HETEROGENEOUS INTEGRATION ROADMAP

2019 Edition

Chapter 5: Automotive

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Chapter 5: Automotive

Executive Summary

This chapter is intended to provide a summary of key disruptive trends in automotive electronics in the upcoming years. The increased emphasis on autonomous driving as well as electrification of vehicles has resulted in enormous changes for semiconductors and batteries used and their packaging and heterogeneous integration in next-generation automobiles.

Key takeaways from this chapter will be the introduction of highly complex packaging for processors used in autonomous driving, integration of advanced communications, and the associated challenges with ensuring higher levels of reliability in all components based on new use cases for automobiles and general transportation going forward. Numerous advances are expected in sensor technology with advancements of Radar, LIDAR, and other sensing techniques. Integration of power systems will continue as cars continue to electrify. Lastly, Artificial Intelligence (AI) will be central to both the functionality and safety of the automobile, as well as in techniques used for advancing reliability of the electronic components.

The highlights are in Section 5 for processors, showing increased challenges of advanced CMOS nodes in automotive environment; Section 6 for sensors, indicating new technology changes for commercialization; and chapters 7 and 8 discussing the major topics of reliability and power train electrification respectively.

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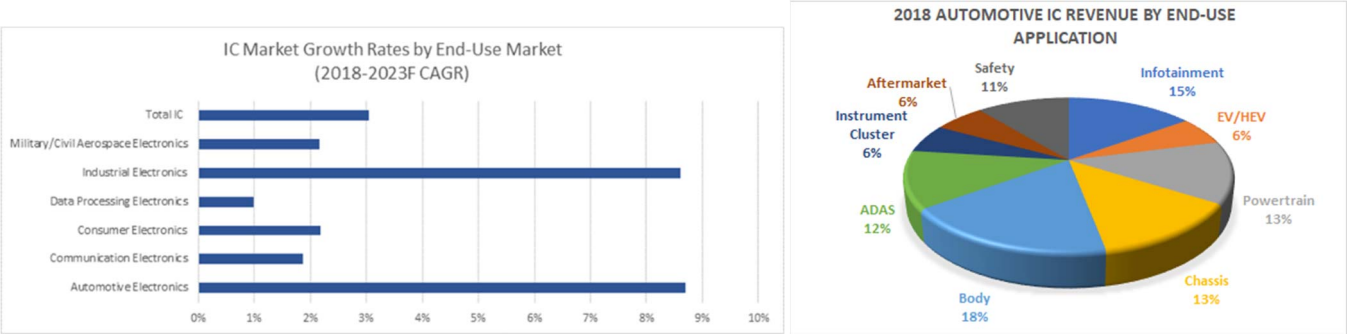
1. Introduction

Automobiles are becoming "Electronic Devices," unlike in the past, where they were mainly viewed as mechanical devices. Automotive electronics are expected to account for about a third of the total cost of the entire car, about $10,000 for each car. There are three major new drivers in Automotive Electronics: 1) autonomous driving, 2) secure, high-speed communications and infotainment, and 3) all-electric cars. Under these megatrends, there are more specific trends such as:

- Increased electronics content in cars without increasing the volume available for in-car electronics, requiring further miniaturization beyond current hardware approaches;
- Integrated electronics with hundreds of sensors and the computing electronics that are necessary to process the information;
- All-electric vehicles that require ultra-high battery power that is efficient and light weight for electric components such as electric motors, inverters, converters, control and driver electronics and high-voltage batteries;
- Data security and privacy;
- Continued emphasis on safety and reliability of new functions and their electronic components; Cost effectiveness of new electronics technologies for mass market adoption.

The new trends in automotive electronics such as autonomous driving, in-car smartphone-like infotainment, privacy and security, and all-electric cars, require enhancements in current semiconductor and packaging technologies as well as an entirely different set of technologies than those being pursued currently.

The automotive IC market is projected is expected to be leading the industry with 2018-2023 CAGR of ~9%, along with industrial electronics. Infotainment, chassis and body electronics will have approximately 15-20% of the total automotive IC market share. This is shown in Figure 1.



Source: Gartner 1Q2019

Figure 1: Automotive IC Market Growth Projection

This Chapter covers the current state of the art briefly and focuses on 5-, 10- and 15-year roadmap needs, challenges, solutions and gaps in the three main drivers for automotive electronics described above. It is organized into 5 sections:

- Connectivity and Communications
- Processor Roadmap
  - Advanced Driver-Assistance Systems (ADAS)
  - Infotainment
  - Other Processors
- Autonomous Driving Sensors (with general discussion about RADAR, and LiDAR. Camera sensors will be addressed in subsequent revisions.)
- Reliability
- Electric Drivetrain – power electronics and thermal management

3. Challenges

The key challenges in each of the three megatrends in automotive electronics are listed below. Development and optimization of new materials will be needed in all of the areas in automotive IC packaging.

- New materials
- Infotainment/ADAS:
  - Processor/memory integration
  - Thermal requirements, ambient conditions
  - Qualification requirement, especially safety for ADAS
- Sensors
  - Cost effective packaging
  - Performance requirements
- E/HEV segment
- Highly efficient power packaging

4. Connectivity and Communications

The electronics content in a car has been continuously growing, and is expected to increase in 2030 to about 50% of the total cost of an automobile. A recent premium vehicle contained more than 11,000 electrical components, more than 80 electronics control units, and more than 100 sensors. This trend in growth of electrical components for electrification and self-driving is going to accelerate as all the future technologies such as IoT, sensor fusion, 5G, artificial intelligence, and green energy start to merge into the future car.

We present an overview of the connectivity and communication requirements in a car and explain the various trends, as well as future roadmap.

Intra Vehicular: Intra-vehicular communication describes the exchange of data within the ECUs of the vehicle, which are involved in vehicular applications. Major intra-vehicular communication is of wired type, i.e. network based. There are some applications wherein wireless intra-vehicular communication is used.

Until approximately 2014, intra-vehicular communication was relatively simple. Two primary protocols were: Controller Area Network (CAN) and Ethernet. Bosch developed the CAN bus in the '80s so that processors could coordinate with each other and join sensors with lower-speed control applications in automotive systems. Then, the

ubiquitous Ethernet protocol promised higher speed communication possibilities in the automobile for navigation and control.

In addition, a flat panel display-link (FPD-link) system had the capability of easily sending video within the automobile with higher bandwidth and lowest latency for such additions as cameras. FPD links were not widely implemented except in premium cars.

However, with the trend towards more powerful Infotainment and ADAS/AV processor and sensor integration, there is a need for high-speed communication that supports high bandwidth and complex transactions. Fast-forwarding to 2017, Gigabit Multimedia Serial Link (GMSL) is emerging. This is SERDES-based and expected to deliver 30x faster data rates than Automotive Ethernet. Several companies, are starting to provide solutions based on this protocol. However, due to high-speed serial SERDES links, packaging and power requirements and thermal dissipation will need to be managed.

Vehicle-to-Vehicle (V2V): Vehicle-to-vehicle (V2V) communication enables vehicles to wirelessly exchange information about their speed, location, and heading. The technology behind V2V communication allows vehicles to broadcast and receive omni-directional messages (up to 10 times per second), creating a 360-degree "awareness" of other vehicles in proximity. Vehicles equipped with appropriate software (or safety applications) can use the messages from surrounding vehicles to determine potential crash threats as they develop. The technology can then employ visual, tactile, and audible alerts – or, a combination of these alerts – to warn drivers. These alerts allow drivers the ability to take action to avoid crashes. These V2V communication messages have a range of more than 300 meters and can detect dangers obscured by traffic, terrain, or weather. V2V communication extends and enhances currently available crash avoidance systems that use radars and cameras to detect collision threats. This new technology doesn't just help drivers survive a crash – it helps them avoid the crash altogether.

Vehicles that could use V2V communication technology range from cars and trucks to buses and motorcycles. Even bicycles and pedestrians may one day leverage V2V communication technology to enhance their visibility to motorists. Additionally, vehicle information communicated does not identify the driver or vehicle, and technical controls are available to deter vehicle tracking and tampering with the system. V2V communication technology can use either wifi-based or cellular technologies.

Vehicle to X (V2X): Vehicle-to-Everything (V2X) communication allows a vehicle to communicate with other vehicles (V2V), pedestrians (V2P), road-side equipment infrastructure (V2I) and the Internet(V2N). With V2X, critical information can be exchanged among vehicles to improve situational awareness and thus avoid accidents. Furthermore, V2X provides reliable access to the vast information available in the cloud. V2V can be considered a sub-section of V2X. Cellular-based V2X communications have already been standardized by 3GPP, based on LTE Release 14, as described in the 2016 5G Americas whitepaper, "V2X Cellular Solutions".

This is represented in Figure 2.

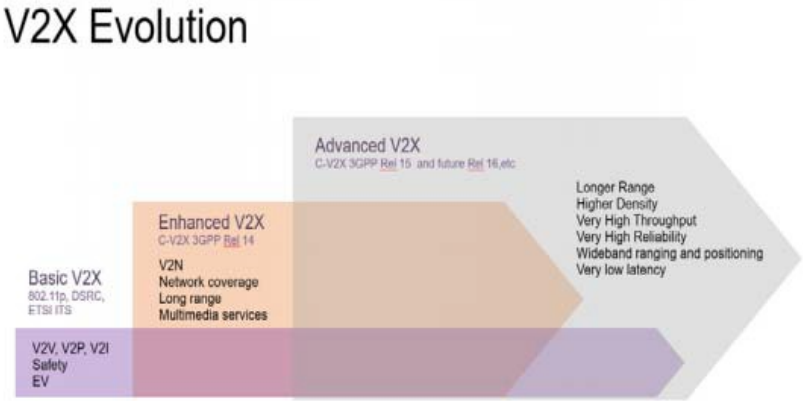


Figure 2: Vehicle communication Evolution

WiFi-based Communication: In the U.S., the NHTSA is considering using IEEE 802.11p-based DSRC technology for V2Vcommunications. The technology was developed specifically for V2V applications that require critical latency of ~100ms, very high reliability, and security authentication with privacy safeguards. The DSRC standard was finalized in 2009 and has been subjected to extensive testing by automakers and select largescale trials. Stakeholders have completed work on use of DSRC to protect vulnerable road users. The Federal Communications

Commission (FCC) allocated dedicated spectrum for transportation safety applications in 1999 in the 5.850-5.925 GHz band to ensure operation without interference that DSRC-based V2V systems plan to leverage.

Cellular-based Communication: Recently, attention has also been focused on cellular LTE technology which is quickly evolving to meet the needs for V2X communications. The current LTE standard in 3GPP Release 13 is not capable of meeting the low-latency and high-speed requirements of safety-critical V2V applications. However, the completed 3GPP Release 14 LTE standard does include support for cellular-V2X (C-V2X) use cases, enabling cellular technology as an additional option for the majority of V2X applications. In addition, the ability to leverage existing cellular infrastructure, with its broad coverage footprint, would reduce costs and accelerate the realization of the safety and efficiency benefits of V2X communication.

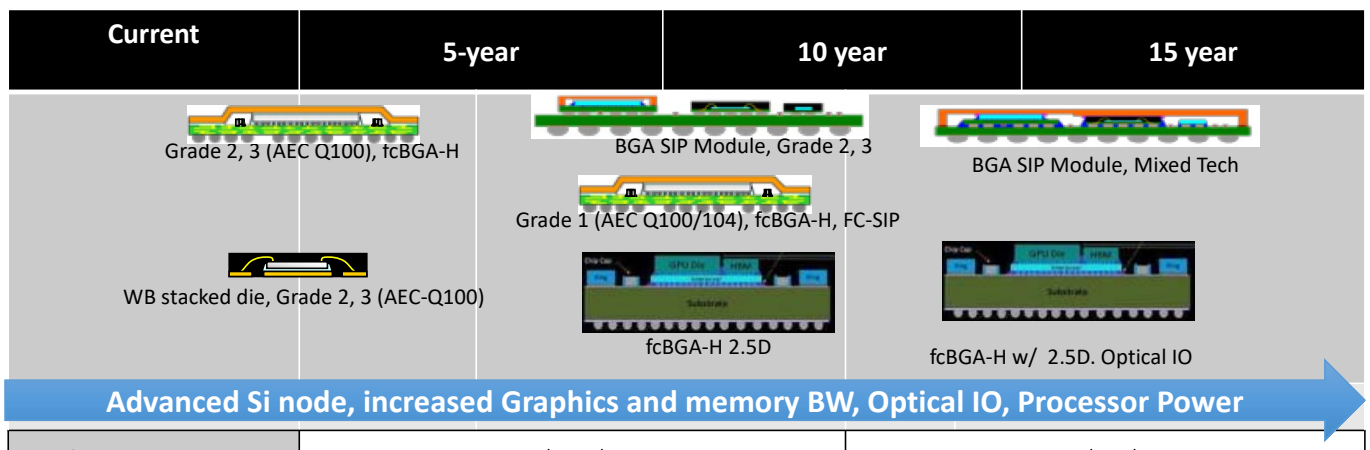
Summarizing, a key trend would be the replacement of a central CPU by a CPU-hub or decentralized CPU system. Even though the entire architecture is still evolving, it's unlikely that cars of the future will have ONE central processor unit. Hence, understanding the processor roadmap and the packaging trends are discussed in the subsequent chapters.

5. Processor Roadmap

One of the major disruptive changes in the automobile electronics component is in the processor – from low processing power MCUs to extremely high-power application processors/ASICs. In Figure 3, we show the overall roadmap.

The primary drivers are:

- ADAS/AV processors with advanced Si nodes, as well as processing powers that parallel high performance computing and massive amounts of artificial intelligence and machine learning algorithms. This clearly changes the traditional low-performance MCUs that were prevalent in earlier generation cars. Especially important are the high speed SERDES IOs as well as the need for higher-bandwidth memory integration.
- Infotainment processors also share the same trends, but with lower performance requirements than ADAS processors.
- The need for the lower-performance MCUs will continue to be there for off-loading mission critical functions.



Si Node	40nm/28nm/14nm		10nm/7nm/5nm
Interface Speed (parallel), opto	High end 128 bit (32bit X 4 channels) →Massive parallelism Mid-end 64 bit (32bit X2 channel)		
Bump pitch	150um		<100um
Mounting structure	PCB Attach		SIP/Module
Reliability	AEC Q100 Grade 3/2/1	AEC Q100 Grade 2/1 AEC Q006 Grade 1	AEC Q100 Grade 1 AEC Q-104 for SIP
Safety	ASIL-B	ASIL-D?	

Figure 3: Automotive processor roadmap

The journey to autonomous driving has already started with Levels 1 and 2 functions available in most cars today. Figure 4 illustrates the five levels of autonomous driving as defined by the automotive industry.

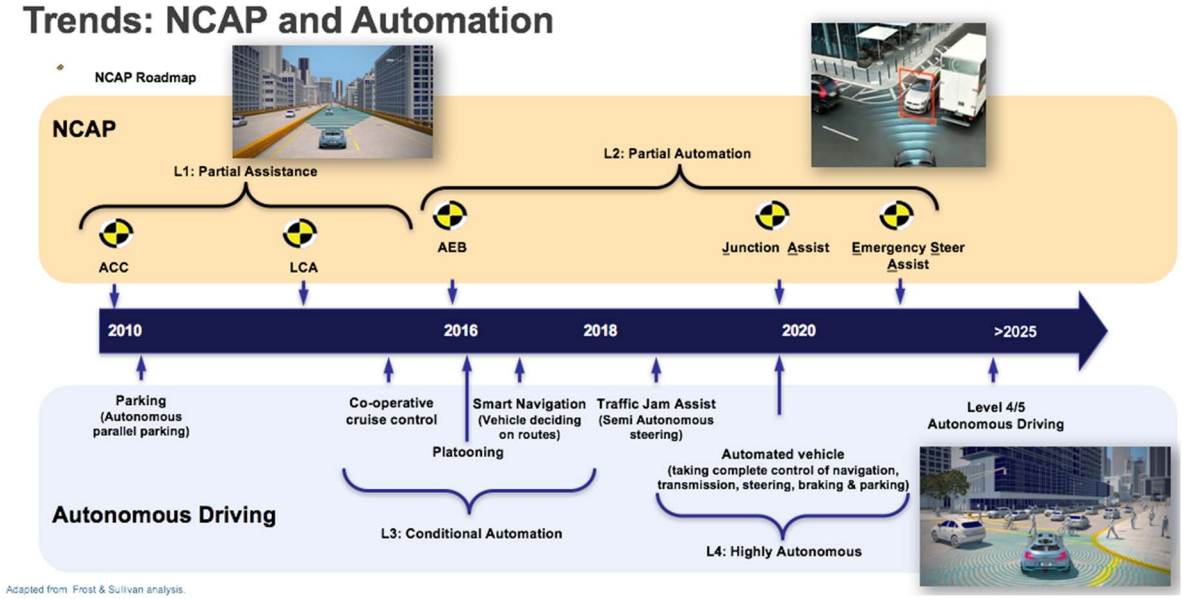


Figure 4. Five Levels of Autonomous Driving and One Example of a Roadmap to 2025.

Car manufacturers have gradually automated heretofore manual operations (parallel parking, adaptive cruise control etc.) that will culminate in fully autonomous (L5) vehicles in the near future. This is being fueled by the availability of inexpensive computational power. The advancement of complex software capability (machine learning) enabled by cheap transistor banks to rapidly execute complicated algorithms will enable delivery of full autonomy at an affordable rate in the next decade. The paradox is that the rate of change generally accepted by the automotive industry is far slower than the rate of Moore's Law phenomenon that has unleashed cheap transistors and exponential increases in performance over the last 5 decades.

The advanced features associated with modern vehicles to deliver ADAS functionality requires products manufactured using the latest technology that deliver higher transistor densities, or seamless integration of multiple IP blocks manufactured across multiple Silicon Nodes. Both approaches bring their respective challenges. The former approach delivers incredible performance/power to enable complex AI algorithms; however, building products on leading-edge silicon technologies implies higher tolerance to defects and higher cost. The latter approach requires use of multiple chips to provide necessary performance; however, that increases integration risks and costs, while not necessarily enabling the latest features. This approach of heterogeneous integration is rapidly evolving across the semiconductor industry. For an autonomous vehicle to be safe and successful, it is critical to deliver high compute power and low latency to support the workloads that a self-driving vehicle demands. It is equally critical to meet high quality, reliability and safety requirements at the lowest possible cost adder to the end consumer. Given the ubiquitous nature of personal entertainment devices that interact with cars (part of the infotainment experience), even the Infotainment processors are now requiring higher performance capability than typical MCUs – ability to support the latest SW capabilities (e.g. Apple Airplay or Android devices) and ability to provide security for the duration of car ownership. Although one can argue the semiconductor requirements (e.g. as measured by metrics such as DMIPS or TFOPS) for this infotainment category are not as stringent, they still need to deliver functionality that is current for the duration of car ownership.

5.1 ADAS

With the implementations of Advanced Driver-Assistance Systems (ADAS) and Sensor Fusion that will enable various levels of autonomy in automobiles, the overall electronic architecture has a great effect on the performance and complexity of individual components. These architectures vary from highly distributed processing points to more centralized processing centers within the system. This, in turn, will affect the component and subsequent packaging choices.

In general today, PBGA is the package of choice for ADAS processors. Wirebond interconnect is still commonplace today, with solder flip-chip interconnect now being applied. Heat spreaders were not commonly used in automotive processors, but are now being implemented within and on top of the package. Typical ball pitches range from 1.0mm down to 0.5mm (depopulation). SoC is the most common component architecture, with few multi-chip packages being deployed.

Over the next 5 years, performance requirements will increase 50X or more to accommodate much higher bandwidths, requiring even higher thermal performance. This will drive higher densities, using Cu pillar interconnect and more advanced thermal techniques to remove the heat from the packages. Multi-die packages in side-by-side and stacked-die configurations will become more commonplace as non-volatile memory is integrated into close proximity of the processors. Quality and reliability are essential, so material sets will be engineered to improve package interconnect thermal performance from 105C Tj to 150-175C Tj. The use of cooling fans could start to become commonplace. Package quality must be at a level <<1dpm, which will require highly automated, repeatable, and robust manufacturing processes. Package on package (PoP) is not expected to enter into this application area in the near future.

Long term, in 10-15 years or more, it is easy to see that the new package architectures and structures using heterogeneous integration for high-bandwidth computing will be applicable due to the rapidly growing performance requirements of ADAS processors. The quality and reliability of these approaches under highly stressful environmental conditions over the next few years will determine the usefulness and implementation of these technologies.

For successful implementation of self-driving vehicles, there are four broad functional areas, namely "acquisition", "perception", "cognition" and "action". Acquisition serves as the sensing element to understand the surrounding environment. Perception/cognition is translation of the sensed data to an actionable item and then finally acting upon that data (decision) to enable some actuators (such as braking, turning, accelerating, etc.). While each of these functional blocks has unique challenges, it is perception/cognition that is most computationally intense as well as being very time sensitive. Figure 5 shows pictorially these functional blocks.

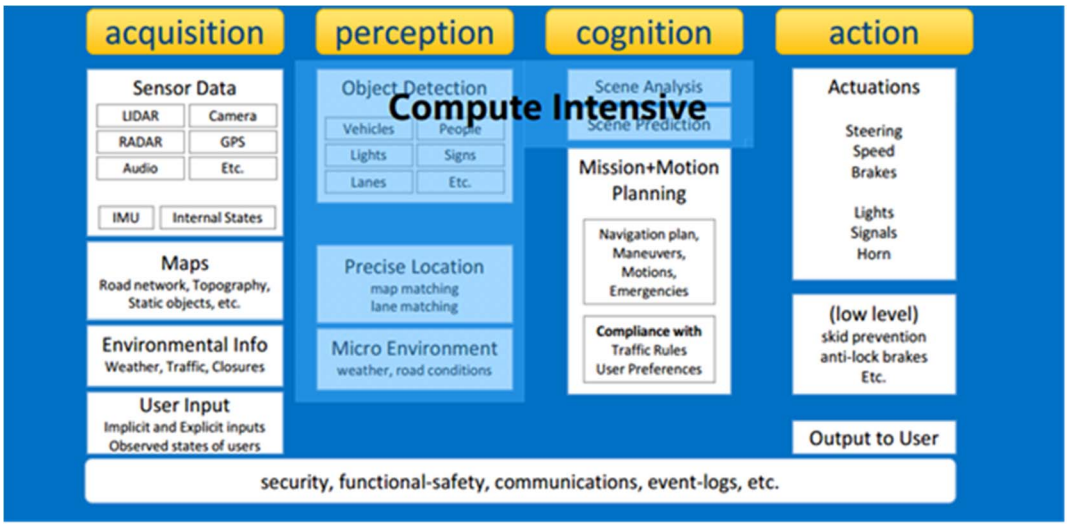


Figure 5: Functional Blocks for Self-Driving Vehicles

In order to deliver autonomy, it is critical to have the right compute capability with high bandwidth to deliver low-latency from acquisition to action demand of <100ms. In addition, the compute devices used in an autonomous vehicle must meet other key design/cost and reliability constraints that are unique to this market.

Broad challenges: As mentioned above, ADAS systems of any level will require significantly higher computational power than infotainment systems. Continuous integration of data from myriad sensors to determine local environmental risks drives the need for a system capable of making continuous decisions to complete complex tasks successfully. Some of the sub-system component requirements include:

- Holistic integration of attendant components necessary for higher performing CPUs, such as high-bandwidth memory, reliable power delivery sub-systems, etc. Although this concept is not new, the new sub-systems also happen to be high performing, new-to-market, perhaps made on latest-greatest technology (thus immature), making it difficult to provide the traditional auto needs of temperature, quality and reliability.
- Delivering highest performance at lowest power and smallest system foot print. This has significant implications to power delivery, thermal requirements and decisions related to system vs component optimization.

- The performance requirements and integration of features on a single device drives higher transistor count that invariably exceeds the transistor density advantage on the latest process node, thus increasing the need for larger-die products. This increased die size on the latest technology node brings real quality and reliability challenges, both from an intrinsic (defect density) as well as form factor (thermo-mechanical challenges) perspective.
- High system availability requirements to keep the system functional and safe require a deeper understanding of transistor, circuit and product behavior across the span of voltage and temperature. This will require a change in how quality, reliability and functionality goals are defined compared to the traditional zero defect (ZD) approach in the auto industry today. There needs to be a paradigm shift to system-level arguments related to quality, availability (reliability) and safety rather than component-level ZD approach.
- One challenge with modern technology is that obsolescence generally is not far from the time new technology/features mature. Given the traditionally rigid, controlled approaches in automotive (for good reason), today's car systems are generally sealed for 12-15 years, making any HW, SW and security upgrades both difficult and expensive. The autonomous world will not survive such rigidity given the complexity of SW and risks around security. An ability to upgrade features (functional or security-related), either via software or peripheral attachments, is becoming paramount, and requires reconsideration of antiquated requirements.

5.1.1: Packaging Challenge and Reliability targets

Beyond silicon, ADAS drives significant challenges in the packaging industry. ADAS-driven package changes can be categorized into three vectors: heterogeneous integration (consolidation of features), package feature scaling, and smaller footprint.

1. Higher functionality and integration at the package level:

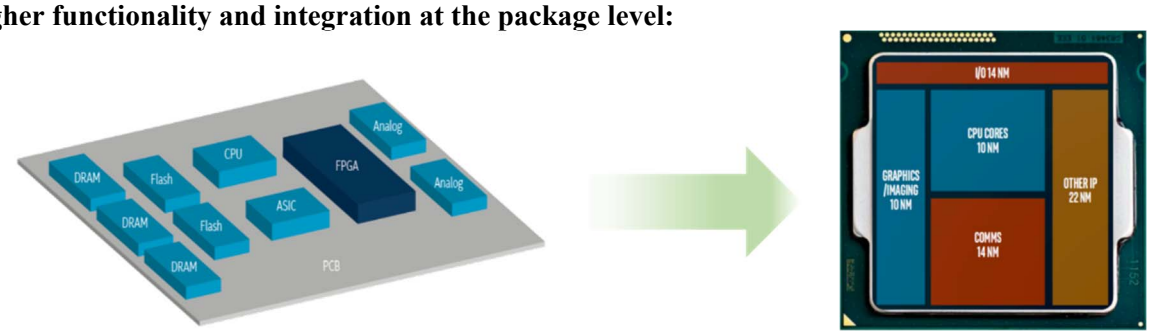


Figure 6: Board level to package level integration; higher bandwidth at low latency & power: integration of different IP blocks to deliver functionality

With increasing computational demand and high bandwidth at low power, the automotive market will follow a path similar to the cloud/HPC market, where integration of a variety of IP/silicon at the package level delivers desired features and performance. Integration of various silicon products on the package using 2.5D/3D architectures are well into development today, with mass adoption of these technologies expected over the next 10-15 years. This will bring challenges associated with integration and yield management; both will add significant cost that the automotive industry abhors. Furthermore, even though individual functional elements may be small, integration of these elements into a single, monolithic product, either silicon or as a multi-chip product (MCP), increases the silicon or package footprint. Increased silicon footprint can bring thermal and thermo-mechanical challenges, while the latter MCP approach drives thermo-mechanical challenges such as interconnect fatigue. A functional safety (FS) concept, a necessary requirement in ADAS space, can aid in the quality and reliability paradigm shift in the automated car space that is not possible in the infotainment space. Functional safety for fully automated cars will require redundancy of function at various levels. Given the built-in redundancy, and the fact that technology has to be updated more frequently than the traditional 15-year car life, what can the industry do to keep the whole system reliable while using less than perfect (but predictable) components.

2. Smaller system-level footprints:

A smaller footprint requirement will be strongly driven by autonomous driving (AD) markets; this is expected to be a unique requirement for this market segment primarily driven by available weight/space constraints in a vehicle.

The smaller system footprint will drive a smaller package footprint, which in turn will drive tighter board/substrate design rules, materials and innovative assembly processes.

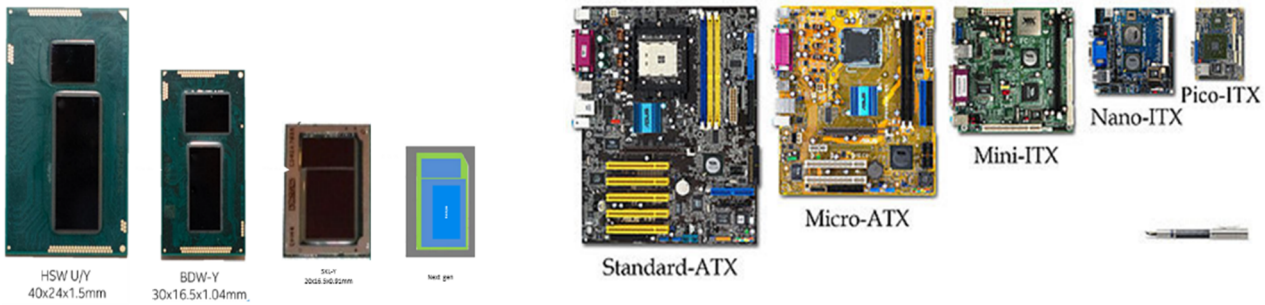


Figure 7: Smaller system footprints through advanced SiP and module integration

Thermal management requirements will be unique to AD markets which will drive significant innovation at the package/system level. On one hand, end products will require high compute capability driving high thermal design power (TDP), while on the other hand these products will be subjected to harsh environmental conditions with ambient temperature (Tamb) significantly higher in comparison to their traditional use conditions (aka: cloud/server); additional stringent cooling requirements will take away power from the overall car, potentially impacting fuel efficiency – which may be a non-starter for these markets; hence these markets pose a unique optimization problem of delivering high compute at lowest TDP and smallest system footprint.

3. Delivering reliability and Defects per million (DPM) targets

One the key challenges for the packaging community is to deliver highly functional capabilities at the package level while meeting the quality and reliability requirements at extremely low dpm goals.

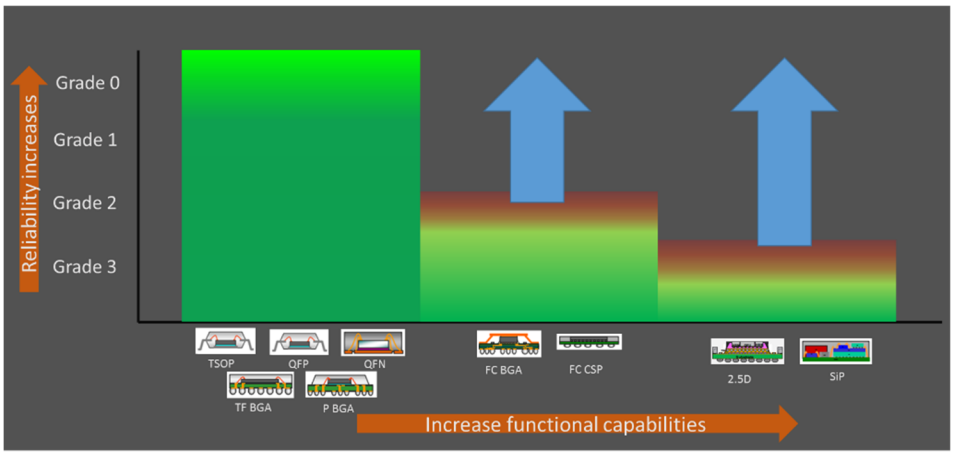


Figure 8: Role of Reliability requirements and functional capabilities

Figure 8 highlights on the y-axis the AEC-Q100 Grade qualification requirements (Grade 3-to-Grade 0) with Grade 0 requirements being the most stringent. Similarly, the x-axis shows the current capability of packaging technologies ranging from low I/O count QFN, QFP to FCBGA, to current state of the art technologies such as 2.5D/SIP. The figure highlights the key gaps for higher functional packaging technologies to meet higher reliability standards, important to AD markets. To improve the reliability while delivering higher functionality, significant investments are required to optimize design, materials and assembly/test processes. One vector is to invent/develop materials/processes to meet the high-temperature, harsh environment conditions and high usage-life requirements for these markets; another vector that needs attention is understanding the real-use condition these devices will see in a vehicle and translating to relevant reliability goals. The self-driving vehicle is expected to revolutionize the transportation segment from the trucking industry to the end-customer market. It is important to understand the reliability requirements for these segments and design products to these conditions rather than blindly chasing some standards-based requirements. Another point to keep in mind is perhaps the higher total cost of packaging to address these reliability goals; can the industry support it and amortize it to create profitable business for all.

One of the fundamental changes coming to the automotive industry is definition of mission profile (usage model or use conditions) for the transportation as a service (TaaS) segment. For decades, semiconductors were expected to

last for the equivalent of ~1000 operating hours/year. Different car manufacturers required components to operate for 12-15 years, despite a 3-5 year car warranty period. The ADAS usage model (especially L5), on the other hand, will make these assumptions invalid since cars will no longer be restricted in operation by the physical presence of drivers; rather, they may be expected to operate closer to 18-24 hrs/day.

Given that ADAS is a fledgling concept, the usage models or mission profiles are not very well defined. That implies that following AEC-Q standards (by the Automotive Electronic Council) designed for infotainment systems based on decade-old technologies is inadequate. This is one area where OEMs and Tier 1s will have to work with semiconductor manufacturers to ensure alignment and optimization across the chain to deliver high-quality products. Rather than tweaking the existing system, a fresh approach to agree on quality standards and goals is necessary. Understanding the use conditions under which these components will operate will allow analysis of the product under the entire operating range of variables (V, T, RH, time in state), and thus enable higher quality designs/products that can withstand the electrical and thermo-mechanical stresses a device will be exposed to during ADAS-type operation.

These increased operating hours will change the semiconductor infant mortality and reliability expectations, given the compressed operating time. As an example, a component qualified to operate ~10,000 hrs in life is now expected to operate for ~30,000 hrs in life. This ~3x shift in usage is bound to impact how the products are qualified, or impact their behavior in the field, without making significant changes to the existing specifications (e.g. AEC100) that govern such qualifications. Constant exposure to high humidity and high temperatures during operation will also have a detrimental impact on packaging components that will require a change in design and construction to provide the desired reliability. Finally, given the fact that higher performance at lower power and small footprint generally requires use of the latest technology (silicon or package), thorough characterization of that latest technology to ensure no latent failure mode lurks to provide zero defect is not easy.

Given that this higher performance/power ratio and smaller footprint generally requires use of the latest technology (for products), thorough characterization of that technology (silicon or package) is paramount to ensure no new and latent failure modes exist if a zero-defect mindset is to prevail. This is generally not practical given the lack of maturity of new processes early-on and a lack of early, high volume production in the automotive space, both of which drive processes to become cleaner and healthier, thus delivering the zero-defect product.

One approach being considered by OEMs is to utilize commercially available, off-the-shelf systems. As shown in Figure 9 below, typical consumer electronic components are generally manufactured with a different quality mindset, and a shorter useful life span, contrasting with automotive market expectations. One of the factors in this consumer space is the tradeoff between time to market and quality; faster access to higher performance (or new features) invariably requires taking higher risk. Both are not achievable at a low cost, especially if the desire is zero defects for the traditional automotive market. Differences such as these will have to be carefully considered before relying solely on the off-the-shelf commercial part utilization in ADAS-type systems.

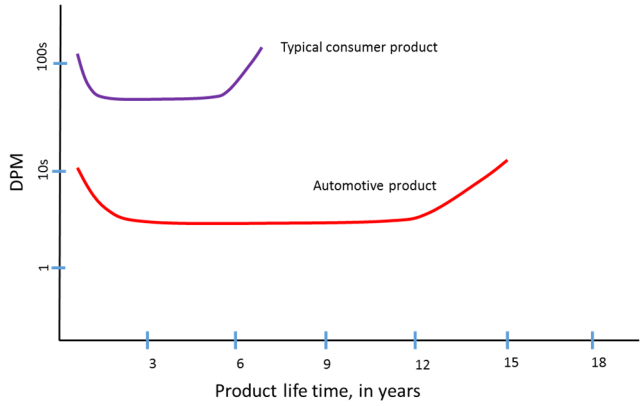


Figure 9: Quality requirements for different market segments

5.2 Infotainment

Infotainment processors will generally lag device performance requirements as compared to ADAS processors. The packaging technologies used will likely mirror those of ADAS, with less harsh thermal dissipation requirements. With V2X communications becoming critical to the function of the automobile, system security will be of immense importance. These measures will be implemented through software, IC architecture, and other places in hardware which might include the physical semiconductor package.

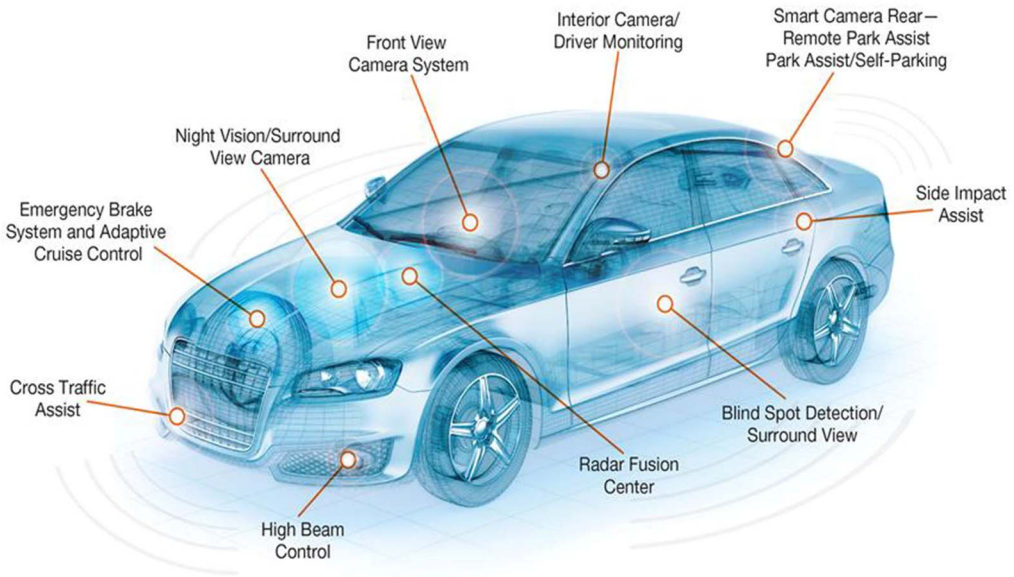
5.3 Other Processors

Other processors, such as microcontrollers or MCU's, have a wide variety of uses, including powertrain, chassis dynamics, cockpit controls, lighting, entry, and many more. These IC's have typically used leadframe packages such as QFPs with wirebond interconnect. This trend will continue with some increased use of fine-pitch BGA and flip-chip interconnect in the next 5-10 years as pin counts increase.

6. Autonomous Driving Sensors

Google's self-driving cars are reported on the road in several states [1]; Tesla announced that its cars will be fully autonomous in 2019 [2]; and Uber has opened a test facility in Pittsburgh [3] to develop an autonomous taxi fleet, in addition to road testing in selected cities. In addition, the regulatory framework for testing and operation of autonomous vehicles on public roads has been established in California. European car makers predict that the implementation of highly-automated self-driving cars will start in 2020 [4]. Autonomous driving technologies have progressed rapidly in recent years due to advances in vehicle sensors and communication technologies. These advances have led to better visibility and awareness – around the vehicle – and to features such as parking assistance, adaptive cruise control, lane-keep assistance, traffic sign recognition and pedestrian detection, as illustrated in Figure 10.

Sensing technologies are the key elements to enable migration to autonomous vehicles. The broad categories of sensors in AV are: Cameras, RADAR and LiDAR, and ultrasonics to a lesser extent. Table 1 below shows that, in general, combinations of various sensors are needed for the fully autonomous vehicle. Cameras provide vision, but not completely. RADAR, LiDAR, and ultrasonics are also essential for enabling autonomous driving. Autonomous driving demands highly robust sensing technologies all around the car for real-time detection, surround-view, and collision avoidance. By integrating the information obtained from all these sensor systems and processing the data in real time, through machine learning and artificial intelligence, fully self-driven autonomous vehicles can be realized. Table 1 shows the role of each sensing technology in autonomous vehicles.



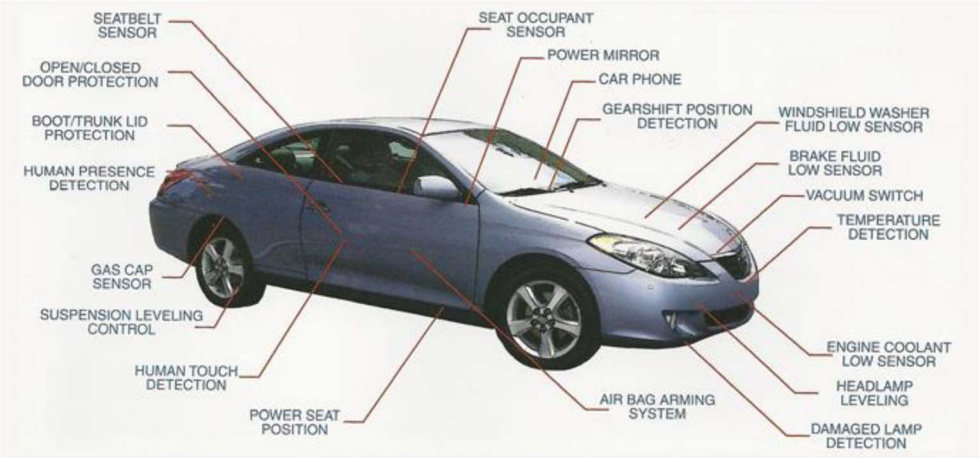


Figure 10(a) and (b). Advanced Driver Assistance Systems (ADAS) application example [5].

Sensor Objective	Camera	RADAR	LiDAR	Ultrasound
Adaptive Cruise Control		X	X	X
Emergency Braking	X	X	X	X
Pedestrian Detection	X	X	X	X
Collision Avoidance		X	X	X
Traffic Sign Recognition	X			
Lane Departure Warning	X		X	
Cross Traffic Alert	X	X	X	
Surround View	X			
Blind Spot Detection	X	X	X	
Park Assist	X	X	X	X
Rear Collision Warning	X	X	X	X
Rear View Mirror	X			
Drowsiness Detection	X			

Table 1: Sensing Technologies in Automated vehicles

6.1 Camera

Cameras are image-sensing devices that recognize and record objects. Typically, the automotive camera sees the object with the image sensor and processes the information using computer algorithms. The cameras are used while driving to recognize lane markings, traffic signs, traffic lights, animals, and pedestrians. The information obtained from these cameras goes through additional data processing to aid the decision of a vehicle to slow down, change lanes, or make a stop. Cameras are excellent in distinguishing and classifying objects, but their performance is often limited by environmental conditions such as rain, clouds, and non-illuminated or light-varying conditions.

The detailed trends and roadmaps for camera-based automotive sensors will be addressed in the next revision of this Roadmap.

6.2 RADAR

RADAR stands for RAdio Detection And Ranging. It is a system that transmits and receives electromagnetic waves in the millimeter range. The wave signals sent out by radar bounce off objects and are then reflected back. The radar system then captures these signals to discern the range, velocity, and angle of an object. Radar is particularly useful in detecting large objects, and in calculating speed and distance of vehicles and obstacles. Unlike vision-based systems, such as cameras, which deteriorate in harsher driving conditions such as rain, fog or snow, radar works in all weather and lighting conditions, day or night. However, radar cannot distinguish color or differentiate between objects. For example, all same-size objects would look the same to the radar.

For radar we will have to move from the 24 GHz band, which will be phased out, to the 77 and 79 GHz band. The higher frequency will allow better resolution for the radar signal. Today, in the 77 GHz frequency region SiGe semiconductors are the technology of choice, but RF CMOS is just starting to also enter the market,.driven by TI. At these high mm-wave frequencies, packaging of the semiconductor chips becomes very challenging. For example, a careful determination of high frequency material parameters is required (e.g. of package mold compound and dielectrics) to achieve a good design. We also need a careful chip-package co-design to achieve a reflexion-free

interconnect transition between chip and package as well as package and board. At 60 GHz and higher the integration of antennas in packages becomes attractive. Antenna dimensions becomes smaller than 1 cm. This topic of integration of antennas in a package at mm-wave frequencies will continue to be a topic of research for the next years with rising frequency.

In general, mm-wave performance and reaching automotive reliability are two critical challenges we need to solve. Both challenges dependent on the chosen materials. The next version of this roadmap will consider the RADAR aspect in more detail.

6.3 LiDAR

LiDAR stands for Light Detection and Ranging. It is a detection system that works on principles similar to RADAR, but uses light from laser diodes instead of millimeter waves. LiDAR transmits light pulses and interprets back-reflection from objects as shown in Figure 11. The lasers emit pulses to targets that return back to its source. LiDAR measures the distance by the time it takes for the light photon to return. By using a scanning device such as a rotating mirror with multiple channels, LiDAR detects the distance over a wider range and recognizes the object with high accuracy.

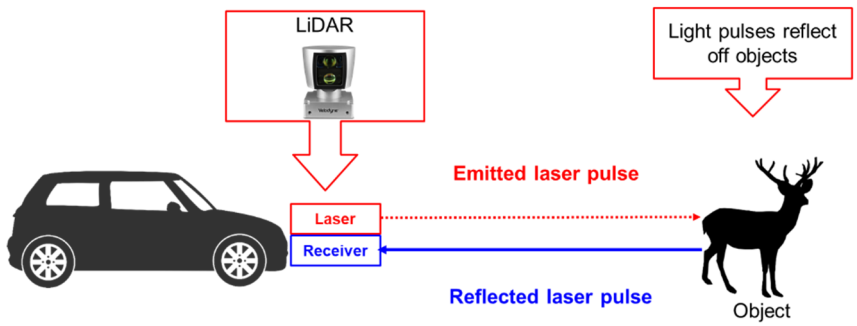


Figure 11: LiDAR sensor operation

A high level roadmap for LiDAR sensors is shown in Figure 12.

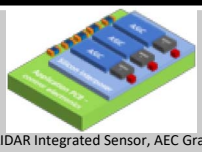
Packaging Architecture	Current	5-Year	10-year	15-year
LiDAR Module/SiP	 LiDAR SiP Stacked die, FBGA, AEC Grade 1, 2		 LiDAR Integrated Sensor, AEC Grade 0	 LIDAR Integrated Sensor, AEC Grade 0, High Density Si Interconnect
LiDAR Detection Range : Short Range (100m) to Long Range (100-250m)				
Package	Detector: C2W, bumped, FC, W/B ASIC: W/B, F/C Package: LFBGA, QFN, LGA, SiP	Detector: FC, PoP, W/B ASIC: W/B, F/C Package: LFBGA, QFN, LGA , MLP, WLCSP		Detector: FC ASIC: FC Package: WLCSP, FO WLP
Detector/ASIC per pkg Footprint	1 Detector / 1 to 3 ASIC 10x10mm	1 Detector / 1 to 2 ASIC 9x9mm	2-4 Detector/ 3 to 4 ASIC 8x8mm	>4 Dectector/ASIC
Substrate	Laminate, Leaded, Ceramic	Laminate or Ceramic	Laminate or Ceramic	Laminate w/high density Interposer
Optical Grade Window or Filter	Filter, Glass, or Plastic	Filter, Glass, or Plastic	Filter, Glass, or Plastic	Filter, Glass, or Plastic
Ball Pitch	0.8mm	0.7mm	<0.7mm	<0.7mm
Reliability	AEC Q100 Grade 1, 2	AEC Q100 Grade 0		>AEC Q100 Grade

Figure 12: LiDAR Detector Roadmap

Currently there are different configurations of LiDARs with different technologies as well as price targets. A summary is shown in Figure 13 with key vendors playing in this field.

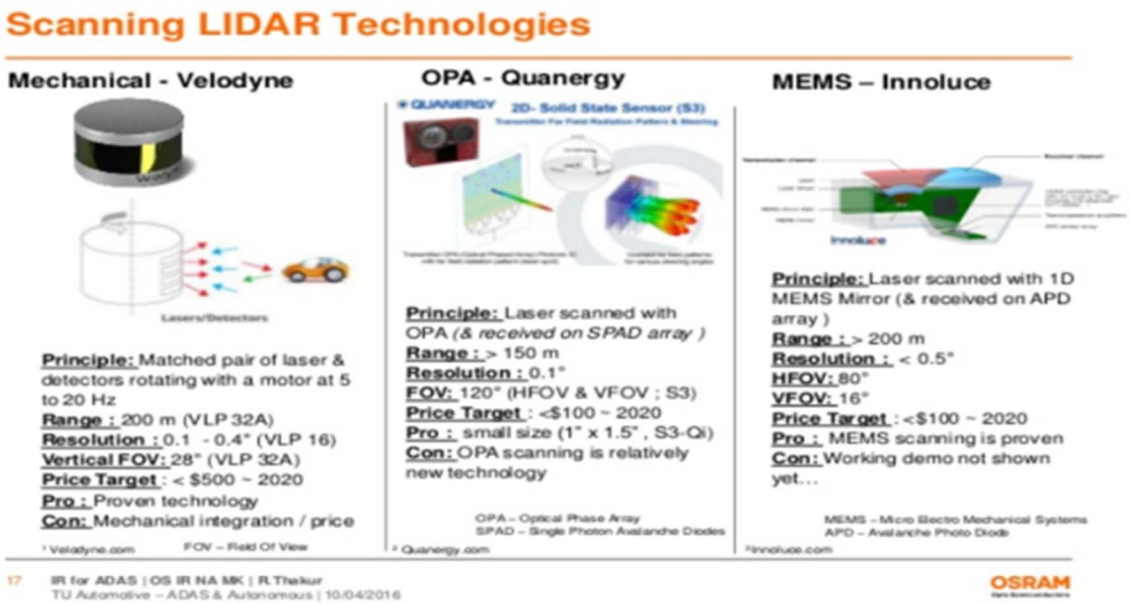


Figure 13: Scanning LiDAR Technologies

Table 2 summary of LiDAR technologies with key attributes.

Table 2 summary of LiDAR technologies with key attributes.

LiDAR System	Range	Reliability	Cost	Size	Systems per car
Mechanical	Long	Good	Mid to high	Bulky	1
MEMS Based	Medium to long	Good	Low	Compact	1-4 or more
Flash	Short	Very good	Low	Compact	1-4 or more
Optical Phase Array	Advantages: solid state design with no moving parts Disadvantages: loss of light that restricts the range				

Figure 14 shows two product examples of LiDAR systems from two different companies. They all have the laser emitter and receivers co-located on a single platform.

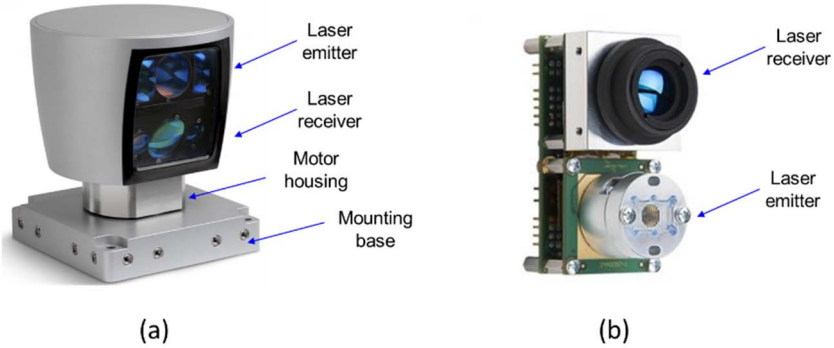


Figure 14: Two LiDAR systems from (a) Velodyne and (b) LeddarTech

As LiDAR technology gets more mature, the industry and the primary manufacturers are trying to overcome the many challenges in this nascent technology, such as cost, reliability, and performance in severe weather conditions (snow, ice, dust).

The next paragraphs provide the vision from one of the leading providers of LiDAR. This is one of the many approaches that could eventually be commercialized:

LiDAR is the most underdeveloped technology among the sensor technologies, and LiDAR manufacturers are investing heavily in R&D and manufacturing. Velodyne LiDAR has been leading the way for more than 10 years and is the single largest capital investment for LIDAR in the world. Over the next 5, 10, and 15 years, new developments in LiDAR technology will push Autonomous Vehicles into our everyday lives.

Currently, Velodyne offers 360-degree spinning LiDAR sensors which can capture the world in full 3D in real-time. Over the next couple of years, the product focus will split between L4-L5/full autonomy and L1- L3/ADAS solutions. The 360-degree spinning LiDAR sensors will be focused more towards full autonomy, while lower cost, forward-facing products such as the Velarray will be used for ADAS applications.

New core technology will also be introduced in the next few years. This includes Velodyne's solid-state LiDAR chip module, coined the "Multi-Chip Module" or MCM. LiDAR sensors that leverage this new design will be less expensive, easier to integrate due to their smaller size, and more reliable as a result of fewer moving parts. The technology will also be integrated into Velodyne LiDAR's existing Puck form factors.

Velodyne LiDAR's new approach to the development of solid-state LiDAR sensors reflects the application of a monolithic gallium nitride (GaN) integrated circuit, developed in partnership with Efficient Power Conversion (EPC). The design consolidates components, and results in significant advances in sensor miniaturization, reliability, and cost reduction. Each integrated circuit is less than 4mm square.

Along with cost reduction and reliability, LiDAR sensors will also need to have both an increased range, and be able to deliver more geospatial data points per second. The automotive industry has stated that their target in 10 years is for 30 million points per second of data with at least 200m of range on a 10% reflectivity target.

High-resolution LiDAR is critical for navigating autonomous cars and providing vehicle safety. It is expected that the VLS-128™ will become the new standard for fully autonomous cars and cars equipped with advanced safety features because of the unchallenged quantity of data it produces in real time at top speed.

Looking into the future, LiDAR sensors will also become more intelligent. Velodyne is developing several new features which will help with sensor health and monitoring, ASIL B safety ratings, and onboard sensor intelligence and algorithms. In the next 10 to 15 years, LiDAR sensors for automotive will be safety-rated, and will also be capable of advanced LiDAR data processing. Features such as onboard SLAM (Simultaneous Localization and Mapping), object identification, ground truthing, and lane recognition will all be possible at the sensor level.

Overall, for industry adoption, the cost targets have to come down to the ~$100 range (vs ~$3000 that is currently the standard price). This is a significant challenge to the manufacturing community.

6.4 Ultrasonic Sensors

An ultrasonic sensor is a device that measures the distance to an object by using sound waves. It measures distance by sending out a sound wave at a specific frequency and listening for that sound wave to bounce back, as illustrated in Figure 14. By recording the elapsed time between the sound wave generated and the sound wave bounced back, it is possible to calculate the distance between the sonar sensor and the object. Ultrasonic sensors are widely used in parking-assist functions, attributed to their typically short-range (< 2m) detection characteristics. The ultrasonic sensor monitors the area immediately ahead of or behind the vehicle, and recognizes obstacles in real time. If an object is detected, the sensor system sends a signal to the driver indicating the distance to that object. An example of an ultrasonic sensor used in an automotive application is shown in Figure 15.

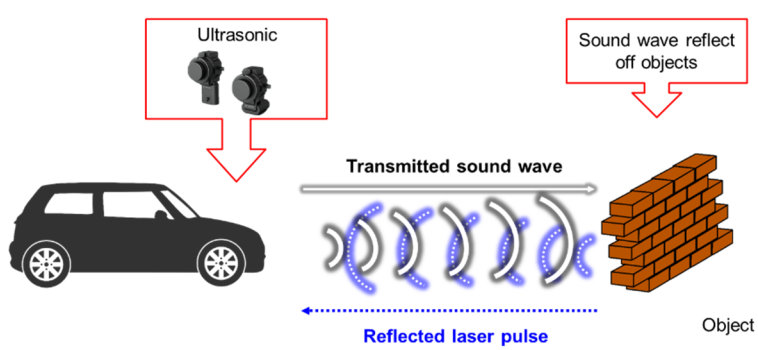


Figure 14: Definition of Ultrasonic Sensors

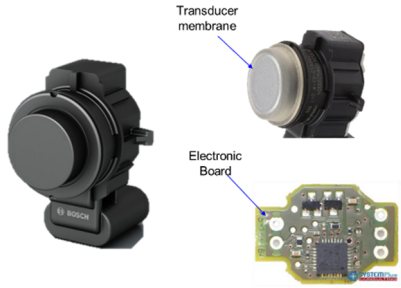


Figure 15: An example of Ultrasonic Sensor: Courtesy: Bosch

6.5 Sensor Fusion and Heterogeneous Integration of Sensors with FPGA/Embedded Machine Learning Chips to Enable Efficient Edge Perception

To further reduce the footprint of various sensors such as RADAR, LiDAR and image sensors, and their costs, and facilitate sensor fusion efficiency by reducing their data communication path length, it is desirable to pursue the heterogeneous integration of these sensors in close vicinity, rather than only take individual components with separate packaging and housing. Furthermore, there is now the pursuit of direct integration of sensors with data processing chips, such as the integration of image sensors with FPGAs to form a programmable image array, or embedding a chip with a machine-learning algorithm to dynamically control the sensor parameters to improve the sensor quality while reducing bandwidth from the sensor.

7. Reliability

Development of automotive electronic systems is driven by three major trends: Electrification, Autonomous driving and Connectivity. Each of these trends will bring specific reliability challenges:

- Electrification will revolutionize entire powertrain units and required road infrastructures. Slowly, combustion engines will decrease their market share. Power electronics will be one of the key drivers. For instance, utilizing SiC and silver sintering will increase the efficiency of power electronics and will raise the maximum operational temperature (200°C and above). New encapsulating materials are required to fulfill these new requirements. In addition, sensors and microelectronic components will be added to these systems so that heterogeneity and complexity is increased further. Still, the systems will have to be developed in a shorter time and at lower cost.
- Autonomous driving will revolutionize transportation systems. By 2025, conditionally and highly automated driving will reach SAE levels 3 and 4. By 2030, they will also be available in complex traffic situations, e.g., urban cities, and will even reach Level 5. Autonomous vehicles will increase safety, provide greater comfort, and improve traffic flows, which will lead to a significant reduction in overall emissions, especially when using electrical powertrains. As a consequence, operational time will significantly increase from roughly 9,000 hours towards 50,000 hours and more (considering charging time for the HV/EV).
- Connectivity will introduce components to harsh environments that were originally designed for consumer electronics only. Advanced packaging, such as SiP with small node size technology, will be used soon in automotive, requiring 15-year reliability. Connectivity will be one of the main drives that increases the operational time of IC packaging and ECUs used in automotive (e.g. software update during parking using WLAN instead of expensive GSM connections).

7.1 State of the art (History and Current Status)

The current design for reliability practice is based on the physics of failure approach. For application in passenger cars, the design of controllers and anticipated field loads allow a maintenance-free concept in most of the cases. Due to large efforts to acquire statistical load data from field usage, it becomes more common to refine the load collectives to true field loads. The targeted reliability can be validated in success-run tests. The electronic system is broken up into design elements along the system structure in such a way that the lowest-level entities fulfill a well-defined and well-assessable function under the given conditions of the use case. Therefore, the reliability design and validation process can be based on the following action points:

- Know the requirements and transform them into loads (legal requirements, environmental conditions, use-cases);
- Know the system (how it combines and shapes load paths);

- Calculate the loads on design elements (based on load paths and requirements);
- Transform loads into stresses per design element;
- Know the strength of the design elements (e.g. material models, formulated lifetime models);
- Compare stress and strength per original load domain on design elements;
- Validate reliability target by accelerated lifetime tests.

The depicted action plan requires a deep understanding of the failure mechanisms involved as well as validated material and lifetime models applying to them. The reliability "budget" is distributed over the design elements and loads. In many cases, finite element method-based calculations can contribute to reliability design and optimization by e.g. virtual design of experiments for sensitivity analysis and calculation of damage sums. The second step is an extensive study of interactions of different load types on design elements (e.g. temperature and vibration). The final validation also addresses corrosive loads.

Reliability of electronics systems as a professional discipline has existed since the 1960s. The first generation of reliability prediction relied on fixed sets of tests according to standards such as MIL Handbook 217 without accounting for the specifics of the individual product and application use case in detail. In the 1980s, numerous organizations found this procedure to be inaccurate. In the late 1990s, the 2nd generation of reliability prediction had been established based on specific mission profiles, the strength of the individual materials, and a detailed knowledge of the failure modes, degradation mechanisms and propagation speeds. Using modeling and simulation of the degradation mechanisms as well as data-driven approaches, the characteristic end-of-life reliability of the new product can be estimated. However, it does not capture the onset and the propagation of the degradation in an individual part.

7.2 Potential solutions

The 3rd generation of reliability methods is currently being developed. This new approach is based on condition monitoring in first wave and on prognostics and health management (PHM) as the second step. It will be supported by multi-domain numerical simulations and implementation of machine learning algorithms for fault detection and classification. It aims at determining the remaining useful life (RUL) of the individual system under its specific use conditions.

In general, the PHM methods are based on pre-indicators, which allow capturing the onset and the progression of the defects. They can be derived from the physics of failure (PoF) or from data-driven (DD) approaches. The PoF schemes often involve numerical modeling and simulation to replicate and to study the physical failure mechanisms in detail. The DD approach relies on statistical methods to deduce the RUL from the actual trends of functional or assessment parameters. The fusion prognostic methodology combines PoF and DD approaches and the advantages of both methods. It reduces uncertainty in the damage prediction by involving the full knowledge about the failure mechanisms but also taking into account the specifics of the actual system and its possible anomalies.

In order to develop the specific PHM measures for future automotive applications, a metro map-type of plan has been established (Fig. 16), to support five destinations of methodology research:

- Developing the required infrastructure, sensors, electronics hardware;
- Studying and characterizing the failure mode and mechanism effect by thorough analyses (FMEA) for both PoF and DD approaches;
- Providing appropriate solutions to data acquisition, management, and secure data transfer;
- Performing the data fusion for reaching at one integrating global health assessment, diagnostics, and prognosis score per application;
- Establishing a highly efficient digital twin for electronic control units based on precise metamodeling and model order reduction (MOR) schemes that can be executed in each of the individual cars locally (or in the cloud) assisted by self-learning capabilities provided by cloud services.

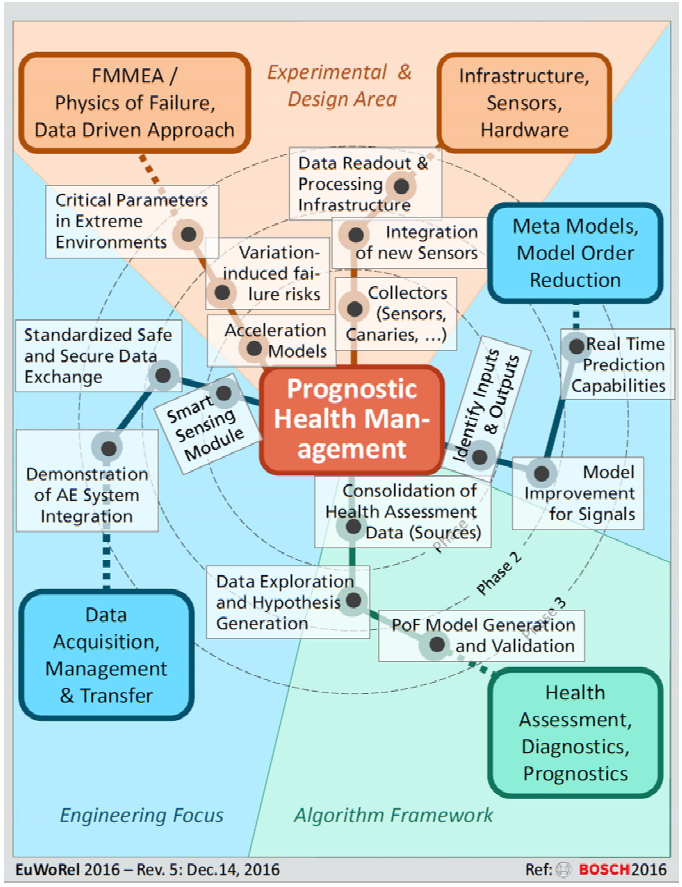


Figure 16. PHM Methodology Metro Map [7]

Dedicated stops have been identified and assigned to the methodology research phases 1-3, which aim at a seamless integration of the PHM strategy in the architecture of electronics systems for future fully autonomous vehicles.

High performance computation required for an autonomous vehicle does require new cooling concepts never used in automotive. This will have an enormous impact on reliability assessment. In addition, chip-package-board-ECU-car interaction does play a significant role on final lifetime. Product qualification cannot be done any more at the board level because real use conditions cannot be represented by this kind of simplified construction. What is necessary is a paradigm shift in the development of advanced electronics for future automotive applications. As of now, development of new electronic systems is done in a hierarchical way: the material supplier is at the bottom of the supply chain, then the flow of information is through the chip/packaging/system developer to the OEM. In the future, due to the complexity of the system and interaction between different components of the system, development of the advanced electronics systems will be done more as a teamwork effort, in which the OEM (or final product) will be at the center and all the suppliers will be linked as satellites. We expect more collaboration between industry partners, strongly supported by academia and research institutes.

- Virtual pre-qualification using numerical methods and knowledge-based qualification (JESD94) [8-9] will play an even more important role and will be a key enabler for reducing the costs of reliability assessment and shortening the qualification time. The following actions are required to achieve these ambitious plans:
- Definition of the exchange format between different suppliers that will secure the IP rights;
- Development of the metamodels and reduced models (MOR) for data exchange between supply chain for quantitative numerical modeling, including legal aspects;
- Further development of material characterization and modeling technique for advanced materials, such as encapsulants, thermal interface materials, adhesives, sealants, new joint materials, etc., including toughness of the interfaces. This is especially needed in the mm-wave technologies;
- Implementation of artificial intelligence (AI)/machine learning (ML) algorithms in the design and optimization process;

- Standardization and implementation of a simulation-driven design approach in the design process of advanced packaging and electronic control units;
- Definition and standardization of the modeling approach for a digital twin of ECUs for in-situ health assessment;
- Identification and standardization of pre-indicators and key failure indicators for the PHM approach, including development of tools and algorithms using AI/ML;
- Careful analysis of use cases which might cause damage of interconnect technology;
- Identification of new failure modes, especially for new materials, and field-relevant failure modes, including strategies for acquiring field data.

Automotive electronics, especially for autonomous driving, will be based on 3rd generation smart systems [10] and cyber-physical systems [10]. There is an urgent need to define new standards for reliability assessment and qualification criteria that can account for the complexity of these systems, including advanced packaging (SiP, PoP). Especially important is defining the responsibility for the specific design elements. Here the suppliers will require significantly more detailed information about the loading conditions in real field application. The chip/package/board/system interaction will play a major role.

8. Electric Drivetrain – Power Electronics and Thermal Management

Autonomous driving also brings simultaneous development and introduction of more environmentally friendly propulsion techniques using alternative energy, including the all-electrical-energy system. The powertrain electrification trend in all-electric cars is picking up speed at every major automotive company and is expected to account for more than 10% of the market share in the next five years, growing faster over the next two decades.

Figure 17 illustrates the three critical component technologies in electric cars that include the inverter, battery charger and the battery itself, to be designed and developed to serve this market.

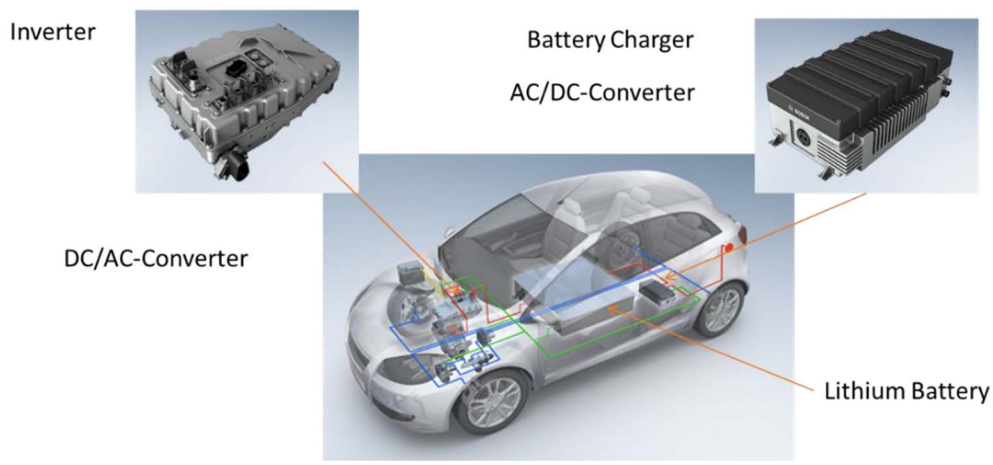


Figure 17. New era in automotive electronics – the powertrain of electric vehicles.

The progression of vehicle electrification has been from full hybrid electric vehicles (HEV) to plug-in hybrid vehicles (PHEV) to fully electric battery-electric vehicles (BEV). Energy storage and efficiency become the key metrics toward mass adoption of BEVs.

The primary impact for electronics is the powertrain electronics. The main demand will be on batteries and the electronics that manage the battery – for example, charging, safety, thermal management and power electronics. In hybrid vehicles, additional electronics may be needed.

ELECTRIC VEHICLE TAXONOMY

Vehicle Type	EV Category	Battery Capacity (Typ.)	Electric Range (Typ.)	Characteristic Feature	Charging Type
ICE	Micro Hybrid (Micro HEV)	<1kWh	none	Start-stop	Engine charging or regenerative braking
	Mild Hybrid (Mild HEV)	<1kWh	<<1mi	Some ICE assist (few seconds at low speed)	
Electric Vehicle (EV)	Full/Strong Hybrid (HEV)	~2kWh	~2mi	Frequent ICE assist and purely electric propulsion at low speed	
	Plug-in Hybrid EV (PHEV) *Range-Extender EV (REEV/EREV)*	4~20kWh	10~50mi	Primarily electric propulsion, with ICE providing supplemental propulsion and/or battery charging	Designed for grid charging: Plug-In EV/ Plug-in Vehicle (PEV)
	Battery EV (BEV)	20~100kWh	60~300mi	Purely electric propulsion, no ICE	

- Charging Mechanism: The charging mechanism subsystem for batteries provides the correct voltage and current for charging. One point to remember is that the electronics may be on during the charging and safeguards are needed to protect all the active components. The all-electric vehicle will require a PCB/module providing this function, as shown in Fig 18 below.

CHARGER EXAMPLE: ON-BOARD CHARGER MODULE FOR CHEVROLET VOLT

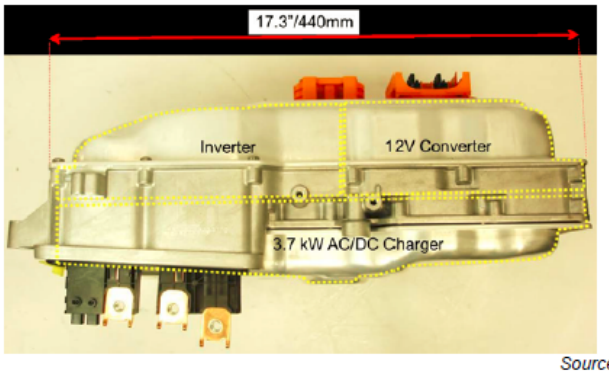
Source: Delta Electronics

Figure 18: Battery-charging module

- Inverter Module: Converts DC voltage from the battery to three-phase AC. For specific needs, such as during regenerative braking, additional DC/DC converters may be needed.
- DC-DC Buck converter: Converts the high voltage (typically 360V from the battery pack) to 12V for the accessory electrical system.
- Others including system supervision and control electronics.

Some of these modules can be further integrated into a higher-level module. For example, the DC-DC converter is typically integrated into the inverter. An example shown in Figure 19 is from the BMW i3 where the inverter, DC-DC converter and the charging functions are combined.

PCU EXAMPLE: BMW i3



Source: Oak Ridge National Lab.

Figure 19: Integrated module

The primary impact will be on batteries; however, other semiconductors and passives will also show small but positive growth. Apart from MCUs for supervisory and control functions, specialty components will include power

transistors such as IGBTs. Power outputs can increase to 100KW or more, requiring costly and next-generation power transistors and diodes. Specialty passives for supporting high energy efficiency will be needed.

9. Summary and Conclusion

This chapter summarizes key trends in automotive electronics including advanced processor technology, heterogeneous integration of multiple advanced sensors and processors for automated vehicles, and major changes in battery and power management technologies for adoption of fully electric vehicles. Special emphasis on understanding the challenging reliability requirements has been provided. The topic of automotive electronics is undergoing tremendous disruptive changes and future revisions will capture the roadmap of these technologies.

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