



HETEROGENEOUS INTEGRATION ROADMAP

2020 Edition

Chapter 5: Automotive

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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.

Summary of changes in this new revision include new additions of section 6.2 (RADAR), update of section 6.3 (LiDAR) and update of section 7 (Reliability).

1. Introduction

Automobiles are becoming “Electronic Devices,” unlike in the past, where they were mainly viewed as mechanical devices. Automotive electronics (Figure 1) are expected to account for about a third of the total cost of the entire car, about US \$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 has experienced a significant contraction in 2020 due to the COVID-19 worldwide pandemic. Going forward from 2020, the automotive semiconductor market is projected to rebound with a 2020-2024 CAGR of ~13%. HEV, ADAS, and infotainment and telematics will capture the largest areas of growth. This is shown in Figure 2.

2. Chapter Outline

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

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- 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



Source: Deloitte

Figure 1. Components of the Connected Car

| Auto Semi Forecast by Application | | | | | | | |
|-----------------------------------|---------------|---------------|---------------|---------------|-------------|------------|--------------|
| (US\$M) | 2019 | 2020 | 2021 | 2024 | 19/20 YoY | 20/21 YoY | 20 - 24 CAGR |
| Total | 41,184 | 32,798 | 40,596 | 53,161 | -20% | 24% | 13% |
| ADAS | 5,058 | 4,407 | 6,393 | 11,184 | -13% | 45% | 26% |
| Body & Convenience | 6,884 | 5,646 | 6,627 | 7,644 | -18% | 17% | 8% |
| Chassis & Safety | 6,068 | 4,768 | 5,537 | 6,486 | -21% | 16% | 8% |
| HEV/EV | 2,017 | 1,810 | 2,279 | 5,646 | -10% | 26% | 33% |
| Infotainment & Telematics | 10,382 | 7,959 | 10,350 | 13,412 | -23% | 30% | 14% |
| Other Automotive, Trucks, AM | 4,581 | 3,678 | 4,575 | 3,167 | -20% | 24% | -4% |
| Powertrain | 6,194 | 4,530 | 4,835 | 5,621 | -27% | 7% | 6% |

Source: IHS auto semi market tracker, Jun'20

Figure 2. Automotive Semiconductor Market Growth Projection by Application

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 3.

V2X Evolution



Figure 3. Vehicle communication Evolution

WiFi-based Communication: In the U.S., the NHTSA is considering using IEEE 802.11p-based DSRC technology for V2V communications. 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 4, 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.

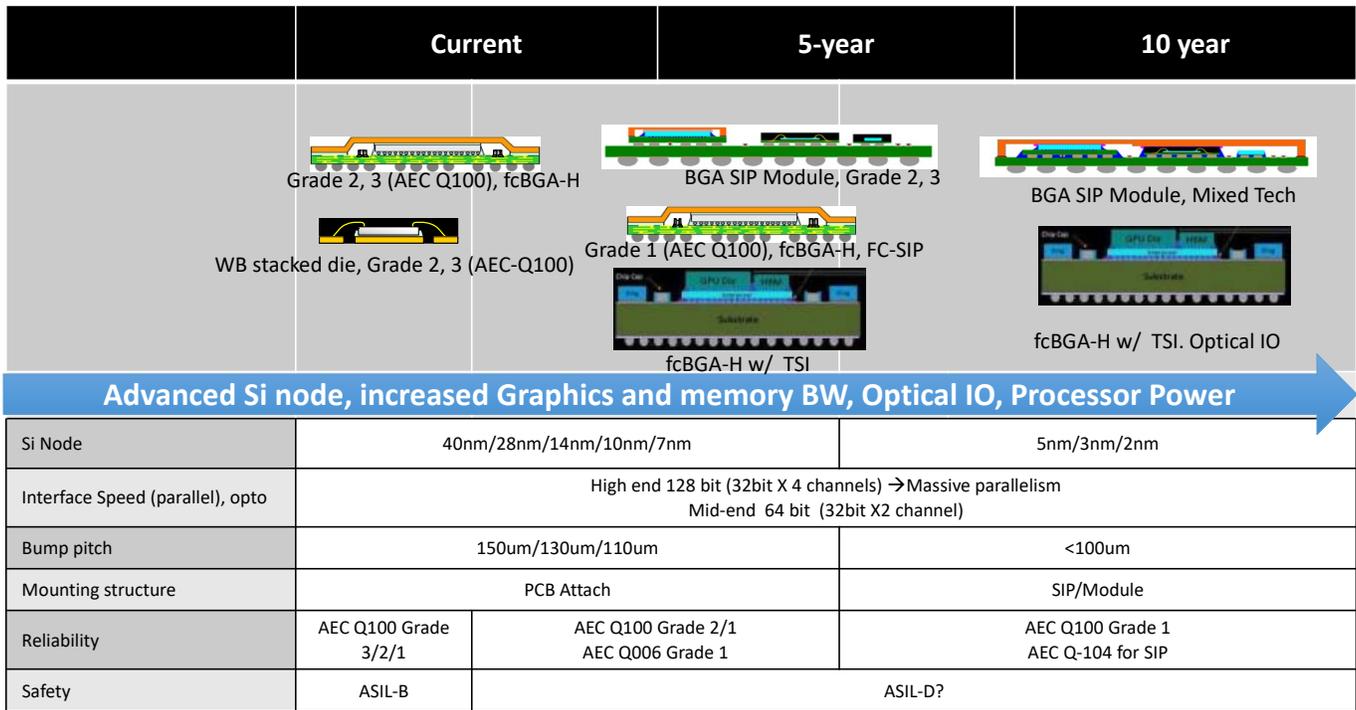


Figure 4. Automotive Processor Roadmap

The journey to autonomous driving has already started with Levels 1 and 2 functions available in most cars today. Figure 5 illustrates the five levels of autonomous driving as defined by the automotive industry.

Trends: NCAP and Automation

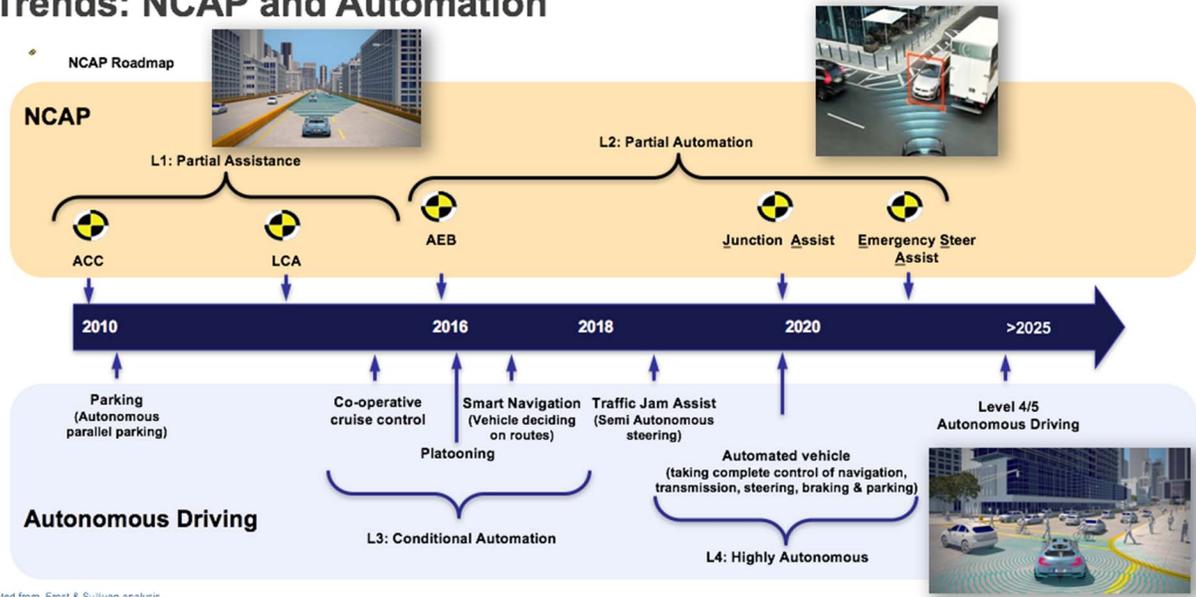


Figure 5. Five Levels of Autonomous Driving and One Example of a Roadmap to 2025

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 added 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 $\ll 1$ dpm, 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 6 shows pictorially these functional blocks.

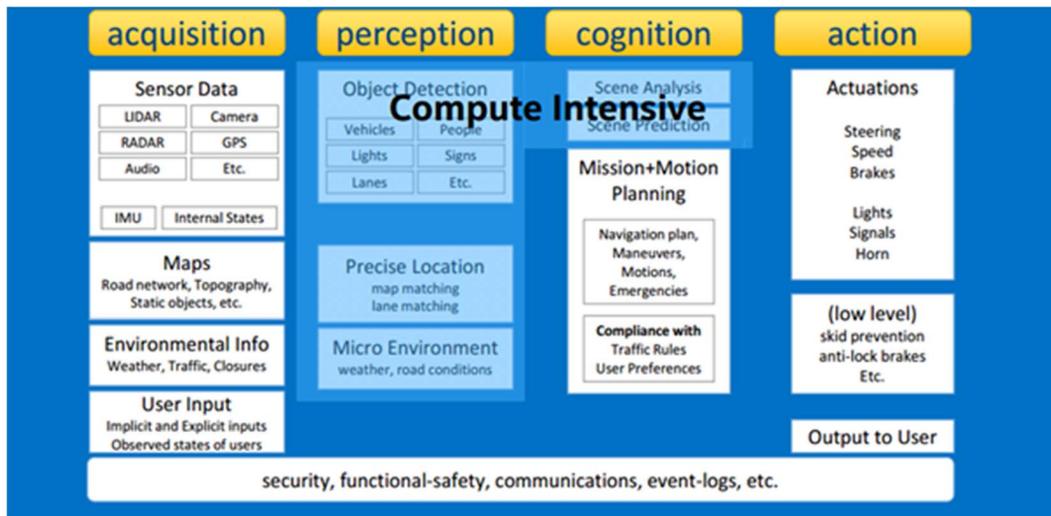


Figure 6. Functional Blocks for Self-Driving Vehicles

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 footprint. 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 counts 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.

A. Higher functionality and integration at the package level:

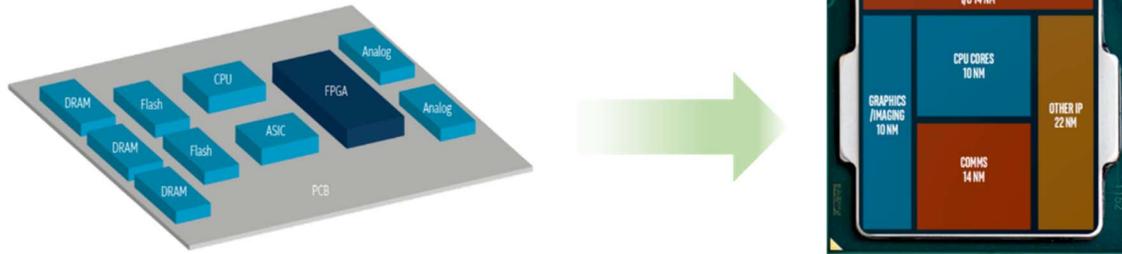


Figure 7. Board level to package level integration; higher bandwidth at low latency & power: integration of different IP blocks to deliver functionality

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.

B. 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 8. 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.

C. 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.

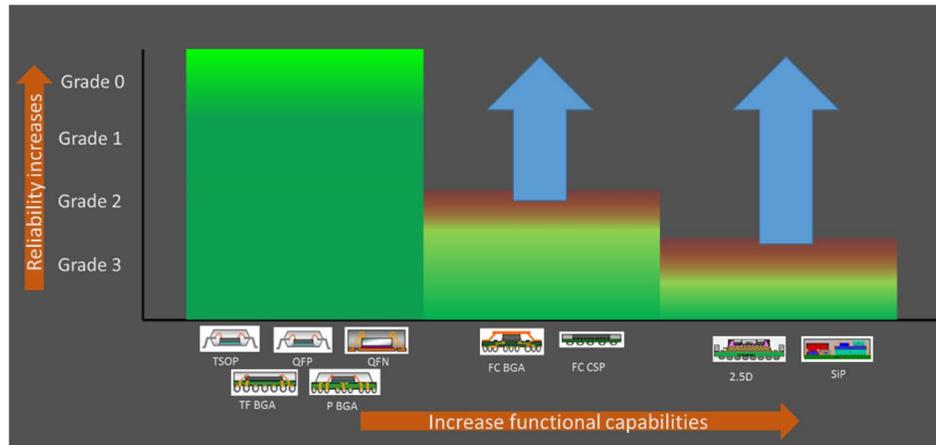


Figure 9. Role of Reliability Requirements and Functional Capabilities

Figure 9 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 FC BGA, 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.

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 ensuring that no new and latent failure modes exist for a zero defect product. 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 10 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.

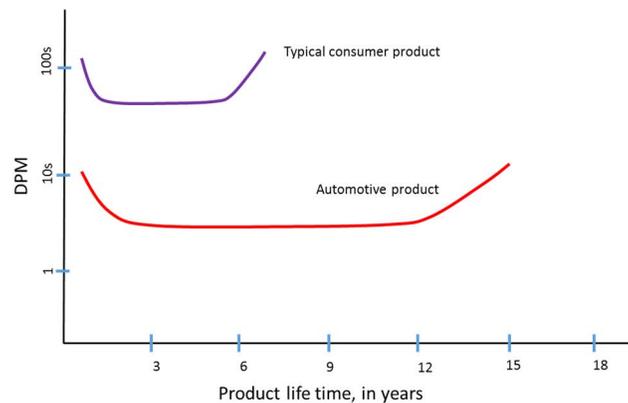


Figure 10. *Quality Requirements for Different Market Segments*

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 11.

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. Figure 11 shows the role of each sensing technology in autonomous vehicles.

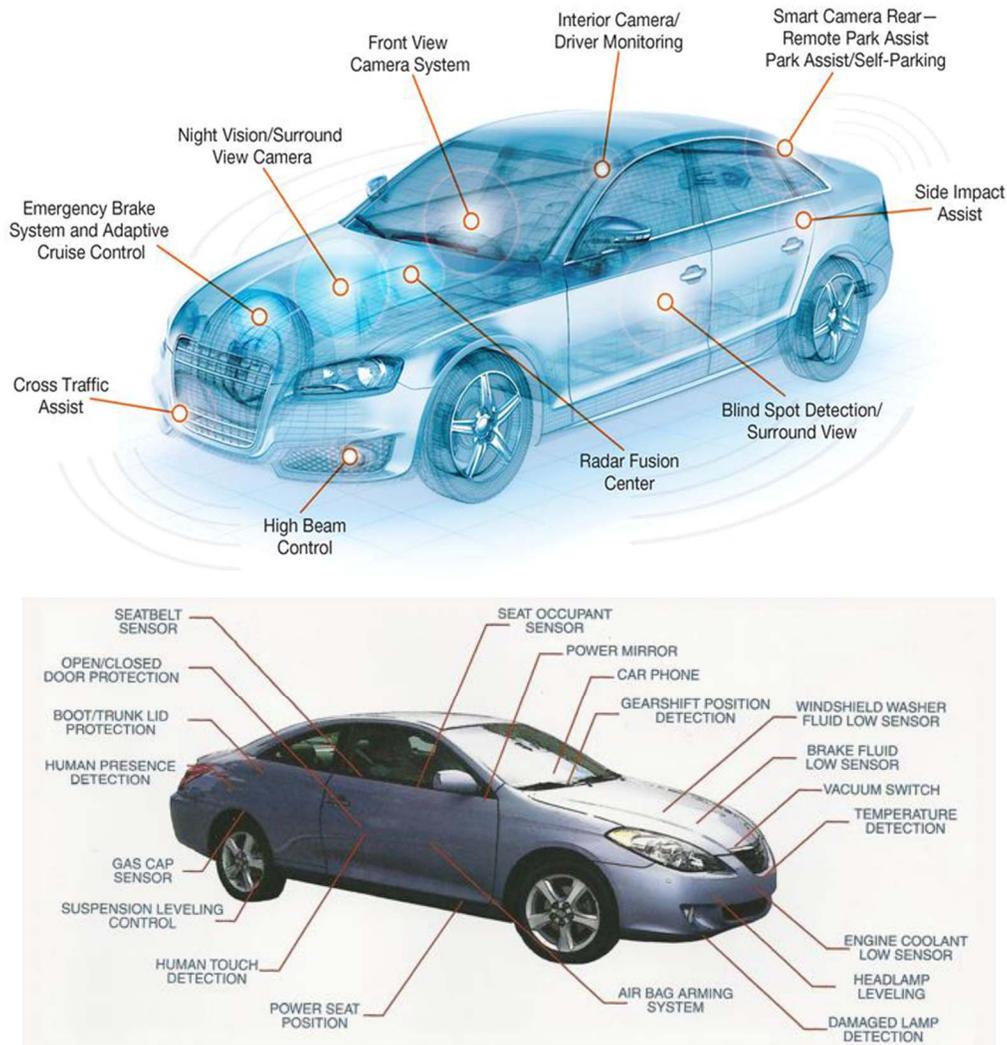


Figure 11(a) and (b). Advanced Driver Assistance Systems (ADAS) Application Example [5]

Table 1: Sensing Technologies in Automated Vehicles

| 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 | | | |

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. As with most path-breaking technologies, wartime needs and technology innovation translating into battlefield advantage drove the first RADAR developments prior to WWII. From the initial maritime and aircraft military applications, the progression to civilian land-based RADAR technology for automobiles followed in the next decades. The past two decades have seen increasing adoption of RADAR technology by leading automobile manufacturers such as Toyota, Honda, GM, Ford, BMW, Mercedes, etc.

The development of several parallel mega-trends – internet ubiquity, sensor fusion, compute power advances, mobility, data analytics – drove a multitude of applications in the automobile that utilize RADAR technology. These mega-trends also led to the automobile as a sensory experience more than a utilitarian transport vehicle – one that has seamlessly integrated into a way of life and a second home, as shown in Figure 12.



Figure 12. Global Trends - The Main Drivers of Innovation

The first radar automobile applications focused on Collision Warning Systems and were sold as an aftermarket unit that alerted truck drivers if they were approaching a vehicle in front of them. This served as an early warning and helped reduce accident rates involving truck fleets. The system used a 24 GHz monopulse radar to transmit, and a CPU analyzed the received signal to estimate if the truck was approaching the vehicle ahead too quickly and warned the driver. From these, other applications evolved such as Blind Spot Detection and Proximity Sensing that continued to use the 24 GHz frequency for transmission. Soon, the limitations of bandwidth at 24 GHz forced automotive manufacturers to look further as applications moved from passive safety to active safety.

A prime example of a more complex application is adaptive cruise control – a simple concept but one that involves decisions on when to brake and when to accelerate while the steering wheel is controlled by a human driver. For such continuous operation applications, a higher-bandwidth signal was required, as well as more processing power to analyze large streams of data and decision-making.

As with other compute intensive technologies, the advent of semiconductor processing enabled the miniaturization of these systems from bulky Gunn diode-based systems into solid state devices suitable for small cars. The semiconductor devices were initially based on GaAs (Gallium Arsenide, a compound semiconductor material based device fabrication technology) pHEMT (pseudomorphic High-Electron-Mobility-Transistors) MMIC (Monolithic Microwave Integrated Circuit) technology which enabled the integration of VCO (Voltage-Controlled Oscillator), mixers, and amplifiers along with small patch antennas to create the first semiconductor radar systems.

Miniaturization allowed multiple radar systems linked into a cohesive sensor fusion environment for adaptive cruise control, blind spot warning, lane departure warning, and parking sensors applications.

As mentioned earlier, parallel mega-trend developments in communications and mobility opened new frontiers in semiconductor technology, such as SiGe-based devices (Silicon Germanium compound semiconductor device fabrication technology that is more tuned for high volume manufacturing scale than GaAs devices) at 60 GHz (802.11 wireless protocols etc.). These quickly led to development of SiGe technology for higher frequency ranges, displacing GaAs MMICs from the burgeoning automotive radar industry and expanding its application footprint. SiGe adoption, and more recently RF CMOS Si (Radio Frequency CMOS silicon device fabrication) technology development, through miniaturization, high volume and low cost that an industry-standard technology platform offered, greatly accelerated automotive RADAR deployment into the mainstream. Thus, higher frequency radar gained traction – 77-81 GHz mmWave radar became the industry norm for automotive safety applications, as it allowed the utilization of a wide bandwidth Frequency Modulated Cyclic Wave scheme [6] that improved accuracy in addition to increasing bandwidth.

6.2.1 Autonomous Driving Mega-Trends

As radar proliferation increases, attention to packaging technologies to enable more complex radar techniques is also evolving. The advent of autonomous driving vehicles, and the drive for technology that enables its various elements, has created another mega-trend that is spurring the creation of start-ups, technology innovations, and multiple new applications. This is shown in Figure 13.

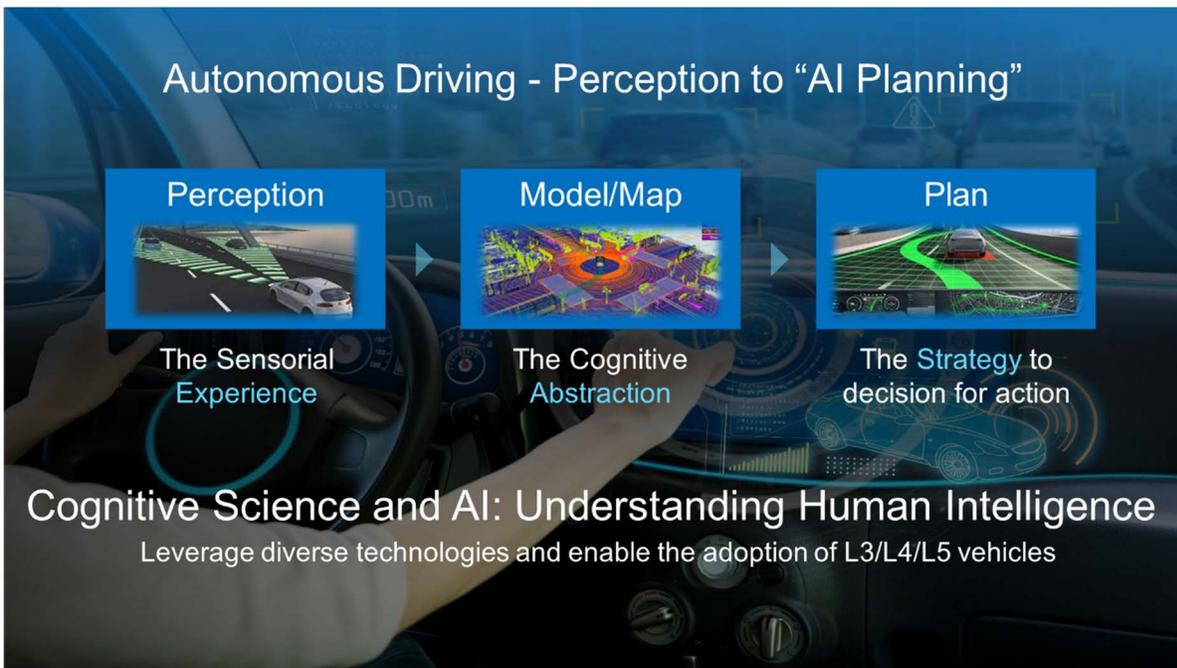


Figure 13. Autonomous Driving - Perception to "AI Planning"

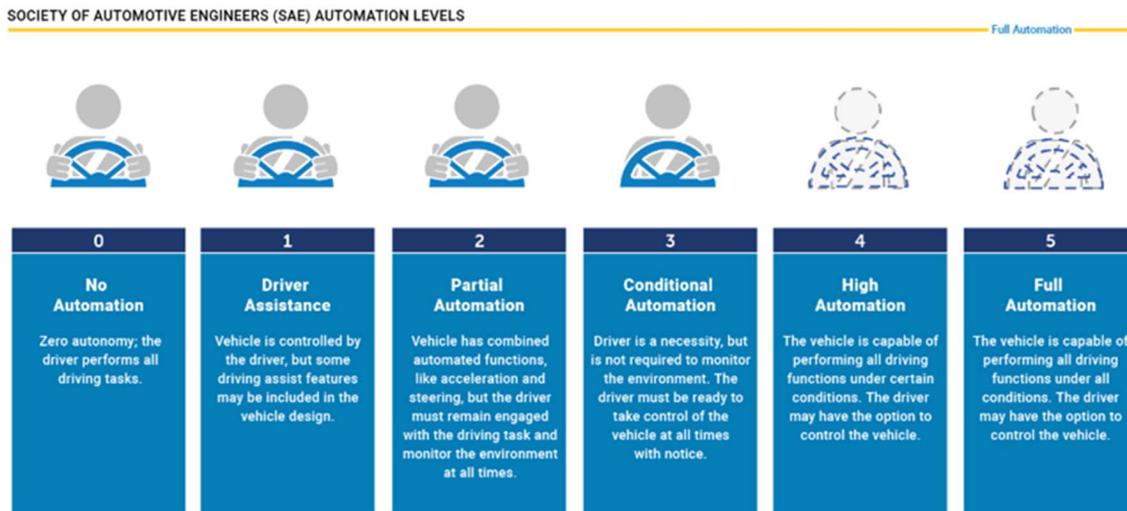


Figure 14. Autonomous Driving Levels

The U.S. NHTSA (National Highway Transportation Safety Administration) [7] has defined autonomous driving into distinct levels depending on the human interaction needed – from Level 0 (No automation) to Level 5 (Full automation), illustrated in Figure 14. Each of the levels has implications for sensor technologies and fusion as a myriad of traditional and new sensing devices like cameras, LiDAR, Radar, ultrasound, touch, pressure, etc. work together to create the seamless experience that now defines driving. Target applications include ADAS Adaptive Cruise Control (ACC), ADAS Crossing Traffic Alert (CTA), ADAS Parking assist, Automated Emergency Brake (AEB), Blind Spot Detection (BSD) & Corner Radar. These and other complementary vision, ultrasound and laser sensors create a cocoon of sensing that the processors in the car use to assess the environment around it while traveling at speed limits in streets, lanes, city roads and highways.

6.2.2 Radar Technology and Applications

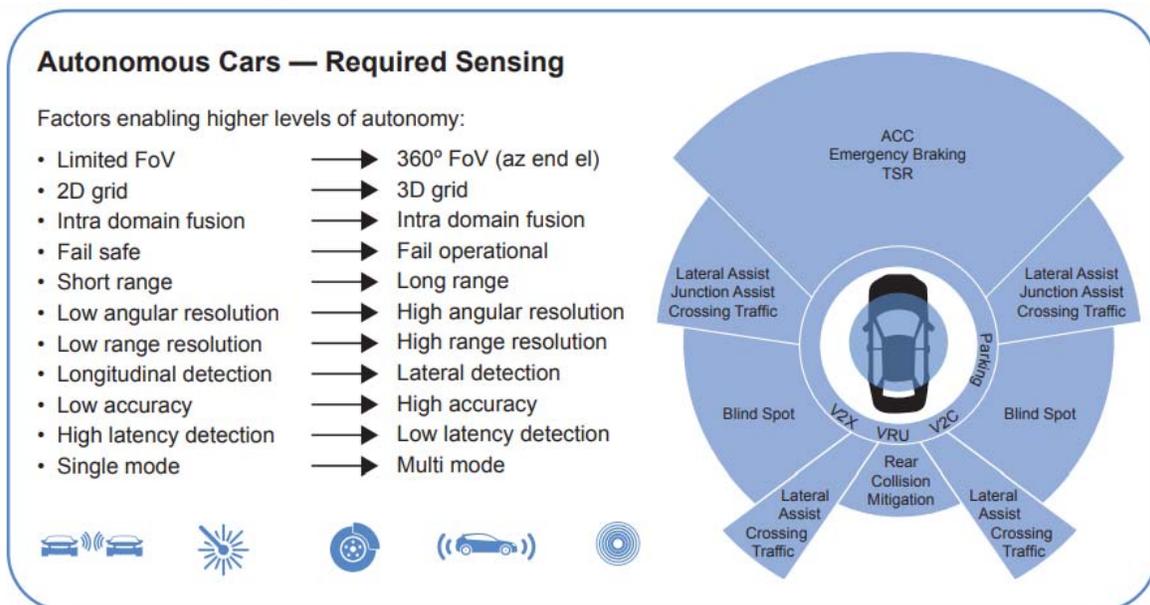


Figure 15. Autonomous Cars - Required Sensing

The sensing requirements in autonomous cars are shown in Figure 15. RADAR sensors can be classified by their operating distance ranges: Short Range Radar (SRR) 0.2 to 30m range, Medium Range Radar (MRR) in the 30-80m range and Long Range Radar (LRR) 80m to 200m+ range. Long Range Radar (LRR) is used in Adaptive Cruise Control (ACC) and highway Automatic Emergency Braking Systems (AEBS), while short-range radar is deployed for Blindsight detection, and medium-range sensors are deployed to work in parking-assist functions. In many of the

current systems, the limitations of radar technology are overcome by using radar in conjunction with camera sensors to provide additional context to detection.

Automotive OEMs and Tier-one suppliers are racing to meet these expanding requirements for multiple safety features while driving cost downward to commercially acceptable price points. This requires a careful price/performance balance among camera, RADAR, and LiDAR technologies, taking into account their relative strengths and weaknesses, shown in Figure 16.

Current technology costs make LiDAR a niche platform and not suitable for mass market adoption. There are multiple start-ups engaged in competitive development or collaborative partnerships with OEMs, car manufacturers and semiconductor suppliers to define the first solid-state LiDAR for the automotive autonomous driving market. There are multiple device technologies (VCSEL-based, MEMS-based, Memory-based, etc.) by leading startups (Innoviz, LeddarTech, Luminar Technologies, Ibeo, etc.) that are being evaluated and developed in the race to be the technology adopted for automotive LiDAR. In summary, solid state LiDAR technology, though rapidly gaining ground, is still about a decade behind radar technology in maturity.

The relative maturity and expense of LiDAR in comparison to other sensors also drives significant development of high-resolution radar to eliminate weaknesses in localization, mapping and classification of features that radar sensors suffer from – factors that LiDAR technology solves with great efficiency but at higher cost. The adoption of higher-resolution radar and its proliferation into multiple applications also creates the need for high processing power.

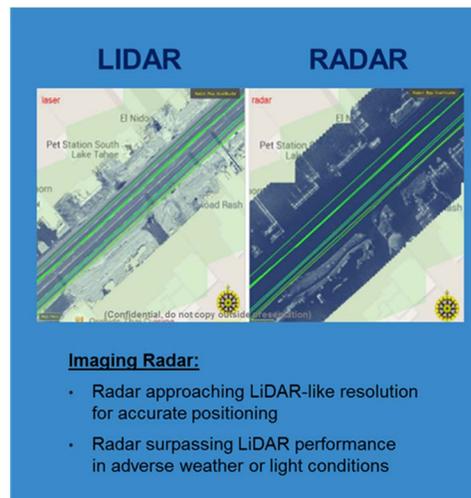


Figure 16. Lidar vs. Radar Resolution

RADAR sensors are similar at the processor level to imaging camera sensors in that they impose significant computational workloads. Achieving higher-resolution RADAR sensors introduces exponentially larger demands on the underlying processing platform. As pointed out earlier, the phase-out of 24 GHz frequency radar in favor of the 76-81 GHz frequency regime for automotive radar applications has improved range resolution and the ability to distinguish between two closely spaced objects and their independent motion vectors. This is enabled by the available frequency bandwidth. The improved resolution also affects the ability to discern between multiple object classes (e.g., a vehicle and a pedestrian), allowing for the ability to attach independent attributes that drive more decision-making for autonomous control.

The improvements in resolution also drive a need to improve azimuth and elevation resolutions [8], as these are critical to applications such as adaptive cruise control and automatic braking. Improving azimuth resolution provides the ability to distinguish a small object such as a pedestrian from a large object such as another automobile in close proximity. Improving elevation detection has a major impact on capabilities targeting small obstacle detection on roadways, such as tunnels, bridges, and signposts, and provide appropriate vehicle clearance leeway information. Manufacturers achieve resolution gain by using multiple-input multiple-output (MIMO) techniques whereby virtual antennas arrayed around a vehicle behave like $N \times M$ receive antennas from only N physical transmit and M physical receive antennas, shown in Figure 17.

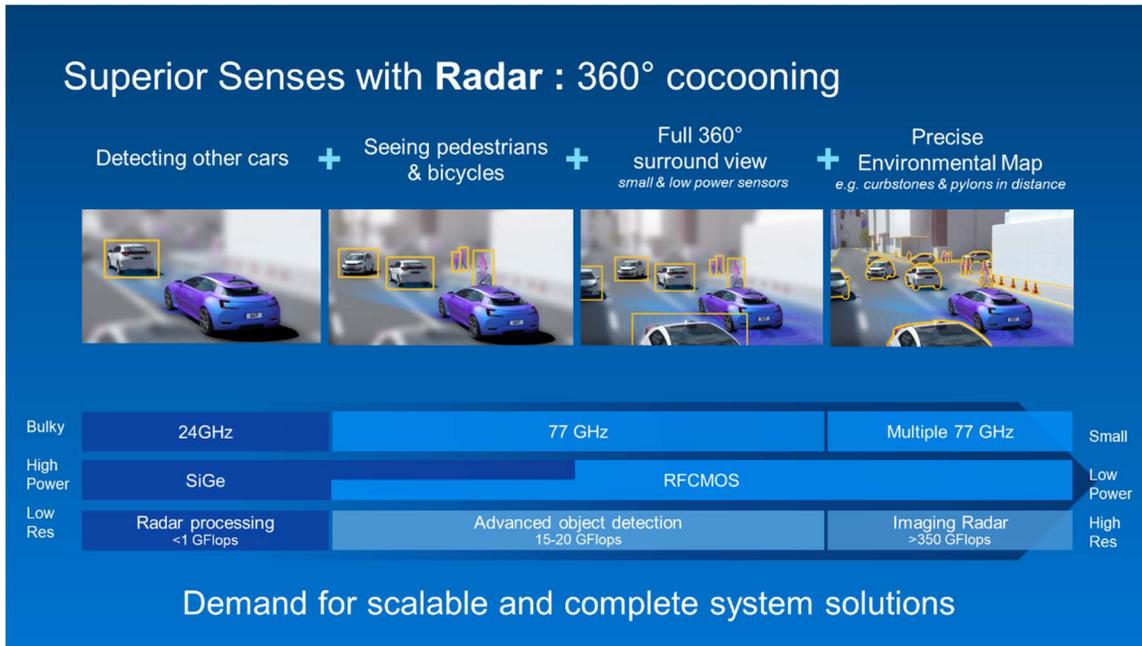


Figure 17. Superior Sensing with Radar

The adoption of higher-resolution radar and its proliferation into multiple applications also creates the need for high processing power. Coupled with this, processor performance demands imposed by MIMO beamforming across the virtual antenna array require a highly capable processing platform with ample memory, bandwidth and signal processing capabilities in order to realize the aforementioned improvements in angle resolution.

All these vectors of radar technology development – the sensor itself, processors, and antenna technologies – come together in a radar module, and multiple cascaded radar modules work together with multiple camera and other sensor modules to deliver the autonomous driving experience at different levels of automation (L1 – L5).

The current modules all rely on assembling these technology elements on a board, then mounting the board in a module, and finally placing a module in its application location in the automobile. Increasing space constraints, and new locations demanding miniaturization of the modules, are now leading to the development of assembly technologies designed to accommodate these varied technologies, combining digital, analog, antenna and RF sensing into one highly integrated miniaturized module.

6.2.3 Global Safety Mandates

In addition to the technology elements above, global safety mandates are also placing new demands on the overall safety of autonomous vehicles. These demands will only grow as heightening safety standards around the globe are met with increasingly adept RADAR sensor implementations. Global NCAP (New Car Assessment Programme) [9] mandates are expected to establish and enforce stringent safety rating requirements in 2020 for advance RADAR-driven capabilities such as cross-traffic AEB and occluded object classification to pedestrian detection in low light.

Euro NCAP 2020 protocols are improving proposed test conditions for crash prevention and driver assistance systems by adding new, challenging test scenarios to rate AEB technology for cars and vulnerable road users, including back-over situations and turning at a crossing. Evaluating the driver is also being taken more seriously, and tests are being defined to evaluate driver fatigue and distraction. Technologies that provide better post-crash safety in addition to safe driving assistance are also being tested, such as better data availability, and automated detection of safety personnel to open and extricate victims from automobiles. A representative requirement from France is shown in Figure 18.



Figure 18. Road Safety Reform Strategy

The impact of these mandates will be significant in driving more processing power requirements and inter-vehicle communication amongst multiple architecture domains. Achieving a top “five star” rating, whether it is by Global NCAP, continental NCAP or NHTSA crash tests, will involve effective and efficient deployment of advanced sensing and processing capabilities.

As technologies enable L3 autonomous driving for the mainstream and usher in L4 and L5 driving in the future, these global mandates will only increase the technology complexity and challenges for achieving required safety ratings that will make autonomously driven vehicles safer than human driving.

6.2.4 Radar Packaging Technology

In current deployment, radar modules consist of a processor chip, RF radar sensor, analog drivers, and antennas assembled on a PCB and enclosed in a module for mounting in automobiles. Depending on the requirements, the radar sensor can be a one-chip sensor combining transmit and receive functions and include analog functions, or it can be a separate chip for each function.

6.2.5 Key Performance Metrics

Insertion loss is the key performance indicator of a mmWave circuit – build-up materials used in packaging technology contribute to insertion losses through conduction loss, dielectric loss, radiation loss, and negligibly, leakage loss. The insertion loss impacts the effectiveness of the radar solution over the expected performance range as well as the distance of application (Short, Medium or Long Range Radar).

Conductor loss and dielectric loss are directly correlated to the choice of material for both. Radiation loss is frequency dependent, increasing with increasing frequency, and also inversely proportional to the material’s dielectric constant (Dk). The thickness of the dielectric stack is also important, especially for waveguide launcher packages – the lower Dk will drive a thicker dielectric layer for radar performance (consistent phase angle, minimizing impedance) but a thicker stack has the potential for greater radiation loss. Therefore, the need for a low dielectric constant material has to be balanced with thickness considerations for radar performance.

6.2.6 Package Platform

Radar sensors for 77 GHz mmWave frequency require low frequency loss to provide the required resolution and range capability. This has led to the adoption of flip chip or wafer-level packaging as the platform of choice depending on the application. Despite being well entrenched package platforms, the mmWave RF frequency places new demands on materials and processing capabilities due to circuit performance requirements for low loss and extremely consistent phase angles needed for the short wavelengths at 77 GHz. These requirements will only get more challenging as the industry evolves further from 77 GHz to the 120-140 GHz frequency ranges for specific applications. This is shown in Figure 19.

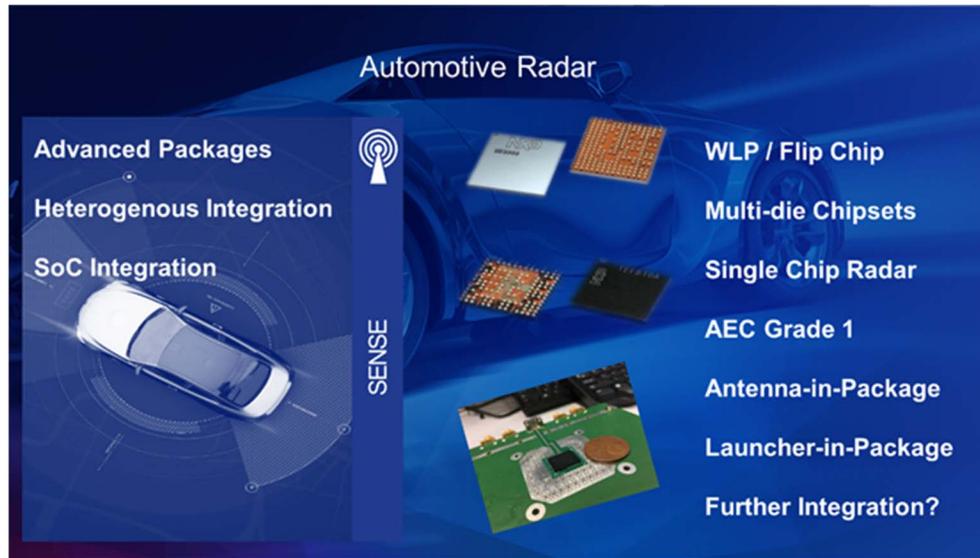


Figure 19. Automotive Radar Packaging Trends

Current products from major electronics suppliers such as NXP, Texas Instruments, ST Microelectronics, etc. offer automotive radar in low density fan-out WLP or Flip Chip packages. Integration of different board elements into the package, leading to larger die with more power and thermal requirements, is leading the development of next-generation packaging solutions in high density fan-out and flip chip technologies (FCCSP). Flip chip structures have an advantage in enabling antenna-stacked-on-chip configuration in a cost-effective manner and hence shrinking the package size/board footprint compared to a conventional side-by-side antenna-in-package (AiP) configuration. Antenna in package (AiP) has the antenna built into the package and radiates the signal coming from the RFIC to/from the environment directly. Because the antenna is scaled down to fit the small package, there are performance limitations of the antenna, making it suitable only for short to medium range radar applications.

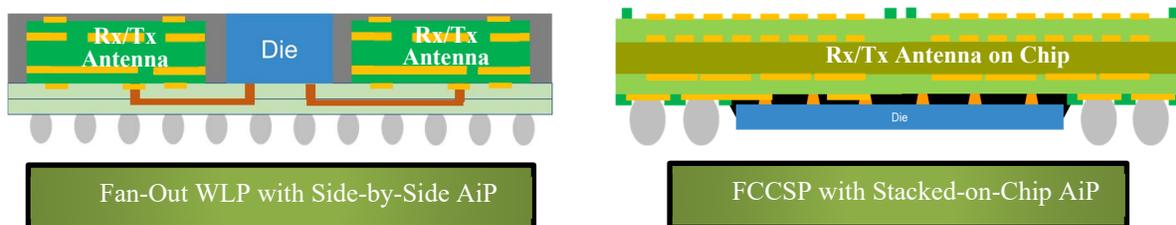


Figure 20. Automotive Radar - Current Package Technologies

6.2.7 Materials Requirements [10]

Dielectric constant, Dk: More than low dielectric constant, a critical need is a consistent Dk, as variations will cause variations in phase angles of the 77 GHz frequency RF signal that decreases circuit performance. Thus, tolerance of the material’s Dk is an important factor and contributes to the design Dk (as extracted from circuit performance).

Dissipation factor, Df: This property is another key contributor to the design Dk. Low-loss circuit performance requires not only a low dissipation factor, but also a stable dissipation factor with a very narrow tolerance window for Df over the frequency range of operation. Loss tangent or dielectric loss directly translates to insertion losses or degradation in Q factor. This stability over the entire frequency range of operation is critical to maintaining frequency and phase stability at mmWave frequencies.

Temperature and humidity performance: Similar to stable dissipation factor and consistent dielectric constant, the variation of these factors with temperature over the frequency range should also be minimized compared to the current materials in production. This is directly tied to the finer design rules for substrates that are needed for 77 GHz performance, especially for Long Range Radar applications. The finer line/space requirements drive a low tolerance for feature size changes due to temperature of operation as well as changes due to moisture absorption. TCDk and TCDf (Temperature Coefficient of Dielectric Constant and Dissipation Factor) are critical parameters and would likely need to be less than 3ppm/deg. C. Similarly, moisture absorption is another critical factor, as it can

impact Dk and Df – the variation in Dk and Df due to moisture absorption has the same impact of variability of Dk and Df over the required frequency range and is detrimental to 77 GHz circuit performance.

Trace surface roughness: For substrate or build-up based packages, the roughness of the copper trace is critical for mmWave frequency performance. Conductor loss is influenced by the roughness of the copper trace – if the surface roughness is of the order of the same dimension as the skin depth, the conductor loss is significant. The skin depth – how deep the RF current is within the copper – is frequency dependent, with loss increasing at increasing frequency due to the reduction in wavelength and increase in current scatter.

6.2.8 Design Rules

From a package technology perspective, the future design rule roadmaps by the top packaging OSATs cover the requirements for automotive radar. There are a few key developments that are unique to automotive and especially unique to automotive radar:

Design rule reliability: The design rule roadmaps that govern Flip Chip and Wafer-level packaging (FCCSP, eWLB etc.) are constructed for the most part around meeting mobile and commercial quality requirements for lifetime and defectivity. These technologies should be validated for Automotive AEC Grade 1 reliability and performance in the operating temperature range of -40 to 125C. Materials evaluation to ensure performance at a junction temperature of 150C may be required, so the glass transition temperature for the substrate dielectric should be above this operating range to avoid signal hysteresis and loss.

Design rule tolerance: Substrate design tolerances need to be tighter than what is accepted in the industry currently. As design rules tighten, lithography techniques such as cost-effective implementations of stepper technology will be required to deliver consistent and tight process distributions. Critical design rules should have a tolerance of less than 10% in actual process conditions in volume, both within a unit and across multiple batches. This aspect of technology is currently not as tightly controlled as required for multi-layer substrate design, since the signal wavelengths of conventional digital and analog devices are not short enough to be significantly impacted by design rule tolerances. With the advent of mmWave RF and complex designs requiring multiple routing layers, the tolerances become critical to delivering consistent RF signal integrity across the frequency spectrum.



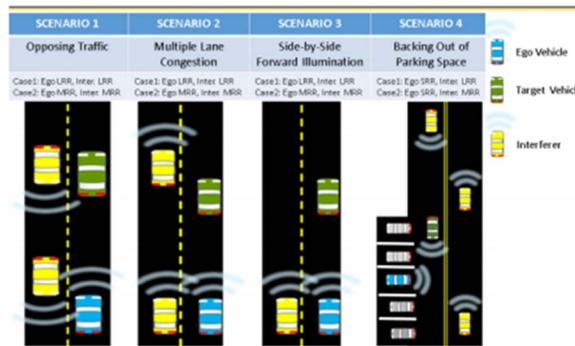
Figure 21. Ensuring Product Quality - An Integrated Platform

6.2.9 Technology Integration

With the industry movement from 24 GHz to 77 GHz radar mandated by technology requirements and global spectrum regulations, mmWave RF technology is now the mainstream for automotive radar, with the signal wavelength being less than 5 mm.

While current applications for automotive radar are well-served by the 76-81 GHz spectrum (76-77 GHz for LRR and 77-81 GHz for MRR and SRR applications), the march towards machine learning and artificial intelligence has spurred development toward improving the accuracy of radar signals so that small changes in environment or even humans can be monitored without security or privacy violations. This development has introduced 140 GHz radar as a niche solution for applications requiring high precision. A 140 GHz RF frequency leads to a sub-2.5mm signal wavelength, enabling range accuracy of better than 15mm with 10GHz of bandwidth for specific short range radar applications. 140 GHz radar is an excellent choice of technology for in-car vital sign monitoring systems, able to detect acute health hazards in time to prevent accidents. It can also overcome barriers such as cloth to monitor the presence of humans (e.g., children left unattended in an automobile), and provide an appropriate alert to spur action.

In addition to development of different frequency spectra depending on application need, the ubiquity of radar sensors in automobiles is expected to create significant interference between radar signals amongst all the automobiles and other systems that deploy them. This interference concern is a leading cause in the development of digitally modulated radar, as it can filter interference from other ambient radar signals – such devices are in their infancy for automobiles, though digital radar technology is prevalent in military applications.



NHTSA Simulation Scenarios for Radar Interference

Figure 22. Radar Interference Scenarios

DMR, or Digitally Modulated Radar, is a digitally manipulated Phase Modulated Cycle Wave (PMCW) radar as compared to the current analog controlled Frequency Modulated Cyclic Wave (FMCW) radar. In theory, PMCW radar offers exceptional angular resolution, enabling differentiation of different object classes such as large targets from small targets in close proximity. DMR innovation has attracted start-ups, such as Uhnder (<https://www.uhnder.com/>), that have demonstrated functional prototypes, as well as government labs and industry consortia such as IMEC (<https://www.imec-int.com/en>).

The progress in digitally modulated radar can also serve to develop imaging radar applications, since the DMR technology allows for power-efficient digital design with intelligent system partitions (HW-SW). DMR signal processing is primarily done digitally rather than by analog circuitry such as mixers and filters. Utilizing DSPs enables adoption of advanced silicon technology nodes, driving power and thermal requirements down to automotive levels even for higher processing requirements – this is essential if the data rates needed for imaging need to be supported by radar.

Advances in frequency, radar technology and application space are driving the adoption of newer silicon CMOS technology nodes. Current radar sensors are offered at the 40nm silicon node with the principal semiconductor electronics manufacturers focusing on developing radar solutions in 28/22nm CMOS technology and progressing to 16/14FinFET vertical transistors. FinFET nodes allow for utilizing lower power device in product development for the higher data processing needs of future radar applications.

The drive for Silicon CMOS adoption into radar technology is leading SoC development, combining the sensing and processor elements in contrast to the current use of multiple packages/die on a PCB. The drive for miniaturization also gets a boost from this development of single-chip radar due to a smaller board footprint and board size. SoC devices today are currently utilized for SRR applications with development ongoing to target single-chip radar across SRR and MRR applications. Future technology will also enable LRR applications with more enhancements, driving package-level integration.

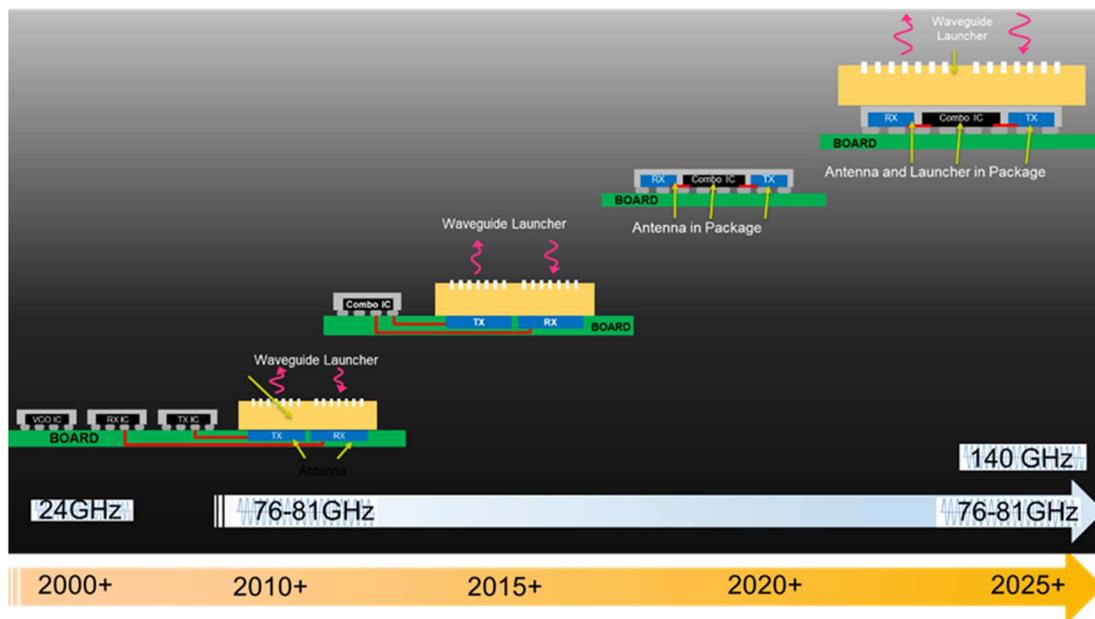


Figure 23. RF Frequency Evolution and Radar Module Evolution

One such enhancement is having the ability to design the antenna as part of the package, as discussed in earlier sections – currently the antenna for radar is a part of the PCB. Development for the next generation, in conjunction with 5G mmWave radar technology, will target Antenna-in-Package for SRR and MRR applications. There are several design elements and manufacturing considerations that need to be worked out, such as the placement of the antenna (e.g., on top of the chip or a side-by-side construction), materials for performance and reliability, as well as product metrics such as antenna radiation efficiency and radiation pattern at specific frequency of use.

Greater system-level integration is possible for LRR applications by adding a Launcher. Launcher in package (LiP) couples the signal from the RFIC to/from the 3D antenna (normally through a waveguide) mounted above the package. The external 3D antenna then radiates the signal to/from the environment. Because the external 3D antenna is not limited to the package size (due to the ability to fan-out the coupled signals from package to antenna using waveguides), the antenna can be designed for the higher performance that long-range radar requires. This is shown in Figure 23.

The design complexity is exponentially higher at the package level as the insertion loss of introducing a waveguide launcher on top of a package becomes a critical parameter. The antenna signal has to travel through a dielectric medium, potentially an air cavity, prior to being picked up by the launcher, and the design has to precisely account for the signal integrity and efficiency.

In addition to adapting wafer level fan-out and flip chip package platforms for tighter design rules and tolerances, new materials development for mmWave RF performance, new factory technologies and processing techniques are expected to play a big part in products produced 2025 and beyond. Panel-level processing is one such new factory technology that is seeing accelerated development to enable radar structures – challenges lie not only in package manufacturing but also in the ability to embed critical design IP such as Baluns and antennas in this new processing form factor. Depending on integration methodology and materials choice, improvements in stack tolerances and reliability can also be achieved.

Panel-level processing can also accelerate adoption due to its lower cost over WLP. The reliability gains due to a thicker dielectric in the build-up substrate has to be balanced with the potential for greater radiation loss. Hence, mmWave RF performance will need to be evaluated against conventional Wafer Level Packaging or Flip Chip packaging (see Chapter 23).

6.2.10 Radar Product and Module Performance

Board integration has specific thermal, mechanical and electrical design challenges that are spurring development of radar-specific board materials by all the major materials suppliers for PCBs. High frequency circuit materials are required for the top layer of the PCB that interfaces with the radar SoC – the electrical and mechanical characteristics for this material are unique and have to be taken into account during product design at the component level. Dielectric material properties such as CTE, moisture absorption, dielectric constant, loss tangent, TCDk, etc., have a strong impact on signal power and stability and have to be engineered similar to fan-out or flip chip substrate component

designs. For current automotive radar applications, within-board and board-to-board manufacturing variations have to be minimized as the circuits must be extremely thin and consistent to minimize phase angle variations for accurate radar measurements. Through advances in Antenna-in-Package and Launcher-in-Package designs, future radar products may allow for standard board materials and build-up processes so the RF signal can bypass the board completely.

In conclusion, parallel developments in radar technology, physics, silicon technology, SoC integration with RF sensing and processing, and antenna integration offer a rich continuum of interlinked devices – integration of these heterogenous technologies is complex but is the wave of the future. It is leading development in package technology, package design rules, materials development and new package manufacturing techniques requiring greater chip-package-board-module co-design. Heterogenous integration of multiple technology tangents in radar will lead the evolution of our society into a fully autonomous, seamlessly connected world.

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 24. 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.

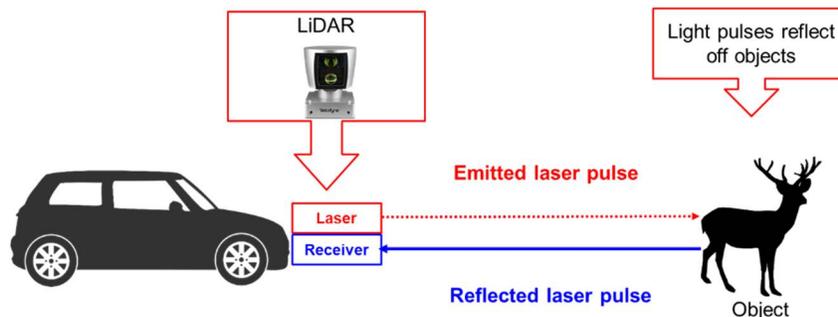


Figure 24. LiDAR Sensor Operation

A high level roadmap for LiDAR sensors is shown in Figure 25.

| 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 |
| <div style="background-color: #4a90e2; color: white; padding: 5px; display: inline-block; border-radius: 10px;"> LiDAR Detection Range : Short Range (100m) to Long Range (100-250m) </div> | | | | |
| 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, QFN, FO WLP | Detector: FC ASIC: FC Package: WLCSP, QFN, 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 25. Lidar Detector Roadmap

Currently there are different configurations of LiDARs with different technologies as well as price targets. Presently there exist four types of LIDAR: Flash LIDAR, LIDAR based on orientation, LIDAR based on scanning mechanism, and LIDAR based on platform (see table below). Meanwhile the applications of LIDAR are emerging in many fields such as agriculture, archaeology, autonomous vehicles, etc.

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 27 shows representative LIDAR technologies – mechanical, optical phase array, and MEMS based. InnoLuce is now part of Infineon Technologies.

Scanning LIDAR Technologies

Mechanical - Velodyne

Principle: Matched pair of laser & detectors rotating with a motor at 5 to 20 Hz
Range : 200 m (VLP 32A)
Resolution : 0.1 - 0.4° (VLP 16)
Vertical FOV: 28° (VLP 32A)
Price Target: < \$500 ~ 2020
Pro : Proven technology
Con: Mechanical integration / price

¹ Velodyne.com FOV – Field Of View

OPA - Quanergy

Principle: Laser scanned with OPA (& received on SPAD array)
Range : > 150 m
Resolution : 0.1°
FOV: 120° (HFOV & VFOV ; S3)
Price Target : <\$100 ~ 2020
Pro : small size (1" x 1.5" , S3-Qi)
Con: OPA scanning is relatively new technology

OPA – Optical Phase Array
 SPAD – Single Photon Avalanche Diodes

² Quanergy.com

MEMS – InnoLuce

Principle: Laser scanned with 1D MEMS Mirror (& received on APD array)
Range : > 200 m
Resolution : < 0.5°
HFOV: 80°
VFOV: 16°
Price Target : <\$100 ~ 2020
Pro : MEMS scanning is proven
Con: Working demo not shown yet...

MEMS – Micro Electro Mechanical Systems
 APD – Avalanche Photo Diode

³ InnoLuce.com

17 IR for ADAS | OS IR NA MK | R.Thakur
 TU Automotive – ADAS & Autonomous | 10/04/2016



Figure 26. Scanning LiDAR Technologies

Figure 27 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.

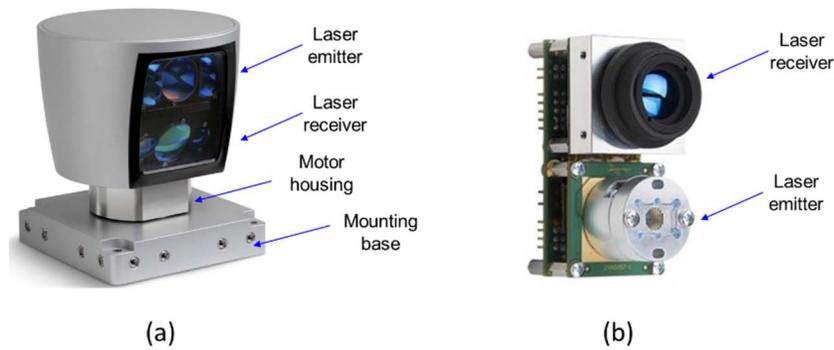


Figure 27. Two LiDAR systems from (a) Velodyne and (b) LeddarTech

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). Today’s LiDAR technology needs further improvements; cost targets and reliability are major challenges.

Another major challenge is the short pulsewidth requirement for the laser. A laser pulse width of less than 5-6ns is required, or the eyes of pedestrians could be potentially be damaged by the high Amps per channel. When integrating the whole system, the mirror technology is a key challenge due to resonance frequencies. Thus, a package with low parasitics such as inductors and capacitors is required. GaN technology is required because Si MOSFET technology cannot provide the required high frequencies.

New approaches to the development of solid-state LiDAR sensors include application of a monolithic gallium nitride (GaN) integrated circuit. Such designs result in significant advances in sensor miniaturization, reliability, and cost reduction.

Overall, for industry adoption, the cost targets have to come down to the ~\$100 range (vs ~\$3000 that is currently the standard price). This poses 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 28. 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 29.

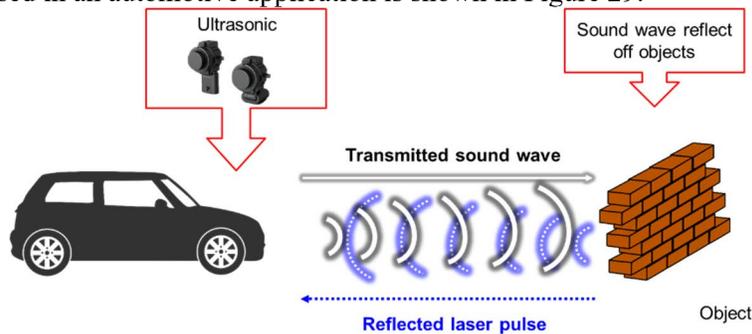


Figure 28. Definition of Ultrasonic Sensors

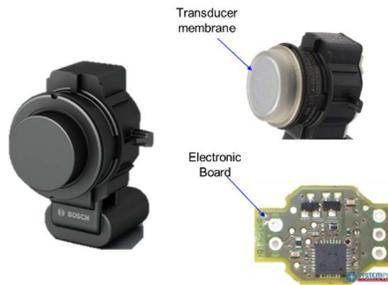


Figure 29. An Example of Ultrasonic Sensor: Courtesy: Bosch

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 electronics systems is driven by four major trends: Electrification, Autonomous driving, Connectivity, and Smart mobility. Each of these trends will bring specific reliability challenges:

- **Electrification** revolutionizes the entire powertrain units and the road infrastructure required. Combustion engines have already started decreasing their market share. New power electronics technologies are among the key drivers for electrification. For instance, utilizing SiC or GaN semiconductors and silver sintering for their bonding increases the efficiency of the power electronics and allows higher operational temperatures (200°C and above), which directly reduces cooling efforts and therefore the weight and cost of the inverters. However, new encapsulating materials are needed to meet the new requirements. In addition, sensors and microelectronic components will be added directly 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. This all challenges the reliability prospects.
- **Autonomous driving** will fundamentally change the complete transportation system. By 2025-30, conditionally and highly automated driving will reach SAE levels 3 and 4, respectively. After 2030, it 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. Consequently, operational time will significantly increase from roughly 9,000 hours (today) towards 50,000 hours and more (including the charging time for the HV/EV).
- **Connectivity** will introduce components to harsh environments that were originally designed for consumer electronics only. For example, the functionality and performance of advanced packaging solutions, such as SiPs using small node size technology, will be needed soon in automotive, requiring 15-year reliability. Hence, connectivity will be one of the main drivers that increase the operational time of IC packages and ECUs used in automotive (e.g. software upgrade, dynamic updates and interactions with the cloud during parking, using WLAN instead of expensive GSM connections).
- **Smart mobility** and sharing services. Connectivity and highly automated and autonomous driving pave the way for a fourth trend in the automotive industry: smart mobility and sharing services. The typical passenger car is used today as all-purpose vehicle [11]. That means we use the same car going to work alone and taking the family for vacation. Smart mobility solutions will change this trend, leading to more flexible solutions. We will be able to decide what kind of car we need in which situation exactly. Instead of being the owner of a car, we will simply use mobility as a service. Cars will be operated by mobility service providers. As of today in Europe, more than 60% of the new cars are sold to commercial business. More precisely, around 50% of cars go to the five largest fleet operators [12]. For their new business models, availability of the cars will be one of the major concerns.

7.1 State of the art (History and Current Status)

The current reliability practice in automotive electronics is based on the physics of failure (PoF) approach. The design of the controllers considers the anticipated field loads in order to allow a maintenance-free operation for the entire service life of most passenger cars. 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. In the first decades, the reliability assessments 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, a new approach to 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, the characteristic end-of-life (EoL) reliability of a 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

Currently we are seeing another major expansion in reliability methods. Condition monitoring has been introduced in a first wave, followed by prognostics and health management (PHM) as the second step. Moreover, the 'physics of failure' (PoF) approach is complemented by data-driven (DD) methods for fault detection and classification, supported by multi-domain numerical simulations and the implementation of machine learning algorithms. The goal of the added methods is to enable the determination of the remaining useful life (RUL) of an individual system under its specific operating conditions, in addition to the existing capabilities of estimating the typical EoL reliability for well-defined test (and operating) situations.

In general, the PHM methods are based on pre-indicators that allow capturing the emergence and the propagation of the defects. They can be derived from the PoF or from DD approaches. The PoF methods often involve numerical modeling and simulation to replicate and to study concrete physical failure mechanisms. The DD approach relies on statistical methods to deduce the RUL from the actual trends in functional or assessment parameters. The fusion or hybrid prognostic methodology combines both approaches, PoF and DD, with their respective advantages. It allows focusing the damage prediction by involving knowledge about the critical failure mechanisms but also takes into account the uncertainties of the actual system with its possible anomalies and the stochastics of the operational conditions. In order to develop the specific PHM measures for future automotive applications, a metro map-type of plan has been established (Figure 30), 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.

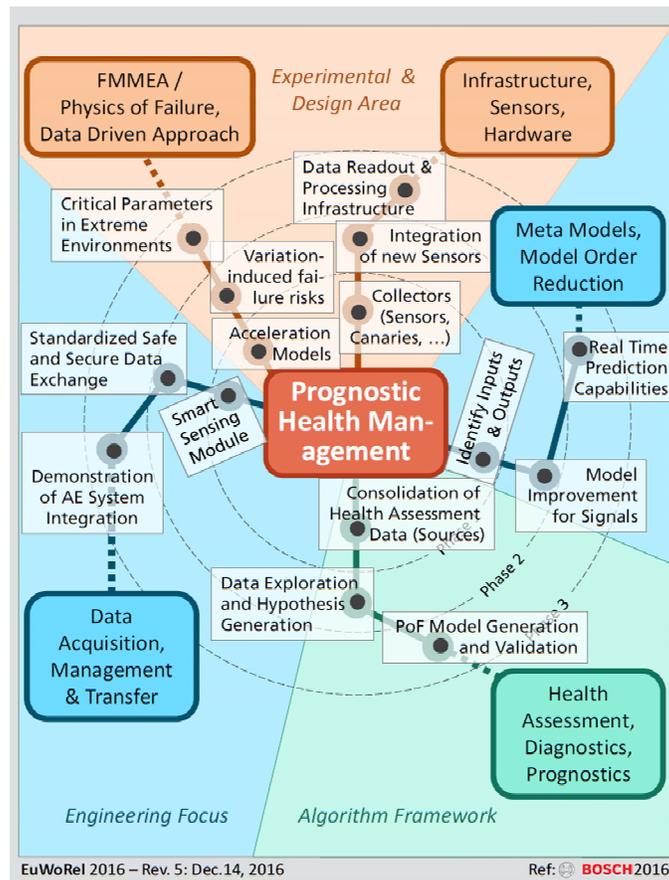


Figure 30. PHM Methodology Metro Map [12]

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) [13-14] 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:

- Development of the metamodels and reduced models (MOR) for data exchange between supply chain for quantitative numerical modeling, including legal aspects;
- Definition and standardization of the format for model exchange across the supply chain that will secure IP rights;

- 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.

Before the implementation of the hybrid PHM approach, fundamental work on both sides, i.e., on the PoF models as well as on the DD methods, needs to be conducted individually:

- Data-driven approach requires:
 - Application of available sensor or implementation of new sensor for in-situ monitoring of device and system life;
 - Identification of early failure indicators for different failure modes that can be in-situ monitored during the lifetime of electronic products;
 - Using AI/ML-based algorithms for anomaly detection and failure identification;
 - Hierarchical, local (at device level) and global (at ECU level) state of health evaluation schemes that will enable a damage calculation for each single ECU level;
- Main research activities for the PoF model-based approach will focus on:
 - A generalized multi-domain and multi-scale simulations flow for virtual design and testing under accelerated and field conditions;
 - Using AI/ML-based algorithm for deducing compact models and digital twins of electronic components, modules, and complete ECUs that are capable of accounting for the coupled-field, nonlinear and transient effects adequately;
 - Deeper physical understanding of the root cause of damage, especially under multi-domain (electrical/thermal/mechanical/chemical) loading conditions that design elements experience in the field;
- Subsequently, the following activities will enable the implementation of a PHM hybrid approach for automotive:
 - Definition and standardization of the modeling methods and tools for compact digital twins of ECUs that enable in-situ health assessment during the product service life;
 - Identification and standardization of pre-indicators and key failure indicators for the PHM approach, including development of tools and algorithms using AI/ML;
 - Analysis of the use cases, and determination of all relevant failure modes they can trigger;
 - Identification of the failure modes, such as for new materials used, during the actual field use, including strategies for acquiring field data;
 - Hierarchical and scalable PHM architectures and platforms including integration of diagnostics and prognostics capabilities from device to system level (ECU).

Automotive electronics, especially for autonomous driving, will be based on next generations of smart systems [17] and cyber-physical systems [10]. There is an urgent need to define new standards for reliability assessment and qualification that can account for the complexity of these future systems. This includes the definition of the responsibility for the specific design elements. Here, the suppliers at all integration levels will require significantly more detailed information about the loading conditions in real field application since 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 31 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.

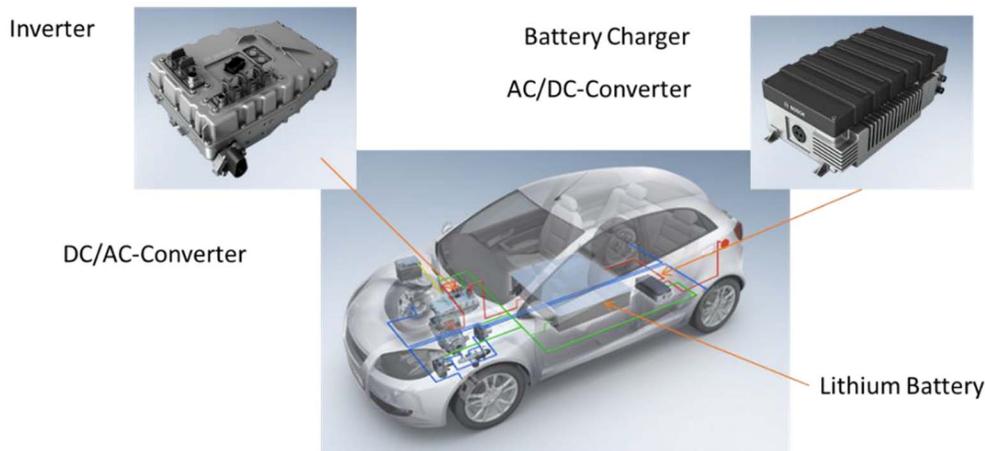


Figure 31. New Era in Automotive Electronics – the Powertrain of Electric Vehicles

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.

Table 3: 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 Figure 32 below.
- **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 33 is from the BMW i3 where the inverter, DC-DC converter and the charging functions are combined.

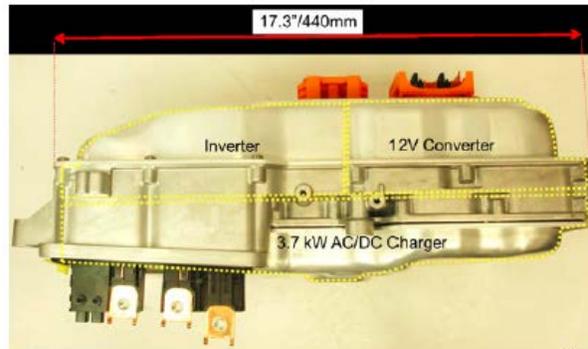
CHARGER EXAMPLE: ON-BOARD CHARGER MODULE FOR CHEVROLET VOLT



Source: Delta Electronics

Figure 32. Battery-Charging Module

PCU EXAMPLE: BMW i3



Source: Oak Ridge National Lab.

Figure 33. 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. For a comprehensive discussion of this topic, please refer to HIR Chapter 10: Power Electronics which will provide insights and roadmaps for developing next generation power delivery solutions that include wide band gap materials.

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.

10. Cross References to other HIR chapters [18]

Many of the discussions related to radar and LiDAR include key technologies that are reviewed in detail in Chapter 11 “MEMS”. The processor technologies covered in section 5 include utilization of system in package technologies also addressed in Chapter 21: “SiP and Module System Integration”. Finally, the reader is advised to consult Chapter 10 “Integrated Power Electronics” for more detailed information of Power electronics packaging,

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11. References

- [1] D. Newcomb, “Google Takes Self-Driving Car Testing to Texas,” Forbes, 2015 [online]. Available at: <http://www.forbes.com/sites/dougnewcomb/2015/07/14/google-takes-self-driving-car-testing-to-texas/>.
- [2] J. Hirsch, “Tesla CEO Musk: Some Mosel S owners to get hands-free steering,” Los Angeles Times, 2015 [online]. Available at: <http://www.latimes.com/business/autos/la-fi-hy-tesla-shareholders-meeting-musk-20150609-story.html>

- [3] J. Coyne, “Exclusive: Here’s your first look at Uber’s test car (and why you’ll see it around Pittsburgh),” Techflash, 2015 [online]. Available at: <http://www.bizjournals.com/pittsburgh/blog/techflash/2015/05/exclusive-heres-your-first-look-at-ubers-self.html>.
- [4] J. Dokic, B. Muller, and G. Meyer, “European Roadmap Smart Systems for Automated Driving,” European Technology Platform on Smart Systems Integration, 2015 [online]. Available at: http://www.smart-systems-integration.org/public/documents/publications/EPoSS%20Roadmap_Smart%20Systems%20for%20Automated%20Driving_V2_April%202015.pdf.
- [5] Staff, “Advanced Driver Assistance Systems (ADAS),” Freescale, 2015 [online]. Available at: <http://www.freescale.com/webapp/sps/site/overview.jsp?code=ADAS>.
- [6] <https://www.radartutorial.eu/index.en.html> : An excellent source for understanding the principles of radar technology such as different types of radar (FMCW, DMR, Pulse Modulated Radar), antenna concepts etc.
- [7] <https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety> : Resource for understanding standards for defining technology for autonomous vehicles in the USA.
- [8] https://www.uhnder.com/images/data/DCM_Radar_for_Automotive_Application_Final.pdf : An excellent white paper describing the technical elements for optimizing radar performance.
- [9] <http://www.globalncap.org/> : Resource for understanding global partnerships for defining safety standards for autonomous vehicles.
- [10] <https://www.isola-group.com/wp-content/uploads/Making-Sense-of-Laminate-Dielectric-Properties.pdf> : A white paper on dielectric material properties and impact on RF performance.
- [11] McKinsey & Company, Automotive revolution – perspective towards 2030 https://www.mckinsey.com/~media/mckinsey/industries/automotive_and_assembly/our_insights/disruptive_trends_that_will_transform_the_auto_industry/auto_2030_report_jan_2016.pdf
- [12] Deloitte, Fleet management in Europe, Growing importance in a world of changing mobility <https://www2.deloitte.com/content/dam/Deloitte/cz/Documents/consumer-and-industrial/cz-fleet-management-in-europe.pdf>
- [13] Prisma Discovery Series report, “Electric Vehicles: A Growth Driver for the Electronic Industry?,” June, 2018 . Limited Distribution.
- [14] Rzepka S., Gromala P.J. “Smart Features Integrated for Prognostics Health Management Assure the Functional Safety of the Electronics Systems at the High Level Required in Fully Automated Vehicles”. In: Zachäus C., Müller B., Meyer G. (eds) Advanced Microsystems for Automotive Applications 2017. Lecture Notes in Mobility. Springer, 2018
- [15] <https://www.jedec.org/sites/default/files/docs/JESD94A.pdf>
- [16] <https://www.intel.com/content/www/us/en/quality/qualification-approach.html>
- [17] Electronic Components and Systems, Strategic Research Agenda 2018, <https://www.smart-systems-integration.org/system/files/document/2018%20ECS-SRA.pdf>
- [18] <https://eps.ieee.org/technology/heterogeneous-integration-roadmap/2019-edition.html>

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