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Sensors for Active Safety and Driving Automation Systems: Technology Review

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Authors:
Taufiq Rahman, PhD
Research Council Officer

Ryan Myers, B.Eng.
Research Council Officer

Automotive & Surface Transportation
National Research Council Canada

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Table of contents

List of tables

List of figures

List of Abbreviations

Abbreviation	Definition
ADAS	Advanced Driving Assistance Systems
ADS	Automated Driving System
AMCW	Amplitude Modulated Continuous Wave
ASIL	Automotive Safety Integrity Level
CAGR	Compound annual growth rate
CCD	Charged Coupled Device
CMOS	Complementary Metal Oxide Semiconductor
CW	Continuous Wave
DB	Decibels
DDT	Dynamic Driving Tasks
DGNSS	Differential Global Navigation Satellite System
DOF	Degrees of Freedom
EGNOS	European Geostationary Navigation Overlay
FMCW	Frequency Modulated Continuous Wave
FOG	Fiber Optic Gyroscope
FOV	Field of View
FPGA	Field Programmable Gate Array
FSK	Frequency Shift Keyring
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
L1	Level 1 Automation
LiDAR	Light Detection and Ranging
LKS	Lane Keep Assist Systems

Abbreviation	Definition
LRR	Long Range Radar
MEMS	Micro Electro Mechanical System
OPA	Optical Phase Array
PPP	Precise Point Positioning
RF	Radio Frequency
RLG	Ring Laser Gyroscope
ROI	Region of Interest
RTK	Real Time Kinematic
SAE	Society of Automotive Engineers
SBAS	Satellite Based Augmentation System
SLAM	Simultaneous Localization and Mapping
SRR	Short Range Radar
SWAP-C	Size, Weight, and Power - Cost
TOF	Time of Flight
TPU	Tensor Processing Unit
TTFF	Time To First Fix

Executive Summary

Reliable and robust characterization of the driving environment is a prerequisite of developing performant driving automation and active safety systems. Characterization of the environment includes identification and classification of features in the driving environment (i.e., object recognition), and their corresponding relative locations from the vehicle (i.e., ranging). Sensors such as LiDAR, camera, radar, IMU, GNSS, and ultrasonic sensors are deployed on production and development vehicles to acquire perception data to this end. It should be noted that the terms “sensing” and “perception” offer two different yet related connotations in the related literature. While sensing refers to measurement of physical signals (e.g., light, sound, forces, radio waves, etc.) representing some state of the environment, perception tasks utilize these acquired data to make meaningful inference about those states. For example, a camera *senses* the environment by acquiring an image of the environment, but *perception* is obtained by applying appropriate image processing techniques to identify and classify the various elements present in the scene. In addition to robust and reliable performance irrespective of weather condition, feature richness of the sensor data to enable meaningful perception is also an important factor for driving automation sensors. Since sensor data feeds perception algorithms, accurate representation and noise resilience can be considered as prerequisites of robust perception. The widespread integration of sensors into vehicular systems is a more recent development with many industrial players now making significant investments in innovative new products to enter this highly competitive market.

Each perception sensors employed in active safety and driving automation systems offer certain advantages and limitations. In some cases these limitations are borne by technologies in an early state of development that are unable to realize the full sensing/perception potential. In other cases the principles of physics do not allow for further performance improvement, and a paradigm shift in the sensing technique is required. In addition, the advantages offered by each sensor can be attributed to their distinct sensing modalities suitable for different weather conditions, and to the advancement of the corresponding perception algorithms that transform raw sensor data into useful information. These aspects of the sensors studied in this technical review are described in greater detail throughout.

The research team concluded that perception represents the largest barrier to realizing fully automated and reliable driving automation systems. This is because the task of driving becomes an exercise comprehensively defined by traffic regulation only when sufficient understanding/characterization of the driving environment is available. Furthermore, since the sensors studied provide functionalities that address performance gaps of other sensors, full autonomy can only be realized by employing sensor fusion techniques to achieve redundancy and weather resistant performance. For example, the sensing mechanisms of LiDAR and radar sensors are generally more conducive to ranging than other sensors. However, the sensing energy spectrum (infrared for LiDAR – 300 GHz to 430 THz, and radio waves for radar – 24 GHz to 77 GHz) are different, radar sensors are more resistant to weather conditions. Furthermore, camera sensors provide more feature-rich data to aid in identification and classification tasks.

Correspondingly, sensor fusion techniques are employed to take advantage of the strengths of each sensor so that the driving environment can be sufficiently characterized in variety of weather conditions. Cost and ease of mass production have been identified as two principal drivers that influence hardware and software sensing technologies innovation. The research team found that performance of the sensors in the current state of the art is limited by a number of factors. In particular, performance degradation as a function of weather and ageing are two important areas of study in this regard. Furthermore, it is important to note that physical attacks such as sensor spoofing and sensor jamming are points of vulnerabilities for future driving automation systems.

The research team also found that the current vehicular data networks (e.g., CAN-bus) will be unable to address the requirements of determinism, bandwidth, and low-latency operation associated with driving automation systems. The entire supply chain will need to adopt more advanced data networks such as BroadR-Reach standard as a solution; however, this transformation is still evolving, and it remains to be seen how the automotive supply chain will respond to these technology demands. Nonetheless, most academic research work relating to CAN-bus security focuses on intrusion detection employing a number of techniques including frequency domain analysis, neural network based anomaly detection, etc. It should be noted that intrusion detection is a reactive counter-measure. Since the actuators in late year production vehicles are being activated by CAN-bus messages, security flaws in vehicular data networks can result in safety-critical events.

1 Introduction

1.1 Driving Automation & Active Safety Systems

A driving environment is typically composed of dynamic and static elements/features. The static features such as traffic signs, road edges, and lane markings remain spatially fixed, while the dynamic elements such as other vehicular traffic, pedestrians, cyclists etc. are in motion to impose constantly evolving constraints on the *dynamic driving tasks* (DDT). Human drivers rely on their visual and auditory sensing systems to evaluate and understand the driving environment so that DDT can be performed in a safe manner. The principal function of *driving automation systems* is to assist in limited scope deployments and ultimately replace human drivers in full scale implementations to perform DDT so that objectives of improved safety, convenience, and resource utilization efficiency can be realized. Indeed, driving automation technologies are expected to increase safety for all road users due to their insusceptibility to human related errors, such as distraction, fatigue, and emotional driving, which currently are a contributing factor in approximately 94% of crashes according to a recent study completed by the National Highway Traffic Safety Administration (NHTSA) [1].

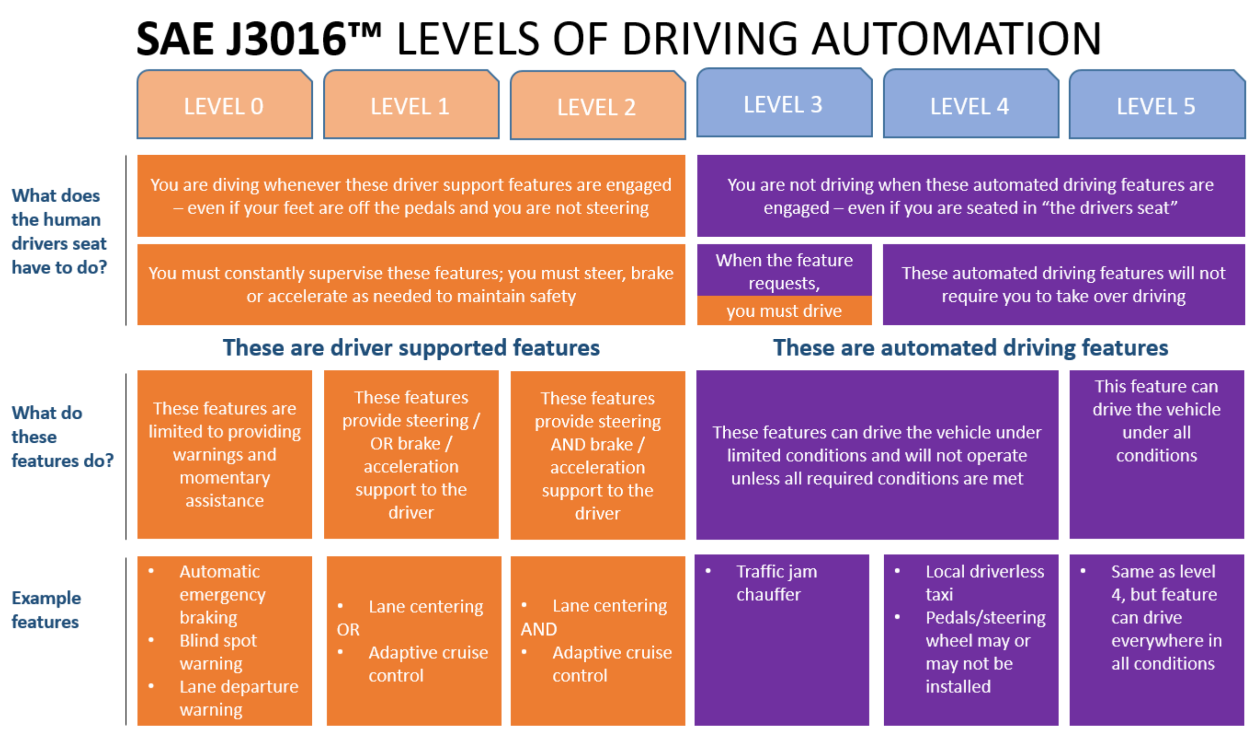


Figure 1: SAE Levels of Driving Automation.

Automation of DDT can be summarized on a wide spectrum where in one end driver assist systems exist to help human drivers but attentive driver supervision at all times is considered imperative, and in the other end exist fully automated vehicles where human participation/intervention is no longer required and the system is capable of performing all DDT functions to an extent as good as or better than human drivers. However, it should be noted that this expectation of performance being "as good" or "better than" human drivers is informal, and developing a performance standard is an ongoing discussion in the automated driving technology community involving government, academia, and industrial entities. Given the wide variance of the competencies and functions of these systems, a number of different terms referring to systems enabling some form of automated driving can be found in the literature. It is therefore necessary to establish an unambiguous nomenclature for the sake of consistency and academic rigor in this technical review. SAE J3016 standards [2] attempts to achieve this by making a clear distinction between *automated driving systems* (ADS) and the generic term "*driving automation systems*." Any L1-L5 system or feature that performs part or entirety of the DDT function on a sustained basis is regarded as *driving automation system*, whereas the term ADS is limited to refer to L3-L5 vehicles exclusively. A pictorial description of the SAE driving automation levels is provided in Figure 1. However, current production vehicles typically include L1 and L2 automation features, primarily due to the high cost of perception sensors [3].

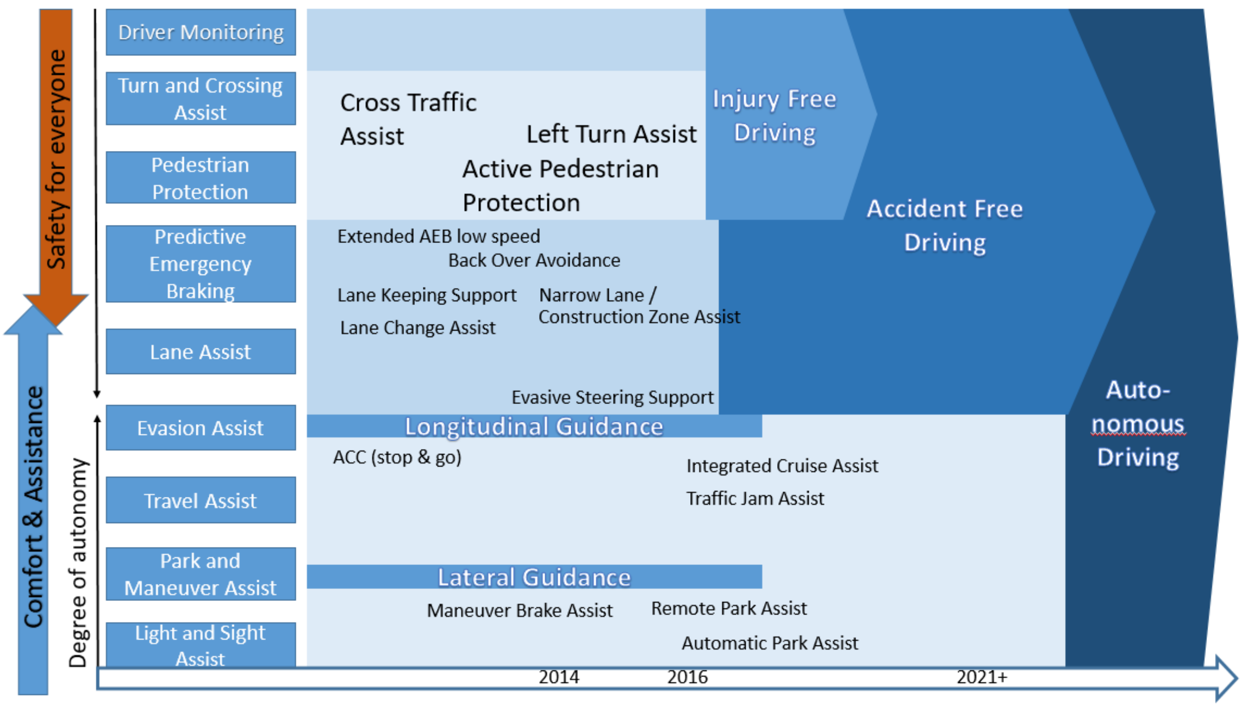


Figure 2: Roadmap for driver assistance functions [4].

Advanced driver assistance systems (ADAS) colloquially refer to those driving automation features that focus on improving human drivers' perception and awareness of the driving environment to primarily improve safety. Examples of ADAS features include adaptive cruise control, lane keep assist systems, collision imminent braking etc. (see Figure 2). A more informal comparison between ADAS and ADS features is provided in Figure 3.

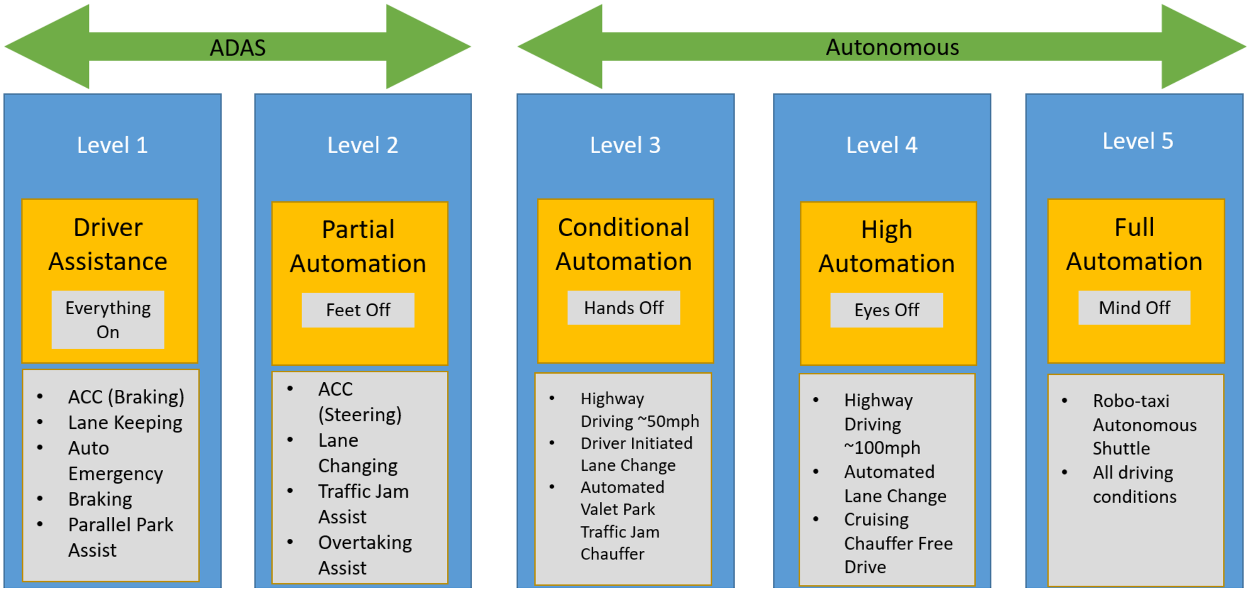


Figure 3: ADAS and Automated Driving Features in SAE Automation Levels provided in [5].

The advent of ADAS/ADS features can be attributed to the recent advancements made in mobile robotics and computational capacity of field deployable computers. Functionally, a driving automation system can be decomposed into a number of building blocks [6]. Sensing constitutes the interface where information relating to the environment is collected, and perception refers to the identification and ranging of all the relevant elements of the environment, which is typically implemented by filtering and analyzing the acquired sensor data. In addition, perception also enables localization which is the ability to determine the vehicle location with respect to mapping. Based on the detected and ranged environmental constraints (e.g., number of available lanes, behaviour and motion of other traffic, negotiating traffic signs etc.) and the localized position, the system can dynamically plan a path to follow (path planning), and can subsequently engage control actuators such as steering, braking, and acceleration to manipulate vehicle motion (control) to realize the mission objectives. Figure 4 illustrates this technology pipeline for ADS/ADAS systems.

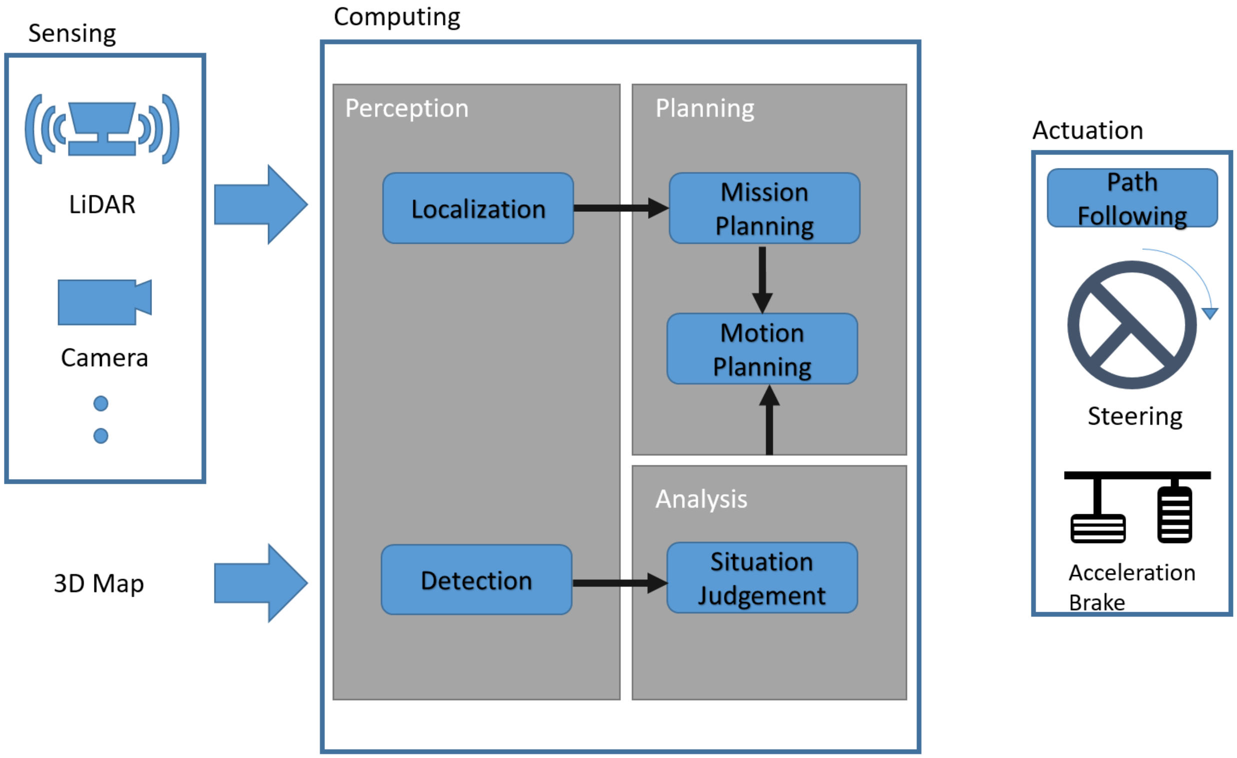


Figure 4: Functional system architecture of driving automation [7].

In mobile robotics literature such as [8], the terms "sensing" and "perception" convey different connotations: sensing refers to the measurement of some physical signal such as light, sound, vibration etc., and perception is the ability to make inferences about the surrounding environment from those sensed signals. In [9] Matri *et al* offer a relevant remark: "*The task of a perception system is to bridge the gap between sensors providing data and decision algorithms requiring information. A classical differentiation between both terms is the following: data is composed by raw, unorganized facts that need to be processed, while information is the name given to data that has been processed, organized, structured and presented in a proper context.*" Further to this argument, *Moravec's paradox* [10] appropriately points out that while sensing is comparatively simple, perception requires significant computing resources to be performed in a robust and reliable manner. Being cognizant of this distinction, this technical review focuses on sensing technologies employed in ADAS/ADS systems. It should be noted that, in addition to driving automation systems, the perception capabilities provided by these sensors enabled active safety systems in mass marketed vehicles. Active safety systems are defined in [2] as "*vehicle systems that sense and monitor conditions inside and outside the vehicle for the purpose of identifying perceived and potential dangers to the vehicle, occupants, and/or other road users, and automatically intervene to help avoid or mitigate potential collisions via various methods including alerts to the driver, vehicle system adjustments, and/or active control of the vehicle subsystems (brakes, throttle, suspension, etc.)*." The primary objective of active safety systems is to assist the driver to maintain positive control of the vehicle to avoid accidents under various road conditions and traffic patterns [11]. Assistance may be provided in a passive manner by alerting the driver (steering wheel vibration, auditory signal, or visual warning in the instrument cluster) about the imminent hazardous condition so that corrective actions can be taken. These systems may assume more active roles by providing momentary intervention such as emergency braking, actuated braking to maintain tractive contact with the road surface (anti-lock braking system - ABS), regulating power through transmission to realize electronic stability control, etc. to avoid a crash or, if that is not possible, to mitigate its impacts. SAE [2] distinguished active safety systems from driving automation systems because they do not perform DDT on a *sustained* basis. Nonetheless, whether it is driving automation systems or active safety systems, the ADS/ADAS sensors enable these important functions to potentially enhance safety for all road users.

1.2 Driving Automation Sensors

Sensors for automated driving and active safety systems may vary in terms of sensing modality, operating principle, performance, susceptibility to ever-changing weather and environmental conditions, cyber-vulnerability, etc. Therefore, a brief classification of the sensors can provide a strong foundation for a subsequent detailed discourse by distinguishing the basic differences. Similar to [8] sensors for ADS/ADAS and active safety systems can be categorized according to (a) whether the sensors acquire information internal or external to the vehicle, and (b) whether the operating principle requires emission of energy to facilitate sensing. Sensors that measure signals internal to the vehicle (e.g., wheel rotation, inertial forces acting on the vehicle) are categorized as *Proprioceptive* sensors, and *Exteroceptive* sensors acquire information from the driving environment. Furthermore, *active* sensors emit energy into the environment so that the corresponding response can be measured (e.g., LiDAR), and *passive* sensors measure energy ambient in the environment (e.g., camera). The aforementioned classifications are very important to understand issues relating to cyber vulnerability, performance, and reliability of the sensors. For example, *spoofing attacks* on proprioceptive sensors are generally difficult to perform because the signals they measure are internal to the vehicle, and consequently are more challenging to tamper with, while the passive sensors are typically more susceptible to weather induced performance degradation because they rely on ambient signals which might be too noisy in sub-optimal weather conditions.

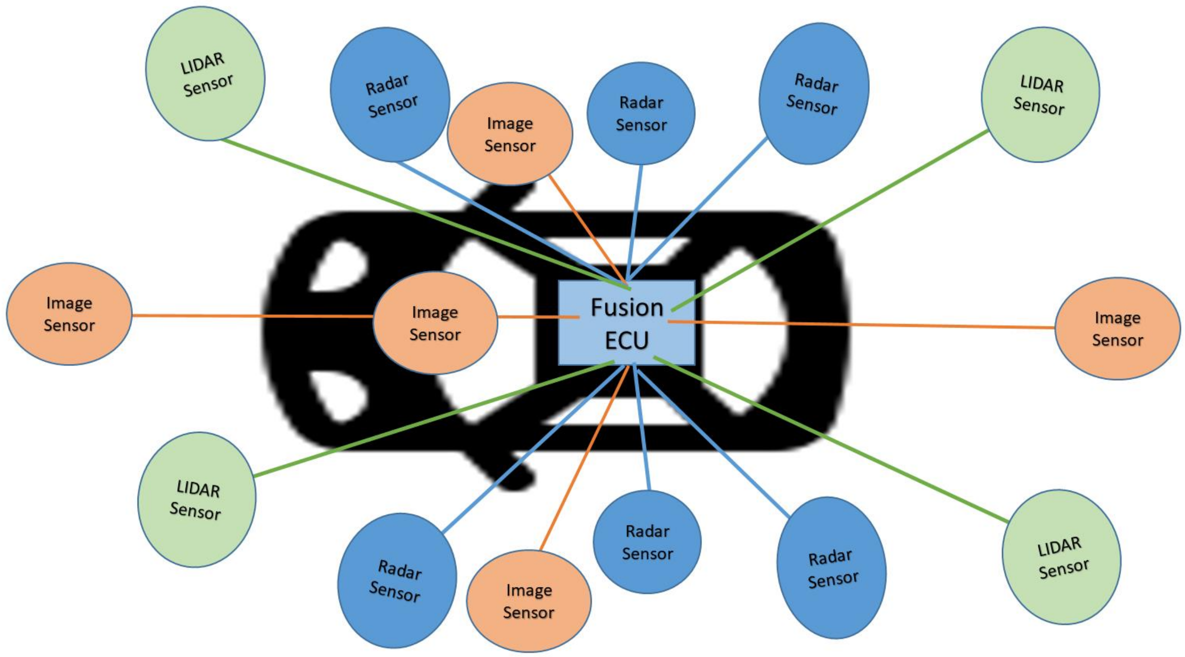


Figure 5: Use of different sensors in automated driving systems [12].

Although there are a number of sensors that are employed to realize ADS/ADAS functionalities, this report limits the discussion to LiDAR, radar, ultrasonic/acoustic sensors, stereo/mono cameras, inertial measurement units (IMU), and global navigation satellite system (GNSS) sensors for the sake of a relevant and concise report on sensing technologies prevalent in the industry (see Table 1). These sensors are categorized in Table 2. It should be noted that although global positioning system (GPS) is colloquially used to refer to GNSS systems, other systems including GLONASS (Russia), BeiDou (China) and Galileo (EU) offer the same general functionality. GPS, similar to the aforementioned systems, can be considered as one of the few implementations of the broader GNSS technologies.

Source: BCC Research, Advanced Driver Assistance Systems: Technologies and Global Markets, 2017.
*Calculated by National Science Library

Sensor	2016	2021	CAGR%	2021 % Share*
Radar	10,678.2	26,971.2	20.4	57%
Vision	3,813.6	10,349.4	22.1	22%
LiDAR	1,716.1	4,146.1	19.3	8.8%
Ultrasonic	1,525.4	4,089.4	21.8	8.6%
Infrared	1,334.7	1,688.2	4.8	3.6%
Total	19,068.0	47,244.3	19.9	100%

Table 1: Global ADAS market shares of different sensors.

Typical placements of LiDAR, radar, and image sensors on vehicle chassis are depicted in Figure 5. In addition, IMU sensors can be placed anywhere on the vehicle chassis with appropriate compensation for angular motions. In addition, GNSS sensors integrate an antenna to facilitate communication with the satellite constellations, and the location provided by GNSS sensors usually refer to the location of the antenna. Therefore, as long as unimpeded visibility to the satellite signals can be ensured, placement of the GNSS sensor is not too critical.

Sensor	Proprioceptive/ Exteroceptive	Active/ Passive	Energy domain
LiDAR	Exteroceptive	Active	Electromagnetic
Radar	Exteroceptive	Active	Electromagnetic
Ultrasonic/acoustic	Exteroceptive	Active	Mechanical
Stereo/mono camera	Exteroceptive	Passive/Active	Electromagnetic
IMU	Proprioceptive	Passive	Mechanical
GNSS	Exteroceptive	Passive	Electromagnetic

Table 2: Classification of major ADS/ADAS sensors.

It is noted despite having been categorized as proprioceptive in some literature [13], Siegwart and Nourbaksh in [8] points out that GNSS sensors rely on receiving satellite signals to obtain global position estimation, which renders their operating principle exteroceptive in nature.

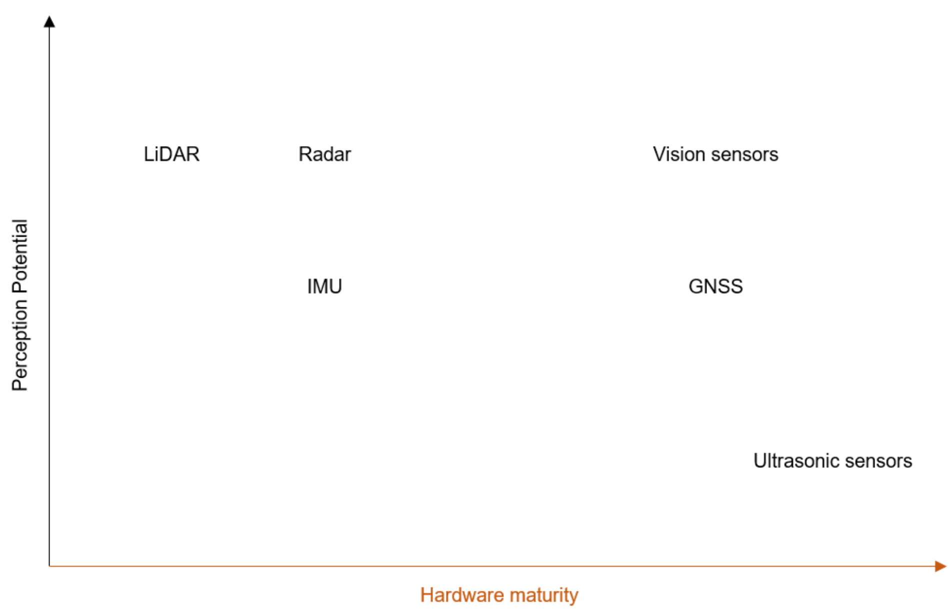


Figure 6: Potential vs hardware maturity of the current state-of-the-art of common perception sensors.

The sensors listed in Table 2 have been profiled in the following sections of this report. Since they are represented on a wide spectrum of hardware maturity and performance potential, their profiles reflect these characteristics of the current state-of-art. A subjective representation of perception potential vs hardware maturity is provided in Figure 6. Each sensor profile in this report correspondingly emphasizes these points in accordance these subjective aspects of the current state of the art. For example, topics related to LiDAR hardware have been described in greater detail than those involving ultrasonic sensors because LiDAR hardware is still evolving, whereas ultrasonic sensors hardware can be considered to have gained maturity to a point where the perception potential has been fully realized.

2 LiDAR

Sensing Characteristics	Active & Exteroceptive
Sensing Energy Domain	Light (principally in the infrared band)
Sensing Output	3D point cloud and velocity (only for continuous wave technologies)
Perception Potential	Low (identification & classification) High (ranging)
Prevalence in Future Automated Vehicles	High
Mass Market Deployment Challenges	High cost and complex scanning mechanisms
Vulnerability to Physical Attacks	Medium
Performance Degradation with Weather	Medium

Table 3: LiDAR sensor overview (assessments are subjective and intended as guidelines only).

LiDAR (Light Detection and Ranging) sensor provides high resolution ranging capabilities for driving automation systems. In its basic implementation, LiDAR in automotive applications can be regarded as an elaborate laser ranging technique that has been extended and ruggedized to acquire/image the surrounding environment at an acceptable sampling rate. LiDAR technology has come a long way since it was one of the first demonstrated applications in ranging tasks in 1960s, when MIT's Lincoln Laboratory measured the distance of the moon with only 12 return photons originating from a pulse laser of 50 joules energy [14]. One of the first mass marketed automotive applications of LiDAR technology include a pulsed time of flight (TOF) sensor with three beams developed by Continental Automotive Systems [15]. Today LiDARs provide unprecedented perception capabilities to mobile robots and driving automation systems. With some reservation, they are considered one of the major enablers of driving autonomy. A relevant market overview can be found in [16].

Warren in the invited paper [17] tabulated a set of *desired* performance requirements, as shown in Table 4. It should be noted that this table represents the author's idealistic view on the characteristics of sensors that can be deployed on production vehicles. Currently available systems are approaching these desired performance specifications, and are expected to realize them in the near future with continual development and advancement of support technologies. Nonetheless, even in current commercially available units LiDARs generally provide good ranging performance in terms of robustness, high resolution, and long range. Correspondingly, they are extremely prevalent in ADS systems as demonstrated through recent prototypes of driving autonomy. Examples include collaboration between Volvo and Luminar [18], Waymo's fully self-driving cars [19], etc. However, the current high cost and skepticism about the prospects of future cost-efficient designs have generated debate about whether LiDAR technology should be considered for production vehicles with driving automation features. As the technology matures towards a solid-state design featuring monolithic implementation enabling mass production at low-cost as described in [20], adoption of LiDARs in production vehicles is expected to rise.

Although LiDAR technologies have predominantly employed pulsed time-of-flight (TOF) based distance measurement, continuous wave technologies such as frequency modulated continuous wave (FMCW) and amplitude modulated continuous wave (AMCW) techniques are emerging. In TOF LiDARs a short pulse of photonic energy is dispatched from the emitter, and subsequently the time required to obtain an echo of this emission is recorded to determine range. In FMCW and AWCM LiDARs, instead of a short laser pulse, continuous emissions of light are dispatched, and the frequency/amplitude of the echoes received from the environment are continually checked against the transmitted signal to determine position and instantaneous velocity. Commercially available LiDAR technologies, therefore, can differ significantly in terms of implementation, sensing principle, cost, sensitivity to weather, etc. Correspondingly, a number of classification attempts can be found in the literature [17] [21], [22], and these different categories of LiDARs are described in the subsequent paragraphs.

Parameter	**Short Range**	**Long Range**
X, Y resolution	~1^{o}	0.1-0.15^{o}
Z (depth) resolution	a few cm	
Frame rate	> 25 Hz	
Range	20-30m	200-300m
Temperature range	AEC-Q100 grade 2 (-40-105C) or better	
Reliability	AEC-Q100	
Laser safety	IEC60825-1 Class 1	
Size	100-200 cm^3	
Cost	$50	$100-200

Table 4: Suggested automotive LiDAR performance specifications, obtained from [17].

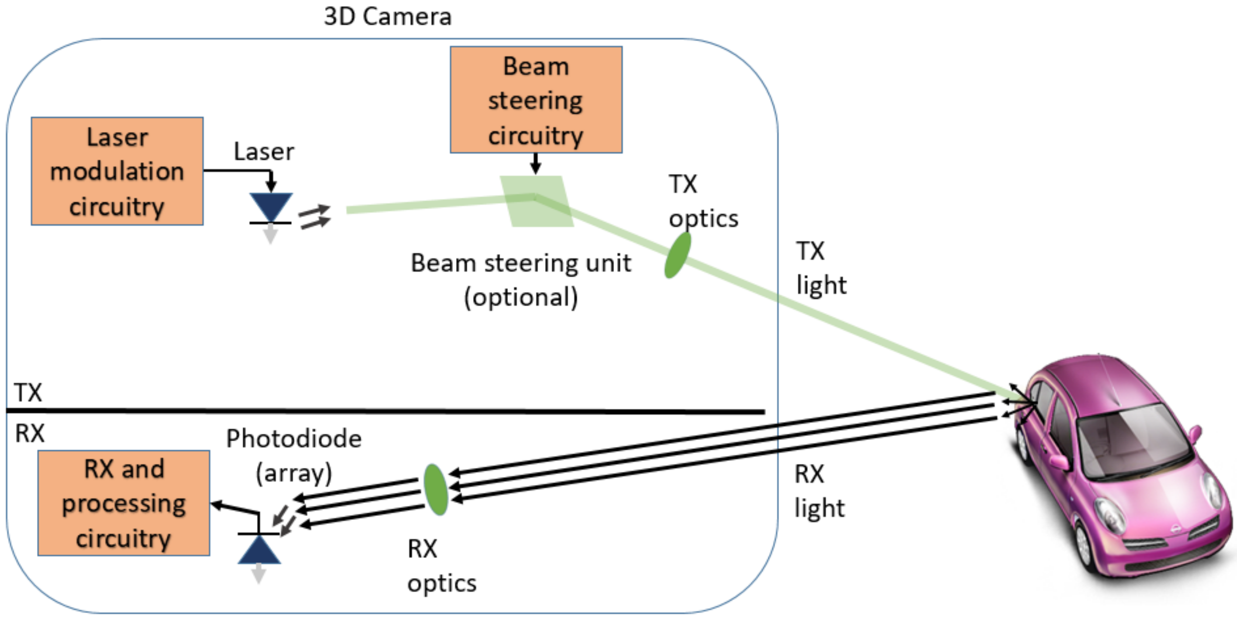


Figure 7: Basic architecture of automotive LiDAR, obtained from [23].

LiDARs are active systems that emit laser light into the environment to enable sensing. The 850 nm, 905 nm, and 1550 nm lasers are mostly reported in the current technology with each offering certain advantages and disadvantages. Since human eye is transparent to 850 nm and 905 nm emissions allowing the electromagnetic waves corresponding to these wavelengths to reach the back of the retina, the peak power of sensors employing the 850 nm and 905 nm lasers must be kept within eye safety range. On the other hand, 1550 nm lasers are opaque to human eye, and correspondingly they can operate at much higher power (i.e., potential to provide longer range detections) without causing any concern for eye safety. However, unlike the 850 nm and 905 nm lasers, photo detectors for the 1550 nm lasers cannot be constructed using ubiquitous silicon technologies. Instead, expensive gallium arsenide materials must be used [24], [25].

LiDAR technology in its fundamental form is capable of determining the distance of a single point. Additional subsystems are augmented to extend this sensing capability in horizontal and vertical directions. Beam forming techniques are employed to this end. In terms of beam forming techniques, LiDARs can be categorized into two classes; namely, scanning LiDARs and solid state LiDARs. Typically scanning LiDARs manipulate the optical path of multiple laser beams by employing high grade optics and a rotating mirror assembly to cover a wide FOV (often 360^o) in the horizontal direction and a significant portion of the vertical FOV. Solid state LiDARs create wide coverage without the aid of any mechanical means. Multiple implementations exist including microelectromechanical system (MEMS) LiDAR with cascaded MEMS beam manipulators, 2D detector array LiDAR (flash LiDAR), and optical phase array (OPA) LiDARs. Since the OPA technology allows *random access* scan patterns over the entire FOV [9], computing resources can be better utilized by analyzing data from the regions of interest (ROI) of the FOV, as opposed to having to filter the entire dataset to remove extraneous data points. Details of these implementations can be found in [17], [14], [23], [21], [22], [26].

In addition to emitting and beam forming technologies, LiDARs can further be categorized based on the technology employed to detect the reflected light. These technologies include avalanche photo diode (APD), single photon avalanche diode (SPAD), etc. [17], [21].

2.1 Function

LiDARs first appeared in production vehicles as an active safety system to detect an imminent crash [15]. In contrast, the major functions of LiDAR in ADS/ADAS systems include obstacle detection and 3D mapping [3], [27]. In addition to pulsed LiDARs providing 3D discrete positions of the sampled points in the FOV, they can measure the reflectivity of the corresponding surfaces based on the strength/intensity of the reflected signal. The output of such a pulsed LiDAR is provided in Figure 8. Besides the obvious function of spatial interpretation of the surrounding environment in the form of mapping and obstacle detection, the surface reflectivity measures are employed for lane marking detection in development vehicles; examples include [28], [29]. However, information regarding whether car manufacturers are planning to implement this functionality for production vehicles is scarce.

Unlike images acquired by camera, LiDAR data represent the surrounding environment in the form of a set of discrete points. As a result, color and texture information is lost, and it may seem that this loss negates the possibility of implementing object classification capabilities for LiDAR. Nonetheless, many efforts from academia are being reported where neural networks are being deployed to realize object classification from unstructured point cloud data [30]. Using neural networks for object identification and classification from 3D point cloud provided by LiDARs is an emerging perception technique.

2.2 Current State of the Art

The desired performance characteristics from short range and long range applications are somewhat competing for LiDARs. High angular resolutions in the vertical and the horizontal axes are absolute requirements for meaningful detection at range. For example, the reported angular resolution for one of the more advanced automotive LiDAR Velodyne VLS-128 is 0.11^{o} which translates to a 0.47 m gap at the reported range of 245 m ultimately resulting in sparse sampling. On the other hand, the relatively high angular resolution dramatically increases the number of sampled points for objects at short range, which adds to the computational load of perception algorithms, and renders achievement of real-time performance employing embedded computing platforms very difficult. As a solution the LiDAR manufacturer AEye and Lumotive are reported to be developing systems with the ability to produce random scan patterns so that sampling of points can be directed towards regions of interest only [31], [32], which adds to the perception reliability and computational efficiency.

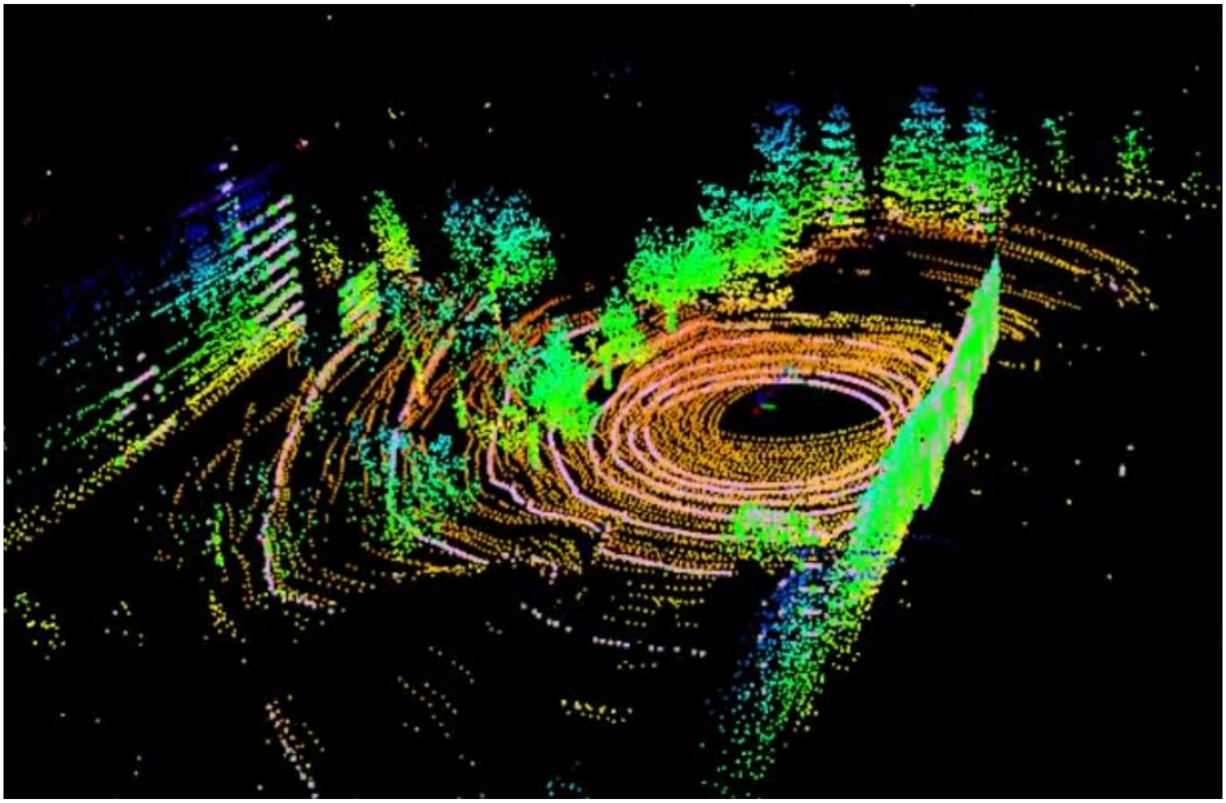


Figure 8: Point cloud data acquired by an automotive grade LiDAR. Inferred reflectivity values of the environment is represented by color.

Another limitation of LiDARs can result from photonic absorption of certain surfaces, which might render detection untenable. For example, since the black paint of cars absorbs most radiation with a non-Lambertian material (material that does not reflect light in a diffused fashion), scatter radiation does not travel back to LiDAR receivers, which can potentially make black cars appear invisible to LiDARs [9]. Other environmental phenomena such as rain, dust, and fog can also limit sensing capability of LiDARs. Studies described in [33], [34], [35] show that currently available commercial products are not immune to bad weather conditions, and they can be less performant than radars [9]. Nonetheless, multiple echo detection technologies are reported to be employed to improve performance in sub-optimal weather conditions [36].

Advantages	Limitations
• Native distance measurements • Native velocity measurements (continuous wave implementations only) • Large FOV with high spatial resolution • Multi-beam sensors enable 3D mapping • Potential for implementation of software techniques to improve weather resistance	• Computationally expensive because of extraneous points • Sparse sampling at longer ranges • Performance can degrade in bad weather • Not suitable for ultra-short range (<2m) applications (especially TOF systems) [37] • Performance in bad weather is lacking

Table 5: Summary of advantages and limitations of performance of automotive LiDARs.

In long range applications, scanning units are favored over flash technologies. Because the scanning LiDAR can concentrate the entire power of the emitter at long range, potentially a strong reflected signal can be expected, even from long ranges. In comparison, the power from the emitter is distributed over the FOV in flash LiDARs. However, longer integration period can be employed in flash LiDARs to average the noise and retain a similar signal-to-noise (SNR) [23].

In contrast to pulsed TOF LiDARs, FMCW LiDARs rely on Doppler Effect (Doppler frequency shift between the transmit and the received signals) for sensing can also provide additional functionalities of instantaneous velocity measurement [38], which can add to the perception competencies of automotive LiDARs by providing computationally inexpensive evaluation of collision potential, activity recognition, and behavior prediction [9]. Furthermore, they are natively more resistant to environmental noise and interference from other sensors operating in the same electromagnetic bandwidth because modulation signatures in the reflected wave allow reliable filtering of extraneous signal. In order to summarize the above discussion, the advantages and limitations of automotive LiDARs is summarized in Table 5.

2.3 Notable Industrial Players

With each design offering certain strengths, it is difficult to perform a consistent performance benchmarking. Nonetheless, tabular comparisons of performance characteristics of commercially available LiDARs can be found in [21], [39]. The references cited in this report were consulted to identify key LiDAR manufacturers in Table 6. In terms of market share, despite lack of reliable sources, it can be said that Velodyne, Ouster, and Luminar are the leading LiDAR firms that have demonstrated strong market presence and mass deployment potential through OEM/supply chain partnerships. Nonetheless, Velodyne is recognized as the market leader [40]. In terms of Canadian presence in the global market, Leddertech can be regarded as the market leader from Canada. Notable among commercially available units is the Velodyne VLS-128 sensor, and with respect to the competition "*other types cannot even deliver comparable performance*" [21]. In addition, the Valeo Scala sensor is reportedly one of the first LiDARs to be deployed in production L3-capable vehicles (Audi A8) [41].

LiDAR Firm	Technology	Deployment Partner(s)	Location/URL
Velodyne	Mainly mechanical scanning TOF	Ford, Daimler, Baidu, Volkswagen, Volvo, Veoneer	CA, USA https://velodynelidar.com/
Ouster	Spinning TOF	nVIDIA, May Mobility	CA, USA https://ouster.com/
Luminar	MEMS, 1550 nm	Toyota, Volvo	CA, USA https://www.luminartech.com/
Innoviz	MEMS, 905 nm	BMW, Aptiv, Magna	Israel https://innoviz.tech/
Strobe	MEMS,1550 nm, FMCW [42]	GM	CA, USA
Quanergy	OPA, 905 nm	Jaguar, Hyundai, Nissan, Aptiv, Mercedes-Benz	CA, USA https://quanergy.com/
AEye	Solid state random access scanning and fusion with camera	Infineon, Tata Elxi	CA, USA https://www.aeye.ai/
Valeo	MEMS, 905 nm	Audi	France https://www.valeo.com/
Leddartech	MEMS, Flash	Aptiv, Valeo	QC, Canada https://leddartech.com/
Phantom Intelligence	MEMS, Flash	(information unavailable)	QC, Canada https://phantomintelligence.com

Table 6: Notable LiDAR firms building driving automation systems.

2.4 Deployment Configuration

Early adopters of automotive LiDAR technologies have typically been teams that aim to construct *a priori* maps for automated driving. It is noted that *a priori* maps are accurate spatial representation of the static elements of the driving scene. They can significantly improve robustness and reliability by providing a ground truth to compare against the real-time perception provided by the sensors. These activities involve a survey vehicle equipped with a suite of laboratory quality and usually expensive sensors including survey grade LiDAR such as the Velodyne VLS-128. Since accurate map construction is the principal goal, much attention is given to dense point data collection, as opposed to being able to achieve real-time performance. Survey vehicles are usually equipped with a primary LiDAR that produces a dense point cloud of the surrounding environment. Typically this primary LiDAR is mounted on the roof of the vehicle, sometimes with some elevation to maximize the FOV. In addition, several complementary LiDARs can be mounted around the vehicle to produce 360^o surround view by filling-in blind spots in the primary LiDAR FOV and to achieve redundancy.

Waymo and Uber's prototype and pilot project vehicles feature a roof-top mounted LiDAR. However, further details on the sensor stack installed on these cars is scarce. Since automated vehicles (L3 and higher) are still a number of years away from being commercially offered, information relating to the LiDAR configurations on these vehicles is limited. However, unlike survey vehicles that map the entirety of the driving environment, driving automation systems in production vehicles need to primarily focus on the road ahead. Correspondingly, initially production vehicles with L3 and higher levels of automation are likely to equip a single LiDAR to perceive the road ahead only. Correspondingly, the Valeo Scala LiDAR is reported to be mounted inside the front grille of the Audi A8 (see Figure 9).

Figure 9: LiDAR deployment on Audi A8 [41].

2.5 Future Development Trends

High cost and a difficulty to produce at mass scale are the two main barriers that are keeping LiDARs from ubiquitous presence in production vehicles. However, it can be opined that they are more than likely to be adopted as the primary sensor for future commercial driving automation systems because of the reliable and robust sensing capabilities they can provide. Technology start-ups are being launched in this market segment to capitalize on this *potential* opportunity, and this space continues to grow with the introduction of new players. These companies aim to establish a strong foothold in the automotive supply chain by developing products that feature solid state designs in a compact form factor, robustness against weather conditions, eye safety even when operating at high power, low-cost, and resistance to ambient noise (e.g., interference created by other LiDARs operating at the same wavelength). All these requirements favor 1550 nm (eye safe at high power) in terms of emitting laser type, FMCW techniques for distance measurement (resistant to ambient noise and additional functionality of instantaneous velocity measurement), and OPA beam steering with CMOS detectors (solid state beam steering and potential of cost efficient chip-level implementation). In addition, random access scanning or ROI selective scanning as demonstrated by AEye constitutes another exciting development trend [43]. However, it remains to be seen how the LiDAR community will solve the existing shortcomings of their current products to reach the ultimate goal of low-cost, rugged, and mass producible sensors.

Besides the activities revolving around developing better LiDAR sensors, software centric approaches such as fusion of LiDAR data with vision sensors to extend perception capabilities [44], [45] is an active area of research in academia. Information available from driving automation system manufacturers usually focus on system performance and reliability, and because the underlying perception algorithms are considered proprietary intellectual property, these development trends involving perception algorithms including object classification and sensor fusion are not reported in literature available from industrial entities. Nonetheless, a section focusing on sensor fusion techniques is offered later in this technical review to highlight these trends.

3 Vision Sensors

Sensing Characteristics	Passive/active (implementation dependent) & Exteroceptive
Sensing Energy Domain	Light (principally in the visible band)
Sensing Output	2D scene representation in terms of light intensity and color
Perception Potential	High (identification & classification) Low (ranging)
Prevalence in Future Automated Vehicles	High
Mass Market Deployment Challenges	Computational complexity of perception algorithms and weather induced performance degradation
Vulnerability to Physical Attacks	High
Performance Degradation with Weather	High

Table 7: Vision sensor overview (assessments are subjective and intended as guidelines only).

Cameras constitute the principal sensing element for monocular and stereo vision sensors. A typical camera is composed of three major components (see Figure 10): (a) the optical system to acquire photons from the scene, (b) a 2D image sensor to measure light intensity and color, (c) the control electronics that regulate sampling, digitization, data buffering, and transmission. While monocular cameras provide 2D images of scenes in the form of color and light intensity information from one such system, stereo vision integrates two monocular cameras to realize ranging capabilities by employing triangulation to resolve range ambiguity (see Figure 11). Correspondingly, monocular and stereo vision systems can be regarded as two embodiments of the same *sensing* technology with the latter employing *perception* algorithms to realize depth sensing. Given this technical review primarily focuses on sensing technologies, monocular and stereo systems are encapsulated as a single sensor technology to facilitate discussion. The term “vision sensors/systems” is therefore adopted to refer to stereo and monocular systems hereinafter.

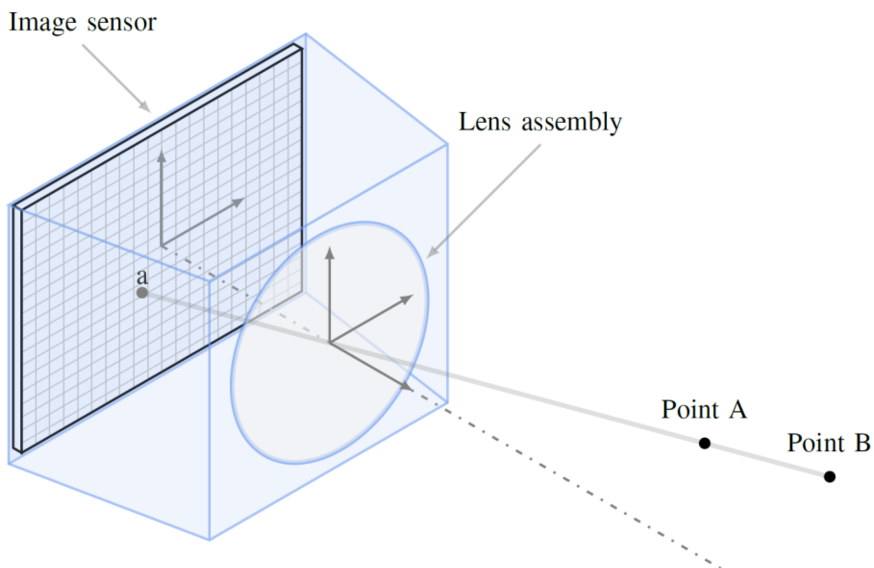


Figure 10: Components of a camera system (control electronics not shown) and the range ambiguity associated with monocular vision. Points A and B produce the same image point a, and recovering the ranges of points A and B through geometric means is not possible.

Vision sensors are generally passive systems because they rely on ambient photonic energy to produce images. However, some stereo systems illuminate the scene to implement depth sensing strategy. For example, Intel RealSense depth-cameras employ laser projectors [46] to assist in solving the problem of *stereo correspondence* or *stereo matching*, which is defined as the task of ascertaining what scene points in one of the stereo images correspond to what scene points in the other image. As demonstrated in Figure 11 the scene point A produces two different image points in the left and the right camera (a and b), and determining that these two image points indeed corresponds to the same world point is called stereo correspondence/stereo matching. This is a fundamental perception problem in computer vision, and finding solutions that deliver reliable performance in a computationally efficient manner still remains an active research topic [47].

It is important to note that understanding driving scenes from images is more computation intensive as the position and velocity of scene objects must be *inferred*. This is contrasting to LiDAR and radar sensors because their underlying sensing mechanisms enable them to provide position and velocity of scene objects natively (i.e., without the requirement of resource intensive computation). Admittedly, LiDAR and radar sensors still require some signal conditioning and mathematical interpretation of signal characteristics, but the computation load for vision-based perception is more extensive in comparison. The 2D images provided by vision sensors must be fed into perception algorithms such as stereo matching, optical flow analysis, and deep neural networks to realize objectives of ranging, classification, identification etc. However, some packaged vision systems are offered commercially that can provide high level scene perception. Although it may appear that these systems are providing these information as natively as LiDAR or radar sensors, embedded computation hardware integrated within their architectures enables abstraction of these perception tasks from the next elements of the technology pipeline such as path planning and decision making.

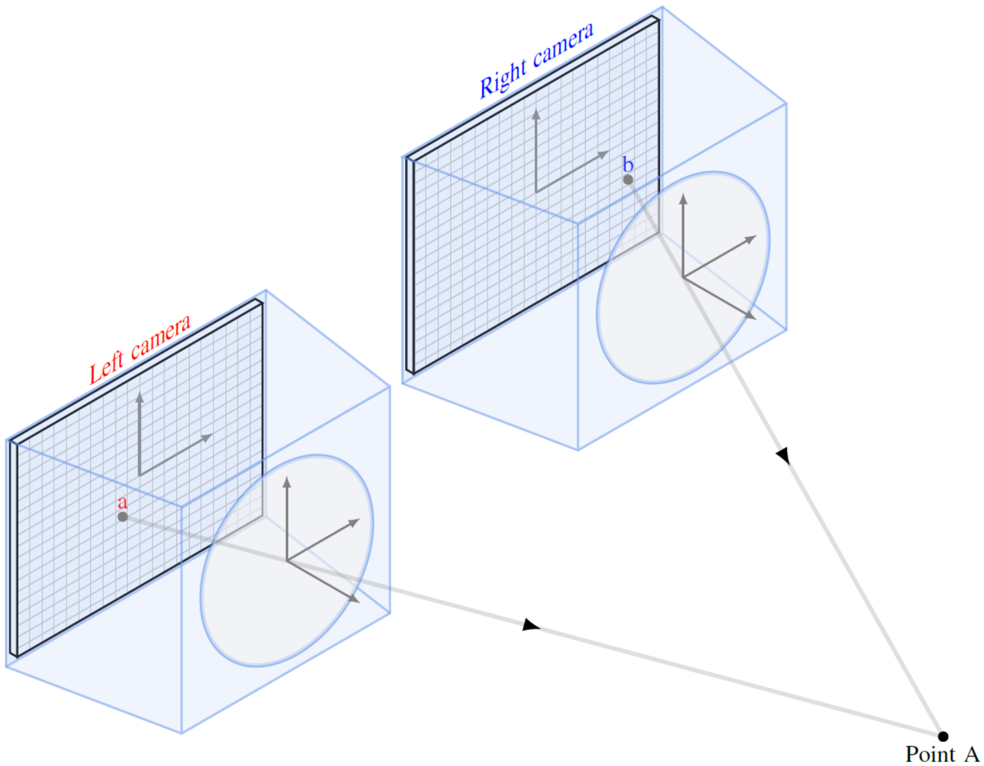


Figure 11: Recovering range (3D imaging) in a stereo system by triangulating the imaging vectors from two cameras. Scene point A produces the image point a in the left camera, and the image point b in the right camera (see above).

The optical system in vision sensors is composed of lens assembly, aperture, and shutter. The lens assembly acquires photonic information from the scene, and the incidence of these photons on the image sensor is controlled by the shutter and the aperture for exposure regulation (Figure 10). In modern automotive cameras the functions of the aperture and shutter are realized by electronic means on the image sensor to reduce system complexity by excluding moving components. Furthermore, the lens assembly typically has only fixed focal length to obtain a simple design free of moving parts required to actuate the lens system. The optical system of the camera primarily determines the FOV of the vision sensor. Major performance requirements for optical systems include low lens distortion, low chromatic aberration, and high optical efficiency. The lens assembly primarily determines the application of the vision sensor. For example, fish-eye lens are employed for a large FOV to enable surround view, wide angle lenses for short and medium range applications, and telephoto lens for long range but narrow FOV applications. The image sensor in a vision system is a rectangular array of photosensitive discretized elements or pixels (see Figure 10). The ambient photons acquired and regulated by the optical system create an analogous electric signal in each discretized pixel, which is sampled and characterized by the imaging processor (i.e., control electronics) to obtain the light intensity of each pixel. In order to detect color, automotive vision sensors employ Bayer filters (see Figure 12). There are two major types of image sensors: charged-couple device (CCD) and complementary metal oxide semiconductor (CMOS) sensors. With continual improvements CMOS sensors are being adopted widely in automotive applications due to attributes of low cost, low power, and relatively simple design requirements [48]. The control electronics interfaces with the image sensor to assemble each pixel information to obtain a full image of the scene by performing sequential tasks such as de-Bayering (the task of creating color information with respect to the Bayer filter structure), de-noising, and high dynamic range processing [49]. In general, performance expectation from vision systems includes low-light sensitivity, high dynamic range (HDR) operation, accurate color reproduction, high frame rates, functionality over a wide range of temperatures with minimal performance degradation, and resistance to artifacts from flickering light sources such as LED traffic signs and car taillights [50], [51]. In addition, spatial resolution of cameras employed in driving automation system ranges from 0.3 megapixel to 2 megapixel [52], [53]. In terms of frame rate 10-30 frames per second (fps) is considered sufficient for most applications [54].

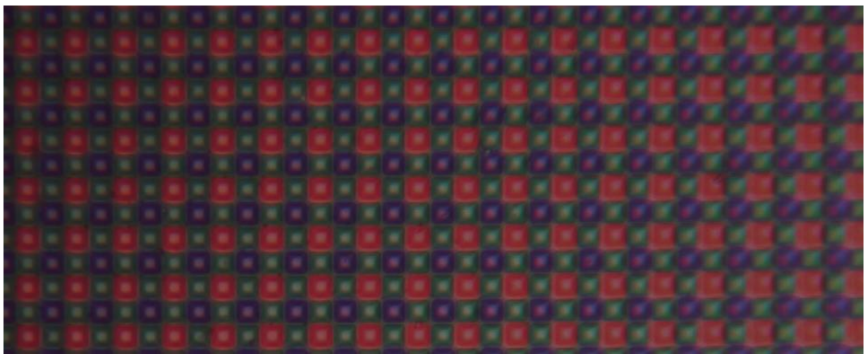


Figure 12: Bayer filter substrate covering the image sensor of a consumer grade camera to detect scene color. Each 4X4 grid comprised of two green, and one of each red and blue elements constitues a single pixel.

3.1 Function

Vision sensors in driving automation systems can be found both in monocular and stereo configurations. The principal functions they provide for ADS/ADAS and active safety systems include:

- Improving environmental awareness of driver: Even basic ADAS features in late year production vehicles are enabled with several cameras installed on the vehicle chassis. Cameras installed at the rear of the vehicle provides a presentation of the scene behind to the driver on an in-cabin video screen. The back-up camera has been one of the most popular standard ADAS features because it offers a safety against back-over crashes, and protects vulnerable road users such as children and senior citizens by providing enhanced visibility [55]. In addition, surround view cameras equipped with fisheye lens capture and present the surrounding environment on in-cabin video screens to improve driver awareness especially when the vehicle is being parked [56]. Side-view cameras provide improved visibility of the adjacent lanes when a lane change event is initiated.
- Object detection and classification: Learning methods (neural networks and support vector machines) are employed for driving scene understanding such as detection and classification of pedestrians, cyclists, other traffic, traffic signs, etc. [57], [58], [59].
- Lane detection and lane-level localization: One of the basic competencies that vehicles with L3 and higher automation levels must achieve is the ability to maintain vehicle position within driving lanes. Provided the accuracy of GNSS technologies is deficient in this regard,

vision sensors are being deployed for lane detection to enable lane-level localization for features pertaining to L3 and greater systems. Pertinent technical overviews can be found in [60], [61], [62].

- Mapping and localization: Vision sensors have been reported to be used in simultaneous localization and mapping (SLAM) applications for driving automation. Examples include [63], [64], [65].

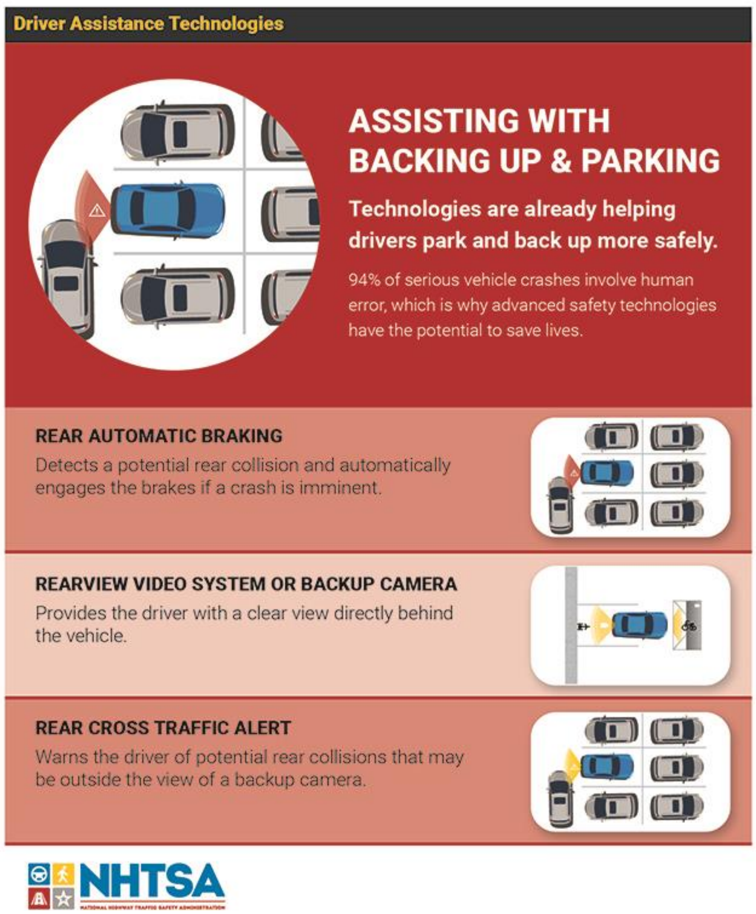


Figure 13: Some functions of vision sensors in production vehicles (source: NHSTA).

3.2 Current State of the Art

Because of the wide range of perception competencies vision sensors can provide in terms of contextual references such as colour and texture of roadway scenes, spatial reconstruction obtained from stereo depth sensing, and motion estimation through optical flow [66] at price points orders of magnitude lower than LiDARs, they are prominently represented in production vehicles featuring ADAS functionalities ranging from highly effective back-up cameras to lane-limited supervised automation functionalities as claimed by Tesla [67]. Besides production vehicles, full automation principally enabled by vision sensors has been demonstrated in [68], [69]. Their current sensing bandwidth as evidenced by these demonstrations point to their continuing strong presence in driving automation products. However, with the exception of Tesla, all major industrial players active in developing driving autonomy (see Table 6) are relying on LiDAR sensors to complement vision sensors because of two principal reasons. The first is the deficient robustness against snow, rain, dust, and low-light conditions in terms of sensing hardware [70], and the second is unavailability of deep neural network models for image-based recognition and classification over varying types of road scenes across jurisdictions and international borders.

The ubiquity of vision sensors integrated in consumer electronics such as smart devices and laptop computers have garnered an extensive amount of investment and R&D activities to advance camera technologies to a mature state. It is noteworthy that, at a hardware level, the image acquisition technologies in consumer electronics and automotive application are very similar with a few minor exceptions for application specific requirements (e.g., robustness against vibration in automotive applications). Further to the advancements already achieved in the hardware aspects, recent development activities involving vision sensors for driving automation focus on *vision perception* techniques to better utilize the acquired image data for robust driving scene characterization. Correspondingly, state-of-the-art development efforts are centered on producing more performant perception from image data provided by mature hardware. Regardless of how vision sensing is being deployed, Table 8 summarizes the advantages and limitations of the state-of-the art.

Advantages	Limitations
• Wide FOV with scene characterization in terms of color and texture • Cost-efficient with comparison to other perception sensors • Particularly suitable for object identification and classification • Spatial interpretation in terms of depth sensing	• Corresponding perception algorithms are computationally expensive • Position and velocity must be inferred contrasting to native availability from radar and LiDAR • Lack of high dynamic range (e.g., solar glare and drastic change in ambient photonic energy)

Table 8: Advantages and limitations of vision sensors.

3.3 Notable Industrial Players

The manufacturers of vision sensors can be represented by a wide spectrum. Traditional image sensor manufacturers that supply sensing hardware exists on one extreme. For example, Sony, Samsung, OnSemi, etc. are major manufactures of image sensors and corresponding control units [71], [72], [73]. On the other extreme exist companies that are developing packaged systems with perception algorithms embedded within. Such system and system components include hardware accelerators for real-time evaluation of vision perception algorithms (e.g., Intel Movidius vision processing unit – VPU [74], specialized FPGA technology for improving vision processing throughput from Xilinx [75]), and software/hardware platforms aiming to provide *actionable* perception data at system boundaries (e.g., Nvidia Drive Platform [76], Mobileye EyeQ technology [77]). Tesla claims they have already developed and deployed the hardware (vision and radar) required for full driving automation, and with subsequent software updates this goal will be fully realized in future [67]. In addition, the existing automotive supply chain started offering deployment ready vision sensor units; examples include Bosch [78], Denso [79], etc. Although many companies are active in automotive vision sensing in various capacities, information regarding their individual market share is scarce. Besides these industrial entities, there exists the open-source initiative **openpilot**, which is enabling limited driving automation using vision only [80]. Car owners, even with limited technical skill, can retrofit production cars with simple hardware and openly available software to enable driving automation. The information provided above is summarized in Table 9.

Industrial Player	Technology	Location/URL
Sony	Image sensor & processor	Tokyo, Japan
Samsung	Image sensor & processor	Seoul, South Kora
OnSemi	Image sensor & processor	Phoenix, Arizona, USA
Intel	Stereo camera, VPU, FPGA	California, USA
Xilinx	FPGA acceleration for vision	California, USA
Nvidia	GPU acceleration for vision	California, USA
Mobileye	Embedded VPU	Jerusalem, Israel
Bosch	Automotive stereo	Gerlingen, Germany
Denso	Automotive stereo	Kariya, Japan

Table 9: Notable industrial players active in vision sensing for driving automation systems.

3.4 Deployment Configurations

Production vehicles are realizing a number of ADAS features by integrating vision sensors. A pictorial overview of these features and the corresponding vision sensor configurations is provided in Figure 14. It is noted that vision sensors are more suitable for mid to long range applications because the perception pipeline cannot meet the stringent timing requirements for short range applications due to the associated high computational load. For automated vehicles (L3 and higher) vision sensing would be principally focused at the road ahead. Since production vehicles are already deploying forward facing camera behind the rear-view mirror (e.g., Audi A8, Tesla, etc.), this trend is expected to continue in future driving automation implementations.

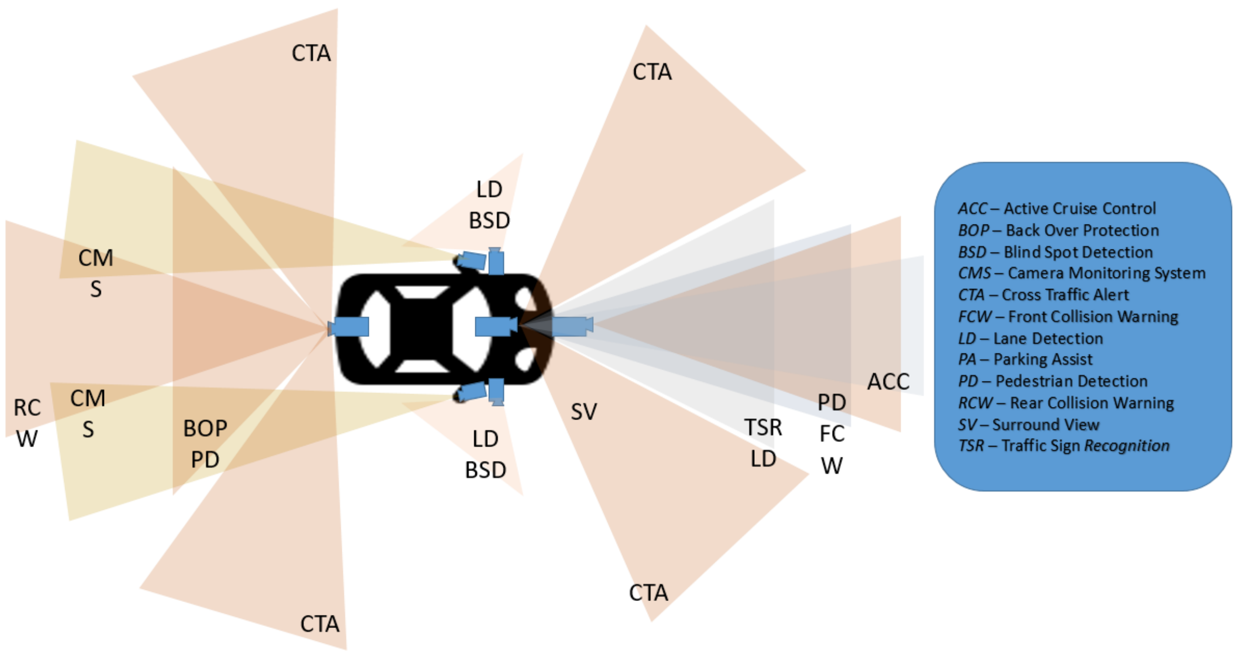


Figure 14: Camera based ADAS applications and their respective field of view, obtained from [49].

3.5 Future Development Trends

In addition to traditional image sensors that capture the photonic intensity field of the scene in a time window defined by the exposure of the camera, a new type of vision sensing is emerging that relies on light intensity deltas, and the pixels of the camera are sampled in a random access fashion to provide reliable visual information during high-speed motion or in situations where the scene is characterized by high dynamic range [81]. These vision sensors are called event cameras, and their ability to randomly access individual pixels provides a dynamic range of 120 dB that renders implementing high speed applications in low-light conditions possible [9]. In one of the reported realizations of this vision technology [81], Rebecq *et al* created photometric depth maps from an event camera to achieve 6 degrees of freedom (DOF) tracking at an update rate of 1000 Hz in regular indoor lighting conditions. The advent of event cameras is contributing to new ways to realize visual odometry and SLAM applications [82], [83].

Although images captured in the electromagnetic spectrum visible to human eye (i.e., visible band) are clearly favored in the vision sensing literature, other bands such as near infrared (NIR), short wave infrared (SWIR), and long wave infrared (LWIR) are being investigated as well [84], [85], [86]. The retro-reflectance characteristic of lane markings and traffic signs, more prominent signatures from wild-life, pedestrians and cyclists even in bad weather are some of the benefits of infrared imaging. As the cost of infrared sensors keeps falling and the research community keeps developing new techniques to obtain better performance from them, vision sensing in the infrared spectrum can potentially improve the reliability and robustness of driving automation and active safety systems. In order to further enhance the capabilities of infrared imaging for driving automation and active safety, an active gating imaging system (AGIS) has been proposed in [87] wherein a pulsed illuminator and a time-synchronized image sensor operate in tandem to acquire images from a selected range of interest. AGIS can potentially enhance perception capabilities in a variety of ambient light conditions.

Another development trend observed in the literature is to find imaging solutions that provide robust performance against inclement weather conditions. Notable *dehazing* techniques have employed polarization [88], convolutional neural network [89], gated imaging [90], etc.

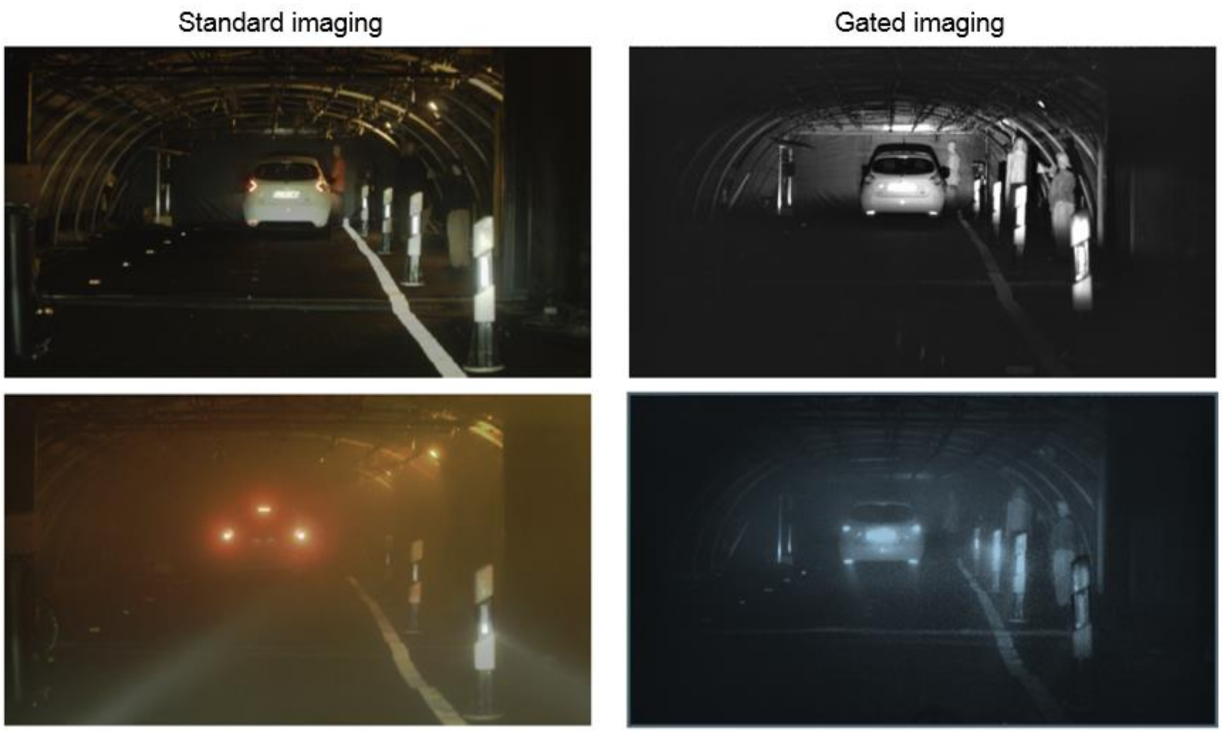


Figure 15: Comparison of standard and gated imaging in clear (top) and foggy (bottom) conditions, obtained from [90].

In light of the large computational load associated with vision perception, academia and industry are also focusing on hardware accelerators (e.g., application specific silicon resources such as neural computing unit – NPU from ARM, tensor processing unit – TPU from Google, various FPGA designs to improve processing throughput) and software techniques (e.g., neural network models for robust identification and classification such as YOLO [91] or YOLOACT [92]).

4 Radar

Sensing Characteristics	Active & Exteroceptive
Sensing Energy Domain	Radio waves (typically 24-77 GHz)
Sensing Output	Position and velocity
Perception Potential	Low (identification & classification) High (ranging)
Prevalence in Future Automated Vehicles	High
Mass Market Deployment Challenges	Low spatial resolution
Vulnerability to Physical Attacks	Medium
Performance Degradation with Weather	Low

Table 10: Radar sensor overview (assessments are subjective and intended as guidelines only).

Radar (RAdio Detection and Ranging) technologies leverage particular waveforms to measure the distance, angle, or velocity of objects in the surroundings. The first experiments showcasing the basic principles of radio waves are attributed to Heinrich Hertz in 1886, validating that radio waves could be reflected and refracted, that the waves are polarized, and the waves are able to interfere with each other [93]. Utilizing these basic principles of radio waves, the first radar systems were devised. Simply, a radar system functions by emitting a controlled waveform via a transmitter in a predetermined direction. Upon making contact with the object, the wave is then scattered, reflected, and absorbed. The waves that are reflected directly back at the radar system are then captured via a receiver and the radar equations are used to calculate the range and relative velocity. The distance is determined by measuring the time of flight of the radar signal traveling to the target and back to the radar. The angle or orientation of the object can be inferred from the direction of arrival of the reflected wave. Finally, the relative velocity can be determined using the Doppler Effect, which is a shift in the carrier frequency of the reflected wave, providing the target's relative (radial) velocity [94].

Automotive focused radar applications began to appear in the early 1970's with the goal of reducing the number of accidents [95] as shown in Figure 16. The frequency ranges initially used varied from 10GHz up to 60Hz. The long range automotive radar frequency of 77 GHz that is highly popular today was first shown in Germany during the early 1980's [95].

Figure 16: 10 GHz automotive radar system built by VDO, early 1970's [95].

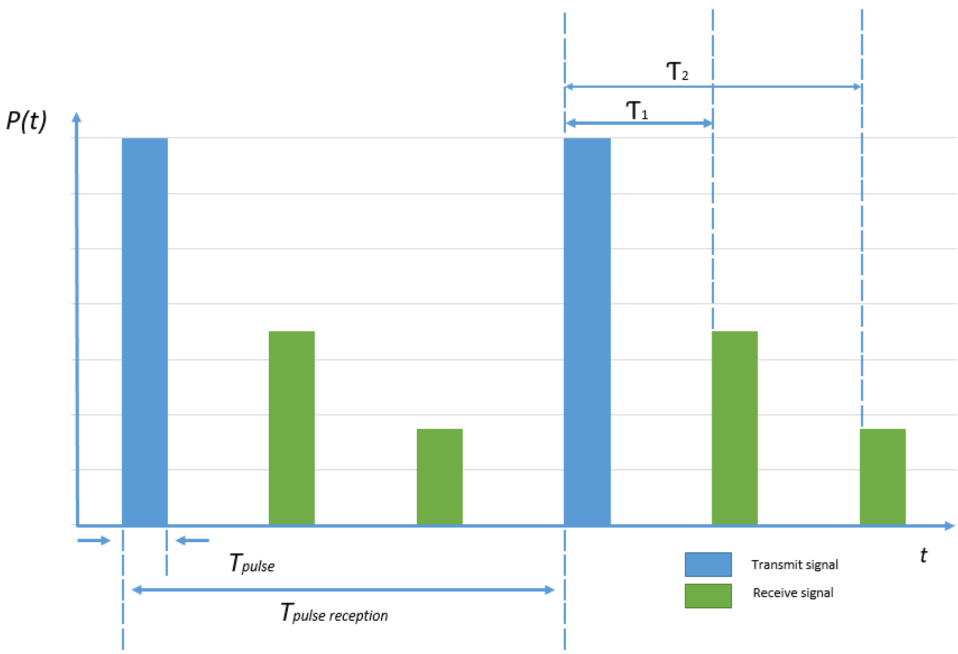


Figure 17: Pulse Radar [96].

The simplest and most intuitive radar systems utilize a single pulse to determine the information about neighboring objects. Figure 17 depicts the operations of a single pulse waveform radar system. Due to the nature of time of flight based distances measurements, limitations are imposed on the simple pulse based waveforms to ensure correct operation. One such limit is the rate at which the transmitted pulse is emitted by the radar. If the radar is pulsing too quickly, mapping the return signal to initial pulse becomes challenging. To overcome this, a target operating range (distance range) is provided for these type of systems, which ensures that pulse frequency is low enough to allow for the wave to travel the maximum distance and back before providing another pulse. While the principles are simple, this approach leads to high computation complexity [96] when calculating the velocity and distances.

To compensate for the complexities, continuous wave (CW) radars continuously transmit and receive the targeted signal waveforms. When the waveform is received via the receiver, the time delay results in a frequency shift. With this approach, range and radial velocity cannot be measured independently based on a single signal chirp [96]. In Figure 18, the frequency shift of a FMCW waveform between the transmitted and the received signals is illustrated in the left. If the frequency modulation of the CW transmit signal is linear (as depicted in Figure 18), the range of the target from which the received signal has echoed back is proportional to the frequency shift Δf.

Another class of waveforms called Frequency Shift Keyring (FSK) consists of two carrier frequencies which are linked together. In order to determine the Doppler frequency a Fast Fourier Transformation is applied to the two echoed signals. Using this methodology the range and radial velocity can be measured independently on a single transmission. Unfortunately, with this approach stationary targets cannot be resolved [96]. Figure 18 depicts the two intermittent carrier frequencies of the waveforms in the right.

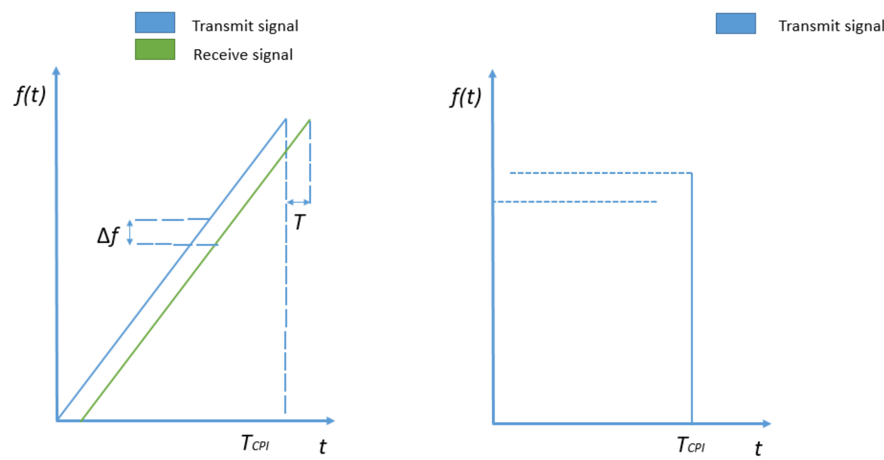


Figure 18: FMCW (frequency modulated continuous wave) waveform (left) and FSK (frequency shift keyring) waveform (right) [96].

Both CW and FSK offer distinctive advantages and disadvantages. In order to achieve the best of both strategies another approach to waveforms is deployed. This methodology is the fusion of the FSK and FMCW waveforms, this is called Multiple Frequency Shift Keyring (MFSK) and can be seen in Figure 19 where the transmit signals are shifted in frequency in a stepwise fashion, but a constant shift is maintained in-between steps. Using this approach both moving and stationary targets can be resolved in both range and velocity even in multi target situations [96].

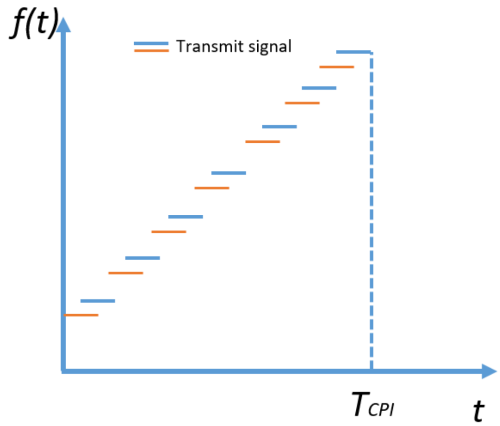


Figure 19: MFSK (multiple frequency shift keyring) waveform [96].

More recently, automotive radar systems have been combining multiple transmitters and receivers acting in defined directions and observing the relative power that each of the systems receives. In doing so additional information can be derived such as the angle at which the object is oriented relative to the radar system [96]. Figure 20 showcases the concept of utilizing multiple predefined direction radars to determine the azimuth angle.

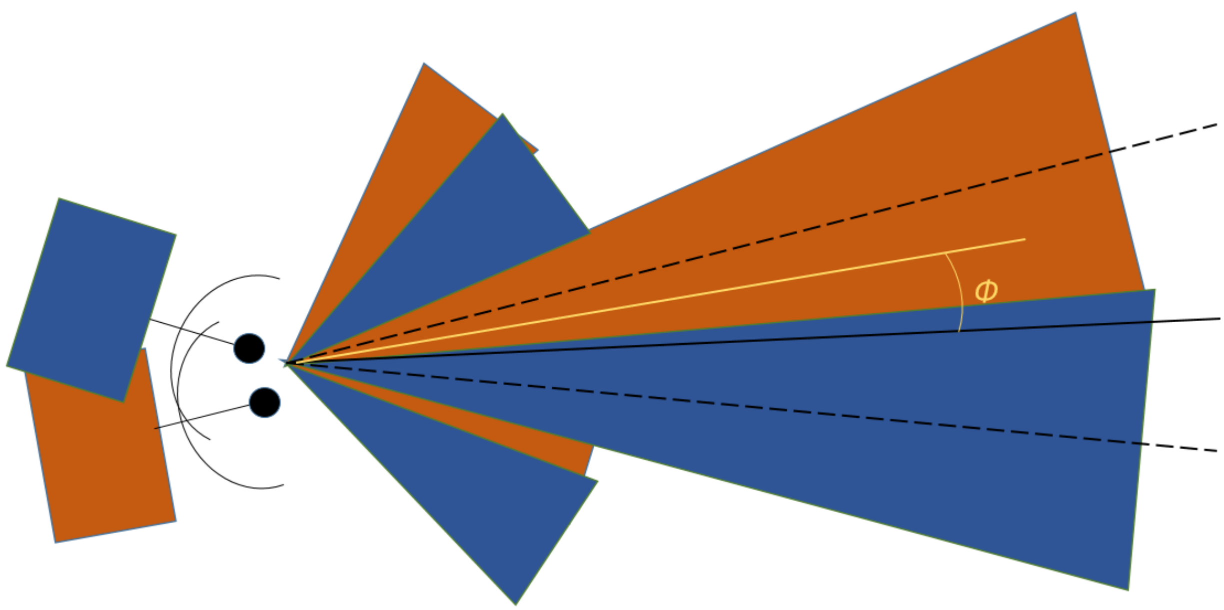


Figure 20: Mono-pulse technique (two adjacent antennas and their directivity shown in different colors) [96].

To take further advantage of this principle, significant effort is being spent in designing and developing new digitally controllable antennas which will allow for beam forming. The underlying principal of beam forming leverages the interference patterns generated by the batch antennas to shape the observed area. Figure 21 showcases two approaches to beam forming, a) showcases a standard dielectric lens, b) showcases a proposed Rotman lens for digitally controlling the wave shapes. In addition to the additional beam shaping functionality, the transition to these digitally controlled antennas reduces the technical complexity and cost of systems as parallel radio frequency mixers and baseband paths can be avoided [97].

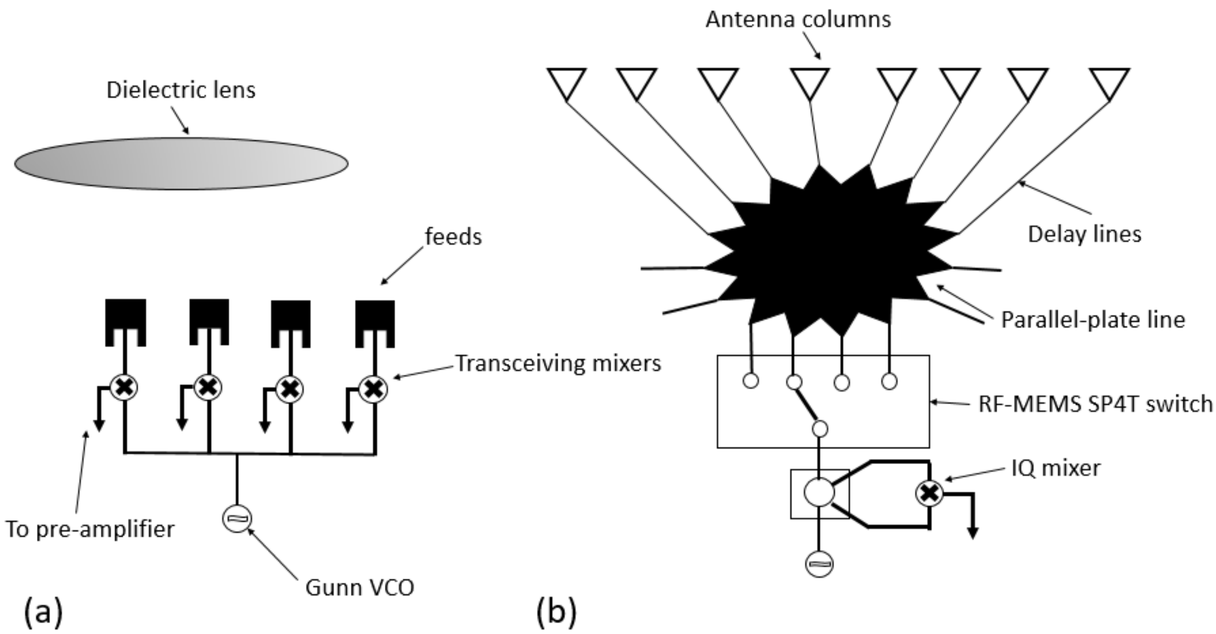


Figure 21: Radar front-end concepts. (a) Current lens antenna system. (b) Rotman lens and beam switching with RF MEMS. [97].

4.1 Function

Radar sensors provide direct distance and velocity measurement capabilities for driving automation systems. In recent years Radar has become widely adopted within the automotive industry. Due to radar utilizing wavelengths outside of the visible spectrum, there are some distinctive advantages that can be gained over other sensors. One major advantage is the robustness of detection during adverse weather conditions such as snowfall or rain. This makes radar a great candidate for critical safety systems, such as adaptive cruise control, that need to function regardless of external conditions. In addition to the robustness to weather conditions, depending on the surface materials of the target, radar is able to sense a large variety of targets without adaptation to the hardware or software [98]. This makes radar a highly reliable perception sensor in an unstructured field of objects.

4.2 Current State of the Art

In general there are two different major frequency types of automotive radar systems commercially available, long range radar (LRR) operating at 77 GHz and short-range radar (SRR) operating at 24 GHz. While sensors are being developed using other frequency ranges such as 81 or 79 GHz, 24 GHz and 77 GHz are by far the most common. Typical performance characteristics as described by [99] can be seen in Table 11, and typical automotive safety applications for these types can be seen in Table 12. While there are many promising prototypes within the higher frequency zone, the majority of applications still operate at 77 and 24 GHz.

LRR	SRR
• Transmit frequency = 76-77 GHz • The mean transmitted power level <50 dBM (peak level is 55 dBM) • Target range = 2-150m • Range resolution ±1m • Azimuth Angular Coverage = ± 8º with 3º minimum resolution • Elevation Angular Coverage = 3º – 4º (single beam) • Antenna gain = 26-34 dBi	• Transmit frequency = 22-26 GHz • The mean transmitted power level <0 dBM (peak level is 20 dBM) • Target range = 0.05-25m • Range resolution ±0.2m • Azimuth Angular Coverage = 55º (typical, 3 DB beamwidth) • Elevation Angular Coverage = 3º – 4º (single beam) • Antenna gain = 26-34 dBi

Table 11: Typical performance characteristics as described by [99] and [100].

Applications	Safety	Technology
Adaptive cruise control	Normal driving; accident avoidance	77 GHz radar
Pre-crash	Accident; mitigation of impact	77/24 GHz radar
Blind spot detection	Normal driving; accident avoidance	77/24 GHz, 76/81 GHz radar
Stop and go	Normal driving; accident avoidance	77/24 GHz, 76/81 GHz radar

Table 12: LRR and SRR frequency bands and examples of ADAS applications within the vehicle [99].

In terms of sensing principle, the frequency modulated continuous wave (FMCW) technology is the most prevalent in the automotive industry. Furthermore, digital beamforming techniques are employed to regulate the direction of the emitted wave. Immunity to ambient lighting and weather conditions renders radars a strong perception mechanism for automotive applications. Table 13 summarizes the advantages and the limitations of radar sensors.

Advantages	Limitations
• Direct measurement of velocity and position • Superior accuracy when the target is aligned with the emitted beam • Performance does not degrade with weather or ambient conditions • Relatively less expensive than LiDAR sensors	• Sensitive to target reflectivity (e.g., a discarded metal beverage container can produce disproportionately large signature) • Low angular resolution • Long range radars have small FOV • Sensor data is not feature-rich to enable classification

Table 13: Advantages and limitations of radar sensors.

4.3 Notable Industrial Players

Different market reports provide different evaluations of market shares of individual companies that produce automotive radar. Regardless, Table 14 is compiled to represent the companies that are frequently cited [101] in this market segment.

Industrial Player	Location
Bosch	Gerlingren, Germany
Continental AG	Hanover, Germany
Denso	Kariay, Japan
Aptiv	Dublin, Ireland
Texas Instruments	Texas, USA
Valeo	Paris, France

Table 14: Notable industrial players producing automotive radars.

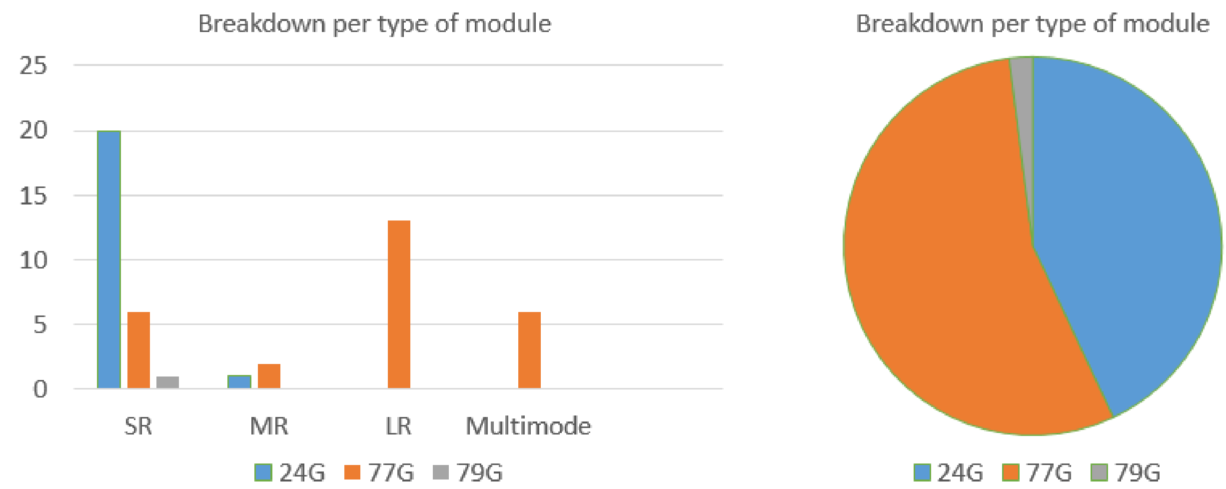


Figure 22: Breakdown of Radar Sensors by Frequency, 2018 [102].

4.4 Deployment Configurations

The most common applications for radar within the automobile are listed below;

- Lane Change Assist (LCA)
- Adaptive Cruise Control (ACC)
- Automated Emergency Braking (AEB)
- Blind Spot Detection (BSD)
- Forward Collision Warning System (FCWS)
- Intelligent Parking Assistance (IPA)
- Vulnerable road user detection
- Others (Exit Assist, Rear Collision) [103]

While each application has desired performance criteria, all applications still utilize the same core principles for detection of angle, relative velocity, and distance. In addition, the mounting location of the radar units will vary significantly between makes and models of vehicles. Figure 23 depicts an ideal configuration of radar systems for the core automotive applications.

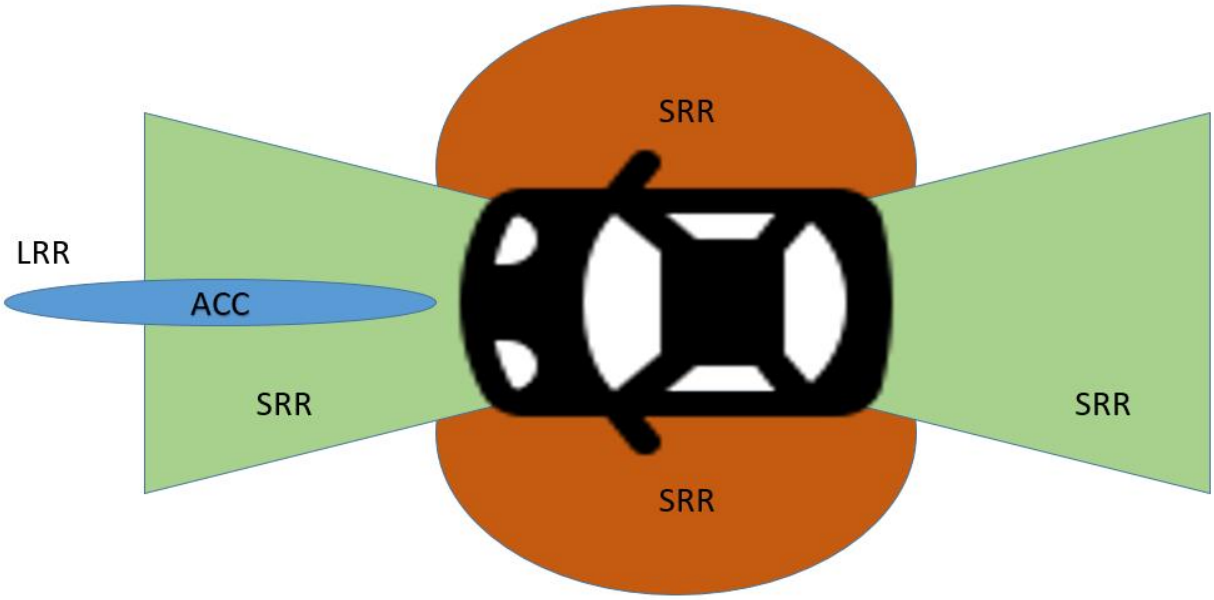


Figure 23: Placement and coverage area of automotive radar antenna [104].

4.5 Future Development Trends

Radar as a technology continually proves itself to be highly robust and effective at sensing of objects at a distance. It is predicted that the global radar sensor market for ADAS technologies will continue to grow and should reach nearly $27B USD by 2021, which is approximately 57% of the ADAS market share [102]. In terms of radar hardware, frequencies ranging from 90GHz to 300GHz is being investigated to improve performance of the current state of the art. In addition, synthetic aperture and superior beam forming techniques are being investigated to improve the resolution. In a more recent research work [105] micro-Doppler characteristics of a 77GHz radar was employed to aid target classification (pedestrians and cyclists).

5 GNSS Sensors

Sensing Characteristics	Passive & Exteroceptive
Sensing Energy Domain	Radio waves
Sensing Output	Global positioning
Perception Potential	Localization only
Prevalence in Future Automated Vehicles	High
Mass Market Deployment Challenges	Service unavailability in urban canyons, tunnels, etc.
Vulnerability to Physical Attacks	High
Performance Degradation with Weather	N/A

Table 15: GNSS sensor overview (assessments are subjective and intended as guidelines only).

Global navigation satellite system (GNSS) provides geo-spatial localization with global coverage. In comparison to other ADS/ADAS sensors, GNSS is by far the most elaborate sensor system in terms of its vast infrastructure characterized by state owned constellation of satellites, ground stations, atomic clocks, etc. Automotive is one of the many applications that benefit from GNSS provided localization. The GPS system developed by the USA was the first realization of GNSS technology. Eventually three other GNSS systems became operational, which include Europe's Galileo, Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS), and China's third generation BeiDou Navigation Satellite System. Although identified as GNSS systems in some literature (despite "G" standing for global availability), Japan's QZSS, the first two generations of BeiDou systems (BeiDou-1 and Beidou-2), and India's IRNSS provide regional coverage only [106]. However, the term "RNSS" or regional navigation satellite system has been used in [107] to distinguish the limited scope of these systems. BeiDou-3 is expected to provide global coverage in 2020 with accuracy better than the other global systems [108]. GNSS technologies were developed for the military first, and then their applications started to evolve to include commercial operation such as surveying, mapping, marine navigation, civil aviation, agriculture, etc., and finally consumer products such as vehicle navigation, mobile communications, athletics etc.

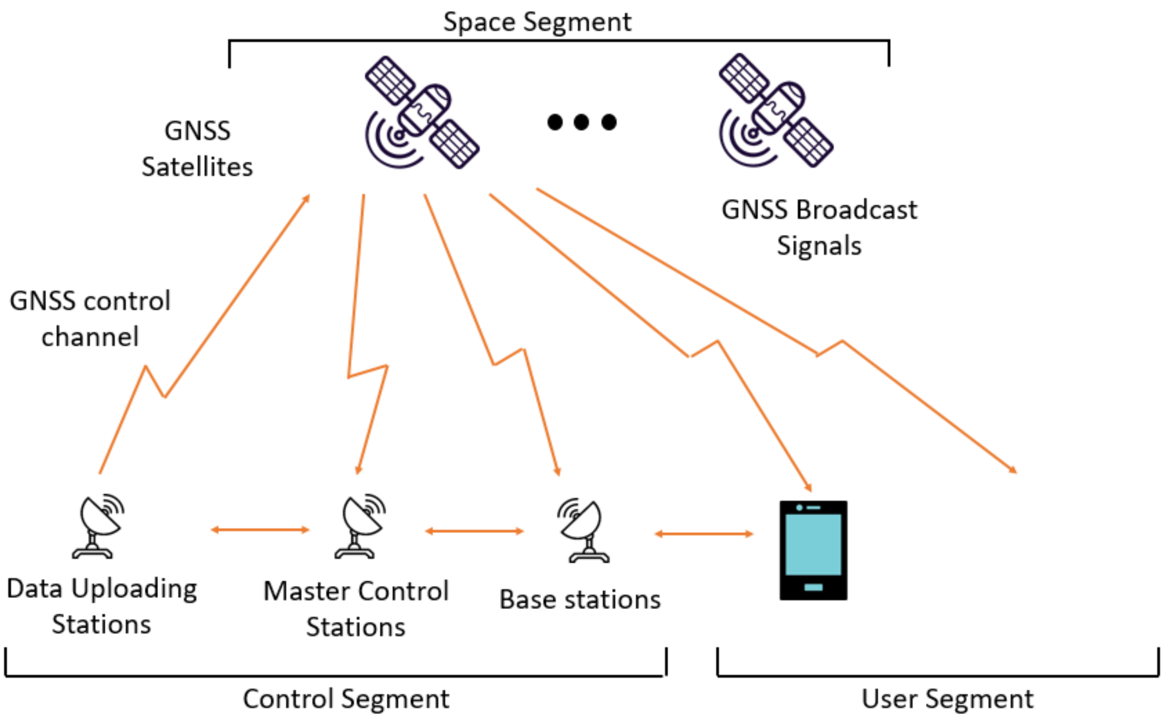


Figure 24: GNSS segments, obtained from [109].

The GNSS system architecture is composed by three major segments: (a) the space segment, (b) the control segment, and (c) the user segment [110]. The space segment consists of a constellation of satellites orbiting ~20,000 km above the earth [109]. Each operational GNSS service has deployed its own constellation. As of December 2017, there were over 100 GNSS satellites in orbit [111]. These satellites collectively provide global coverage for each GNSS service. Each satellite broadcasts a signal with a self-identifying signature, time from an on-board precision atomic clock, its orbit, and its status. The control segment realizes closed loop control on the satellite orbits and the broadcast times. It is comprised of a network of ground-based stations that monitor satellites' signal and status (function of monitor stations) so that adjustments of their orbits and offset of the broadcast time in reference to an even more accurate ground-based atomic clock can be determined (function of master station/stations). Subsequently, the calculated adjustments are employed to dispatch appropriate actuation commands to the satellites (function of data uploading stations) for time synchronization and orbit regulation. The user segment refers to radio communication and computation equipment that receive signals from the GNSS satellites to determine time and location of the user. These types of equipment vary and range from wrist-worn smartwatches to elaborate systems composed of sophisticated electronics and radio antennas, which are used for precision survey and mapping applications. This report will limit its focus on the user segment only. In addition, the term "GNSS sensors" will be used to refer to these types of user equipment.

The main components of GNSS sensors include antennas for acquiring radio signals broadcast by satellites, and receiver units that process the acquired signals to calculate position and time. The calculated position and global time refers to the antenna position and time at the time of signal acquisition. Since multiple GNSS services are available now, some GNSS sensors are designed to receive signals from multiple constellations. The propagation time of the signals broadcast from the satellites and received at the GNSS sensor provides the distance/range of each satellite. Propagation time is calculated from the timing component of the broadcast signal. Once ranges from multiple satellites are obtained, a geometric method called *trilateration* is employed to determine the geo-spatial coordinates of the GNSS sensor. Therefore, timing is an extremely important component in GNSS positioning. Since the radio signals are in the electromagnetic spectrum traveling at the speed of light, an offset of a single nanosecond corresponds to a distance measurement error of 30 cm. However, timing is not the only error source in GNSS localization. Other error sources include signal propagation errors and system errors such as satellite orbital errors, receiver noise, etc. [112]. Different GNSS errors have been characterized in Table 16.

Source	~Error Range
Satellite clocks	±2.0 m
Orbit errors	±2.5 m
Ionospheric delays	±5.0 m
Tropospheric delays	±0.5 m
Receiver noise	±0.3 m
Multipath	±1.0 m

Table 16: GNSS error sources, obtained from [109].

Localization accuracy from a *standalone* GNSS service is accurate to within a few meters [109]. The relatively coarse accuracy is not adequate for localizing a vehicle within a single roadway lane, which is a requirement for automated lane keeping. This deficiency has resulted in current mass marketed ADAS features of lane keeping systems to employ a forward looking camera to implement vision based localization. A standalone GNSS service can be augmented to eliminate the sources of the various errors. A more readily implementable error resolution technique is multi-constellation and multi-frequency position estimation to remove/mitigate errors caused by timing offsets, ionospheric attenuation, and by taking advantage of the broader spatial spread of the reference satellites from multiple constellations. However, this technique is yet to be offered for current production vehicles because appropriate equipment with mass market readiness have only been introduced recently by GNSS equipment manufacturers. In addition, other augmentation systems requiring more elaborate and additional support infrastructure include satellite based augmentation system (SBAS), ground based augmentation system (GBAS), and differential GNSS (DGNSS) [113].

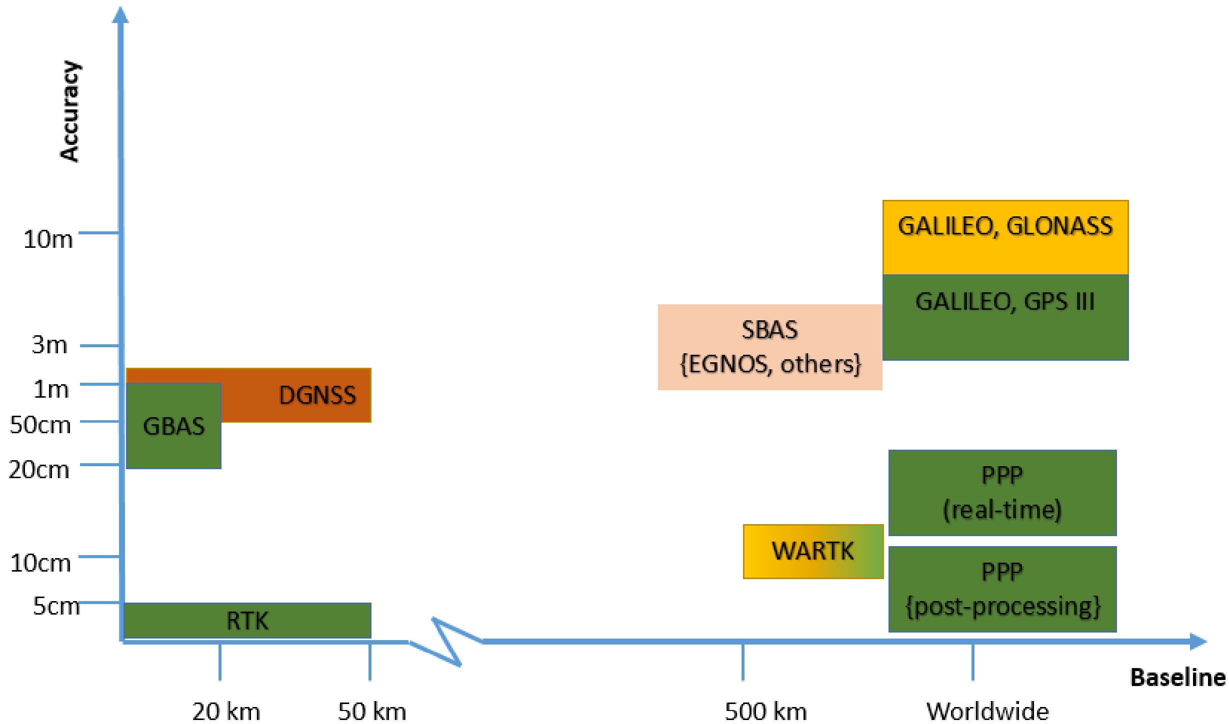


Figure 25: Accuracy Performances for GNSS and GNSS Augmentation Techniques, obtained from [113].

In SBAS geostationary satellites providing regional coverage broadcast correction information to be used by GNSS receivers for improving accuracy (e.g., EGNOS – the European Geostationary Navigation Overlay Service). On the other hand, GBAS employs ground based stations located at accurately surveyed positions. These ground stations compute the correction factors and broadcast it to enable superior positioning accuracy. DGNSS enhances standalone GNSS positioning estimates by the use of ground-based reference stations (also called the base stations) that broadcast differential correction information to the positioning service client (called the rover). Several techniques can be found in the literature of which notable in driving automation applications are real-time kinematic (RTK) [114] and precise point positioning (PPP) [115]. The main difference between RTK and PPP techniques is that the later does not require observations from a relatively close base station, rather it utilizes data from reference stations sparsely distributed over thousands of kilometers. On the other hand, RTK can achieve sub-decimeter accuracy without the support of an elaborate network of reference points. The most basic implementation of RTK requires wireless communication between the rover and the base station(s) for broadcasting correction information to the rovers. However, the range over which RTK is determined by the range of wireless communication which is typically few tens of kilometers.

5.1 Function

The main function GNSS sensors serve in automotive vehicles is to provide global localization of the vehicle in reference to available driving maps (such as Google Maps, Open Street Maps) to assist in navigation by providing turn-by-turn driving direction. Although some vehicles may lack onboard GNSS equipment, consumer focused driving apps such as Android Auto and Apple CarPlay take advantage of the GNSS sensors embedded in smart devices to provide the same functionality. Positioning capabilities enabled by GNSS have been the main driver for creating many value added services in road transportation such as:

- Tracking system for managing fleets of light and heavy duty vehicles (example: Geotab fleet tracking system [116]).
- Automated payment for parking spots, tolled roads, and high occupancy lanes utilization (example: PayBySky parking payment system [117]).
- Pedestrian detection enabled by GNSS-enabled consumer devices (example: Viziblezone pedestrian detection system [118]).
- Vehicle-mounted GNSS trackers as anti-theft devices.
- Ride sharing apps such as Uber and Lyft.

Since GNSS alone cannot deliver the sufficient localization accuracy for vehicles with L3 or higher automation levels, other sensors such as IMU, wheel odometry, LiDAR, camera, etc. are employed to augment the GNSS provided position through sensor fusion. Nonetheless, GNSS continues to be a prominent enabler of driving automation systems. For example, lane level positioning has been achieved in [119] using a PPP augmented GNSS sensor.

Advantages	Limitations
• Global coverage with global localization for standalone applications • Readily available service in open sky conditions • Relatively low cost and low power requirement • Position, time, and velocity parameters are provided without significant computational load	• Must be fused with other sensors to obtain useful localization capability • Unavailable/unreliable in certain areas such as urban canyons, tunnels, underpasses, parking garages, etc. • Susceptible to cyber-attacks with widely accessible devices

Table 17: Advantages and limitations of GNSS.

5.2 Current State of the Art

GNSS positioning can be regarded as a one of the central technological foundations on which future mobility products such as driving automation, ride sharing, automated valet, automated tolling etc. will be built on. The features of global coverage and absolute positioning are powerful perception capabilities. Furthermore, GNSS is a major component in *a priori* maps that aid mass marketed driving automation systems (e.g., super cruise by GM) to obtain robust and reliable performance. However, the technology suffers from several limitations, which are being addressed through sensor fusion in mass marketed and developmental driving automation systems. The advantages and limitations of GNSS technology are summarized in Table 17.

Accuracy of standalone GNSS positioning can be improved by SBAS, PPP, and RTK augmentations for driving automation systems. However, the corresponding real-time performance requirement is yet to be realized due to long convergence times (i.e., time to first accurate fix), prerequisites of elaborate support infrastructure, only local coverage, maintaining accuracy in urban areas with sub-optimal satellite connectivity, etc. In light of these challenges, whether PPP or RTK techniques will find traction in mass marketed driving automation systems remains to be seen. Positioning performances and the corresponding requirements of support infrastructure of various GNSS positioning techniques are reviewed in Table 18.

Feature	Standalone	RTK	PPP	SBAS
Positioning	Absolute in the GNSS reference frame	Relative	Relative	Relative
Frequency: Single – SF Dual – DF Triple – TF	SF or DF	Mostly DF	SF/DF/TF	SF
Time to first accurate fix	Rx TTFF	As standalone + time to receive corrections + time to resolve ambiguities	As RTK with significantly higher time requirement for resolving ambiguities	As standalone + time to receive corrections
Horizontal accuracy	5-10 m DF 15-30 m SF	1 cm + 1ppm baseline	< 10 cm to < 1m	< 1 m
Coverage	Global	Up to 10's km	Global	Up to 1000's km

Table 18: GNSS positioning performance and features (some metrics obtained from [111]).

5.3 Notable Industrial Players

Major producers of automotive GNSS equipment (receivers and antennas) as identified in [111] and [120] are summarized in Table 19. However, information relating to their individual market shares are scarce in the literature.

Name	Base
Broadcom	California, USA
U-Blox	Thalwil, Switzerland
STMicroelectronics	Geneva, Switzerland
Infineon	Neubiberg, Germany
Intel	California, USA
Qualcomm	California, USA
Mediatek	Hsinchu, Taiwan

Table 19: Leading GNSS equipment manufacturers.

5.4 Deployment Configurations

The radio antenna deployed on roofs of production vehicles are typically configured to function as GNSS antennas. The vehicle roof is an obvious choice for the antenna placement because it maximizes lines of sight with satellite constellations. The received signals are then sent to on-board GNSS receivers to determine vehicle positon. The on-board GNSS receiver is part of the vehicle's internal electronics architecture and connected to the other ECUs through a data bus such as CAN-bus. This typical configuration of GNSS sensors (i.e., antenna on the roof and the receiver internally integrated) is not expected to change in future mass marketed driving automation systems. However, the underlying antenna and receiver designs are definitely expected to improve to offer superior positioning accuracy, robustness, and resilience against jamming and spoofing.

5.5 Future Development Trends

The European Space Agency in [121] characterized the road transportation GNSS value chain in several verticals: (a) GNSS components and receiver manufacturers, (b) system integrators such as automotive suppliers and OEM, (c) aftermarket device vendors and service providers (Garmin, Google, Uber), and finally (d) the users (e.g., car owners, fleet operators, insurance companies, etc.). In this value chain the GNSS components and receiver manufacturers are being driven by market pressures of producing sensors with better performance such as increased accuracy, improved reliability in difficult environments characterized by spotty satellite connectivity, and reduced time to first fix (TTFF) [111]. Possible innovations in order to achieve these performance goals are going to happen in hardware development for superior satellite signal reception and characterization, and in software development for better position inference with low latency. Given the state ownership of GNSS infrastructures including atomic time keeping, satellite constellations, and their ground stations, it is not surprising that commercial entities that produce GNSS sensors are more active in the user segment of the technology.

The frequency bands of the radio signals broadcast from the GNSS satellites ranges from 1176.45 MHz to 1610 MHz, with different constellations employing different bands for broadcasting (see Figure 26). GNSS sensors available on production vehicles today typically employ a single band receiver to favour design simplicity and low cost. However, components with chip-scale packaging featuring multi-frequency and multi-constellation tracking with conformance to automotive safety critical systems standard (ISO 26262 ASIL) are being offered by GNSS component manufacturers [122]. In order to complement these breakthroughs in automotive grade GNSS receivers, a push for miniaturization of antennas with multi-band and multi-constellation reception capabilities can be observed in the academia; examples include [123], [124].

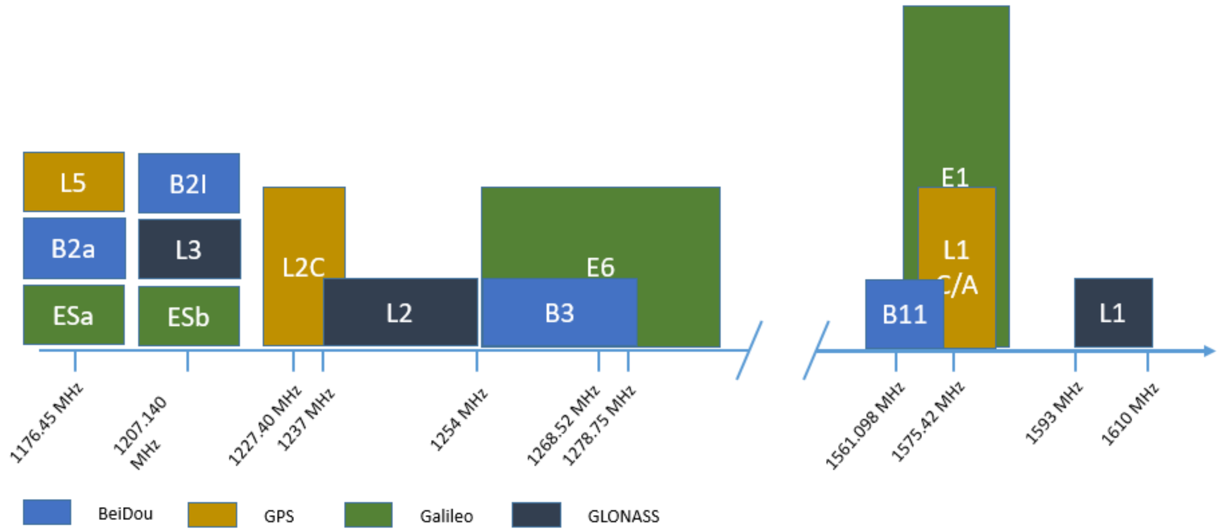


Figure 26: GNSS frequencies in the L band, obtained from [111].

In order to improve localization accuracy, sensor fusion involving GNSS (e.g., [125], [126]) continues to be an active research topic.Maintaining robust and accurate performance in challenging conditions characterized by obstructed lines of sight such as urban canyons, tunnels, underpasses, etc. through sensor fusion constitutes an exciting research avenue with immense market potential; examples include [127], [128].

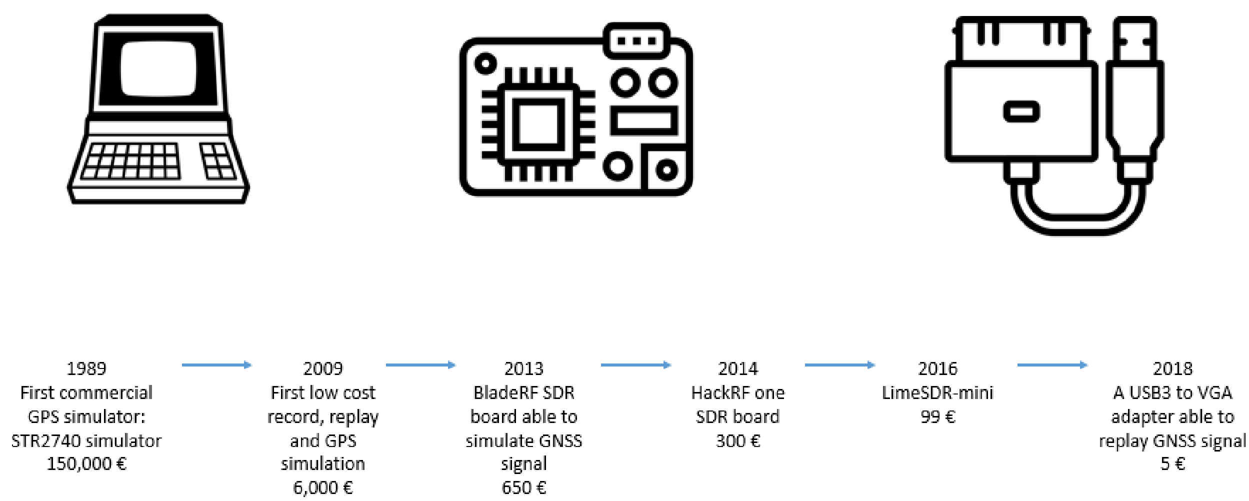


Figure 27: Evolution of GNSS spoofing devices, obtained from [111].

Besides jamming and interference, spoofing in the form overpowering authentic satellite signals with fabricated GNSS messages is a growing concern caused by the recent surge in software defined radio (SDR) technologies (see Figure 27). SDR is an easily accessible cyber threat for GNSS applications with the potential to cause devastating safety and security occurrences involving driving automation systems. Although strict regulation of public usage of SDR is one way to address this threat, it should be noted that SDR can be assembled from readily available hardware and software components, and effective control of their supply can be difficult to achieve.

Therefore, cyber-hardening of GNSS technologies is expected to be a prominent future development trend for GNSS technologies. This may take many forms including introduction of satellite signal authentication features at the infrastructure level, spoof detection and countermeasure techniques development for user equipment, etc. Some of these cybersecurity concerns for GNSS positioning are addressed in [129].

6 Inertial Measurement Unit

Sensing Characteristics	Passive & Proprioceptive
Sensing Energy Domain	Radio waves
Sensing Output	Velocity & relative position
Perception Potential	Localization only
Prevalence in Future Automated Vehicles	High
Mass Market Deployment Challenges	Noise resilience and sensor drift
Vulnerability to Physical Attacks	Low
Performance Degradation with Weather	N/A

Table 20: IMU sensor overview (assessments are subjective and intended as guidelines only).

Inertial measurement unit (IMU) is a proprioceptive sensor typically composed of six inertial sensors, of which three are rate-gyroscopes that measure angular velocity, and the remaining three are accelerometers that measure linear acceleration. An IMU typically provides its orientation, position, angular velocity, linear velocity, and linear acceleration computed from the measurements provided by the gyroscopes and the accelerometers. Angular velocity can be natively obtained from an IMU with rate-gyroscopes and linear acceleration can be measured by the accelerometers. Double integration of linear acceleration provides position, and integration of angular velocity provides orientation. IMUs are ubiquitous in modern consumer electronics embedded with miniaturized systems weighing a few grams (e.g., touch devices, smart watches, etc.). On the other end of the spectrum, navigation grade IMU in aircrafts are elaborate systems weighing a few kilograms. Navigation-grade IMU performance is characterized by low noise, stable bias, and scale factor outputs to provide positioning errors less than 10 meters for a period of several tens of seconds computed solely from inertial sensor measurements [130].

Ideally the gyroscopes and the accelerometers are configured to be mutually orthogonal on three axes with each axis integrating a pair of gyroscope and accelerometer. The orhtogonalized configuration ensures that measured motion/forces in one axis does not bias measurements in the other two axes. However, due to manufacturing tolerances, perfect alignment during assembly is difficult to achieve, and for accurate performance the misalignments must be compensated in the computation. This process is called IMU calibration. Similar to GNSS, driving automation systems is one of the many application areas of IMU technologies. Nonetheless, inertial measurements found wide automotive adoption when Bosch supplied the very first MEMS gyroscopes to realize electronic stability control in Mercedes SL and S class vehicles in 1995 [131].

6.1 Function

Given the relatively low update rate of GNSS, inertial navigation system (INS) employ IMU readings to obtain 3D position, velocity, and attitude information in-between GNSS fixes [129].This feature is already available in production vehicles for navigation applications. In addition, inertial sensors provide the following functionalities in production vehicles:

- Accelerometers for airbags [131].
- Gyroscopes for electronic stability control and rollover detection [132], [133].
- Deadreckoning in GNSS denied areas [134].
- Identification of faulty GNSS signal in challenging areas [135].

Since navigation grade IMUs are cost prohibitive for mass market adoption (order of tens of thousands of dollars), MEMS IMU sensors (typically <$100) are expected to maintain their relevance in future automated vehicles not only in driving automation systems, but also in conventional capacities such as enabling active safety features. However, IMUs will continue, despite their limited performance, to complement other perception sensors (GNSS, camera, LiDAR, etc.) through sensor fusion. Considering their inaccurate localization performance, future driving automation system will continue to employ automotive grade IMUs as auxiliary sensors that provide one more input to the sensor fusion functions.

Advantages	Limitations
• Provides PVT (position, velocity, time) without significant computational complexity • Proprioceptive sensing principle provides inherent resistance to cybersecurity threats • Performance does not degrade with weather	• Inherently susceptible to noise and vibration • Cost increases exponentially with performance • Accurate performance requires calibration of each sensor to account for axis misalignments

Table 21: Advantages and limitations of inertial sensing.

6.2 Current State of the Art

IMU deployment configurations are categorized into two classes: stable platform systems, and strapdown systems [136] (i.e., rigidly attached to the vehicle frame). Automotive applications of IMU heavily favor strapdown systems owing to their integration simplicity. As inertial sensors MEMS gyroscopes and accelerometers are widely used in automotive applications because they can be manufactured at mass scale using silicon micro-machining techniques without requiring intricate assembly. MEMS-based inertial sensors suffer from unstable performance mainly due to various sensor biases and increased sensitivity to vibrations and shock. In contrast, optical gyroscopes such as fiber optic gyroscopes (FOG) and ring laser gyroscopes (RLG) can provide navigation grade performance, and they are being investigated for driving automation systems in research and development scope [137], [138]. Nonetheless, their mass market deployment remains prohibitive because of high SWAP-C (size, weight, and power – cost) requirements with prices ranging more than $10,000 per axis [139]. Mass marketed IMUs used in automotive applications are supplied as a packaged system which provides motion and pose parameters of the vehicle. This packaged system integrates gyroscopes, accelerometers, computation units, and data interface components (e.g., CAN-bus interface – see section 10.1). The advantages and the limitations of inertial sensing are summarized in Table 21.

6.3 Notable Industrial Players

Reliable literature identifying key market players for inertial sensing is scarce. Nonetheless, reports compiled by market research firms can be used as data sources. Two such sources [140], [141] were consulted to identify the leading producers of IMU sensors in Table 22.

Name	Base
Honeywell	Charlotte, North Carolina, USA
Bosch	Gerlingen, Germany
Northrop Grumman	Falls Church, Virginia, United States
Sarfan Electronics & Defense	Boulogne-Billancourt, France
Thales Group	La Défense, France

Table 22: Notable industrial players in IMU technologies.

6.4 Deployment Configurations

Strapdown IMUs are used in production vehicles to realize the functions of active safety, and inertial navigation aided by GNSS. Depending on the architecture, multiple units can be deployed strategically on the vehicle chassis for active safety functions of airbags, electronic stability control, and rollover detection. For driving automation systems, if a low-drift IMU is used for localization, it must be deployed in a location which is known relative to other sensors for spatial consistency.

6.5 Future Development Trends

Current limitation of performance of IMUs constructed of MEMS sensors cannot provide navigation grade performance. They can be manufactured at scale at significantly lower cost [142]. In order for IMU based navigation to be relevant for vehicles with L3 and higher automation levels, a performance breakthrough is warranted. Contrastingly, automotive applications are unlikely to adopt FOG or RLG IMUs because of the associated high cost. The future development trend for inertial sensing in driving automation systems will involve development of performant hardware and appropriate software techniques to gain navigation grade accuracy from MEMs IMUs. Correspondingly, the following trends are identified:

- Hardware improvements for inertial MEMS to obtain navigation grade performance; examples include improving the electrical operation scheme in [143], piezo-resistive sensors in [144], and vacuum-packaged birdbath shaped resonator gyroscopes in [130].
- Software techniques to eliminate/remove inertial MEMS sensor errors; for example, employing deep learning in [145], and low complexity Kalman filtering in [146].
- Unconventional mounting schemes for MEMS IMU on vehicles to remove drift noise; examples include mounting sensors on vehicle wheels to primarily remove constant bias in [147].
- Development of low cost FOG gyroscopes for driving automation systems [139], [137].

7 Ultrasonic Sensors

Sensing Characteristics	Active & Exteroceptive
Sensing Energy Domain	Sonar waves
Sensing Output	Relative position of targets in FOV
Perception Potential	Ranging
Prevalence in Future Automated Vehicles	High (limited low-speed and short range applications)
Mass Market Deployment Challenges	Already deployed in several production vehicles
Vulnerability to Physical Attacks	High
Performance Degradation with Weather	N/A

Table 23: Ultrasonic sensor overview (assessments are subjective and intended as guidelines only).

Ultrasonic sensors operate in the mechanical energy domain (i.e., employing vibration for resolving distance). It is an active sensor that employs ultrasound vibration (frequency greater than 20 kHz) to scan the environment, and its echo from a nearby obstacle assists detection and ranging by a TOF working principle. Other terms referring to this sensing technology include acoustic sensor [148] and sonar sensor [3], [9]. In comparison to other driving automation sensors, ultrasonic sensors provide the least range (e.g., 15 cm to 5.5 m for a mass market ready design [149]) covering only the immediate proximity of the vehicle. It must be noted, however, that they provide an important function of ultra-close range obstacle detection which is difficult to achieve with other sensors. Since radar and LiDAR operate in the electromagnetic domain, the corresponding signal conditioning and control electronics must be extremely fast to be able to provide such ultra-short range. In addition, as cameras will require an extremely wide lens to cover the immediate proximity of a vehicle, the resulting image data might prove to be too distorted to make any useful inference.

7.1 Function

The limited range of ultrasonic sensors renders them impractical for driving automation on roads. Nonetheless, the Tesla sensor stack [67] features 12 ultrasonic sensors to provide obstacle ranging in close proximity for parking functions [9], [150]. Rear obstacle detection and parking assist have been identified as two functions of ultrasonic sensors in [151]. Reported functions of ultrasonic sensors in driving automation systems include:

- Environmental awareness at lower speeds by continually evaluating collision potential in close proximity.
- Enabling summon feature for driving out of parking spots (e.g., [67]).
- Bosch claims detection of suddenly appearing obstacles such as pedestrians [149].

Advantages	Limitations
• Distance measurement with obstacle proximity detection at ultra-close range (e.g., 3-15 cm for proximity detection without reliable ranging for Bosch sensors) • Insensitive to weather and ambient conditions (e.g., sudden change in lighting) • Cost effective ($1-$3 per unit **[152]**) • Long history of field deployment in production vehicles with proven reliablity	• Data is not feature-rich enough for object classification • A functional system requires an arrayed configuration consisting of multiple sensors (usually 8-12) • Poor ranging performance at distances farther than 5 meters

Table 24: Advantages and limitations of ultrasonic sensors.

7.2 Current State of the Art

Ultrasonic sensors are relatively simple in terms of construction and operating principle. In comparison to other ADS/ADAS sensors, the sensing capacity is limited in that it provides limited ranging capabilities and the provided data is not suitable for making any useful inferences in terms of obstacle classification due to limited features in the sensor data. However, sensor fusion techniques are employed to address performance gaps that more sophisticated sensors are unable to fill (e.g., localization in GNSS-denied areas such as parking structures). Regardless of the apparent lack of versatility, they deliver the functions that they were designed for; namely, obstacle sensing and ranging functions in the close proximity of the vehicle. A summary of the advantages and limitations of ultrasonic sensors is provided in Table 24.

7.3 Notable Industrial Players

Although information regarding individual automotive market share of ultrasonic sensor manufacturers is scarce, the notable players in the general ultrasonic sensor market have been identified in [153] and [154]. Despite unavailability of automotive sector specific data, a list of automotive suppliers that offer ultrasonic sensor units has been complied in Table 25.

Name	Base	Product Features
Bosch	Gerlingen, Germany	Safety level up to ASIL B
Valeo	Paris, France	Robustness proven in comprehensive testing
Murata	Nagaokakyo, Japan	Hermetically sealed units for automotive application

Table 25: Some suppliers of automotive ultrasonic sensors.

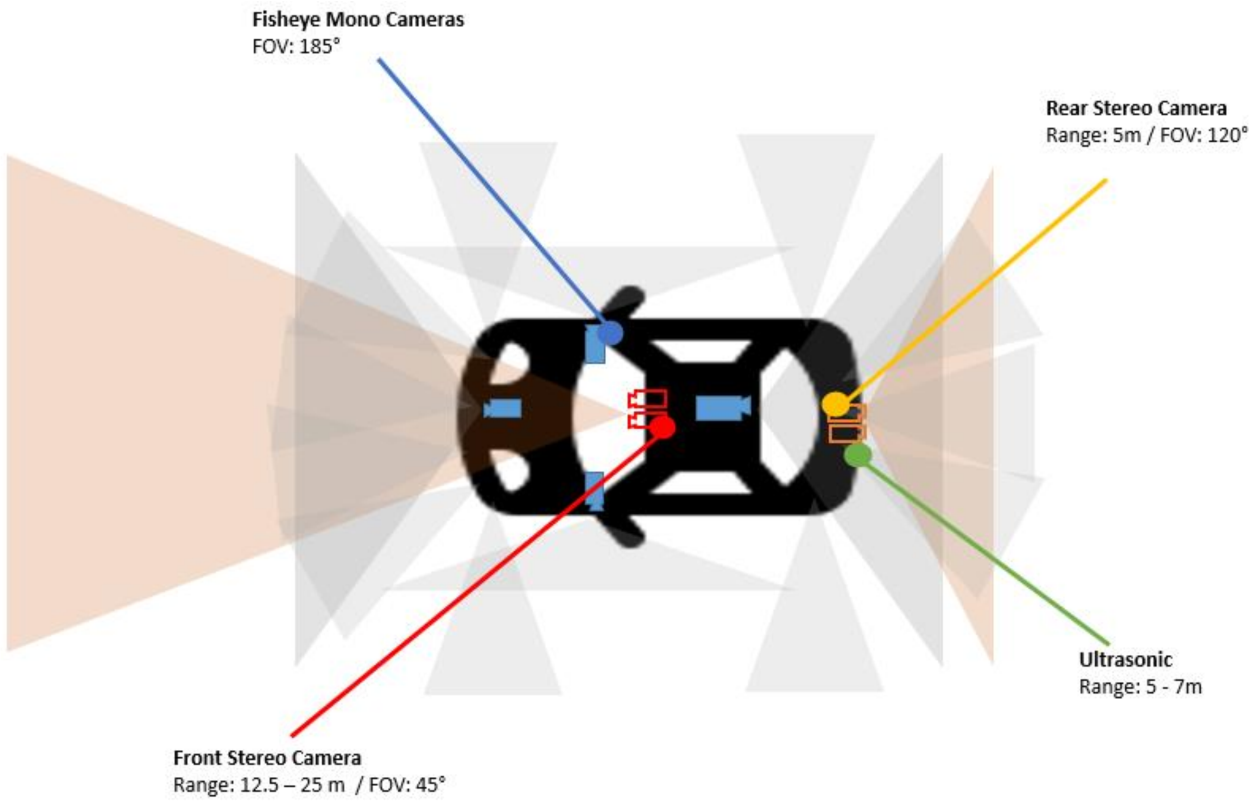


Figure 28: Sensor configuration of the demonstration platform described in [155].

7.4 Deployment Configurations

Given the limited ranging and detection capabilities of ultrasonic sensors, a single unit cannot provide useful value. Production vehicles, if equipped with ultrasonic technology, employ an array around the vehicle. Since collision at lower speeds can occur at the front and rear of the vehicles, the arrays are usually clustered in those regions (see Figure 28). Ultrasonic sensors are primarily used in automated parking functions with limited perception potential at higher speeds. Correspondingly, their deployment configurations are likely to remain unchanged in vehicles with L3 and higher automation features.

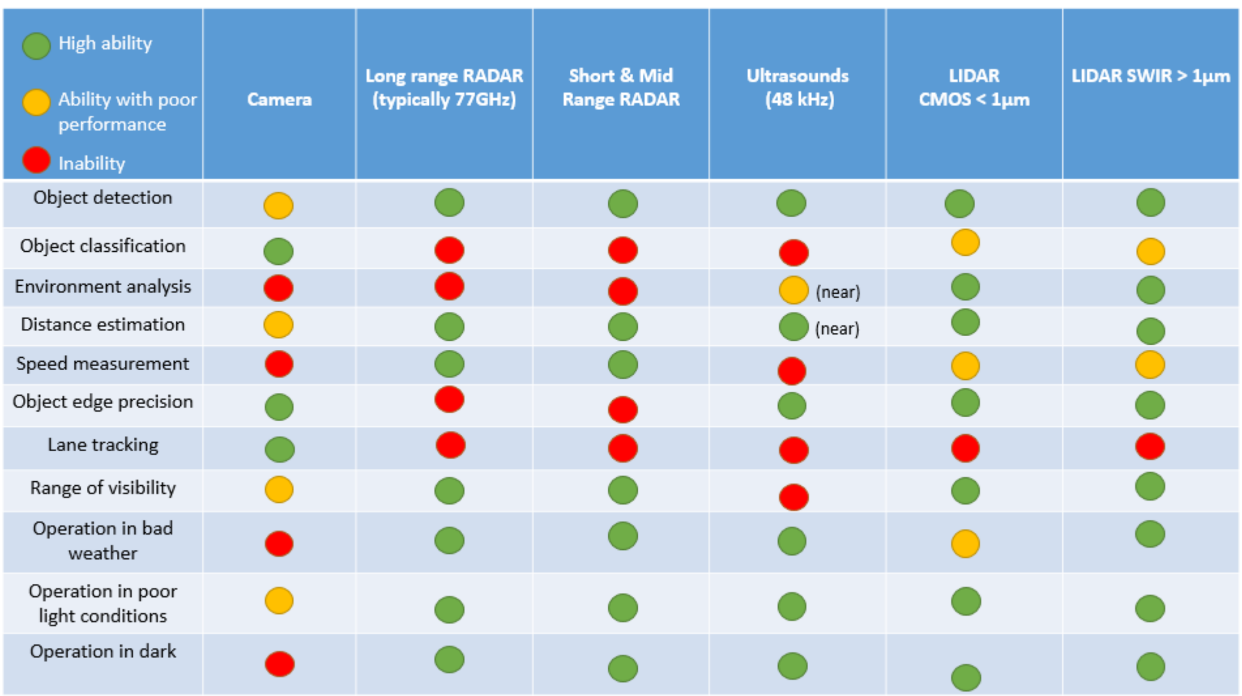
7.5 Future Development Trends

Although ultrasonic sensors are extremely useful for obstacle detection at close range, the underlying physics can be characterized as too limiting for further performance improvement. Furthermore, it can be considered that the hardware and the software in ultrasonic sensing have matured to have realized the perception potential. Correspondingly, research and development initiatives involving these sensors focus on sensor fusion techniques and new use cases to expand their value propositions. Some of the reported trends include:

- The driving automation demonstration described in [53] and [155] employed ultrasonic sensor and camera fusion to navigate and park in GNSS-denied parking structures.
- Blind spot monitoring as disclosed in [156].
- Object tracking using Kalman filtering from data acquired by eight sensors in specific scenarios such as overtaking and passing through intersections [157].

8 Comparison of Sensor Performance

From a technological standpoint, it can be opined that a single sensor is not likely to deliver all the requirements for reliable and performant driving automation system. The performance gaps for next generation ADS systems will rather be addressed by complementing strengths of multiple sensors to achieve safety-critical redundancy and weather-resistant operation. Strong market and deployment presence of multiple ADS/ADAS sensors [12], [158], [3] as opposed to a single sensor, is supportive of this thesis. A related study conducted by Tematys [158] is summarized in Figure 29. Sensor competencies are evaluated in a similar study in [159], and the findings therein are summarized in Table 26. Please note acoustic/ultrasonic sensors were not part of the latter study. Different sensors and their deployments in realizing different ADAS features currently available in the market is presented in Table 27.



🟢 High ability 🟡 Ability with poor performance 🔴 Inability	Camera	Long range RADAR (typically 77GHz)	Short & Mid Range RADAR	Ultrasounds (48 kHz)	LIDAR CMOS < 1µm	LIDAR SWIR > 1µm
Object detection	🟡	🟢	🟢	🟢	🟢	🟢
Object classification	🟢	🔴	🔴	🔴	🟡	🟡
Environment analysis	🔴	🔴	🔴	🟡 (near)	🟢	🟢
Distance estimation	🟡	🟢	🟢	🟢 (near)	🟢	🟢
Speed measurement	🔴	🟢	🟢	🔴	🟡	🟡
Object edge precision	🟢	🔴	🔴	🟢	🟢	🟢
Lane tracking	🟢	🔴	🔴	🔴	🔴	🔴
Range of visibility	🟡	🟢	🟢	🔴	🟢	🟢
Operation in bad weather	🔴	🟢	🟢	🟢	🟡	🟢
Operation in poor light conditions	🟡	🟢	🟢	🟢	🟢	🟢
Operation in dark	🔴	🟢	🟢	🟢	🟢	🟢

Figure 29: Comparison of abilities of ADS/ADAS sensing technologies from [158].

Another detailed and more recent overview of driving automation sensors can be found in [3], where a concise and high level qualitative summary of sensor performance is provided in a tabular format. Despite the availability of a number comparative studies in the literature, because of the different sensing modalities, energy spectrum (vibration, infrared, visible range, etc.), and operating principles, it is difficult to perform a *quantitative* analysis of ADS/ADAS sensor performance. For example, LiDARs provide accurate ranging information in a reliable manner, but photonic signatures in the visible and infrared spectrum captured by image sensors under *good weather conditions* is more conducive to robust object classification. Designing a single quantitative test where both sensors can be evaluated fairly is therefore rendered difficult by their dissimilar strengths. Nonetheless, the qualitative performance comparison provides insight into how these sensors are going to be deployed in driving automation systems. This report also includes a tabular representation of qualitative performance comparison after presenting profiles of prominent driving automation sensors.

Legends: Good ability (+), poor ability (-), not applicable/inability (O)

Sensor Attribute	RADAR	LiDAR	Vision
Range	++	+	++
Range resolution	+	++	O
Angle resolution	O	++	+
Works in bad weather	++	O	-
Works in dark	++	++	--
Works in bright	++	+	+
Color/contrast	--	--	++
Radial velocity	++	O	-

Table 26: Comparison of ADS/ADAS sensor capabilities from [159].

	Camera	LiDAR	Long Range Radar (77 GHz)	Short/Mid-Range Radar (24 GHz)	Ultrasounds (48 kHz)	Option cost
Parking Assist	X	X		X	X	~300 €
Lane Keeping assist	X	X				~600 €
Automatic Emergency Braking	X	X		X		~1500 €
Adaptive Cruise Control	X	X	X			1000 – 1500 €
Blind Spot Detection	X			X	X	~600 €
Traffic Sign Recognition	X					~600 €
Night Vision Systems	X	X				2000 – 2500 €
Adaptive Front-lighting	X					2500 € (LED-matrix)

Table 27: Comparison of driver assistance systems, obtained from [56].

9 Overview of Sensor Fusion

Major perception sensors used in driving automation systems have been profiled in this report. Although the technology community is continually improving these sensing technologies by introducing new hardware and software techniques, the goal of reliable and safe driving automation systems is still unrealized because of gaps in performance of the sensors and the corresponding perception algorithms. Indeed, it can be postulated that once an accurate understanding of the driving environment is gained, driving automation reduces to a well-defined task constrained by a finite number of traffic rules of regulations (e.g., right of way, implications of traffic lights and signs, etc.). Therefore, achieving human-like perception capabilities remains the Holy Grail for fully automated driving systems. Since performance gaps of one sensor can be complemented by another, software techniques can be developed to improve perception capabilities by leveraging strengths of each sensor. For example, despite the ability to provide excellent color and texture information which are particularly suitable for object identification and classification, resolving range of identified objects from 2D image data remains a challenging task. On the other hand, radar sensors provide reliable ranging performance. Fusing data provided by these two types of sensors can provide meaningful understanding of the driving environment in terms of what (object classification) and how far (ranging). These techniques of combining multiple sensor data together to improve perception of the surroundings is collectively called sensor fusion. A more formal definition is provided by IEEE Geoscience and Remote Sensing Society [160]: "*the process of combining spatially and temporally-indexed data provided by different instruments and sources in order to improve the processing and interpretation of these data.*"

The aforementioned definition touches on the important concept of data alignment, which is a requirement for sensor fusion. Multiple data sources must be aligned both spatially and temporally [161].Spatial alignment for multiple sensor data refer to the characteristic of being expressed with respect to a common coordinate frame. For example, an image sensor and an IMU provides spatial interpretation of driving scene and vehicle motion in their respective coordinate frames. In order to fuse the data together, the relative position and the orientation of these two coordinate frames must be known so that spatial alignment of the data provided by the two sensors can be established. Besides spatial alignment, temporal alignment of data sources is required for meaningful sensor fusion. When the acquired sensor data is constantly changing, the data segments to be fused must represent the same point of time. In case of the example above, each image frame must correspond to IMU data acquired at the same time. The widely used robot operation system (ROS), which forms the software basis of many demonstrated driving automation systems, and provides the functionalities of time stamping sensor data to this end. In terms of architecture, sensor fusion can take place at different levels of the perception pipeline (i.e., raw sensor data > filtering > feature extraction > feature tracking > perception with spatial and temporal context). In [161] three basic types of sensor fusion architectures have been identified:

- **Low-level sensor fusion**: Raw sensor data is fused in this scheme. The obvious advantages include easy time synchronization at the cost of high computational load associated with fusing large volumes of raw data. Furthermore, the resulting fusion algorithm is considered rigid because any inclusion/exclusion of sensor inputs warrants significant redesign of the algorithm.
- **Feature-level sensor fusion**: Raw sensor data is analyzed to identify features within. Feature-level sensor fusion occurs at this stage. Since fusion occurs after raw sensor data is converted into feature-identifying information, the computational load of fusion is lower than low-level fusion. The data fused at feature level can serve as an input to a tracking algorithm.
- **High-level sensor fusion**: In this scheme, fusion occurs after the perception pipeline of each sensor is completed. Extremely lightweight and information-rich data is fused to offer low communication overhead and modularity of the system.

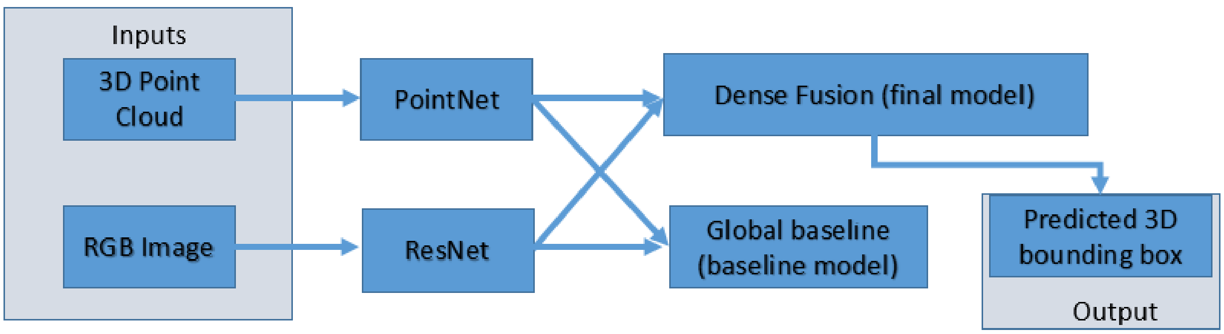


Figure 30: Sensor fusion between image data and point cloud, obtained from [165].

The underlying mathematical models used for sensor fusion employ statistical techniques such as Kalman filtering, convolutional neural network, central limit theorem, etc.

10 Overview of Vehicle Bus Systems

With the strong push from government, customers, and competitors for safer and more comfortable vehicles, automotive manufacturers are continually driven to add additional functionalities. In order to deliver on these pressures, previously simple sub-systems are receiving drastic modernizations with the inclusion of electrical control systems with the ability to sense, actuate, and control all elements within the system to fulfill these needs. As more traditional automotive systems become combinations of electrical and mechanical systems, the computational complexity for managing and controlling these new tasks will continue to grow. The modern day automobile can be imagined as a highly complex distributed computing platform consisting of many sub-systems controlled by Electronic Control Units (ECUs). ECUs can come in many form factors, ranging from simple hobbyist microcontrollers, such as the Arduino platform, all the way to highly complex embedded systems consisting of mixes of Field Programmable Gate Arrays (FPGA), Central Processing Units (CPUs), Graphical Processing Units (GPUs), etc. These devices, which can be viewed as dedicated computing hardware for the sub-system, act as the functional brain of each of the sub-systems.

ECUs provide a platform for the equipment manufacturers and their suppliers to generate action and meaning from isolated sensor data. Currently, production cars are equipped with at least one unit, some of the more advanced vehicles contain 70 or more ECU's that send and receive 2500 or more signals [162]. In order to ensure proper functioning of the vehicle as a system, each of the sub-systems need to be able to communicate efficiently and effectively. This fundamental requirement for robust communications is not unique to the automotive industry and is a challenge facing all major industries. The shared cost related to research and development has allowed significant advancements in current generation technologies and protocols, while also generating the next big communication technology. For almost all industries the goal is to develop frameworks that are capable of providing solutions to the following challenges; high-speeds, determinism, fault-tolerance, security, and flexibility. Unfortunately, these challenges are often coupled, which means that the engineer designing the sub-system will need to make trade-offs when selecting a communication bus technology for their application. These functional requirements for communication are most often derived based on adherence to known safety standards and requirements. A good overview of automotive architectures and application requirements can be found in [163]. Networked systems are already everywhere in production vehicles, everything from the chassis, air-bag, powertrain, body and comfort electronics, diagnostics, x-by-wire, multimedia and infotainment, and wireless and telematics are running off a networked computing platform [164]. Table 28 shows each sub-system and their requirements from their supporting communication networks. While it is desirable for standardization of communication protocols, it has not always been practical.

As the automobile originally began to add more and more complex engineering solutions, the amount of wiring also drastically increased, driving the cost and the weight of the vehicles up. The desire for cost savings and simplicity lead to the first deployment of protocols similar to the more standardized interfaces introduced into the automobile today [164]. The original fieldbus was a simple serial bus which allowed for messages to be sent and received from other devices (nodes) listening on the bus. It was quickly determined that a standardized methodology for interfacing with the bus and components was required, leading into the development of the Controller Area Network (CAN) [164]. Many automotive protocols leverage a layered approach, Figure 31 provides a visual depiction of the layers.

Subsystem	**Fault-tolerance**	**Determinism**	**Bandwidth**	**Flexibility**	**Security**
Chassis	YES	YES	SOME	NO	YES
Air-bag	YES	YES	SOME	NO	YES
Powertrain	SOME	YES	YES	SOME	YES
Body and Comfort	NO	SOME	SOME	YES	YES
X-by-wire	YES	YES	SOME	NO	YES
Multimedia/infotainment	NO	SOME	YES	YES	YES
Wireless/telematics	NO	SOME	YES	YES	YES
Diagnostics	NO	SOME	YES	YES	YES

Table 28: Automotive subsystems and their major requirements.

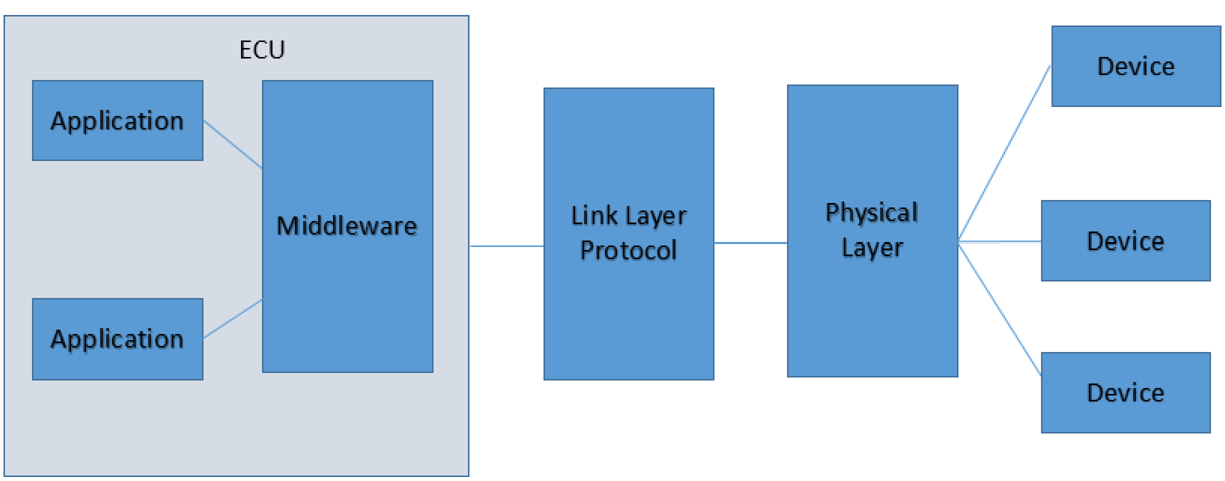


Figure 31: layered view of communication networks.

10.1 Controller Area Network (CAN)

Controller Area Network (CAN) is the most widely adopted communication technology in the automotive industry. A CAN may consist of many devices connected on a single network. This drastically reduces the requirement of wire harnesses within the vehicle as a single CAN can service multiple sub-systems.

CAN has many features that make it a robust choice for automotive networks. CAN leverages the concept of multi-masters, in which any device may send data if there is currently no information being transmitted on the bus. In addition, CAN also gives determinism with a guarantee of latency as the worst-case scenario timing for a message to travel on the bus can be calculated. Finally a priority system is built into the messaging structure that allows for more critical messages to always take priority over the bus. This ensures that these messages are always answered first. However, authorization of sending a high priority message over the bus is not enforced, and any *rogue* node can potentially start sending a series of high priority messages to stage a denial of service (DoS) attack.

Within CAN there are three main application specific configurations that can be seen on vehicles; High speed, fault-tolerant, and single wire. High speed CAN is the most used version as it allows for the highest rates of data transfer at 1 Mbps. In production vehicles, this network is used for real-time systems communications often at a reduced speed (500 Kbps). Fault-tolerant configurations are robust to wiring or configuration problems but operate at much reduced data rates (125 Kbps) to improve noise tolerance. Single-wire CAN uses a single wire rather than the standard twisted pair. It should be noted that a twisted pair CAN network realizes the fault-tolerant advantages of differential signaling, while a single-wire CAN favors cost efficiency over robustness. Nonetheless, the speed of transmission is reduced significantly in single-wire CAN to maintain some amounts of fault tolerance. They often operate between (33.3 – 83.3 Kbps) [165]. On a modern production vehicle there are many combinations of these networks to service the ECUs.

10.2 Media Oriented Systems Transport (MOST)

Media Oriented Systems Transport (MOST) was first developed in 1997 as a means for multimedia applications to communicate at high speeds within the vehicle. The MOST protocol often provides a communication bridge for devices such as GNSS navigation and video displays. One of the unique features of the MOST protocol is the ability for nodes to form a ring topology. Essentially, this means that all preceding nodes are forwarding information or data to the next node in a cycle. Within the network there are some special nodes which handle synchronization and management for the entire ring [165].

10.3 Local Interconnect Network (LIN)

Local Interconnect Network (LIN) was first developed in 1999 by Motorola and an automotive consortia, and was first introduced into production vehicles in 2000. LIN is a lower cost network when compared to frameworks like CAN, but to reduce the cost the speeds are quite low (20

Kbps) when compared to other frameworks. LIN is often found in much less critical systems such as the seat controls and door locks. LIN is often integrated into CAN networks as a simple cost effective extension for non-safety related applications. LIN is added to a CAN using devices known as LIN/CAN gateways. The gateway devices act as translators, converting the message into the desired format to integrate onto a higher level bus.

10.4 FlexRay

FlexRay has been advertised as the next generation automotive bus that will provide solutions to the challenge of high-speed and fault-tolerant communications. The FlexRay protocol was released in 2005 and was first utilized in the BMW X5 in 2006. FlexRay leverages two channels for moving information between devices. Each channel has the capability of working independently but are also sometimes used to transmit the same data for validation and verification purposes [166].

	LIN	CAN	FlexRay	MOST
Application	Low-Level Communication Systems	Soft Real-time Systems	Hard Real-time Systems	Multimedia Telematics
Bus Access	Polling	CSMA/CA	TDMA/FTDMA	TDM/CSMA
Control	Single master	Multiple master	Multiple Master	Timing master
Physical layer	Electrical	Electrical	Electrical/Optical	Optical
Bandwidth	19.6 Kbps	1Mbps	10 Mbps	24.8 Mbps
Bytes/Frame	0-8	0-8	0-254	0-60
Redundant Channel	No	No	Two channels	No

Table 29: Automotive Bus System comparison [162].

10.5 Ethernet

Ethernet as a technology has a highly unique position when compared against the other alternatives for communications within the automobile. Due to the mass adoption of Ethernet within other big industries such as IT and Telecom, significant advancements have been made and cost shared with those other industries. Within the vehicle, Ethernet provides a network that is designed to handle the increasing bandwidth and scalability demands required of future ADAS, driving automation, and active safety systems. Open Alliance Special Interest Group (http://www.opensig.org) is a group of OEM and suppliers that wishes to move to wide scale adoption of automotive Ethernet as a standard. It can be regarded as a special case of Ethernet with additional domain-specific requirements of EMI/RFI emissions and susceptibility, bandwidth requirements, latency requirements, synchronization, and network management requirements. Open Alliance is promoting BroadR-Reach [167] as a physical layer standard for automotive networking to enable multi-access full-duplex communication at 100 Mbit/s with a single unshielded twisted pair wiring. Automotive Ethernet will address some of the latency, bandwidth, and security issues associated with the current industry standard CAN-bus. Furthermore, Ethernet meets the demand for powerful data transmission, while maintaining a reduced cost and improved flexibility when compared to most other network technologies [168]. In addition, utilization of Ethernet allows for much simpler integration when looking at V2V and V2I communications using Dedicated Short Range Communications (DSRC) and Wireless Accessing Vehicular Environments (WAVE). However, this is an evolving network protocol, and it remains to be seen how quickly it can find traction within the industry at a wide scale.

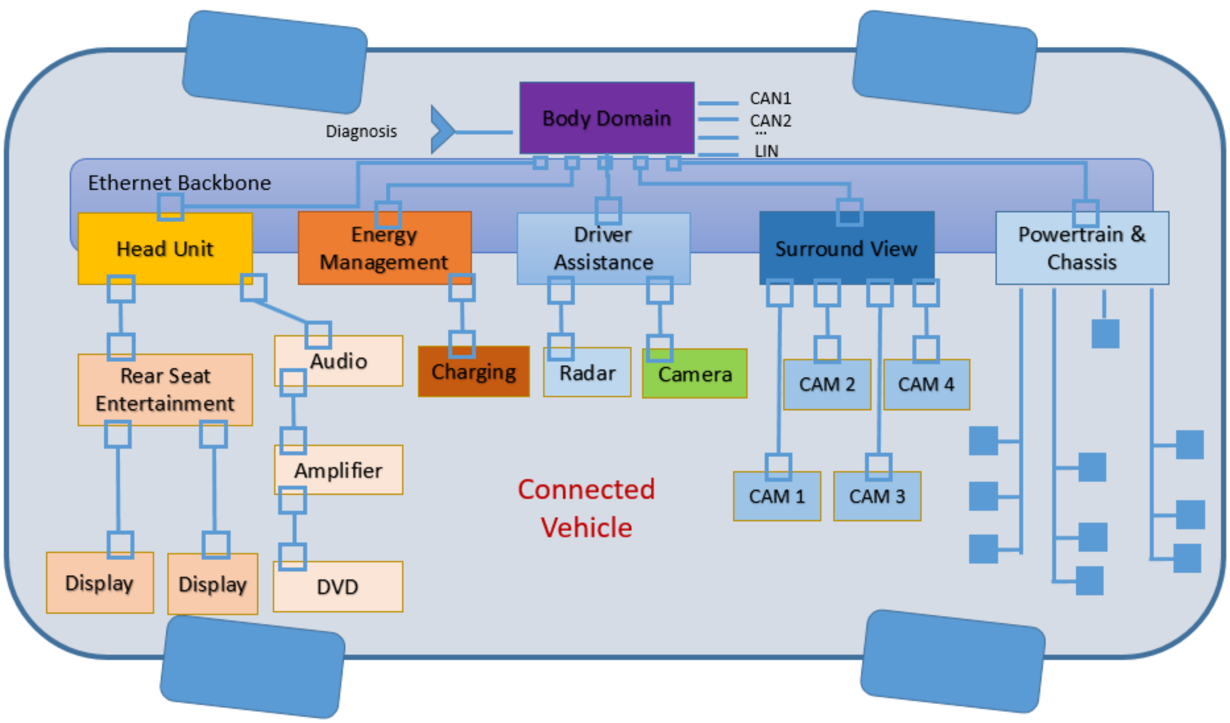


Figure 32: Ethernet backbone in domain architecture [168].

10.6 Wireless

Wireless technologies are being explored due to the cost savings associated with removing of wiring. Table 30 showcases the basic characteristics on the popular wireless technologies.

Technology	Bluetooth	ZigBee	Wi-Fi	UWB
Data rate	1-3Mbps	25-250 Kbps	54 Mbps	27.24 Mbps
Operating Frequency	2.4 GHz only	2.4 GHz, 915 MHz, and 868 MHz	2.4, 3.6, 5 GHz	7.5 GHz

Table 30: Comparison of wireless technologies [102].

11 Conclusion

Driven by a highly competitive automotive market, new investments in mobility innovation have resulted in production vehicles becoming increasingly feature-rich each year at an arguably unprecedented rate. Driving automation and active safety systems have seen the most transformation as a result of these market drivers. The central value proposition of these systems can be characterized as the ability to appropriately respond to the ever-changing driving environments to potentially increase convenience and safety. It must be noted that formulating an appropriate response to the changes in the driving environment is largely deterministic as long as quantitative understanding/characterization of the environment is available. Sensors used in driving automation systems are the means to gain this understanding.

Sensors provide raw data that must be analyzed using appropriate perception algorithms to sufficiently characterize the driving environment so that the vehicle can follow a safe path of travel. Obtaining robust and reliable perception from raw sensor data remains a topic of active research. In recent years, neural network based identification and classification algorithms have gained much attention in the related literature. It can be postulated that the advent of artificial intelligence and the availability of unprecedented computing power at low cost and low power (i.e., deployable computers) have been the strongest drivers behind driving automation system as a prospective mass marketed product. Driving automation systems employ artificial intelligence to utilize perception sensor data for classification, segmentation, and identification tasks. It should be noted that the neural networks that perform these tasks are trained by large datasets that have been mostly annotated by humans. A few openly available datasets are the most prevalent in the related literature.

This technology review has profiled prominent perception sensors to highlight the performance gaps, achievements, and opportunities for improvements. The development of these sensors are expected to continue until reliable and robust driving automation systems are fully realized for consumer market. Nonetheless, the following observations are made from the survey of the related literature:

- In optimal weather conditions LiDAR sensor provide high-fidelity ranging information to achieve reliable performance from driving automation systems. However, weather-induced performance degradation, and high cost are the two major issues keeping LiDARs from being deployed in mass marketed vehicles.
- Radar sensors provide reliable ranging performance, and they are largely unaffected by sub-optimal weather conditions. Correspondingly, production vehicles offering features like automatic braking for collision mitigation or adaptive cruise control are already equipped with radar sensors. However, radar performance in the current state of the art is limited by low angular resolution and narrow FOV.
- Vision sensors are particularly suitable for identification and classification tasks. However, employing them for range measurement is a challenging proposition. Furthermore, vision sensors are highly sensitive to ambient lighting conditions. Despite these drawbacks,

vision sensors are expected to maintain a strong presence in future driving automation systems. Paradigm shifting development trends such as event cameras and imaging in the infrared spectrum are topics of current research and development activities.

- Inertial measurement units are expected to be an integral part of driving automation systems. In addition, active safety features rely heavily on IMU to determine vehicle dynamics and the degree of corrective actions.
- GNSS sensors provide global positioning in a cost effective manner. However, the typical localization accuracy is not sufficient for driving automation systems. Furthermore, roadway features like urban canyons, tunnels, etc. pose a challenge for GNSS-based positioning. Providing lane-level positioning accuracy can be mentioned as a performance goal for GNSS sensors in driving automation systems.
- Ultrasonic sensors will not play a central role in automated driving on highways. However, in low-speed and short range applications such as automated parking and robotic valets must employ them because of their ability to provide sufficiently accurate distance measurement performance at close range.
- Reliable perception regardless of weather conditions cannot be delivered by a single sensor, rather a suite of multiple types of sensors will be necessary to achieve this goal. The strengths of each sensor must be leveraged to address performance gaps of other sensors under a sensor fusion scheme.
- Since sensors provide an important function of characterizing the driving environment, physical attacks staged to confuse (i.e., sensor spoofing) and disable function (i.e., sensor jamming) can lead to catastrophic consequences. These attacks include defacing traffic signs to confuse the neural network models employed for identification and classification of driving scene images, software-define radio (SDR) attacks on GNSS reception, etc. Correspondingly, understanding these attack modalities and formulating appropriate countermeasures are being investigated by the research community.
- Vehicular data networks constitute the framework on which the architecture of a driving automation system is built. Determinism in throughput without any significant latency in the data communication and security are two principal performance characteristics. Since existing technologies are unable to deliver these demands, new types of networks such as automotive Ethernet are being developed as alternatives.

Sensors play an important role in the driving automation technologies. Although these sensing technologies have gained transcendental improvements in recent years, issues such as robust and reliable performance in all driving conditions, and cost will continue to drive innovation.

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