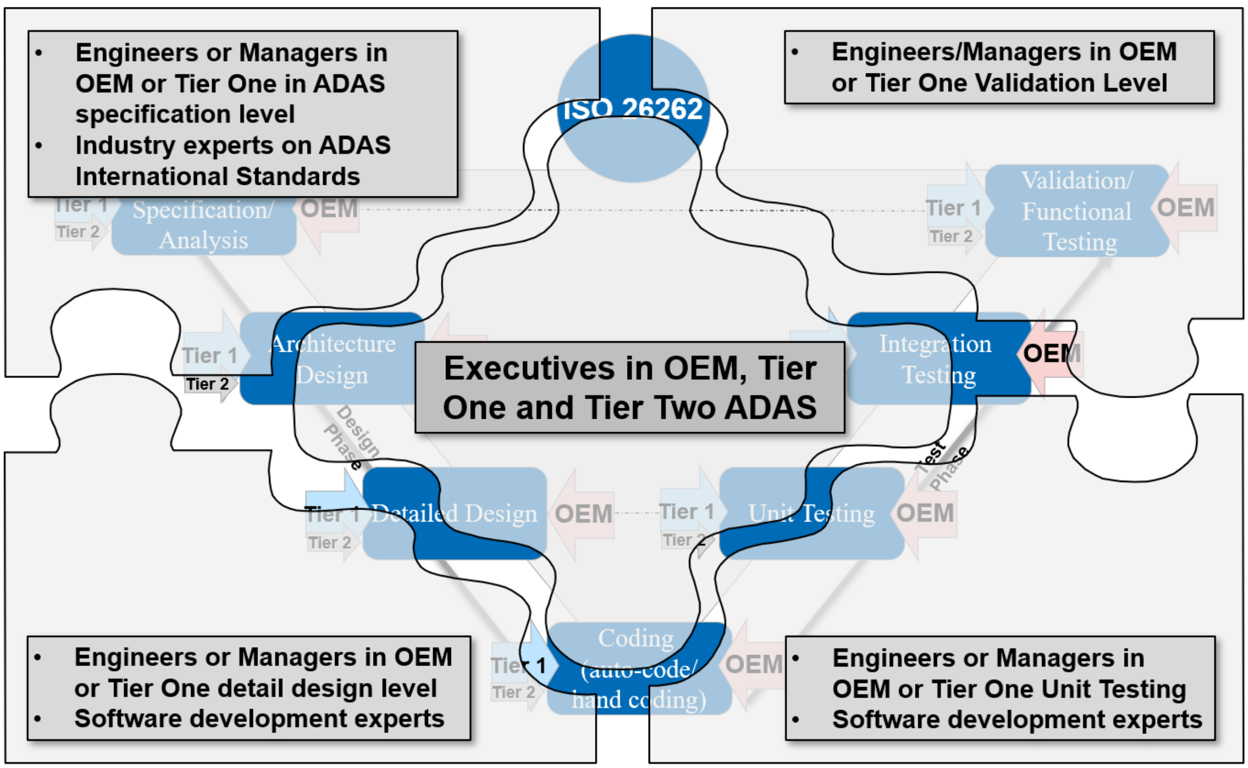


Figure 10 Rationale for interviewee selection

3. Complete Cost Analysis of PAEB Software Development

- Develop structure of cost model for software development.
- Interview selected software experts and leaders.
- Assess portions of the software required for PAEB vs ACC, LKA, and other ADAS features.
- Complete cost estimation of software development, test, integration, etc. required for PAEB functionality.

4. Complete Final Report

- Complete and submit a draft report outlining the incremental cost of PAEB.

The following sections describes in detail relevant cost drivers for the development of software in ADAS.

3.4.1.ISO 26262 Road vehicles – Functional safety

The International Organization for Standardization (ISO) elaborates international standards. ISO defines these standards as a "distilled wisdom" from a group of experts in the specific field. Specific to embedded systems, interviewees repeatedly highlighted ISO 26262 as the main source of guidance for development of ADAS. The software development process is highlighted in ISO 26262-Part 6: Product development at the software level. This standard provides reference for automotive lifecycle and guides the activities for each of development process. It also defines the Automotive-Specific-Integrity-Levels (ASILs) and which requirements are applicable to each ASIL. An ADAS system is a conglomerate of multiple ASILs.

The following is an extract from the abstract of ISO 26262[36] and describes the overall standard and functionality. ISO 26262 consist of twelve different parts. The latest release was on 2018.

> *ISO 26262 is intended to be applied to safety-related systems that include one or more electrical and/or electronic (E/E) systems and that are installed in series production passenger cars with a maximum gross vehicle mass up to 3 500 kg. ISO 26262 does not address unique E/E systems in special purpose vehicles such as vehicles designed for drivers with disabilities.*
>
> *ISO 26262 addresses possible hazards caused by malfunctioning behaviour of E/E safety-related systems, including interaction of these systems. It does not address hazards related to electric shock, fire, smoke, heat, radiation, toxicity, flammability, reactivity, corrosion, release of energy and similar hazards, unless directly caused by malfunctioning behaviour of E/E safety-related systems.*
>
> *ISO 26262 does not address the nominal performance of E/E systems, even if dedicated functional performance standards exist for these systems (e.g. active and passive safety systems, brake systems, Adaptive Cruise Control).*
>
> *With the trend of increasing technological complexity, software content and mechatronic implementation, there are increasing risks from systematic failures and random hardware failures, these being considered within the scope of functional safety. ISO 26262 series of standards includes guidance to mitigate these risks by providing appropriate requirements and processes.*
>
> *The ISO 26262 series of standards is concerned with functional safety of E/E systems that is achieved through safety measures including safety mechanisms. It also provides a framework within which safety-related systems based on other technologies (e.g. mechanical, hydraulic and pneumatic) can be considered.*
>
> *The achievement of functional safety is influenced by the development process (including such activities as requirements specification, design, implementation, integration, verification, validation and configuration), the production and service processes and the management processes.*

Since the ISO 26262 follows the V-Model process, the standard normalizes the discussion with interviewees as the step objectives are clearly defined. The objectives of each step are highlighted in Section 3.4.2. Additionally, Figure 11 shows the overall structure of the ISO 26262 series of standards.

[36] ISO 26262-1:2018(en) Road vehicles — Functional safety — Part 1: Vocabulary, ISO.org, Retrieved from: https://www.iso.org/obp/ui/#iso:std:iso:26262:-1:ed-2:v1:en

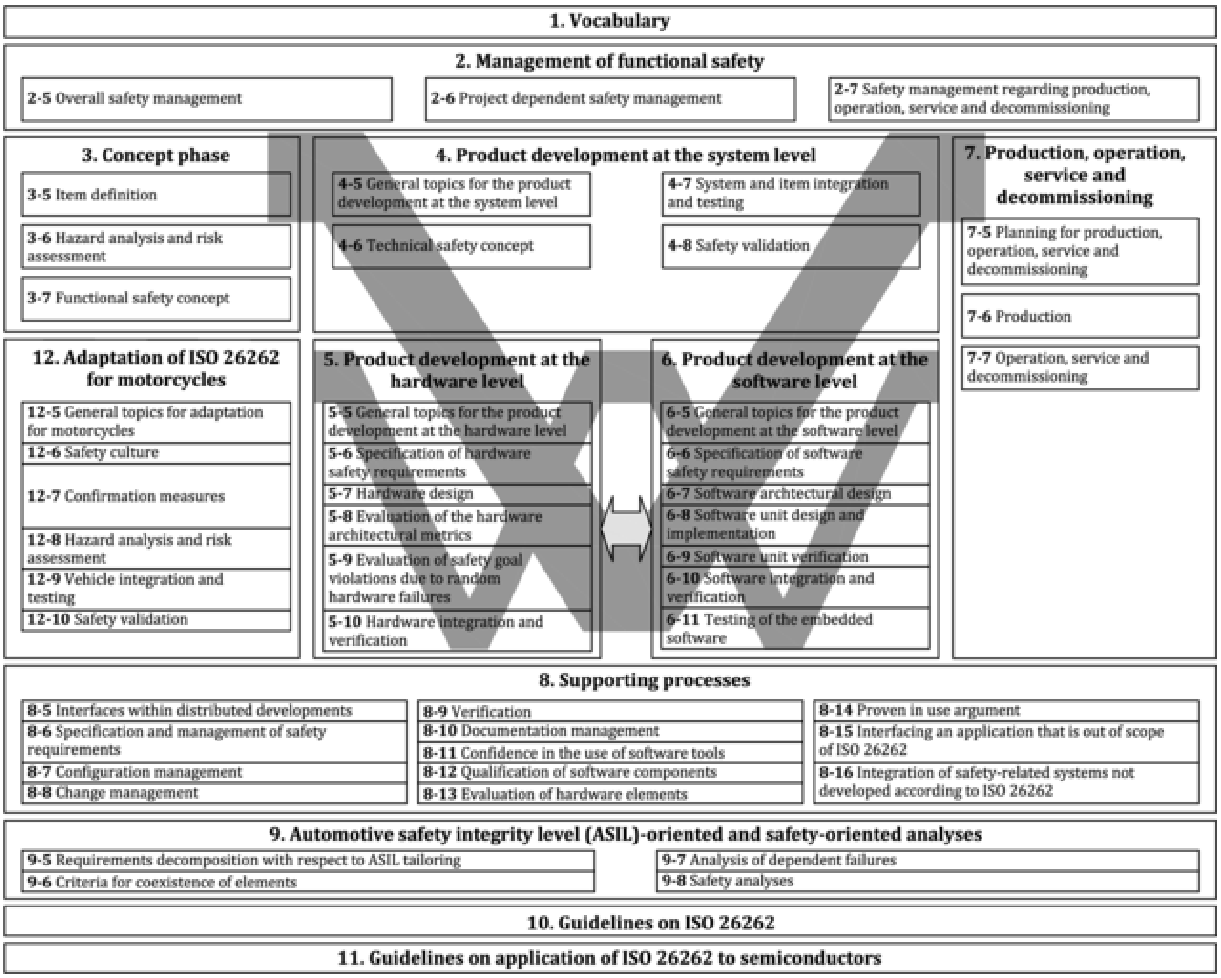


Figure 11 Overview of the ISO 26262 series of standards[37]

3.4.2. V-Software development process

The V-model is a well-established guideline for the integration of mechatronics systems [38]. This model has evolved into many versions across time[39], some common steps are identified and highlighted in V-Software development process Figure 12. These steps are used by RSC to develop a model by estimating the resources used in each step.

Additionally, discussing with experts in the industry highlighted the interaction between OEMs and Suppliers during each step of the progress.

[37] ISO 26262-1:2018(en) Road vehicles — Functional safety — Part 1: Vocabulary, ISO.org, Retrieved from: https://www.iso.org/obp/ui/#iso:std:iso:26262:-1:ed-2:v1:en
[38] VDI 2206 – A New guideline for the design of mechatronics systems, Dr.-Ing J. Gausemeier, Dr-Ing. S. Moeringer. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1474667017340351
[39] V-Model for interdisciplinary systems engineering I. Graessler, J. Hentze and T. Bruckmann, INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018 Retrieved from: https://www.designsociety.org/publication/40489/V-MODELS+FOR+INTERDISCIPLINARY+SYSTEMS+ENGINEERING

Below is a brief description of each step of the model and the objectives of each step.

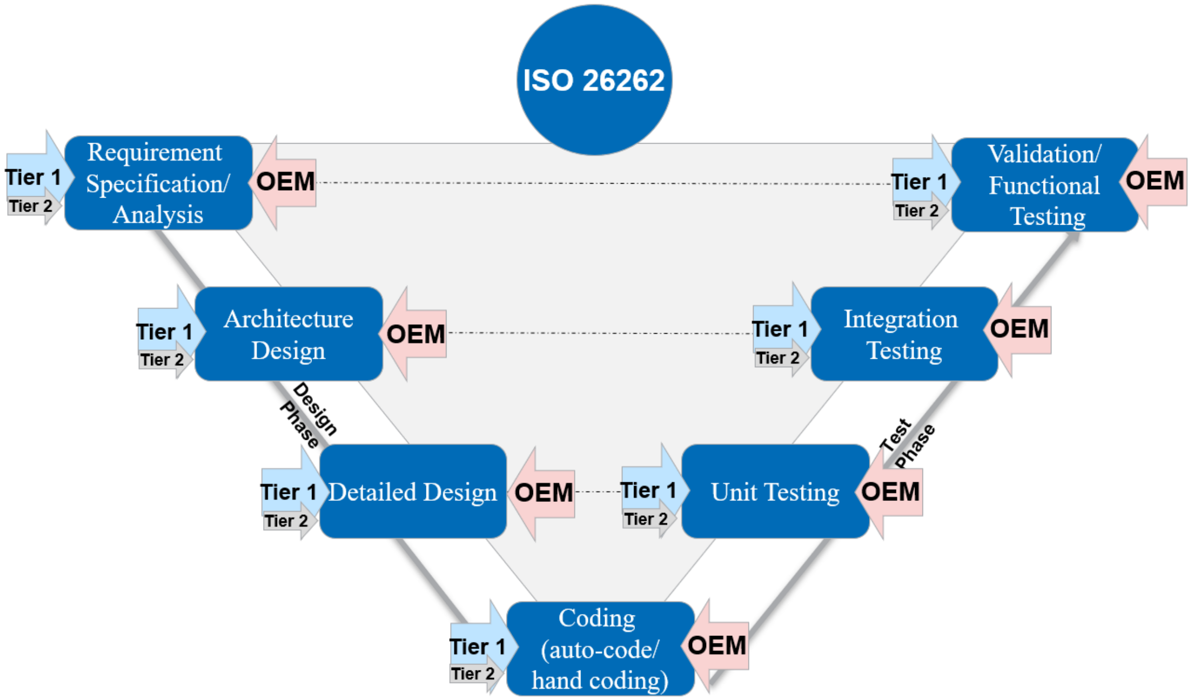


Figure 12 V-Software development process

a. Requirement Specification/Analysis

During this step the requirements are collected by analyzing the needs of the user. The process receives input from the system level.

ISO 26262 Part 6 Product development at the software level software recommends the following objectives in this sub-phase (Specification of software safety requirements)[40]

- *"to specify or refine the software safety requirements which are derived from the technical safety concept and the system architectural design specification;*
- *to define the safety-related functionalities and properties of the software required for the implementation;*
- *to refine the requirements of the hardware-software interface initiated in ISO 26262-4:2018, Clause 6; and*
- *to verify that the software safety requirements and the hardware-software interface requirements are suitable for software development and are consistent with the technical safety concept and the system architectural design specification.*

b. Architecture Design

[40] Road vehicles — Functional safety — Part 6:Product development at the software level Second edition 2018-12. ISO.org, Retrieved from: https://www.iso.org/standard/68388.html

After capturing the requirements, an architecture is developed based on modules highlighting each interface. This is a high-level design that will shape the downstream development. An incorrect architecture design could affect the timeline of the project as detailed design can uncover a need for different architecture.

ISO 26262 Part 6 Product development at the software level software recommends the following objectives in this sub-phase (Software architectural design)[41]

- *to develop a software architectural design that satisfies the software safety requirements and the other software requirements;*
- *to verify that the software architectural design is suitable to satisfy the software safety requirements with the required ASIL; and*
- *to support the implementation and verification of the software.*

c. Detailed Design

In this step the modules are broken into smaller steps to elaborate individual needs. ISO 26262 Part 6 Product development at the software level software recommends the following objectives in this sub-phase (Software unit design and implementation) [42]

- *to develop a software unit design in accordance with the software architectural design, the design criteria and the allocated software requirements which supports the implementation and verification of the software unit; and*
- *to implement the software units as specified.*

d. Coding

This step is the actual elaboration of the code by breaking the algorithm needs in basic logic steps. This step is not highlighted in ISO 26262 Part 6 and is included in implementation section.

e. Unit Testing

In this step the unit codes are tested against its requirements. ISO 26262 Part 6 Product development at the software level recommends the following objectives in this sub-phase (Software unit verification)[43]

- *to provide evidence that the software unit design satisfies the allocated software requirements and is suitable for the implementation;*
- *to verify that the defined safety measures resulting from safety-oriented analyses in accordance with ISO 26262-9:2018 Clause 7 and 8 are properly implemented;*
- *to provide evidence that the implemented software unit complies with the unit design and fulfils*
- *the allocated software requirements with the required ASIL; and*

[41] Road vehicles — Functional safety — Part 6:Product development at the software level Second edition 2018-12. ISO.org, Retrieved from: https://www.iso.org/standard/68388.html
[42] Road vehicles — Functional safety — Part 6:Product development at the software level Second edition 2018-12. ISO.org, Retrieved from: https://www.iso.org/standard/68388.html
[43] Road vehicles — Functional safety — Part 6:Product development at the software level Second edition 2018-12. ISO.org, Retrieved from: https://www.iso.org/standard/68388.html

- *to provide sufficient evidence that the software unit contains neither undesired functionalities nor undesired properties regarding functional safety.*

f. Integration Testing

In this step the software is tested in an architecture level, incorporated in the module and verified the unit tests can coexist. ISO 26262 Part 6 Product development at the software level software recommends the following objectives in this sub-phase (Software integration and verification)[44]

- *to define the integration steps and integrate the software elements until the embedded software is fully integrated;*
- *to verify that the defined safety measures resulting from safety analyses at the software architectural level are properly implemented;*
- *to provide evidence that the integrated software units and software components fulfil their requirements according to the software architectural design; and*
- *to provide sufficient evidence that the integrated software contains neither undesired functionalities nor undesired properties regarding functional safety.*

g. Validation/Functional Testing

During this step the modules of the software are incorporated and validated to communicate with each other. ISO 26262 Part 6 Product development at the software level software recommends the following objectives in this sub-phase (Testing of the embedded software)[45]

- *fulfils the software safety requirements when executed in the target environment; and*
- *contains neither undesired functionalities nor undesired properties regarding functional safety.*

3.4.3.ISO 21448:2019 Road vehicles — Safety of the intended functionality

In addition to ISO 26262 standards, new standards are emerging to support the fast developments of ADAS. For example, the "ISO 21448: Road vehicles — Safety of the intended functionality" complements ISO 26262 in systems that could have safety hazards without system failure. It intends to cover additional scenarios where even if the software is bug free and hardware fully functional, could still fail[46]. This push developers to think its software development and validation strategies. ISO describes this standard as follow[47]:

> *The absence of unreasonable risk due to hazards resulting from functional insufficiencies of the intended functionality or by reasonably foreseeable misuse by persons is referred to as the Safety Of The Intended Functionality (SOTIF). This document provides guidance on the applicable design, verification and validation measures needed to achieve the SOTIF. This document does*

[44] Road vehicles — Functional safety — Part 6:Product development at the software level Second edition 2018-12. ISO.org, Retrieved from: https://www.iso.org/standard/68388.html
[45] Road vehicles — Functional safety — Part 6:Product development at the software level Second edition 2018-12. ISO.org, Retrieved from: https://www.iso.org/standard/68388.html
[46] AV Safety Ventures Beyond ISO 26262, Junko Yoshida. Retrieved from: https://www.eetimes.com/av-safety-ventures-beyond-iso-26262/#
[47] ISO/PAS 21448:2019 Road vehicles — Safety of the intended functionality, ISO.org Retrieved from: https://www.iso.org/standard/70939.html

not apply to faults covered by the ISO 26262 series or to hazards directly caused by the system technology (e.g. eye damage from a laser sensor).

This document is intended to be applied to intended functionality where proper situational awareness is critical to safety, and where that situational awareness is derived from complex sensors and processing algorithms; especially emergency intervention systems (e.g. emergency braking systems) and Advanced Driver Assistance Systems (ADAS) with levels 1 and 2 on the OICA/SAE standard J3016 automation scales. This edition of the document can be considered for higher levels of automation, however additional measures might be necessary. This document is not intended for functions of existing systems for which well-established and well-trusted design, verification and validation (V&V) measures exist at the time of publication (e.g. Dynamic Stability Control (DSC) systems, airbag, etc.). Some measures described in this document are applicable to innovative functions of such systems, if situational awareness derived from complex sensors and processing algorithms is part of the innovation.

Intended use and reasonably foreseeable misuse are considered in combination with potentially hazardous system behaviour when identifying hazardous events.

Reasonably foreseeable misuse, which could lead directly to potentially hazardous system behaviour, is also considered as a possible event that could directly trigger a SOTIF-related hazardous event.

Intentional alteration to the system operation is considered feature abuse. Feature abuse is not in scope of this document.

3.4.4. ISO 21434 Road Vehicles - Cybersecurity Engineering

In addition to development and risk assessment guidelines, experts pointed out the need for high cybersecurity standards to protect the overall system. The guidelines apply beyond ADAS to all the other interfacing subsystems. ISO is working in ISO 21434 (draft), and the preliminary draft scope is defined as[48]:

This document addresses the cybersecurity perspective in engineering of electrical and electronic (E/E) systems within road vehicles. By ensuring appropriate consideration of cybersecurity, this document aims to enable the engineering of E/E systems to keep up with changing technology and attack methods.

This document provides vocabulary, objectives, requirements and guidelines as a foundation for common understanding throughout the supply chain. This enables organizations to:

- define cybersecurity policies and processes;
- manage cybersecurity risk; and
- foster a cybersecurity culture.

[48] ISO/SAE DIS 21434 Road Vehicles - Cybersecurity Engineering, ISO.org, Retrieved from: https://www.iso.org/standard/70918.html

This document can be used to implement a cybersecurity management system including cybersecurity risk management in accordance with ISO 31000. This document is intended to supersede SAE J3061 recommended practice.

3.4.5. International Standards related to Pedestrian detection evaluation

OEMs do not release the specific state of requirements (SOR) of specific ADAS sub-systems to the general public, because it could uncover some competitive advantages. Consequently, software is well suited to trade secret Intellectual Property (IP) protection instead of patent IP protection because it is difficult to look at competitive software and identify violations. As a result, OEMS, Tier 1s, and other tiered suppliers are very reticent to disclose information about their software.

However, the general system testing of vehicles (and procedures) are publicly available through international standards or evaluating entities. These standards are a good indicator of the maturity of the system (software and hardware) installed in a specific vehicle. Some of the relevant standards are described below:

3.4.5.1. ECE R152 Uniform provisions concerning the approval of motor vehicles with regard to the Advanced Emergency Braking System (AEB) for M1 and N1 vehicles

ECE R152 is a new standard to be released internationally and become mandatory in certain countries. It contains a pass/fail criterion based on speed reduction. RSC did not receive any relevant concern on this standard test from experts on pedestrian detection. The standard intent is described as follow[49]:

The intention of this Regulation is to establish uniform provisions for Advanced Emergency Braking Systems (AEB) fitted to motor vehicles of the Categories M1 and N1 primarily used within urban driving conditions.

This Regulation cannot cover all the traffic conditions and infrastructure features in the type-approval process; this Regulation recognizes that the performances required in this Regulation cannot be achieved in all conditions (vehicle condition, road adhesion, weather conditions, deteriorated road infrastructure and traffic scenarios etc. may affect the system performances). Actual conditions and features in the real world should not result in false warnings or false braking to the extent that they encourage the driver to switch the system off.

The pedestrian target shall travel in a straight line perpendicular to the subject vehicle's direction of travel at a constant speed of 5 km/h ± 0.2 km/h, starting not before the functional part of the test has started.

Tests shall be conducted with a vehicle travelling at 20, 30 and 60 km/h (with a tolerance of +0/-2 km/h)"

[49] Uniform provisions concerning the approval of motor vehicles with regard to the Advanced Emergency Braking System (AEBS) for M1 andN1 vehicles UNECE, Retrieved from: https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2020/R152e.pdf

In the scenario that the ADAS detects a pedestrian, at specific conditions, the AEBS shall be able to achieve the maximum relative impact speed shown in Table 6

Subject Vehicle Speed (km/hr)	Maximum Relative Impact Speed (km/hr)	
	Laden	Unladen
20	0	0
25	0	0
30	0	0
35	20	20
40	25	25
45	30	30
50	35	35
55	40	40
60	45	45

Table 6 Maximum Impact Speed (km/h) for M1 vehicles ECE R152[50]

ISO 19237: Intelligent transport systems — Pedestrian detection and collision mitigation systems (PDCMS) — Performance requirements and test procedures

In addition to ECE R152, ISO elaborated a guidance for Pedestrian detection, mitigation and testing. ISO recommends a protocol for pedestrian detection testing. This standard can also be considered by the system requirement and consequently data is required for this test. The standard intent is described as follows[51]:

> *ISO 19237:2017 specifies the concept of operation, minimum functionality, system requirements, system interfaces, and test procedures for Pedestrian Detection and Collision Mitigation Systems (PDCMS). It specifies the behaviours that are required for PDCMS, and the system test criteria necessary to verify that a given implementation meets the requirements of this document. Implementation choices are left to system designers wherever possible.*
>
> *PDCMS reduce the severity of pedestrian collisions that cannot be avoided and may reduce the likelihood of fatality and severity of injury. PDCMS require information about range to pedestrians, motion of pedestrians, motion of the subject vehicle (SV), driver commands and driver actions. PDCMS detect pedestrians ahead of time, determine if detected pedestrians represent a hazardous condition, and warn the driver if a hazard exists. PDCMS estimate if the driver has an adequate opportunity to respond to the hazard. If there is inadequate time available for the driver to respond, and if appropriate criteria are met, PDCMS determine that a collision is imminent. Based upon this assessment, PDCMS will activate CWs and vehicle brakes to*

[50] Uniform provisions concerning the approval of motor vehicles with regard to the Advanced Emergency Braking System (AEBS) for M1 andN1 vehicles UNECE, Retrieved from: https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2020/R152e.pdf

[51] ISO 19237:2017 Intelligent transport systems — Pedestrian detection and collision mitigation systems (PDCMS) — Performance requirements and test procedures, ISO.org, Retrieved from: https://www.iso.org/standard/64111.html

mitigate collision severity. This document, while not a collision avoidance standard, does not preclude a manufacturer from implementing collision avoidance with PDCMS.

Systems that include other countermeasures such as evasive steering are not within the scope of this document.

Responsibility for the safe operation of the vehicle remains with the driver.

ISO 19237:2017 applies to light duty passenger vehicles. It does not apply to other vehicle categories such as heavy vehicles or motorcycles. PDCMS are not intended for off-road use

Similarly, this year ISO will release a standard for cyclist detection. ISO 22078:2020 Intelligent transport systems -- Bicyclist detection and collision mitigation systems (BDCMS) -- Performance requirements and test procedures.

3.4.5.2. EURO NCAP : The European New Car Assessment Programme

The European New Car Assessment Programme (EURO NCAP) was established in 1997[52] to provide consumers safety performance rating of multiple new vehicles. Current members of the Programme are listed in Table 7

Name	Webpage	Country
Allgemeiner Deutscher Automobil-Club (ADAC)	www.adac.de	Germany
Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry of Transport and Digital Intrastructure)	www.bmvi.de	Germany
Department for Transport (DfT)	www.dft.gov.uk	United Kingdom
Ministerie van Infrastructuur en Waterstaat	www.rijksoverheid.nl	Netherlands
Ministère de l'Economie	meco.gouvernement.lu	Luxembourg
Generalitat de Catalunya	web.gencat.cat	Spain
International Consumer Research and Testing	www.international-testing.org	United Kingdom
FIA (Represented by FIA Region 1)	www.fiaregion1.com www.fia.com	France
Swedish Transport Administration	www.trafikverket.se	Sweden
Thatcham Research	www.thatcham.org	United Kingdom
Ministère de la Transition écologique et solidaire	www.ecologique-solidaire.gouv.fr	France
Automobile Club d'Italia (ACI)	www.aci.it	Italy
DEKRA Automobil	www.dekra.com	Germany
Gesamtverband der Deutschen Versicherungswirtschaft Unfallforschung der Versicherer (UDV)	www.udv.de	Germany

Table 7 The European New Car Assessment Programme members

52 The European New Car Assessment Programme: A historical review. van Ratingen M, Williams A, Lie A, et al. Chin J Traumatol. Retrieved from: https://www.researchgate.net/publication/292346612_The_European_New_Car_Assessment_Programme_A_historical_review

The safety rating is based on a five-star scale which reflects how well the car performed in the Euro NCAP Test. Additionally, the five-star scale is correlated to what equipment was included in the vehicle. It is noticed that multiple vehicles have multiple trims and highlighted as optional equipment.

It was noted by industry experts that Euro NCAP goes beyond what is currently specified as the minimum legal requirements and it is a good indicator on where the technology and industry are heading towards. Euro NCAP was pointed out by many software experts as the most challenging test to excel. Test protocols are publicly available in the Vulnerable Road User protocol section of its webpage[53].

EUROCAP describes in its road map the vision for AEB[54]

> *The primary goal of AEB technology is to prevent crashes by detecting a potential conflict and alerting the driver, and, in many systems, aiding in brake application or automatically applying the brakes. The technology was successfully introduced in the safety rating in 2014, and was tested first in rear-end car-to-car collisions and subsequently in pedestrian crossing accidents. The performance of an AEB system is dependent on the type and complexity of the sensors used. More and more manufacturers are adding additional sensors and combining multiple sensor types together in "fusion" to offer the potential to address new and more complex crash scenarios.*
>
> *Euro NCAP expects AEB technology to continue to evolve in the years ahead and has identified three priority areas where the rating scheme will be updated to reflect the progress in industry:*
>
> - *Back-over or reversing crashes usually happen at low speeds at driveways and parking lots. Recent accident research by the German insurers suggests that up to 17 percent of collisions between pedestrians and vehicles with personal injury occur at the rear side of the car. The majority of accident victims (63 percent) were elderly, while children under 12 years of age accounted for 6 percent (German Insurers Accident Research, 2017). It is estimated that, Europe-wide, the number of seriously injured pedestrians in revering crashes could amount to 1,400 per year. A driver assistance system which detects the presence of persons behind the car and automatically initiates braking or prevent acceleration could have significant potential to prevent accidents involving cars and pedestrians (German Insurers Accident Research, 2010). Taking the work done by the insurance industry as a starting point (RCAR, 2017), Euro NCAP plans to adopt the reversing pedestrian scenario to the AEB Vulnerable Road User - Pedestrian test suite in 2020.*
>
> - *Crossing and turning manoeuvres that occur at junctions create opportunities for vehicle-vehicle, vehicle-pedestrian, and vehicle-(motor)cycle conflicts, which often result in traffic crashes. Typically, crossing accidents are the result of running a red light, lack of visibility, driver inattentiveness or speeding. Turning crashes are often caused by misjudging or failing to observe oncoming traffic when turning left or right. In crossing*

[53] PEDESTRIAN TESTING PROTOCOL, EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP) Retrieved from: https://cdn.euroncap.com/media/41769/euro-ncap-pedestrian-testing-protocol-v85.201811091256001913.pdf
[54] Euro NCAP 2025 Roadmap, (Euro NCAP) , Retrieved from: https://cdn.euroncap.com/media/30700/euroncap-roadmap-2025-v4.pdf

scenarios, where the speed of the ego vehicle is relatively low, and in turning scenarios, an AEB intervention could effectively prevent a crash. Testing could include car, pedestrian, cyclist and Powered two-wheeler (PTW) targets and commence in 2020.

- *Head-on scenarios. A combined assessment of steering and braking interventions within the lane to prevent narrow overlap head-on crashes with other road users (cars, PTW, pedestrians) is foreseen from 2022.*

Reflecting this vision, on September 2017 EuroNCAP released a timeline towards 2025 objectives. Figure 13 illustrates the start, protocol release and implementation year of multiple features.

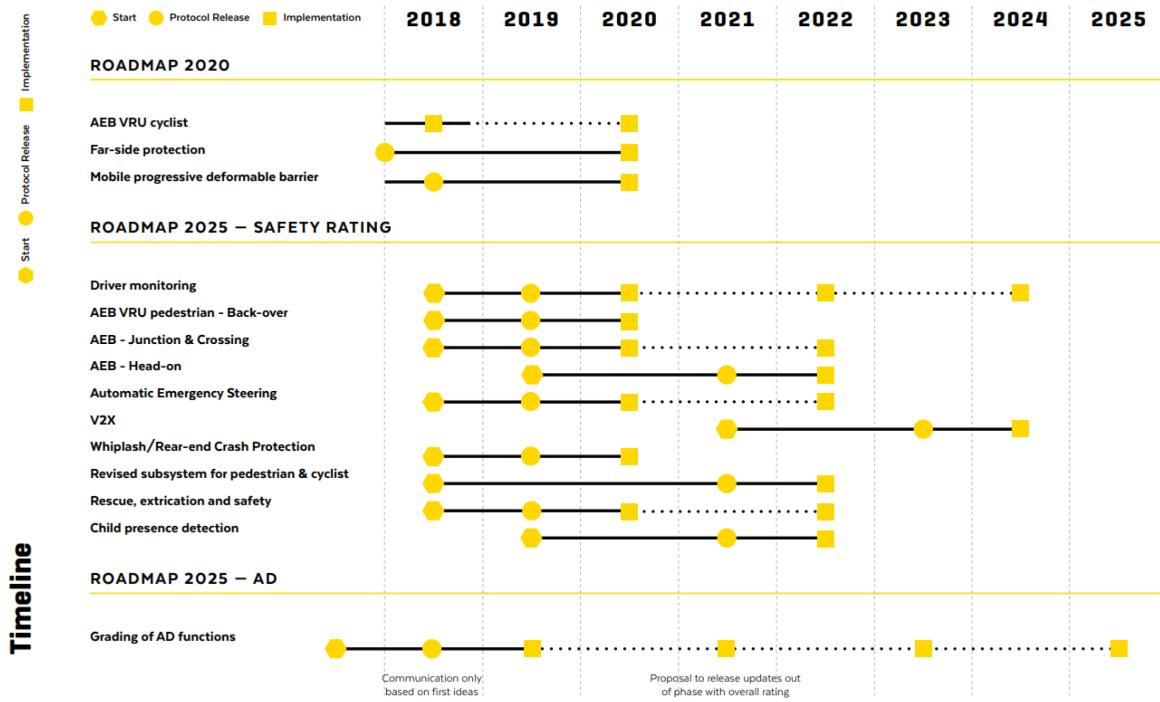


Figure 13 Euro NCAP 2025 Roadmap[55]

NCAP evaluates the performance of pedestrian AEBs under the section of Vulnerable Road User (VRU). The overall scores of the VRU is merged with results of a Pedestrian Impact Assessment. The VRU includes assessment for Pedestrian and cyclist.

NCAP evaluation for VRU AEB is rapidly evolving, for example the 2020 version is including additional tests not included in the 2019 version and different score levels. The score is calculated based on differential speed considering the actual test. Figure 14 illustrates a summary some of the most popular vehicles in Europe (tested with 2019 formatting) and in standard trim. High-end brands such as Mercedes, BMW or Tesla possess scores above 5 in both Pedestrian and cyclist tests[56].

[55] Euro NCAP 2025 Roadmap, (Euro NCAP), Retrieved from: https://cdn.euroncap.com/media/30700/euroncap-roadmap-2025-v4.pdf
[56] ASSESSMENT PROTOCOL – PEDESTRIAN PROTECTION, EUROPEAN NEW CAR ASSESSMENT PROGRAMME (Euro NCAP), Retrieved from: https://cdn.euroncap.com/media/41768/euro-ncap-assessment-protocol-pp-v903.201811091255568319.pdf

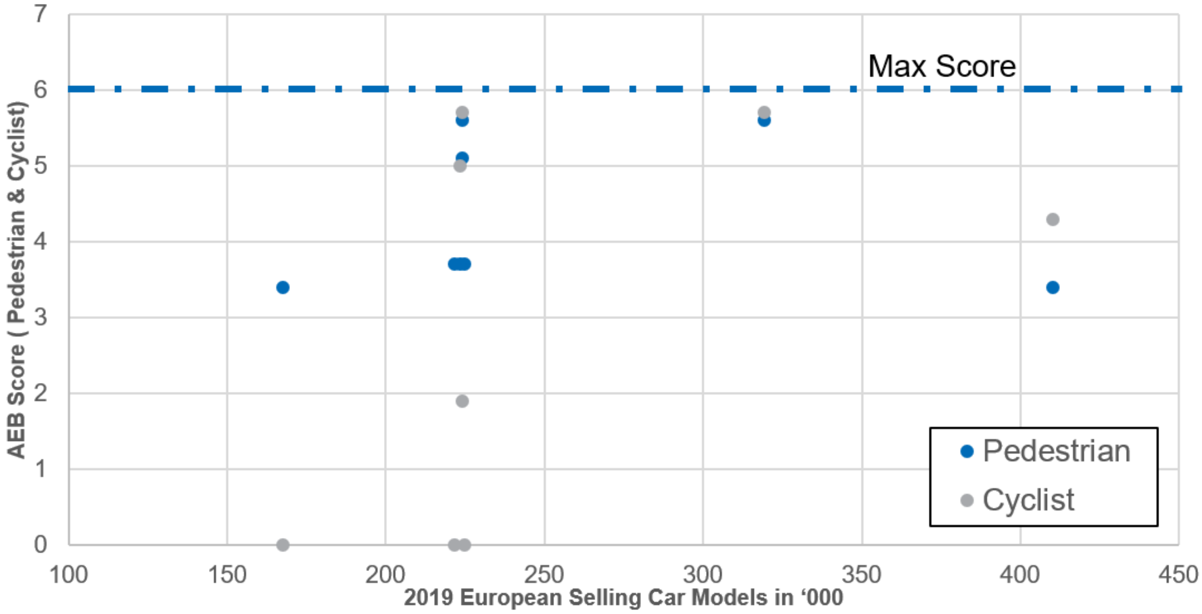


Figure 14 Pedestrian and cyclist status in popular SUV/Cars in EU[57]

3.4.5.3. Insurance Institute for Highway Safety (IIHS)

The Insurance Institute for Highway Safety (IIHS) originally founded by three large insurance company groups in the US on 1959. IIHS defines itself[58]

> *as an independent, nonprofit scientific and educational organization dedicated to reducing the losses — deaths, injuries and property damage — from motor vehicle crashes*

IIHS has a history of highlighting and documenting pedestrian related accidents using a scientific approach. For example, on 1980 IIHS was the first to document the hazards to pedestrians of allowing motorists to turn right at red lights[59]. On 2019, IIHS launched ratings for P-AEB.

IIHS evaluates and provides a qualification in the following aspect of vehicle safety aspects:

- Frontal crash test: Small overlap front configuration, driver-side
- Frontal crash test: Small overlap front configuration, passenger-side
- Frontal crash test: Moderate overlap front
- Side crash test
- Roof strength test
- Head restraints & seats test
- Front crash prevention: vehicle-to-vehicle
- Front crash prevention: vehicle-to-pedestrian
- Headlight evaluation

[57] Ricardo Strategic Consulting Analysis
[58] IIHS, Retrieved from: https://www.iihs.org/about-us
[59] IIHS, Retrieved from: https://www.iihs.org/about-us

- Lower Anchors and Tethers for Children (LATCH)

Specific to Pedestrian detection, IIHS launched in 2019 a new series of ratings of pedestrian automatic emergency braking systems. The first evaluation was performed on 2018-2019 vehicles.[60] IIHS test three scenarios for Pedestrian detection, first is Perpendicular adult walk across run, second is a child runs into road with vehicles parked obstructing view and the last is with pedestrian walking in parallel. Figure 15 summarizes IIHS three different scenarios.

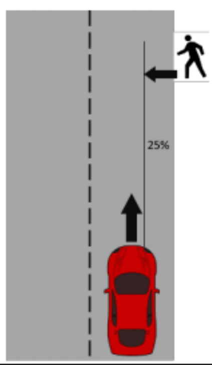
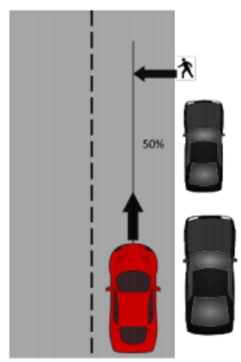
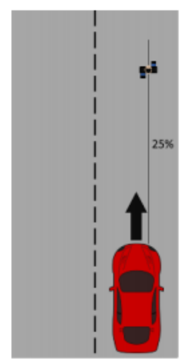
Parameter	*Scenario*		
	Perpendicular adult (CPNA-25)	**Perpendicular child (CPNC-50)**	**Parallel adult (CPLA-25)**
Test vehicle speed	20, 40 km/h	20, 40 km/h	40, 60 km/h
Pedestrian target speed	5 km/h	5 km/h	0 km/h
Target direction	Crossing (R-to-L)	Crossing (R-to-L)	Facing away
Target path (relative to test vehicle)	Perpendicular	Perpendicular	Parallel
Pedestrian dummy size	Adult	Child	Adult
Dummy articulation (fixed rate)	Yes	Yes	No
Overlap	25%	50%	25%
Obstructed	No	Yes	No
Number of valid runs	5	5	5
Test diagram			

Figure 15 IIHS P-AEB Test Scenarios

Points of the tests are based on average speed reduction and showed in Table 8. Points are estimated with the average reduction of five test runs. The two perpendicular scenarios are added and weighted 70%, the other 30% is the parallel scenario. Finally, both scores are added.[61]

Speed reduction range (km/h)	Points
0 to 8	0.0

[60] New ratings address pedestrian crashes, IIHS, Retrieved from: https://www.iihs.org/news/detail/new-ratings-address-pedestrian-crashes
[61] Pedestrian Autonomous Emergency Braking Test Protocol (Version II), IIHS, Retrieved from: https://www.iihs.org/media/f6a24355-fe4b-4d71-bd19-0aab8b39aa7e/TfEBAA/Ratings/Protocols/current/test_protocol_pedestrian_aeb.pdf

9 to 18	0.5
19 to 28	1.0
29 to 38	1.5
39 to 48	2.0
49 to 58	2.5
59 to 61	3.0

Table 8 Points Awarded for Average Speed Reduction

RSC plotted the speed reduction of the most popular cars and SUVs sold in the U.S. during the (trucks are not included). The X-axis indicate 2019 NA annual sales and the Y-axis the average speed reduction. Figure 16 illustrates average speed reduction of the most popular vehicles sold in the U.S.

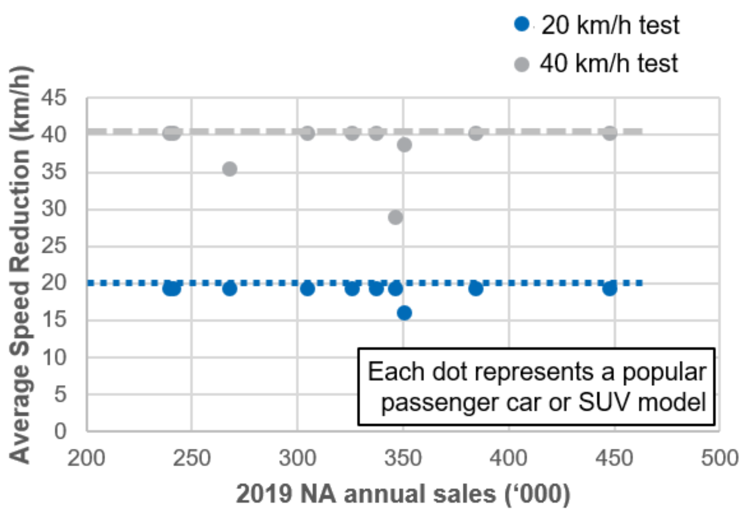


Figure 16 IIHS P-AEB Test Scenarios Perpendicular Adult (CPNA-25) Average Speed Reduction

Figure 17 illustrates IIHS results of 2020 Toyota Camry and 2020 Subaru Outback

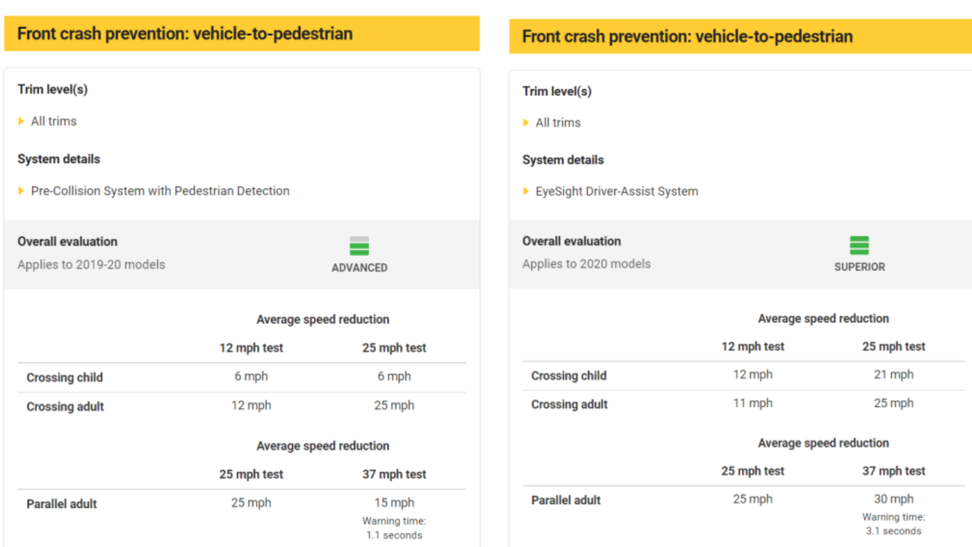


Figure 17 IIHS Pedestrian test results for Camry 2020 and Outback 2020

4. COST AND WEIGHT ANALYSIS

4.1. Hardware cost and weight result summary

For the purposes of this report, the hardware required for Pedestrian AEB systems is not differentiated from the hardware required for overall AEB systems as described in the Final Reports for Contract Number: DTNH2216D00037, Task Order: 693JJ918F000185 – Cost and weigh analysis for automatic emergency braking systems for passenger vehicles. This determination is based on a review of available systems and functionality as part of the AEB cost and weight effort, as well as interviews with industry experts. Specifically, pedestrian and cyclist detection are viewed as a subset of object detection as part of an AEB system. As such, incremental hardware teardown and cost analysis was not completed as part of this effort, but software cost will be incorporated in the overall system cost later in the report. Two scenarios are considered: Follower ADAS and Disruptor ADAS. For Follower ADAS, the basic software for system functionality has been developed and any incremental system functionality is built on that base. This is not meant to imply that these systems are simple, more that they are based on existing, developed technology, and there is minimal novel development effort required for their implementation. For the purposes of this report, the Toyota Camry and Subaru Outback AEB systems will be considered Follower ADAS. Disruptor ADAS are systems where significantly increased functionality is being sought through a first time through development effort. Current Disruptor ADAS systems are seeking Level 2 / Level 3 autonomy capability and require significant development to get there. For the purposes of this report, the Audi A8 systems is considered Disruptor ADAS. Table 9 shows the difference between features of Toyota and Subaru systems.

			Lexus LS with Lexus Safety System+ A	Lexus ES with Lexus Safety System+ 2.0	Toyota Camry with Toyota Safety Sense P	Subaru Outback with EyeSight
Features	**Forward Collision Detection**					
	Vehicle		✓	✓	✓	✓
	Pedestrian (daytime)		✓	✓	✓	✓
	Pedestrian (low-light)		✓	✓	-	✓
	Bicyclist (daytime)		✓	✓	-	✓
	Dynamic Brake Support		✓	✓	✓	✓
	Crash Imminent Braking		✓	✓	✓	✓
	Active Steering Assist*		✓	✓	-	-
	Front Cross-Traffic Alert		✓	-	-	-
Sensors	Camera		Stereo	Mono*	Mono	Stereo
	Radar, forward	Far	✓	✓	✓	-
		Near	✓	✓	✓	-
	Radar, front-side		L & R	-	-	-
Central Processor			Dedicated Driving Support Computer	Dedicated Driving Support Computer	Shared ECU	Shared ECU
Recommendation			✗	✗	✓	✓

*To be confirmed if necessary

Table 9 Comparison of features and equipment relevant to AEB for Toyota and Subaru vehicles

"Follower" ADAS Results

Ricardo has analyzed the cost and weight of the Toyota Camry AEB system which uses a combination of radar and camera and the Subaru Outback AEB system which uses a stereo camera only. Table 10 summarizes the incremental manufacturing costs and weights for the Toyota Camry radar and camera systems and Subaru Outback AEB stereo camera system with associated 'Pre-Collision Braking' switch, overhead console, camera mounting plate, and wiring.

Vehicle	Camera	Radar	Other	Total Incremental Cost	Total Incremental Weight [g]
Toyota Camry	$ 50.68	$ 69.68	$ -	$ 120.36	883
Subaru Outback	$ 136.80	$ -	$ 23.06	$ 159.86	2478

Table 10 Incremental manufacturing cost and weight changes for Toyota Camry and Subaru Outback AEB systems

Overhead burdens, characterized by fixed percentage markups for indirect manufacturing, SG&A, profit, transportation & warranty as well as dealer costs and markup as described in the section 3.3 Hardware cost Methodology , are applied to the total manufacturing costs to determine the end-user price increases as summarized in Table 11. The end-user price increase is the retail price an end-user would pay for the incremental AEB system hardware on a vehicle.

		Toyota Camry			*Subaru Outback*		
		Cost		Markup	Cost		Markup
Variable manufacturing cost			$ 113.44	1.00		$ 147.25	1.00
Fixed manufacturing cost			$ 6.92	0.06		$ 9.65	0.07
Total manufacturing cost			**$ 120.36**	1.06		**$ 159.86**	1.09
SG&A (% of variable)	*6%*	$ 6.81		0.06	$ 8.84		0.06
Profit (% of total)	*3.75%*	$ 4.51		0.04	$ 5.99		0.04
Transportation & warranty (% of total)	*7.5%*	$ 9.03		0.08	$ 11.99		0.08
Wholesale price increase			$ 140.71	**1.24**		$ 186.68	**1.27**
Dealer costs & markup (% of wholesale)	*11%*		$ 15.48	0.14		$ 20.53	0.14
End user price increase			**$ 156.18**	**1.38**		**$ 207.21**	**1.41**

Table 11 End user price increases as calculated from the total manufacturing costs

"Disruptor" ADAS Results

Ricardo has analyzed the cost and weight of the AEB system in the 2019 Audi A8 which employs five types of sensors and a central driver assist control module. The five sensor systems are a laser scanner, a visible camera for lane assist, a night vision camera which includes a separate processor, a long-range radar for distance control and two short-range radars for forward/side object detection. Table 12 lists the incremental manufacturing costs along with assumed production rates, wholesale prices to an OEM, and end-user price increases of the LiDAR-based AEB system in the Audi A8.

Item #	Description	Production volume assumption	Manufacturing Cost	SG&A	Profit	Wholesale price SPC analysis	Transportation & Warranty	Wholesale price Ricardo analysis	Dealer costs & markup	End User Price Increase
	Audi A8 LIDAR-based AEB system		**$1,025.83**					**$1,462.90**		**$1,623.82**
1	**Laser scanner system**		**$158.96**					**$255.11**		**$283.18**
1.1	Laser scanner module	200,000	$140.33	25%	12%	$222.74	7.5%	$233.27	11%	$258.93
	Balance of laser system	200,000	$18.63	6.0%	3.75%		7.5%	$21.84	11%	$24.25
2	**DAS control unit system**		**$353.59**					**$510.40**		**$566.55**
2.1	DAS control unit	200,000	$351.80	15%	12%	$481.92	7.5%	$508.31	11%	$564.22
2.2	Bracket	200,000	$1.79	6.0%	3.75%		7.5%	$2.10	11%	$2.33
3	**Camera, lane assist system**		**$34.56**					**$49.46**		**$54.91**
3.1	Camera, lane assist	200,000	$32.82	15%	12%	$44.96	7.5%	$47.42	11%	$52.64
	Balance of camera system	200,000	$1.74	6.0%	3.75%		7.5%	$2.04	11%	$2.26
4	**Radar, distance control**		**$41.11**					**$65.63**		**$72.85**
4.1	Radar, distance control (LRR)	200,000	$39.51	28%	7%	$60.79	7.5%	$63.75	11%	$70.77
	Balance of LRR system	200,000	$1.60	6.0%	3.75%		7.5%	$1.88	11%	$2.08
5	**Radar, objection detection**		**$73.48**					**$106.01**		**$117.68**
5.1	Radar, objection detection (SRR)	200,000	$72.90	14%	13%	$99.86	7.5%	$105.33	11%	$116.92
	Balance of SRR system	200,000	$0.58	6.0%	3.75%		7.5%	$0.68	11%	$0.76
6	**Night vision camera system**		**$334.83**					**$441.94**		**$490.55**
6.1	NV camera module	200,000	$323.59	12%	8.00%	$404.49	7.5%	$428.76	11%	$475.92
	Balance of NV camera system	200,000	$11.24	6.0%	3.75%		7.5%	$13.18	11%	$14.63
7	**Wiring harnesses**	200,000	**$29.29**	6.0%	3.75%		7.5%	**$34.34**	11%	**$38.11**

Table 12 Incremental manufacturing costs, wholesale prices and end-user price increases for the Audi A8 AEB system

Description	Manufacturing Cost	SG&A	Profit	Wholesale price Yole analysis	Transportation & Warranty	Wholesale price Ricardo analysis	Dealer markup	End User Price Increase
Name / Description of new component or system	MC	SGA_N	P_N	$WP_Y = \frac{MC}{1-(SGA_N + P_N)}$	TW	$WP_R = WP_Y * (1+TW)$	D	$EUPI = WP_R * (1+D)$
Name / Description of existing component or system	MC	SGA_E	P_E		TW	$WP_R = MC * (1 + SGA_E + P_E + TW)$	D	$EUPI = WP_R * (1+D)$

Table 13 shows the equations used for calculating the end-user and wholesale prices in Table 12. Overhead burdens of SG&A and profit are characterized by a marginal percentage of the wholesale price to an OEM for new components or by fixed percentage markup factors for existing components; a fixed percentage markup for transportation & warranty is also factored into the Ricardo wholesale price. Higher SG&A and profit factors were selected because the electronic modules were newer products in the market with high development costs and little or no competition in some cases than the existing parts that were subject to (sometimes fierce) competition and intense cost-reduction efforts by automotive OEMs. Financial statements for the module supply companies were included in consideration in determining the SG&A and profit margins.

Dealer costs and markup are applied to the Ricardo wholesale price to arrive at the end-user price increase. The end-user price increase is the retail price an end-user would pay for the incremental AEB system hardware as if it were offered as an option on the vehicle when manufactured at high production rates.

Description	Manufacturing Cost	SG&A	Profit	Wholesale price Yole analysis	Transportation & Warranty	Wholesale price Ricardo analysis	Dealer markup	End User Price Increase
Name / Description of new component or system	MC	SGA_N	P_N	$WP_Y = \frac{MC}{1-(SGA_N+P_N)}$	TW	$WP_R = WP_Y * (1+TW)$	D	$EUPI = WP_R * (1+D)$
Name / Description of existing component or system	MC	SGA_E	P_E		TW	$WP_R = MC * (1+SGA_E+P_E+TW)$	D	$EUPI = WP_R * (1+D)$

Table 13 Cost and price formulae used in Table 12

Finally, Table 14 illustrates the weights of each of the components of the AUDI A8 subsystems:

Description	Total Weight [g]
Laser scanner system	947
DAS control unit system	1308
Camera, lane assist system	132
Radar, distance control	324
Radar, objection detection	281
Night vision camera system	887
Wiring harnesses	1198

Table 14 Weight of Audi A8 ADAS components

4.2. Software result summary

ADAS is a fast-evolving industry where software is the engine that drives the rapid development and implementation of new features. New algorithms, increased data availability, and novel business strategies are allowing ADAS to be implemented in more vehicles as standard features, but also leads to a proliferation and lack of standardization in ADAS architecture. In order to understand the cost implications of software on ADAS, and particularly PAEB implementation, analysis is required from multiple perspectives. RSC studied financial statements, research papers, industry conferences presentations and proceedings and conducted formal interviews with industry participants in software development from the OEM, Tier 1, Tier 2 and Regulators perspectives.

In the following section we present critical information RSC encountered during the research related to software. Additionally, RSC divides the software cost in two parts, the perception part where we use most of the information from Mobileye and the system burden which is an effort between OEMs and Tier 1s and discussed in interviews.

In the following sections, RSC will first present a top-down analysis of costs for software based on the public financial disclosures of industry participants. RSC presents what the market is charging for state-of-the-art perception sensors (camera) as well as ADAS.

RSC will then present a bottom up cost analysis looking at the software development timeline and resource requirements for ADAS features encountered by the OEM and Tier 1. This section does not include burden of object detection algorithms.

RSC will add both in order to show the overall impact of software development cost on ADAS hardware and comment on changes that are in process in the industry that may impact future costs.

4.2.1. Financial Statements Analysis

In this section RSC analyzes publicly available financial information from Mobileye and Veoneer. Mobileye is a Tier 2, leader of algorithms and processors for object detection. Veoneer design, manufacture and sell software, hardware and systems for occupant protection, advanced driving assistance systems[62].

The intent of this analysis is 1) to identify the cost burden of object detection software and algorithm development and validation and 2) review available data on the current market price of standard vision based AEBs system.

4.2.1.1. Mobileye

Mobileye was highlighted by many industry experts as a historical leader company in the field of vision-based object detection and machine learning-based sensing. The software is deployed in a "System on a Chip (SoC)" EyeQ® based on monocular cameras systems (and in some cases fusion with radar redundancy). Mobileye is considered a Tier 2 supplier since it commercialized its product to Tier 1 that integrate the SoC with the algorithm into the overall system supplied to the OEMs. Mobileye commercializes this product in a bundle of feature and the 2017 Average Selling Price (ASP) was $45.00[63].

> *Mobileye has been able to achieve the power-performance-cost targets by employing proprietary computation cores (known as accelerators), which are optimized for a wide variety of computer-vision, signal-processing, and machine-learning tasks, including deep neural networks.*[64]

Mobileye entered the market for Autonomous Vehicles (AV) beyond level 2 which is generating new products such as REM Mapping for AV, Data for Smart Cities, Mobility as a Service and Full Stack self-

[62] Veoneer, https://www.veoneer.com/

[63] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. Retrieved from: https://www.sec.gov/Archives/edgar/data/1607310/000157104915001638/t1500418-20f.htm

[64] The Evolution of EyeQ, Mobileye, Retrieved from: https://www.mobileye.com/our-technology/evolution-eyeq-chip/

driving systems[65]. Figure 18 shows camera milestones achieved by Mobileye in recent years prior the acquisition by Intel on 2017 for an equity value of $15.3B[66].

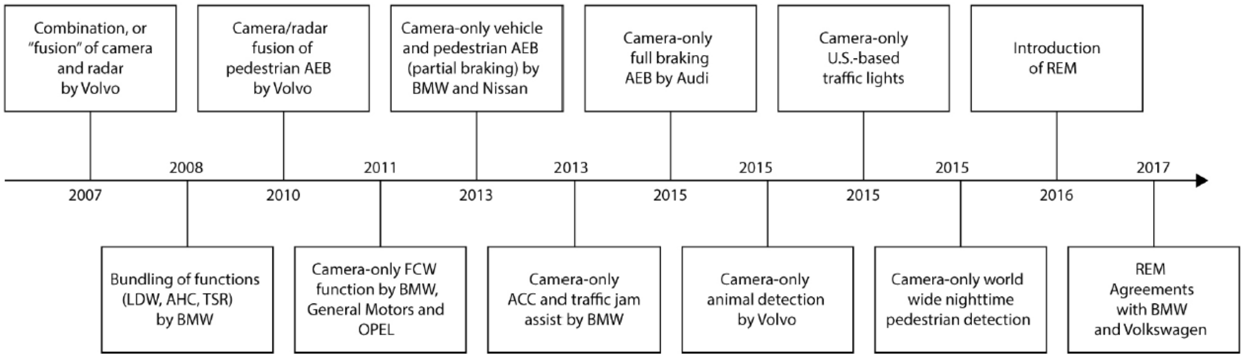


Figure 18 Historical milestones of Mobileye in the ADAS industry[67]

By the end of 2016, Mobileye offered solutions able to detect vehicle, pedestrians, general objects and roadway markings. Mobileye estimated its products are in near to 15.7 million vehicles worldwide (end of 2016 with 21 OEMs) and was selected for implementation with more than 25 OEMs (47 running programs[68]). Mobileye enters the market with the OEM as end customer and Tier 1 as the intermediary[69].

> *Mobileye provides the software and the EyeQ SoC to the Tier 1 companies. Typically, after we work with the OEM so that it can validate our product, the OEM issues an RFQ. We create a reference design for the camera sensor and electronics that are built around our SoC to each Tier 1 company that determines to respond to the RFQ. The Tier 1 company, based on our reference design, builds a module for the complete sensor system that includes the windshield-mounted camera, our proprietary EyeQ SoC and our application software using our software algorithms. This complete sensor system with the required ADAS functionalities is then integrated into new cars by the OEM. We also give the Tier 1 company the pricing of our product per bundle of applications, which is incorporated into its RFQ and is set for the duration of the program. Although our direct customers are the Tier 1 companies, we view the OEM as our ultimate customer and maintain strong direct relationships with the OEMs.*

Mobileye shipped approximately 6.0 million chips by the end of 2016. Additionally, on CES 2020 Prof. Amnon Shashua stated that Mobileye shipped 8.7M in 2017, 12.4M in 2018 and 17.4M in 2019. Since 2007 Mobileye shipped 54M chips[70].

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[65] CES 2020: An Hour with Amnon - Autonomous Vehicles Powered by Mobileye , Mobileye an Intel Company , Retrieved from: https://www.youtube.com/watch?v=HPWGFzqd7pI

[66] CES 2020: An Hour with Amnon - Autonomous Vehicles Powered by Mobileye , Mobileye an Intel Company , Retrieved from: https://sec.report/Document/0001193125-17-079586/

[67] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. https://www.sec.gov/Archives/edgar/data/1607310/000157104917001997/t1700397_20f.htm

[68] https://www.youtube.com/watch?v=HPWGFzqd7pI

[69] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. Retrieved from: https://www.sec.gov/Archives/edgar/data/1607310/000157104915001638/t1500418-20f.htm

[70] CES 2020: An Hour with Amnon - Autonomous Vehicles Powered by Mobileye , Mobileye an Intel Company , Retrieved from: https://www.youtube.com/watch?v=HPWGFzqd7pI

Mobileye OEM market represents close to 80% of its revenue. Table 15 illustrates the OEMs Mobileye has programs, blue indicates models achieving Five Stars in the Euro NCAP 2018 (Standard Feature) with Mobileye content.

Adam Opel AG	Hyundai and Kia Nexo, Santa Fe *(11% 2016 OEM Revenue)*	Renault S.A.
Audi AG A6	IVECO	Scania Aktiebolag
BMW AG X5 *(11% of 2016 OEM Revenue)*	Lucid Motors Inc.	Ssangyong Motor Company
Chrysler Group LLC	MAN SE	SAIC Motor
FAW Automotive	Mitsubishi Group	Soueast Motors
Fiat S.p.A.	Mazda Motor Corporation Mazda 6	Volkswagen Touareg
Ford Motor Company Focus	NIO USA	Volvo Car Corporation XC40, S60, V60
General Motors Company *(22% of 2016 OEM Revenue)*	Nissan Motor Co., Ltd. Leaf *(14% of 2016 OEM Revenue)*	Yulon Motor Co., Ltd.
Honda Motor Company, Ltd	PSA Peugeot Citroën 508	

Table 15 OEMs with Mobileye's products offered or will be available (As 2017)[71][72]

Mobileye was a publicly traded company until 2017, consequently its financial statements are available. Below a summary of its non-GAAP of the last Form 20-F available in public records, shown in Figure 19. Research and development are just slightly lower than the cost of revenues.

[71] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. Retrieved from: https://www.sec.gov/Archives/edgar/data/1607310/000157104915001638/t1500418-20f.htm
[72] The State of AV/ADAS at Mobileye/Intel, Mobileye an Intel Company , Retrieved from: https://s21.q4cdn.com/600692695/files/doc_presentations/2019/01/Mobileye_CES2019.pdf

	Year ended December 31,				
	2016	2015	2014	2013	2012
			(in thousands)		
Statement of Operations Data					
Revenues	$358,162	$240,872	$143,637	$ 81,245	$40,285
Cost of Revenues	87,307	61,420	37,040	21,130	12,219
Gross Profit	270,855	179,452	106,597	60,115	28,066
Operating Costs and Expenses					
Research and Development, net	65,259	43,393	36,930	22,309	15,866
Sales and Marketing	17,416	12,811	12,912	12,331	6,434
General and Administrative	67,241	45,509	71,437	10,277	7,418
Operating Profit (Loss)	120,939	77,739	(14,682)	15,198	(1,652)
Interest Income	5,083	2,888	1,305	1,059	1,531
Financial Income (Expenses), net	(582)	(917)	(4,442)	1,389	402
Profit (Loss) Before Taxes on Income	125,440	79,710	(17,819)	17,646	281
Benefit (Taxes) on Income	(17,070)	(11,260)	(12,265)	2,274	(334)
Net Income (Loss)	$108,370	$ 68,450	$ (30,084)	$ 19,920	$ (53)
Basic and Diluted Loss per Share[1]					
Amount Allocated to Participating Shareholders	$ —	$ —	$ —	$ (16,105)	$ —
Adjustment as a Result of Benefit to Participating Shareholders	—	—	—	(229,832)	—
Net Income (Loss) Applicable to ordinary shares for 2016, 2015 and 2014 and Applicable to Class A ordinary shares for 2013 and 2012	$108,370	$ 68,450	$ (30,084)	$(226,017)	$ (53)
Basic	$ 0.49	$ 0.31	$ (0.28)	$ (6.03)	$ —
Diluted	$ 0.46	$ 0.29	$ (0.28)	$ (6.03)	$ —

Figure 19 Selected financial data of Mobileye prior acquisition by Intel

Figure 20 illustrates the financial segments between After Market products and OEM products. Mobileye define the cost of revenues as follow[73]:

> *Cost of revenues of our OEM segment includes the manufacturing cost of our EyeQ chips as well as royalty fees for a few third parties on intellectual property that is included in the EyeQ SoC, product liability insurance, reserves for estimated warranty expenses and, to the extent relevant, charges to write down the carrying value of our inventory when it exceeds its estimated net realizable value and to provide for obsolete and on-hand inventory in excess of forecasted demand.*
>
> *Cost of revenues of our aftermarket product includes, in addition to the cost of the EyeQ chips (including royalties), direct material, labor costs, depreciation, manufacturing and supply chain overhead, quality control, shipping and logistic costs and reserves for estimated warranty expenses. Cost of revenues also includes charges to write down the carrying value of our inventory when it exceeds its estimated net realizable value and to provide for obsolete and on-hand inventory in excess of forecasted demand. We purchase the majority of the components directly, and our products are manufactured primarily by two contract manufacturers in China.*

[73] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. Retrieved from: https://www.sec.gov/Archives/edgar/data/1607310/000157104915001638/t1500418-20f.htm

	Year ended December 31, 2016			
	OEM	AM	Amounts not allocated to segments	Consolidated
	U.S. dollars in thousands			
Revenues	275,938	82,224		358,162
Cost of revenues	63,796	23,465	46	87,307
Gross profit	212,143	58,759		270,855
Research and development, net	49,848	3,195	12,216	65,259
Sales and marketing	1,241	15,469	706	17,416
General and administrative	13,192	1,415	52,634	67,241
Segment performance	147,862	38,680		120,939
Interest income				5,083
Financial expenses, net				(582)
Profit before taxes on income				125,440
Depreciation	3,798	291		4,089

Figure 20 Mobileye 2016 Financial segment results

At the end of 2016, Mobileye employed 663 full time equivalent employees, with 473 focusing in Research and Development mainly in Israel. Mobileye has more than 18 years of R&D and data collected from tens of millions of miles (60 countries). Data is additionally collected by Mobileye through crowdsourcing and cooperation with partners. Mobileye started developing pedestrian detection in 2002. Currently, Mobileye Research and Development focuses in three main fronts[74]:

- *Core sensing technology, which includes (i) algorithms, including visual processing, camera control, vehicle control, camera/radar fusion and related engineering tasks; and (ii) application software;*
- *Autonomous Driving Functionality, which consists of (i) enhancing the sensing capabilities to fully autonomous driving by conducting "scene understanding," lateral control algorithms and the fusion between sensing and control; (ii) developing the other pillars of autonomous driving, including our REM technology, which enables continuously updated high-definition data for drivable paths with precise-localization using crowdsourcing; and (iii) driving policy using reinforcement technology to allow autonomous cars to co-exist with human drivers and other autonomous cars;*
- *New products and enhancements to existing products in response to OEM requirements; and*
- *Hardware, which includes (i) silicon design for the EyeQ chip including the EyeQ4 EyeQ5 ; (ii) hardware electronics design for testing and other equipment; and (iii) new aftermarket hardware. For example, we are currently developing the next generation of our aftermarket products incorporating the EyeQ4 chip.*

Intel financial statements also illustrates revenue growth of Mobileye on 2018 and 2019 (2017 partial amount due acquisition). See Table 16.

[74] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. Retrieved from: https://www.sec.gov/Archives/edgar/data/1607310/000157104915001638/t1500418-20f.htm

Years Ended (in Millions)	Dec 28, 2019	Dec 29, 2018	Dec 30, 2017
Net Revenue	879	698	210
Operating income	245	143	(28)

Table 16 Revenue and Operating Income of Mobileye as part of Intel

Finally, Mobileye estimates average selling price for the object detection AEB bundle to be $45.0 in 2016:

> *Our Gross Profit is primarily impacted by our Average Selling Price ("ASP") and the associated average costs in the OEM segment. ASP in our OEM segment varies based on the ADAS applications and their complexity. Our ASP was relatively flat at $43.7 in 2014 and $43.9 in 2015 while it increased substantially to $45.0 in 2016. ASP is primarily the result of an ever-changing delivery mix among the different bundles that we deliver — whether it is a high-selling price pedestrian AEB bundle, a lower selling price AEB vehicle or the lowest selling price of road bundles (not including vehicle and pedestrian detection).*
>
> *The increase in our ASP in 2016 was the result of new program launches with pedestrian AEB bundles and the benefit from the full-year impact of the launches we had in the second half of 2015 that included AEB pedestrian.*
>
> *Over the long-term, we expect EyeQ ASP to move up over time once semi-autonomous and fully autonomous vehicles become a material part of our volume. In general, we believe our ASP will increase as less complex legacy programs are replaced by the more advanced feature bundles within already awarded programs and future programs.*
>
> *We are considered a Tier 2 supplier because we sell our product to Tier 1 companies that integrate our product into the overall system supplied to the OEMs. We believe that our business model of being a Tier 2 supplier that subcontracts its manufacturing, together with our market penetration, results in an advantageous cost structure that requires low operational costs and sales and marketing expenses for our OEM segment*[75].

RSC did not obtain public information on Mobileye percentage of Visual ADAS commercialized for specific features such as a Pedestrian detection. Audi A8 presented in this study contains Mobileye Chip EyeQ3 shown in Figure 21.

[75] UNITED STATES SECURITIES AND EXCHANGE COMMISSION WASHINGTON, D.C. 20549 , Form 20-F, Mobileye N.V. Retrieved from: https://www.sec.gov/Archives/edgar/data/1607310/000157104915001638/t1500418-20f.htm

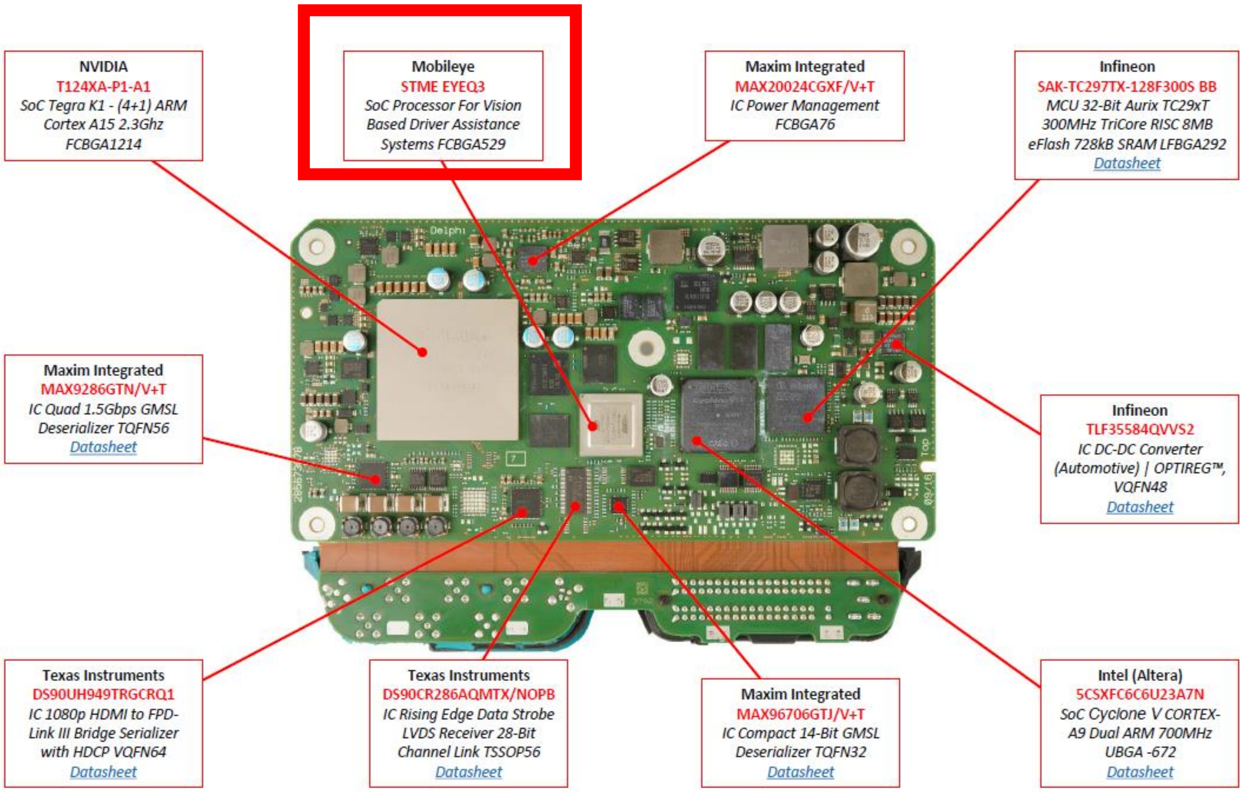


Figure 21 Main components on the zFAS main board[76]

4.2.1.2. Veoneer, Inc

Veoneer is a Tier 1 supplier with a large portion of its revenue from advanced driver assistance systems ("ADAS"), Veoneer divides its financial reports in two sections Electronics and Brake Systems segments. The Electronics segment consists of Active Safety and Restraint Control Systems. Veoneer in its financial statements claims its ADAS content per vehicle is approximately $100 per vehicle to approximately $300 per vehicle. The following is an extract from the most current yearly financial statement[77]:

> *We (Veonner) develop radar and vision technologies (including Veoneer's internally developed vision algorithms for mono, stereo and thermal vision) that monitor the environment around the vehicle with features which can adjust engine output and steering or braking to avoid accidents.*
>
> *The automotive production value chain is split among OEMs such as General Motors, Toyota and Volkswagen and automotive suppliers, such as ourselves, Aptiv, Bosch, Continental, Denso, Magna, Valeo and ZF. Veoneer acts mainly as a Tier-1 supplier to OEMs, meaning that we sell products directly to OEMs.*
>
> *Our underlying market is primarily driven by two critical factors: Global Light Vehicle Production ("LVP") and Content Per Vehicle ("CPV"), whereby CPV is the clear market driver for the growth of our Total Addressable Market ("TAM").*

[76] Image copyright: System Plus Consulting, 2019
[77] UNITED STATES SECURITIES AND EXCHANGE COMMISSION FORM 10-K Veoneer, Inc Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 For the fiscal year ended December 31, 2019, Retrieved from: https://www.sec.gov/Archives/edgar/data/1733186/000173318619000044/veoneer_10k.htm

Light Vehicle Production: Over the last two decades, LVP has increased at an average annual growth rate of around 3% despite the cyclical nature of the automotive industry. The LVP is expected to increase from 85 million vehicles in 2020, to 97 million in 2025, where approximately 86 million where produced in 2019, according to IHS, The market is undergoing a shift from traditional internal combustion engine ("ICE") vehicles, to HEVs and EVs, as emission regulations become more stringent, and battery technology continues to evolve in cost and performance.

Content Per Vehicle: Unlike LVP, we can directly influence the CPV by introducing new technologies to the market. Looking ahead, we expect the safety CPV growth will primarily be driven by Active Safety content (including software), <u>with total Active Safety market growing from approximately $100 per vehicle in 2019 to approximately $300 per vehicle in 2025.</u>

4.2.2. V- Model Results

Implementation of an AEB perception, prediction and planning software in a new architecture is a very complex process impacted by, and dependent on many cost drivers for both, the OEM and tiered supply base. Based on feedback from industry expert interviews, RSC identified several drivers for software development cost and effort variance:

- System requirements: There are multiple qualificative tests such as EURO NCAP or IIHS. Depending on the program business proposition the OEM could chose to development a system to exceed these tests and use it as a differentiator or limit it to be acceptable, could choose to meet the minimum requirements, or could choose to implement a system that pushes the boundaries well beyond any current recommended requirements. This systems specification on the part of the OEM is a significant driver of software development and software cost. Software costs and development efforts are relatively low for common, currently implemented features, when compared to new and novel options. For example, when we spoke to interviewees, there was agreement that there was significant development effort that would have been required for the functionality of the Audi A8 ADAS system because of the advanced level 3 features that were integrated.
- Agile development: ADAS development does not follow the historical OEM development cycles where the full system with all functionality is developed and validated linearly from beginning to end. Instead, agile development methodologies have been adopted from the tech industry where there is an iterative development cycle as basic functionality is created and proven, then additional features are added incremental iterations. This is also partially why incremental functional requirements drive incremental software cost because they lead to further iterations in the development process.

To estimate the software burden and capture the industry perspective, RSC conducted more than 20 interviews to multiple ADAS software experts with experience in OEMs, Automotive suppliers and regulatory entities. These experts have Executive, Manager, Engineer and Regulators consultant positions.

Besides providing their perspectives on industry technology, trends and roadblocks. RSC captured their opinion on the industry status quo on development burden of a hypothetical ADAS.

Subsequently, experts shared how many direct resources (such as headcount-equivalent, licenses or validation equipment) would be required for each step of the software V-development process.

In some scenarios, experts will have better visibility of specific sections of the V-Development where they are most specialized.

RSC considered two fronts of the development process, one on the OEM perspective and second on the Tier 1 perspective. Figure 22 illustrates the level of engagement of each part. As can be seen, the participation level of the OEM is minimal in the coding stage however it is more active in the specification and validation stage.

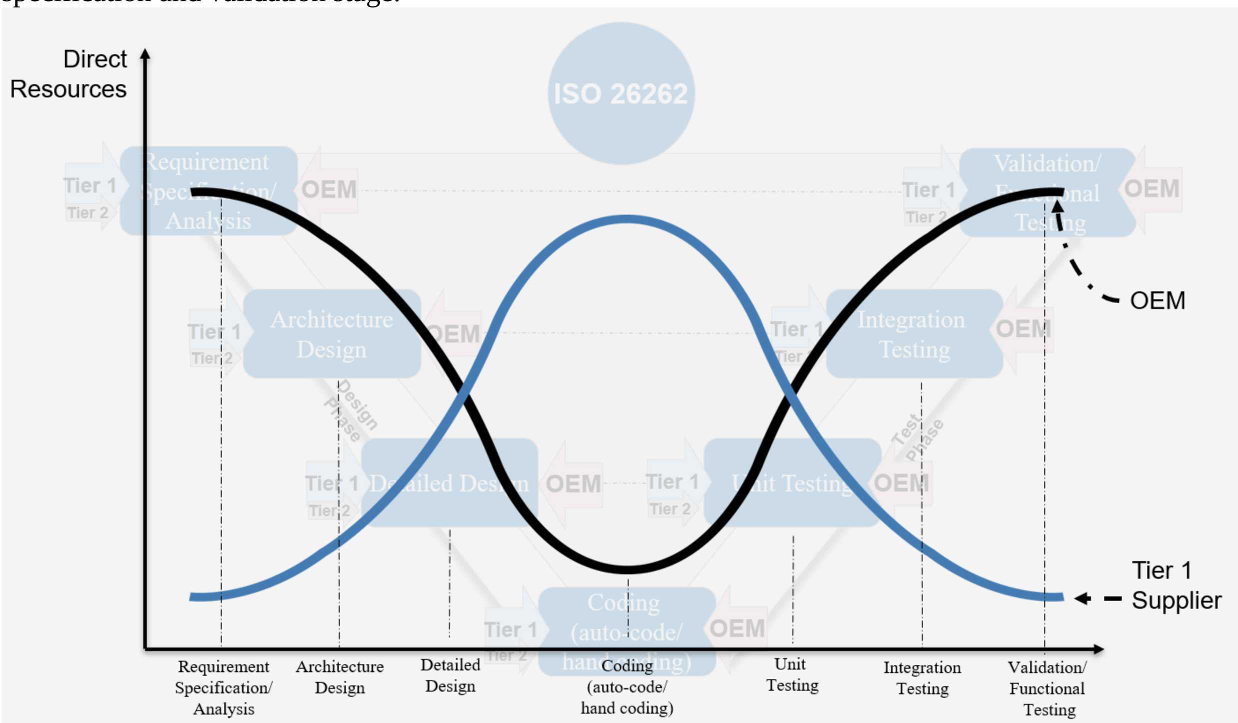


Figure 22 Direct resources by OEM and by Tier 1 supplier

Finally, all inputs are merged into a model and generated a direct resource amount based on the following assumptions:

- Each input had a different project timeline and duration per each step of the process. On average experts agreed on a timeline between 2 to 3 years for a follower ADAS and 4 to years for a disruptor ADAS.
- The assumed salary was $200K per year on head count salary. Inputs from other countries were received but normalized to $200K per year[78].
- When the software overhead cost was not included by the interviewee, industry experts suggested 10% of the overall software cost for this type of expense.
- Experts suggest a 1 to 5 ratio of expense from OEMs as compared to Tier 1s. When the OEM perspective was not provided, this rationale was assumed.

RSC concluded from these discussions there are two tendencies in the industry driven by the adoption strategy of OEMs, the Disruptor ADAS and the Follower ADAS. Figure 23 shows the results of a Disruptor Region and a Follower Region.

[78] May 2019 National Occupational Employment and Wage Estimates
United States, US Bureau of labor statistics Retrieved from: https://www.bls.gov/oes/current/oes_nat.htm#15-0000

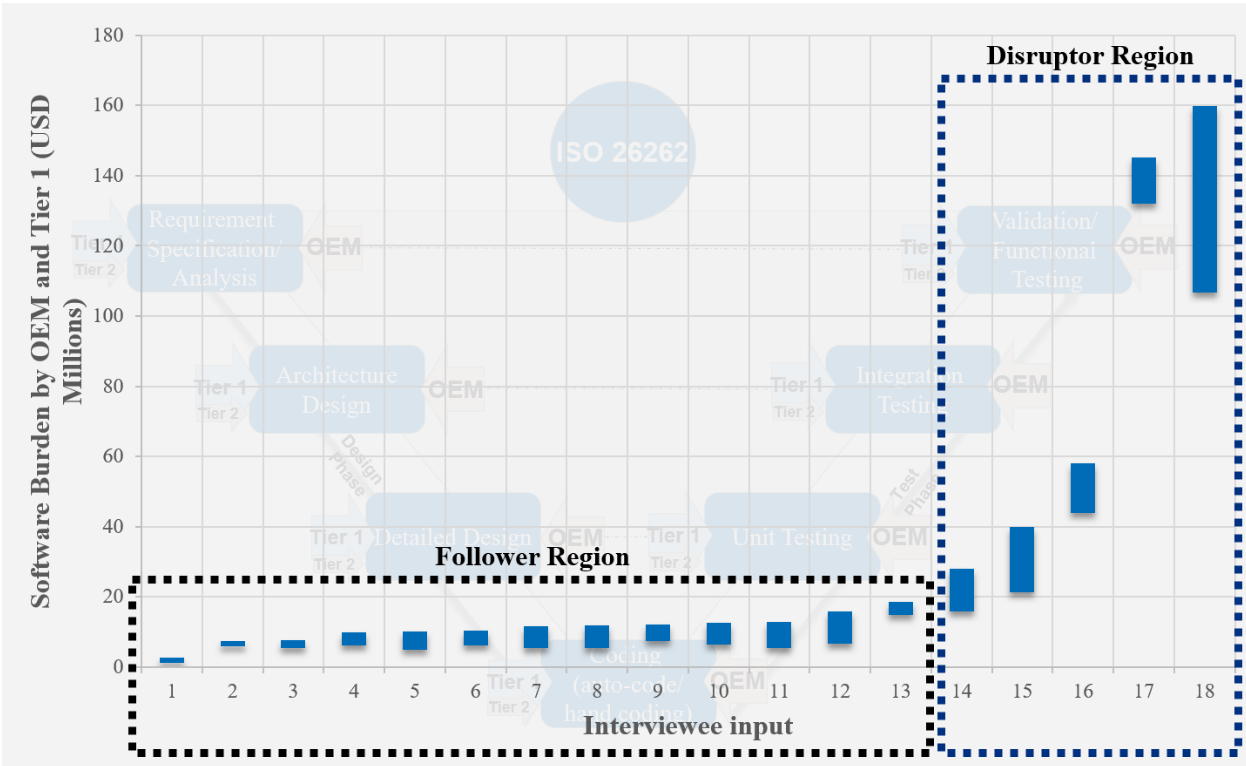


Figure 23 Results of V-Model for ADAS (Ranges)

The disruptor ADAS which is an architecture highly differentiated, targeting to offer high levels and complex features and usually launched in high-end products. Example of disruptor ADAS could be considered Tesla Autopilot, Audi A8 or Cadillac Super Cruise. Example of Tesla Autopilot algorithm is presented and Annex C. Cadillac Super Cruise ADAS price to customer are included in Table 17.

	Luxury	**Premium Luxury**	**Sport**	**Premium Luxury Platinum**	**Sport Platinum**
Driver Assist and Technology Package (required for Super Cruise)	Not available	$3,650	$3,650	Included	Included
Super Cruise	Not available	$2,500	$2,500	$2,500	$2,500

Total Cost	Not available	$6,150	$6,150	$2,500	2,500

Table 17 Cadillac Super Cruise feature cost in Escalade

On the other side of the technology efficient frontier is the follower ADAS, these architecture demands less resources and envision to perform acceptable in qualification test and capable to pass fore coming regulatory tests like ECE R152. The follower ADAS is an evolution from the previous vehicle revision consequently there are scenarios that programs will have the introduction of only one feature using existing ADAS systems. This approach reduces costs in both ends of the V-model (specification and validation). Representative distribution of overhead costs and timeline of a one-feature ADAS program is presented in Table 18. This load represented approximately $5.9 to $7.1M to OEM and Tier 1.

V-Model Step	Head Count equivalent Tier 1	Head Count equivalent OEM	Time (Months)
Requirement Specification/Analysis	4	1	6
Architecture Design	2	4	6
Detailed Design	10	1	12
Coding	5	1	6
Unit Testing	4	1	4 to 6
Integration Testing	4	1	3 to 4
Validation/Functional Testing	4 to 5	6 to 8	6 to 9

Table 18 Representative distribution of head count during the implementation of one feature in an existing ADAS[79]

As previously discussed and due to the nature of the perception part of ADAS pedestrian burden cannot be differentiated. Tier 2 suppliers such as Mobileye provide pedestrian detection in bundles of ADAS features. Once the signal enters the Tier 1/OEM software domain, this feature shares several software development overhead costs with other features and the integration with other sensors. RSC presents the software cost in two parts, the object detection burden (cost per vehicle for object detection) and the expense incurred by the OEM and Tier 1 to develop the system once signal is received from the camera. Table 19 illustrates results for the Follower ADAS and the Disruptor ADAS.

ADAS type	Object Detection Burden (includes SoC)	OEM/Tier 1 Burden
Follower	$45/vehicle	$6.2M to $11M
Disruptor	$45/vehicle	$97M to $147M

Table 19 ADAS software burden

4.3. Overall Total Costs

[79] Experts inputs

Follower ADAS. To estimate the overall cost of the ADAS including the Pedestrian detection the following assumptions were taken:

- Software cost is not included in EDD and fully amortized in the production program (1M units in a 5-year program)
- For object detection Mobileye ASP was considered, this price includes the SoC as well as the corresponding software
- Tier one Software burden OH costs (SG&A 15%, Profit 12%) and a dealer mark up 11%. Tier one OH was also added to Tier 2 prices
- OEM Software burden OH costs (SG&A 6%, Profit 4%) and a dealer mark up 11%
- It is assumed the integration of the Mobileye SoC into an existing vehicle system (not dedicated controller)
- Hardware system integration included in OEM SG&A

Item #	Description	Yearly Production volume assumption	Manufacturing Cost	SG&A	Profit	Wholesale Price Analysis	Transportation and Warranty	Wholesale price Ricardo analysis	Dealer costs &markup	End User Price Increase	Weight (g)
	Toyota PAEB system		**$ 174.02**			**$ 204.78**		**$ 213.81**		**$ 237.33**	
0	**System Integration Costs (software)**		**$ 53.66**			**$ 73.10**		**$ 73.10**		**$ 81.15**	
0.1	Tier 1 Burden	200,000	$ 7.11	15%	12%	$ 9.74		$ 9.74	11%	$ 10.81	
0.2	OEM Burden	200,000	$ 1.55	6%	4%	$ 1.72		$ 1.72	11%	$ 1.91	
0.3	Object detection Burden	200,000	$ 45.00	15%	12%	$ 61.64		$ 61.64	11%	$ 68.42	
1	**Camera**										
1.1	Camera & Radar	200,000	$ 120.36	6%	3.75%	$ 131.68	7.5%	$ 140.71	11%	$ 156.18	**883**

Figure 24 Overall Total Cost of Follower ADAS – Toyota Camry with Pedestrian detection

Item #	Description	Yearly Production volume assumption	Manufacturing Cost	SG&A	Profit	Wholesale Price Analysis	Transportation and Warranty	Wholesale price Ricardo analysis	Dealer costs &markup	End User Price Increase	Weight (g)
	Subaru PAEB system		**$ 213.52**			**$ 247.79**		**$ 259.78**		**$ 288.36**	
0	**System Integration Costs (software)**		**$ 53.66**			**$ 73.10**		**$ 73.10**		**$ 81.15**	
0.1	Tier 1 Burden	200,000	$ 7.11	15%	12%	$ 9.74		$ 9.74	11%	$ 10.81	
0.2	OEM Burden	200,000	$ 1.55	6%	4%	$ 1.72		$ 1.72	11%	$ 1.91	
0.3	Object detection Burden	200,000	$ 45.00	15%	12%	$ 61.64		$ 61.64	11%	$ 68.42	
1	**Camera**										
1.1	Stereo Camera & other	200,000	$ 159.86	6%	3.75%	$ 174.69	7.5%	$ 186.68	11%	$ 207.21	**2478**

Figure 25 Overall Total Cost of Follower ADAS – Subaru Outback with Pedestrian detection

Disruptor ADAS. To estimate the overall cost of the ADAS including the Pedestrian detection the following assumptions were taken:

- Software cost is not included in EDD and fully amortized in the production program (1M units in a 5-year program, 200k upa)
- For object detection Mobileye ASP was considered, this price includes the SoC as well as the corresponding software. It is assumed $25 for software as Audi A8 contains a Mobileye SoC and assumed $20 hardware price.
- Tier one Software burden OH costs (SG&A 15%, Profit 12%) and a dealer mark up 11%. Tier one OH was also added to Tier 2 prices
- OEM Software burden OH costs (SG&A 6%, Profit 4%) and a dealer mark up 11%
- Hardware system integration included in OEM SG&A

In real commercial scenarios and due to the nature of the vehicle (highly differentiated architecture) it is expected that the system software should be amortized only in a 20k units per year production. Additionally, hardware components can be commercialized outside this program[80], consequently a 200k upa for hardware is acceptable. When the system is calculated in this market assumptions the end user cost is $ 3,309.45 and aligns with the market price showed in Table 17 Cadillac Super Cruise feature cost in Escalade.

[80] Valeo Scala®, Valeo. Retrieved from https://www.valeo.com/en/valeo-scala/

Item #	Description	Yearly Production volume assumption	Manufacturing Cost	SG&A	Profit	Wholesale Price Analysis	Transportation and Warranty	Wholesale price Ricardo analysis	Dealer costs &markup	End User Price Increase	Weight (g)
	Audi A8 LIDAR-based AEB system		**$ 1,163.38**					**$ 1,645.58**		**$ 1,826.59**	
0	**System Integration Costs (software)**		**$ 137.56**			**$ 182.68**		**$ 182.68**		**$ 202.78**	
0.1	Tier 1 Burden	200,000	$ 90.31	15%	12%	$ 123.71		$ 123.71	11%	$ 137.32	
0.2	OEM Burden	200,000	$ 22.25	6%	4%	$ 24.73		$ 24.73	11%	$ 27.45	
0.3	Object detection Burden	200,000	$ 25.00	15%	12%	$ 34.25		$ 34.25	11%	$ 38.01	
1	**Laser scanner system**		**$ 158.96**			**$ 222.75**		**$ 255.11**		**$ 283.18**	**947**
1.1	Laser scanner module	200,000	$ 140.33	25%	12%	$ 222.75	7.5%	$ 233.27	11%	$ 258.93	
	Balance of laser system	200,000	$ 18.63	6%	3.75%		7.5%	$ 21.84	11%	$ 24.25	
2	**DAS Control unit system**		**$ 353.59**					**$ 510.41**		**$ 566.55**	**1308**
2.1	DAS control unit	200,000	$ 351.80	15%	12%	$ 481.92	7.5%	$ 508.31	11%	$ 564.22	
2.2	Bracket	200,000	$ 1.79	6%	3.75%		7.5%	$ 2.10	11%	$ 2.33	
3	**Camera, lane assist system**		**$ 34.56**					**$ 49.46**		**$ 54.90**	**132**
3.1	Camera, lane assist	200,000	$ 32.82	15%	12%	$ 44.96	7.5%	$ 47.42	11%	$ 52.64	
	Balance of camera system	200,000	$ 1.74	6%	3.75%		7.5%	$ 2.04	11%	$ 2.26	
4	**Radar, distance control**		**$ 41.11**					**$ 65.63**		**$ 72.84**	**324**
4.1	Radar, distance control (LRR)	200,000	$ 39.51	28%	7%	$ 60.78	7.5%	$ 63.75	11%	$ 70.76	
	Balance of LRR system	200,000	$ 1.60	6%	3.75%		7.5%	$ 1.88	11%	$ 2.08	
5	**Radar, object detection**		**$ 73.48**					**$ 106.01**		**$ 117.67**	**281**
5.1	Radar, object detection (SRR)	200,000	$ 72.90	14%	13%	$ 99.86	7.5%	$ 105.33	11%	$ 116.92	
	Balance of SRR system	200,000	$ 0.58	6%	3.75%		7.5%	$ 0.68	11%	$ 0.75	
6	**Night vision camera system**		**$ 334.83**					**$ 441.94**		**$ 490.55**	**887**
6.1	NV camera module	200,000	$ 323.59	12%	8%	$ 404.49	7.5%	$ 428.76	11%	$ 475.92	
	Balance of NV camera system	200,000	$ 11.24	6%	3.75%		7.5%	$ 13.18	11%	$ 14.63	
7	**Wiring harnesses**	200,000	**$ 29.29**	6%	3.75%		7.5%	**$ 34.34**	11%	**$ 38.12**	**1198**

Figure 26 Overall Total Cost of Disruptor ADAS with Pedestrian detection

APPENDIX A: ACRONYMS & ABBREVIATIONS

AAA	The American Automobile Association
ACC	Asset Center Costing
ADAS	Advanced Driver Assistance System
AEB	Automatic Emergency Braking
ABS	Anti-lock Braking System
AI	Artificial Intelligence
AUTOSAR	AUTomotive Open System ARchitecture
ASIL	Automotive Safety Integrity Level
ASP	Average Selling Price
AV	Autonomous Vehicles
BDCMS	Bicyclist detection and Collision Mitigation Systems
CIB	Crash Imminent Braking
CNN	Convolutional Neural Network
DAS	Driver Assistance Systems
DBS	Dynamic Brake Support
DDT	Dynamic Driving Tasks
ECE	United Nations Economic Commission for Europe
ECU	Electronic Control Unit
Euro NCAP	European New Car Assessment Programme
EU	European Union
GAAP	Generally Accepted Accounting Principles
GVWR	Gross Vehicle Weight Rating
GM	General Motors
GPS	Global Positioning System
HUD	Heads Up Display
IIHS	Insurance Institute for Highway Safety
Inc.	Incorporated
IP	Intellectual Property
IR	Infra-Red
ISO	International Organization for Standardization
LATCH	Lower Anchors and Tethers for Children
LiDAR	Light Distancing And Ranging
Mfg	Manufacture
Mfg'r	Manufacturing
mph	miles per hour
ML	Machine Learning
NA	North American
NAS	National Academy of Sciences
NHTSA	National Highway Traffic Safety Administration
No.	Number
OEM	Original Equipment Manufacturer
OH	Overhead
PCS	Pre-Collision System
PAEB	Pedestrian Automatic Emergency Braking systems
PDCMS	Pedestrian Detection and Collision Mitigation Systems
PTW	Powered two-wheeler
RADAR	Radio Detection and Ranging

REM	Road Experience Management
RFQ	Request For Quotation
RSC	Ricardo Strategic Consulting
SAE	Society of Automotive Engineers
SG&A	Selling, General & Administrative
SONAR	Sound Navigation and Ranging
SOR	Statement of Requirements
SOTIF	Safety Of The Intended Functionality
SPC	System Plus Consulting
upa	units per annum
US	United States
USA	United States of America
VRU	Vulnerable Road User

APPENDIX B: INTERVIEW PROFILE – TRNTY TOOL

Tittle: Software development manager – Advanced Driver Assistance Systems (ADAS)

Ricardo TRNTY has been created to meet the demands of today's rapidly transforming industries such as automotive, mobility, off-highway and transportation, energy and environment.

As an independent professional, your most treasured assets are the track record, skills and knowledge you bring to an organization.

We'll match your capability with the clients that need your expertise to overcome their challenges.

With TRNTY you could be working with global brands and innovative start-ups across a wide range of deployment methods, from hourly advisory through to projects lasting for a year or more.

You'll be in charge of the way you work, and you'll be enhancing your profile with every project you deliver.

We are looking to get insights into ADAS software development through a series of remunerated interviews or hourly advisory.

Qualifications

- We are seeking individuals with previous experience in leading software characterization, development, validation, and launch of vehicle level Advanced driver-assistance systems (ADAS).
- Relevant ADAS include but not limited to Pedestrian detection and automatic emergency braking, lane departure warning, and blind-spot detection.
- It is required experience in a passenger vehicle programs (As Tier 1 or OEM). Preferred previous positions: Principal Engineer, Technical Specialist, Subject Matter Expert, SCRUM master, or equivalent.
- Additionally, the successful candidate has participated in the development of ADAS requirements and is very familiar with current state of regulations such as UN regulations or Euro NCAP 2018

Keywords:
Must Have:
1. ADAS
2. AEB
3. Development
4. Validation
5. Engineer

Wanted:
1. Pedestrian AEB
2. PAEB

3. Active Safety
4. Cyclist AEB
5. Detection
6. Lane Departure
7. PedPro
8. Collision Mitigating
9. Collision Mitigation,
10. Safety System

Nice to Have:

1. Lead
2. Principal
3. Manager
4. Director

Some potential companies:

- Priority 1: Aptiv, Veoneer , Bosch, Continental, Denso, Magna, Mobis, Valeo, ZF, Autoliv, and Intel/Mobileye
- Priority 2: Denso, Lyft, Velodyne, Apple, Waymo, Intel, Lyft, NVIDIA, Qualcomm and Uber
- Priority 3: All OEMs

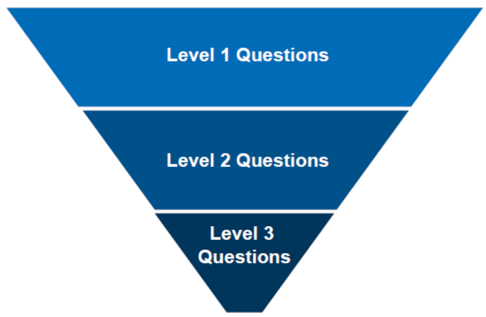
Clarifying questions:

- What considerations should we consider in developing an estimate for the software development cost for a vehicle ADAS system?
- What will be the primary development differences between level 2 and level 3 software programs?
- What is the split of the development work between the tiered supplier and the OEM?

APPENDIX C: INTERVIEW QUESTIONS

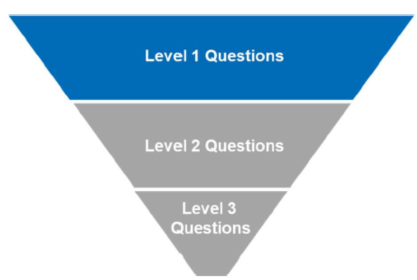
The interview process to determine software development costs for PAEB begins at the highest level and progressively drills down

- We will start with broad high-level questions regarding the software development process for ADAS features in general and PAEB in specific and move down as time permits



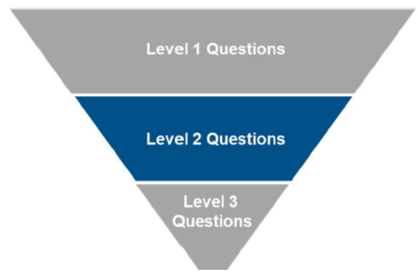
Interview questions for PAEB Software Development costing

- Can you please describe your software development process
  - What are the steps from blank sheet to vehicle?
  - How is the organization structured to complete this?
    - What are the teams?
    - How are people assigned (task, program or both)?
    - Software release process
    - Tools used? Auto-coding vs hand-coding
    - Software version control – how many releases? (2-3 typically expected for a new vehicle program)



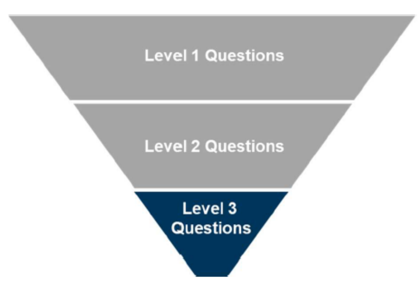
Interview questions for PAEB Software Development costing

- How integrated are ADAS and autonomous development activities?
- How does advancement in detection for PAEB impact software development time and cost?
- Has AI and ML changed the way you develop code for pedestrian detection and object tracking or is that in the future?
- Is software development required specifically for PAEB alone?
- Are individual ADAS features being developed in unison or separately?
- How does the development of PAEB interact with ACC? Other ADAS features?
- Is night vision a necessary component to enable PAEB for your product?



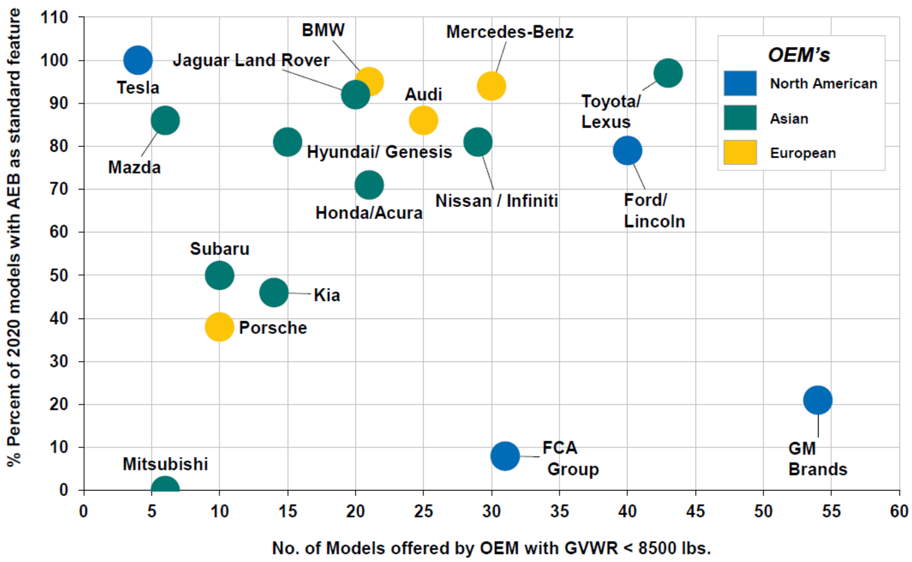
Interview questions for PAEB Software Development costing

- If you were to create a software development team how many people and how long would need:
  - For ADAS as a whole
  - For PAEB and by feature; e.g. AEB, BSD, RCTA, LKA, ACC, etc.
  - Software development
    - Sensor raw data processing
    - Sensor fusion
    - Object recognition
    - Objection classification
    - Decision making
    - Warning
    - Actuation
    - Functional Safety
    - Fault detection
    - Error checking
  - Validating code
- How many people/how long to calibrate?
  - By feature



APPENDIX D: SURVEY OF OEM SYSTEM OFFERINGS

Toyota, MB, BMW and Tesla have AEB fitted as a standard feature on all cars; GM, FCA and Mitsubishi fit on less than 30% of models



Sources: https://www.iihs.org/news/detail/four-automakers-meet-automatic-emergency-braking-commitments-ahead-of-2022-target, Wards Intelligence: '20 Model U.S. Car and Light Truck Specifications and Prices

Cadillac offers Front Pedestrian Braking as a standard feature with optional night vision system to detect and alert driver of pedestrians

2020 Cadillac CT6
Standard Feature

Pedestrian Detection

- System can detect pedestrians up to a distance of 40 m during daytime and limited visibility for vehicles equipped with night vision
- Night vision system helps driver see and alert the driver, Fig. 1, to pedestrians and large animals ahead of the vehicle, beyond the area lit by headlamps, Fig. 2

Automatic Emergency Braking (AEB)

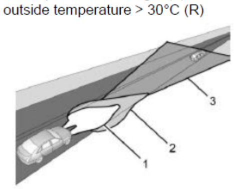
- Front Pedestrian Braking (FPB) system may automatically brake moderately or brake hard to avoid low speed pedestrian crashes or reduce pedestrian injury, system can automatically brake when pedestrians are detected between 5 mph to 50 mph
- Automatic braking will ***not*** occur if Pedestrians are detected by Night Vision system (presumably to limit false positive actuations)

Alert Type

- System provides amber and red flashing alert on the windshield or dashboard, Fig. 3, and rapidly beeps or pulses the driver seat

Feature	Sensor type	Operational Limits	Detection Range
Intelligent Brake Assist	Camera	All speeds	N/A
Front Pedestrian Braking	Camera	5 mph to 50 mph	40 m
Night Vision Pedestrian Detection	Infrared Camera	All speeds	25 m

Fig.1: Night vision dashboard display on detection of pedestrian at night (L) or when outside temperature > 30°C (R)



1. Low-Beam Headlamps
2. High-Beam Headlamps
3. Night Vision System

Fig.2 Headlight and Night Vision system ranges

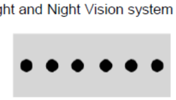


Fig.3 Warning on vehicles w/o Head-up display

Source: 2020 Cadillac CT6 Owner's manual
https://www.cadillac.com/content/dam/cadillac/na/us/english/index/downloads/vehiclebrochures/brochures/2019/19_CAD_CT6_CT6-V_50999.pdf.pdf

Ford F-150 offers a Pre-Collision Alert system which can detect and brake for pedestrians along with vehicles and other objects

2020 Ford F-150
Standard Feature

Pedestrian Detection

- Pre-Collision Assist System can detect pedestrians up to vehicle speed of 50 mph
- AEB System is available on all models as a standard feature

Automatic Emergency Braking (AEB)

- System is designed to provide brake support by applying additional braking force (DBS)
- Active braking is activated if the system detects an imminent collision (CIB)

Alert Type

- The Pre Collision Assist system provides a flashing visual warning and audible tone alert

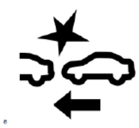


Fig. 1 Display on dashboard on detection of vehicle, object or pedestrian

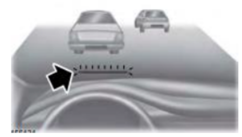


Fig.2 Head-up display warning on detection of vehicle, object or pedestrian

Feature	Sensor type	Operational Limits
Pre Collision Assist	Camera	3 mph to 75 mph
Pedestrian Detection	Camera	3 mph to 50 mph
Pre Collision Assist*	Camera and Radar	All speed range

Notes: * If equipped with Adaptive cruise control
Source: 2020 Ford F-150 Owner's manual

Volvo City Safe claims to be the most advanced system for pedestrian safety

2020 Volvo S90
Standard Feature

Pedestrian Detection

- City Safety system detection is most accurate when it receives clearest contour information on cyclist and pedestrians (i.e. head, arm, shoulders, torso and lower body) in combination with human body movements, Fig. 1, and taller than 32 in.
- City Safety can detect pedestrians in dark conditions as long as they are illuminated with vehicle headlights*
- Volvo pedestrian safety uses a highly sensitive camera combined with advanced exposure control to detect pedestrians in the dark in place of an IR camera as used by other OEMs

Automatic Emergency Braking (AEB)

- System can avoid a collision with a vehicle, cyclist, pedestrians and large animals by reducing the vehicles speeds using the automatic braking function. It can reduce the vehicle speed by 28 mph to prevent a collision

Alert Type

- Front Collision Mitigation and Pedestrian warning provides a flashing visual warning on the dashboard and audible tone alert, Fig. 2

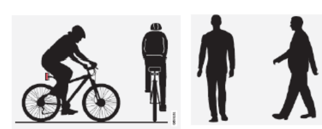


Fig. 1: Examples of clear body contours which City Safety system considers to be cyclist or pedestrian

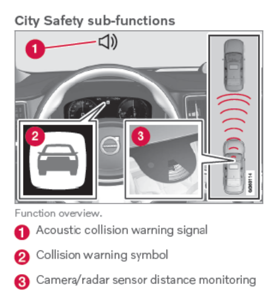


Fig. 2: City Safety system functions

Feature	Sensor type	Operational Limits	Detection Range
City Safe - Cyclists	Camera and Radar	3 mph to 50 mph	< 30 mph
City Safe - Pedestrians	Camera and Radar	3 mph to 50 mph	> 32 in.
City Safe - Large Animals	Camera and Radar	> 3 mph	> 43 mph

Notes: * 2020 Volvo S90 Owners Manual pg. 305 & 308
Sources: https://www.media.volvocars.com/global/en-gb/media/videos/49638/pedestrian-detection-in-darkness

Second generation Subaru EyeSight system offers pedestrian detection and PAEB using color stereo camera sensors

2020 Subaru Outback
Standard Feature

Pedestrian Detection

- EyeSight system can detect pedestrians from their size, shape and movement using color stereo cameras
- It is most accurate when a clear contour of head and shoulders is available
- System is unable to detect pedestrians:
  - Using an umbrella, Lack of contrast to background
  - Suddenly crosses in front of the vehicle
  - Bent over or shorter than 1m and taller than 2m in height, Fig. 1

Automatic Emergency Braking (AEB)

- Pre-Collision braking system operates in 3 stages, see Fig. 2
  - 1st stage is warning only
  - 2nd stage automatically applies moderate braking pressure
  - 3rd stage automatically applies strong braking pressure

Alert Type

- The Pre Collision Assist system provides a flashing visual warning and audible alert

Feature	Sensor type	Operational Limits
Pre Collision Braking System	Stereo Camera	2 mph to 100 mph
Pre Collision Braking Assist System	Stereo Camera	7 mph to 100 mph

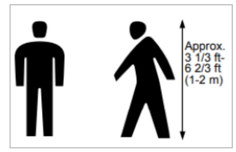


Fig 1: Pedestrians must be in the range of 1-2 m tall to be detectable

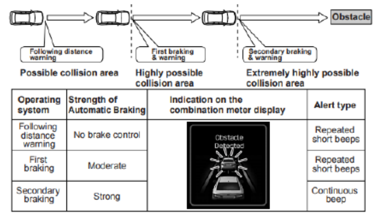


Fig.2 : Pre-collision braking system stages

Sources: 2020 Subaru Outlook owners manual, https://www.subaru.com/engineering/eyesight.html

Honda Accord Collision Mitigation Braking system (CMBS) specifies detailed scenarios for pedestrian detection and braking

2020 Honda Accord
Standard Feature

Pedestrian Detection

- CMBS uses a camera and radar sensor, Fig. 1, to detect pedestrians and objects in front of the vehicle
- CMBS specifies limitations for pedestrian detection:
  - Group of pedestrian walking together side by side
  - Bent over or carrying bulky luggage
  - Shorter than 1m and taller than 2m in height
  - Unusual shape due to holding luggage or body position

Automatic Emergency Braking (AEB)

- CMBS system operates in 3 stages, see Fig. 2
  - 1st stage is warning only
  - 2nd stage applies moderate braking pressure
  - 3rd stage applies strong braking pressure

Alert Type

- Honda CMBS system provides a flashing visual warning and audible alert, Fig. 3

Feature	Sensor type	Operational Limits
Collision Mitigation Braking System	Camera and Radar	3 mph to 62 mph vehicles, pedestrians
Collision Mitigation Braking System	Camera and Radar	> 62 mph - Vehicles travelling in same dir.
Collision Mitigation Braking System	Camera and Radar	Pedestrians between 3.3 ft and 6.6 ft tall

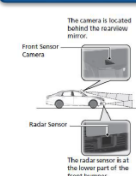


Fig.1 Sensor locations

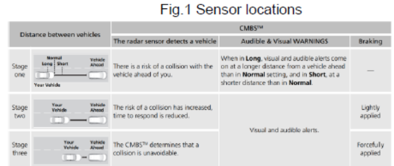


Fig.2 CMBS activation stages

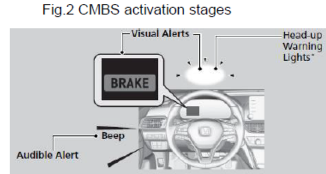


Fig. 3 Driver alerts

Source: 2020 Honda Accord owners manual pp 572,574

Descriptions of the Jeep Grand Cherokee Forward Collision Warning and Mitigation system do not mention pedestrian detection capability

2020 Jeep Grand Cherokee
Optional / Standard Feature

Pedestrian Detection

- Jeep/FCA does not explicitly mention pedestrian or object type or size detection capabilities, although the capability may exist under certain conditions

Automatic Emergency Braking (AEB)

- The system uses a camera and radar for forward object detection
- If a Forward Collision Warning with Mitigation event begins at a speed below 26 mph (42 km/h), the system may provide the maximum or partial braking to mitigate the potential forward collision

Alert Type

- FCW provides a flashing visual warning and audible tone alert, Fig. 1

Fig.1 FCW dashboard alert

Feature	Sensor type	Operational Limits
Forward Collision Warning with Mitigation	Camera and Radar	> 1 mph

Model Type	Front Collision Warning
Laredo	N/A
Laredo E	Optional
Upland	N/A
Altitude	N/A
Limited	Optional
Limited X	Optional
Overland	Optional
High Altitude	Standard
Summit	Standard

Table 1 Varying levels of offering across models

Sources: 2020 Jeep Grand Cherokee owner's manual, www.jeep.com

Mercedes Benz's advanced Night View Assist system can direct the headlamps and warn a pedestrian with 4 short flashes

2020 Mercedes Benz S-Class
Standard Feature

Pedestrian Detection

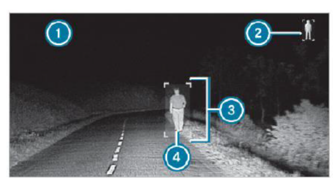
- The vehicle is equipped with two multifunction cameras and radar sensors to detect vehicles, objects and pedestrians
- The system uses an infrared camera to detect pedestrians at night
- A live video feed from the night vision camera is displayed on the multifunction display, Fig. 1

Automatic Emergency Braking (AEB)

- The Active Brake Assist system will help minimize the risk of collision, Based on the detected level of risk of collision and reaction of the driver the system is capable of initiating autonomous braking

Alert Type

- Active Brake Assist provides a flashing visual warning, Heads Up Display (HUD) and audible tone alert
- The spot light feature flashes the headlamps at the detected pedestrian with four short flashes



1. Night View Assist display
2. Standby symbol for active pedestrian detection
3. Highlighting
4. Pedestrian detected

Fig.1 Night View Assist Pedestrian and Object Detection display image

Feature	Sensor type	Operational Limits
Active Brake Assist with Driver assistance package	Camera and Radar	Stationary Pedestrian : < 43 mph Crossing Pedestrian : < 43 mph
Active Brake Assist w/o Driver assistance package	Camera and Radar	Stationary Pedestrian : No reaction Crossing Pedestrian : < 37 mph
Night View Assist – Pedestrian detection	Infrared Camera	Vehicle speed > 5 mph

Source:2020 Mercedes S class owner's manual

BMW's Front Collision Mitigation with City Braking system can detect pedestrians day and night in certain situations

RICARDO

Pedestrian Detection

- Front Collision Mitigation with City Braking system uses a camera and radar sensor to detect pedestrians and cyclists
- Detection zones, Fig. 1, define if collision is imminent and requires braking vs. issuing a warning of a potential pedestrian moving in the detection zone 1
- The system can not respond to pedestrians and cyclists when pedestrian body size is less than 32 in. and if a clear contour is not available
- The system is also equipped with Night Vision to detect pedestrians and animals during night time, Fig. 2 and Fig. 3
- Night vision system relies on heat radiation and temperature difference (i.e. IR camera) to detect pedestrians and animals in the dark

Automatic Emergency Braking (AEB)

- The system warns the driver with a warning prompt to intervene and may also assist in braking if there is a risk of collision

Alert Type

- An audio and flashing visual warning on the dashboard or Heads up Display

Feature	Sensor type	Operational Limits
Front Collision Mitigation	Camera and Radar	3 mph to 155 mph
Person Warning with City Braking Function	Camera and Radar	3 mph to 50 mph
Night Vision Pedestrian and Animal Detection	Infrared Camera	--

Source:2020 BMW 7 series owner's manual

2020 BMW 7 Series
Standard Feature

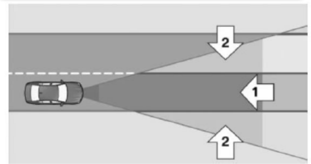


Fig.1 Collision is imminent if pedestrian is located in zone 1, warning will be issued if pedestrian is located in zone 2 and approaching zone 1

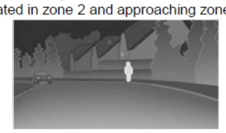


Fig.2 :Thermal image displaying pedestrian detection

Object Type	Detection Range
Pedestrian	100 m
Large animals	150 m
Small animals	70 m

Fig.3 :Night Vision System dashboard warning icons (L), detection range by object type (R)

Toyota Safety Sense™ (TSS 2.0) with Pedestrian detection has enhanced low-light capabilities

RICARDO

Pedestrian Detection

- Using an in-vehicle camera and a radar sensor* that are designed to help detect a vehicle or a pedestrian in front of the vehicle
- A pedestrian may not be detected depending on the surrounding brightness and the motion, posture, and angle of the detected object, preventing the system from operating properly
- System is designed to detect bicycles in daytime situations, as well as vehicles and pedestrians in both daytime and low-light situations
  - Toyota advertises enhanced low-light capabilities to help detect pedestrians at night, Fig. 1, but does not describe the technology used

Automatic Emergency Braking (AEB)

- If driver notices the potential collision and apply the brakes, Pre-Collision System w/ Pedestrian Detection may apply additional force using Brake Assist. If driver doesn't brake in time, system may automatically apply the brakes to reduce speed, helping to minimize the likelihood of a frontal collision or reduce its severity

Alert Type

- If the system determines that a frontal collision is likely, it prompts action using audio and visual alerts, Fig. 3

Feature	Sensor type	Operational Limits
Pre-collision system with Pedestrian Detection	Camera and Radar	Pedestrian height between 1 to 2 m

2020 Toyota Camry
Standard Feature

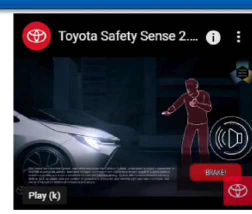


Fig.1 Enhanced low-light pedestrian detection capabilities

	Operation Speed Range (Alert)	Operation Speed Range (Automatic Braking)	Potential Speed Reduction (Automatic Braking)
Vehicle Detection	7-110 mph	7-110 mph	32 mph[10]
Pedestrian Detection	7-50 mph	7-50 mph	25 mph[11]
Bicycle Detection	7-50 mph	7-50 mph	25 mph[11]

Fig. 2 Speed ranges for Pre-collision system

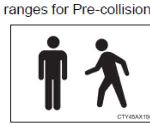
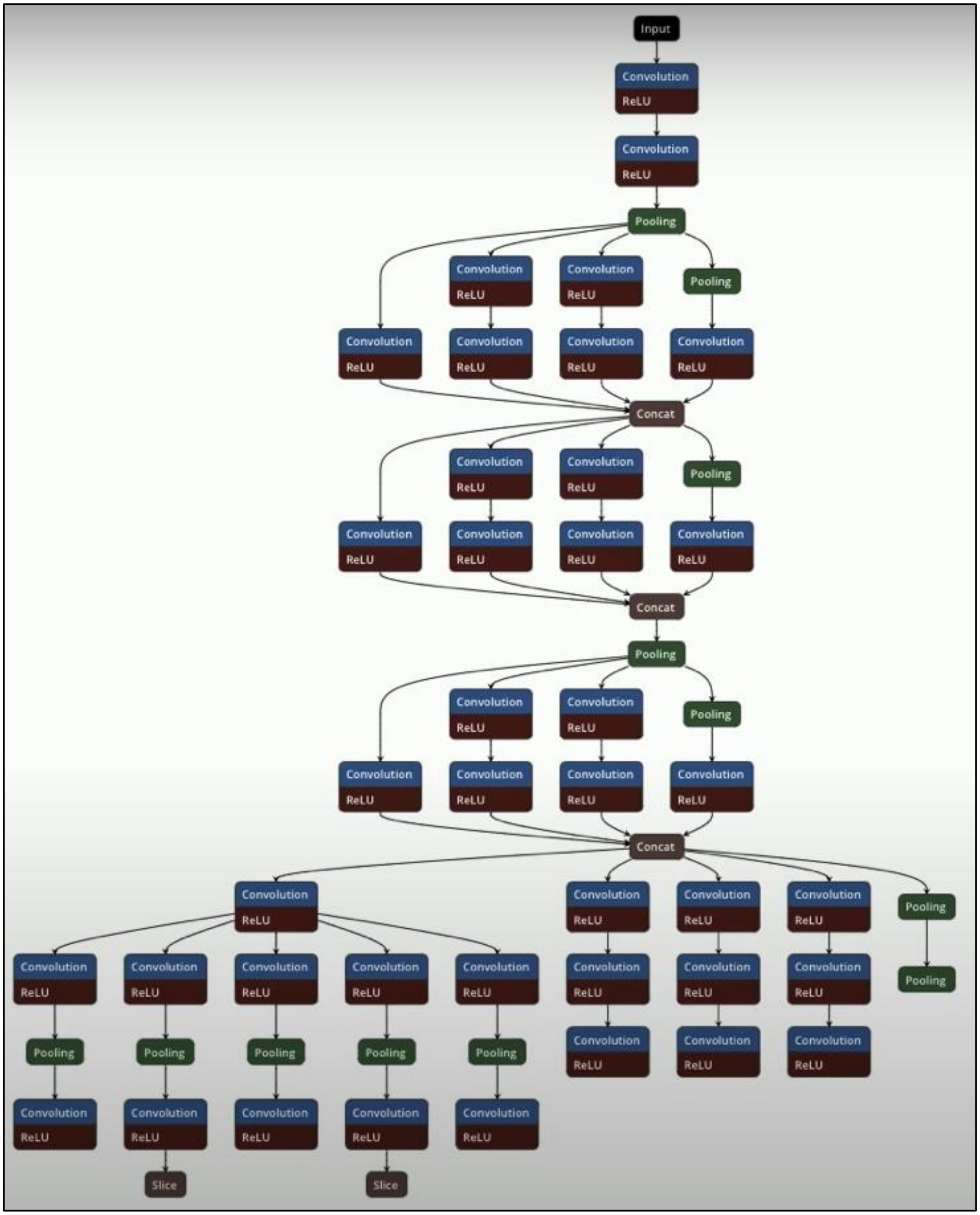


Fig. 3 Pedestrian detection warning symbol

Note: * Toyota Safety Sense brochure says *or a laser* sensor, however Ricardo has not found any substantiating evidence to indicate laser fitment on Toyota vehicles
Sources:2020 Toyota Camry Owner's manual, https://www.toyota.com/content/ebrochure/CFA_TSS_2.pdf, https://www.toyota.com/safety-sense/animation/pcspd

APPENDIX E: TESLA CNN AUTOPILOT SYSTEM[81]



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[81] Tesla Autonomy Day 2019 - Full Self-Driving Autopilot - Complete Investor Conference Event, Tesla Motors. Retrieved from https://www.youtube.com/watch?v=-b041NXGPZ8&t=2649s