HETEROGENEOUS INTEGRATION ROADMAP

2021 Edition

Chapter 5: Automotive

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Executive Summary

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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, and 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 4 for sensors, indicating new technology changes for commercialization; Section 5 for processors, showing increased challenges of advanced CMOS nodes in the automotive environment; Section 6 for advances in power electronics for electrification; and Section 7 discussing the major topics of reliability.

Summary of changes in the new revision include updates to Section 4 on sensors, Section 5 on autonomous driving processing, rewrite of Section 6 on power needs for electrification and update of section 7 (Reliability).

1. Introduction

Automobiles are becoming "electronic devices" or platforms, 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 (Figure 2) 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.

Figure 1. Components of the Connected Car

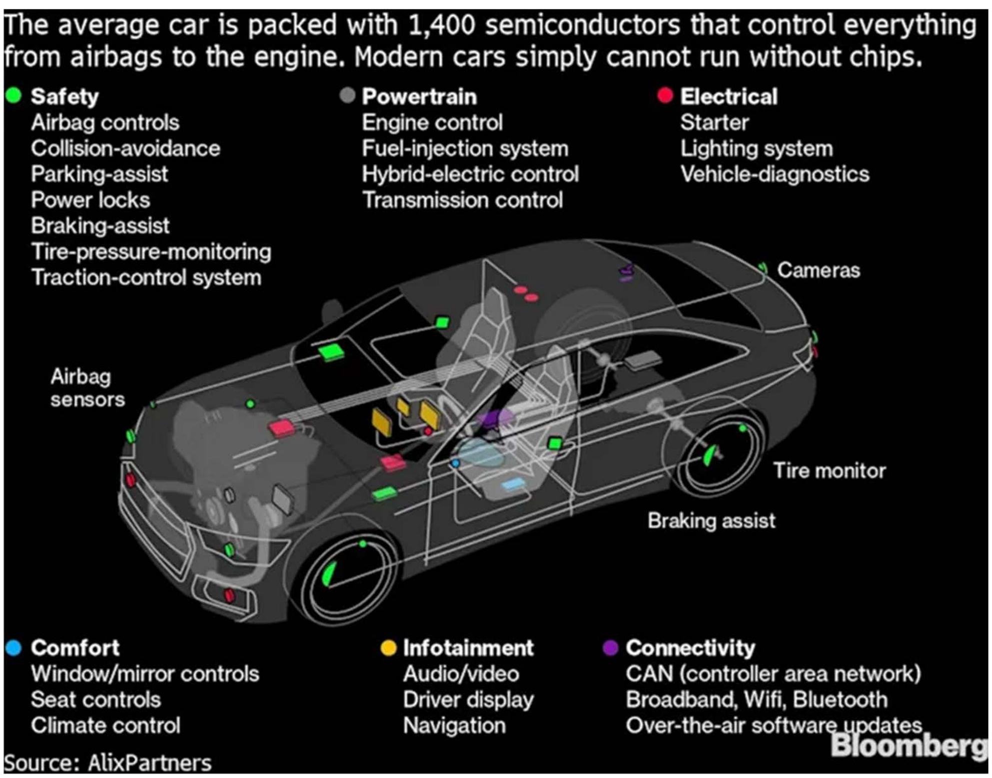


Figure 2. A Computer on Wheels

2. Automotive – The Changing Landscape

Governmental targets for the reduction of CO_2 emissions is the main driver for the electrification of passenger vehicles. Due to rapidly improving battery technologies, decreasing battery manufacturing cost, supply chain consolidation and government incentives around the world, an accelerated deployment of electric vehicles is being observed. Figure 3 shows evolution of the electric vehicle.

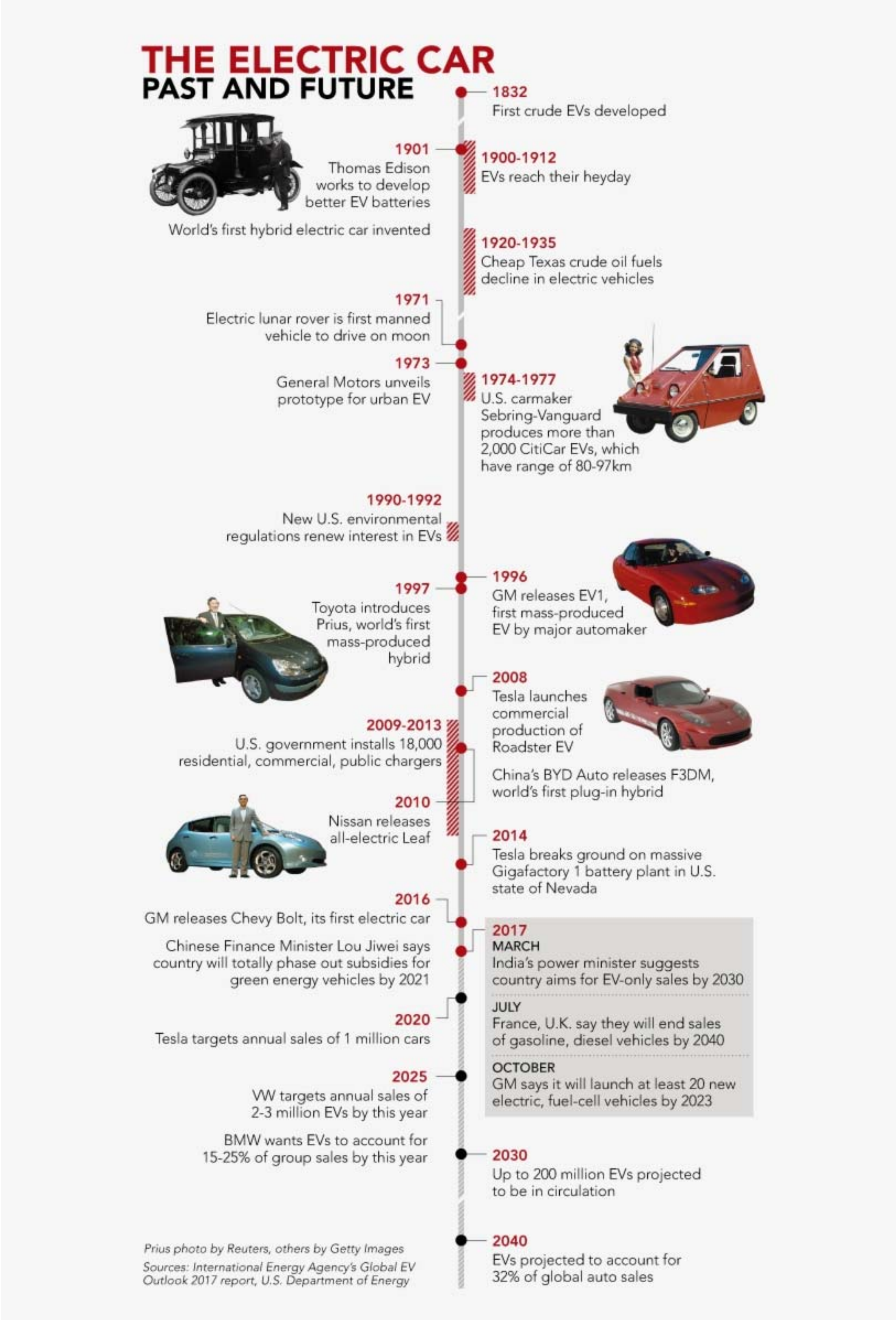


Figure 3. Evolution of Electric Vehicles

The connected car has evolved (Figure 4) in distinct stages, or phases, over the last few decades, showing advances in both technology and the ecosystem in which that technology functions. In the new mobility era, the automotive industry is looking ahead to the autonomous or self-driving car – the vision being of a not-too-distant future where shared vehicles operate autonomously, rarely crash, and provide true multi-modal transport options.

Graphic: Deloitte University Press | DUPress.com

Figure 4. Evolution of the Connected Car

3. Megatrends and Challenges

Electronic components entered the automotive area in the 1950s and 1960s with the introduction of semiconductor transistors in car radios and power diodes in alternators. Since then, electronics have spread into all relevant areas of automotive transportation. Today, up to 80% of all innovations in a modern car are supported by electronics that address applications in all areas of motor and chassis functions, comfort, security, and safety. Automobiles are becoming "electronic devices", with the majority of these innovations in automotive applications supporting four megatrends (Figure 5):

1) Autonomous driving
2) Electro-mobility
3) Connectivity
4) Advanced Security

These trends require enhancements in current semiconductor and packaging technologies as well as an entirely different set of technologies than those being pursued currently. Generally, the increased electronics content in cars without having increased space volume available for in-car electronics will be requiring further miniaturization beyond current hardware (package) approaches. This will be achieved by new (integrated) packaging concepts in combination with new or improved materials. The development of new and the optimization of existing materials will be a prerequisite for electrical and thermal performance, heterogeneous system integration and cost. In general, cost is the main driver of change in packaging and the most important challenge for the effectiveness of new electronics technologies in mass market adoption.

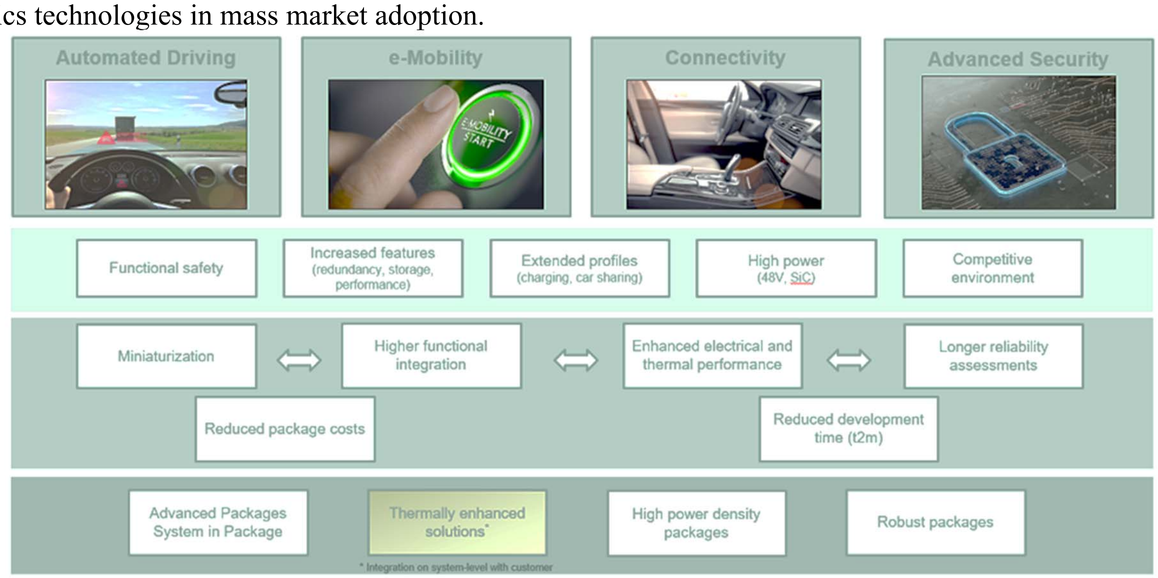


Figure 5. Break-down of Mega-Trends into Packaging Requirements [1]

The four megatrends are coming with specific packaging requirements that will need adjustments, development and the enablement of new, effective packaging solutions. Advanced packages and System in Package (SiP) for miniaturization, SiP for fulfillment of safety requirements, redundancy and advanced heat dissipation options as well as robust packages are key for future automotive solutions. For these future automotive package designs, it will be essential to have the right tools and methods in place. These will have to deal with thermal cycling profiles, temperature-humidity profiles, and profiles based on other stressors, and will as well depend on the application. Security and increased reliability will also play a major role in connectivity solutions for automotive applications. Packaging technology will finally make the difference.

All four megatrends in the automotive arena will require increased integration of components in order to fulfill the performance and reduced dimension requirements. Packages will have to fulfill increased reliability requirements caused by the extension of operational times and thermal/electrical requirements. As complexity increases, there will be no single-package solution that fulfills all needs. System integration with technology and packaging features from consumer electronics, that have been adapted and qualified for the harsh conditions of automotive applications, will therefore be one approach for future uses. Each of the four megatrends will be discussed in the section below.

3.1 Autonomous Driving

The implementation of autonomous driving is divided into five different levels according to the Society of Automotive Engineers (SAE) [2]. In level 1, the driver is only supported by some assistance systems (e.g., anti-lock braking system (ABS), etc.) during the car's operation. In the highest level 5, however, the driver will become a passenger in a fully-automated vehicle.

The higher the automation level, the more support will be needed from advanced driving assistance systems (ADAS). Therefore, ADAS is generating a strong demand for high-performance computing power, as well as various sensor technologies, preferably in complex SiP solutions with multiple integrated components.

For high-performance computing in automotive, one challenge will be the rising gap between ambient and junction temperature requirements, due to increased self-heating of the components. To manage increasing power densities and thereby the resulting heat dissipation, the heat input into the PCB must be reconsidered to avoid a thermal overload. Instead of dissipating the heat to the bottom and into the PCB, top-side cooling options will be required for heat dissipation to the top.

Driverless operation will require highly-reliable, high-performance packaging solutions to cope with the expected use-time extension. Operating times will significantly increase; necessary test times to prove the required reliability will increase significantly for low-accelerated failure mechanisms. The fulfillment of a qualification test at a specified stress test condition and time might no longer be a meaningful design target. Instead, mission profiles may become the central element of the design and validation process. Operating times will significantly increase; mission profiles of microcontrollers will change. There will be a standardization of reference mission profiles.

Autonomous driving means that all people in the car become passengers. All tasks related to driving a car, such as accelerating, braking, and steering, will be taken over by the car itself. The number of sensors, actuators and controllers will see a dramatic increase, potentially exposing mounting locations to direct contact with corrosives and other demanding environments. Furthermore, safety-critical applications such as steering or braking need to be redundant to ensure the highest safety level (Figure 6).

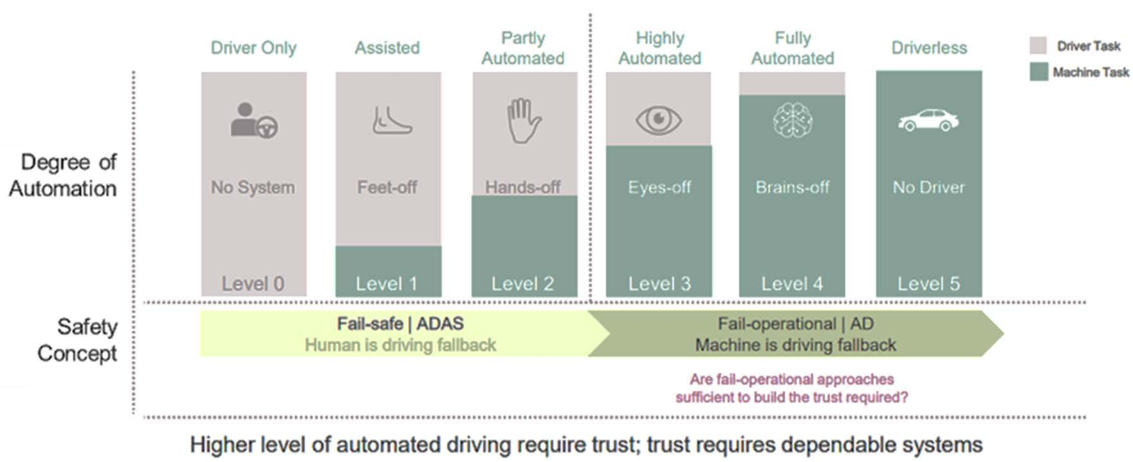


Figure 6. Automotive Dependability [4]

As a consequence of the above considerations, autonomous driving will not only increase the amount of semiconductor components, and therefore the number and different kinds of semiconductor packages [3], but will also demand challenging requirements with respect to power density, heat dissipation, and current capability – all combined in miniaturized packages that meet the highest automotive reliability standards.

3.2 eMobility

Electro-mobility will provide a big step towards the vision of zero emissions; the strict regulations on CO_2 emissions are the main driver for car electrification.

In addition to driving and parking, which are status quo for traditional combustion engines, eMobility requires additional operating states such as on-grid parking, vehicle-preconditioning (for the battery, as well as for driver comfort, e.g., cabin heating) and charging. This will increase operating times of semiconductors and provide the need for highly-efficient power electronics (e.g. SiC) with rising maximum operational temperatures up to 200°C. New packaging materials (e. g. encapsulating materials) will be required to fulfill these needs.

By adding sensors and microelectronic components to eMobility systems, the heterogeneity and complexity of packaging will increase, while maintaining the need for fast time-to-market and low cost. Novel operating states, e.g., for vehicle charging, are coming with the applications developed within this framework. The results are significantly extended lifetime requirements. The AEC-Q100/101 stress test conditions will potentially no longer be suitable to qualify a package to comply with these mission profiles. Package innovation has to provide solutions for increased reliability.

3.3 Connectivity

Despite all the changes brought about by the use of semiconductors, a car remains a car, and comfort and safety remain the key expectations of the users. High-end cars will continue to be the early adopters of high-end comfort and safety features, but those features will trickle down to mid- and low-end cars over time. Connectivity will enable a vehicle to access the internet and to communicate with smart devices, as well as with other cars, and road-based infrastructure will provide "swarm intelligence." thereby enabling the collection of real-time data from multiple sources. Connectivity will develop from connected infotainment to "car-to-x" communication (Figure 7). The different types of communication include:

- In-Car (share of 70%-90% of all data; high volume, high velocity, and high variety data)
- Car-2-Cloud (share of 5%-20% of all data; high to medium volume, low velocity, high variety data)
- Car-2-Car (share 2,5%-5% of all data; low volume, low variety, high velocity data)
- Car-2-Infrastructure (share 2,5%-5% of all data; low volume, low variety, high velocity data)

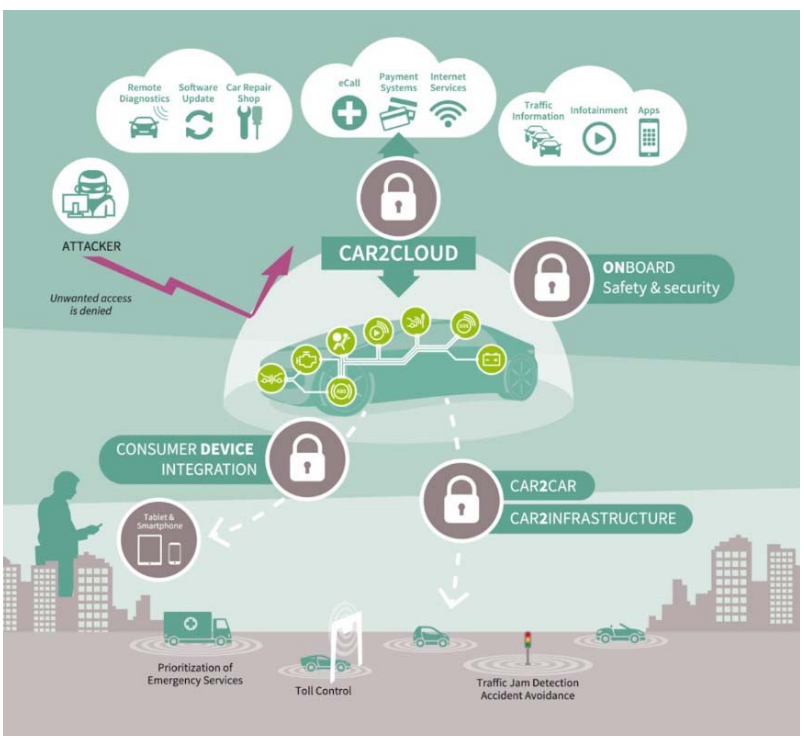


Figure 7. Connected Infotainment for "Car-to-X" Communication

5G technology will be critical for the automotive industry, particularly when higher levels of autonomous vehicles penetrate the roads. The current 4G network is not fast enough to give autonomous vehicles human-like reflexes and cooperative driving capabilities in the future. 5G will also present exciting possibilities for Vehicle-to-vehicle (V2V) and Vehicle-to-everything (V2X) connectivity. Furthermore, the technology's low latency will make future autonomous vehicles extraordinarily safe and reliable on roads. 5G will also be used for HD media streaming and advanced connected services capabilities in vehicles.

Advanced packaging, such as SiP with small node-size chip technology, will be used. Components that have originally been designed for consumer electronics will make their way into the automotive sector. Modifications will help to serve the increased reliability requirements.

With the requirement of permanent accessibility, connectivity will be one of the main drivers that increase the operational time of packages (and ECUs) for automotive applications. In general, there will be a strong link to autonomous driving as well, e.g., the use of swarm intelligence. Software updates have to be possible "over the air;" therefore, the vehicle will be permanently accessible for any requests from the backbone/customer. This will necessitate strong lifetime requirements for the packages.

3.4 Advanced Security

Data security will play a major role in automotive communication. Basic security considerations have to be implemented. Secure on-board communication, undisrupted car-2-cloud, car-2-infrastructure, and car-2-car communication must be provided. A basic protection of the single ECUs is important, as well as a firewall and gateway, and a separate infotainment protection capability.

Basic considerations for advanced security include the concept that there is no safety without security. It is a mandatory precondition and the most important asset to be protected. A dependable architecture is secure and safe. Security is a moving target. Security erodes over time; therefore crypto-agility with the right hardware and a permanent assessment of capabilities is a prerequisite of future security considerations. In order to achieve security, secure end-to-end architecture is required with a certified root-of-trust and a hardware/software co-design. Also, security will need cooperation across the whole supply chain. Security standards will have to be set and will allow transparent risk management over the complete lifecycle of a product. Packaging solutions must support this. See Chapter 19 on cybersecurity for additional information and discussion.

4. Autonomous, ADAS and Sensing Needs

Google's self-driving cars are reportedly on the road in several U.S. states [5]. Self-driving features have been creeping into automobiles for years, and Tesla (TSLA) even calls its autonomous system "full self-driving". Mobileye-Intel announced in mid-2021 it is deploying a fleet of self-driving prototypes in New York City, to test its technology against hostile drivers, unrepentant jaywalkers, double parkers, omnipresent construction and horse-drawn carriages. Mobileye CEO Amnon Shashua said fully autonomous cars could be in showrooms in the next 3-4 years. "We have contracts underway with car makers for the 2024 or 2025 time frame," Shashua told Yahoo Finance. "A level 4 vehicle can be purchased by a consumer at a very, very reasonable add-on cost." Level 4 is the second-highest level of vehicle autonomy, and it means a driver is never needed. In addition, the regulatory framework for testing and operation of autonomous vehicles on public roads has been established in California. Germany has adopted legislation that will allow driverless vehicles on public roads by 2022, laying out a path for companies to deploy robo-taxis and delivery services in the country at scale. While autonomous testing is currently permitted in Germany, this would allow operations of driverless vehicles without a human safety operator behind the wheel. 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 8.

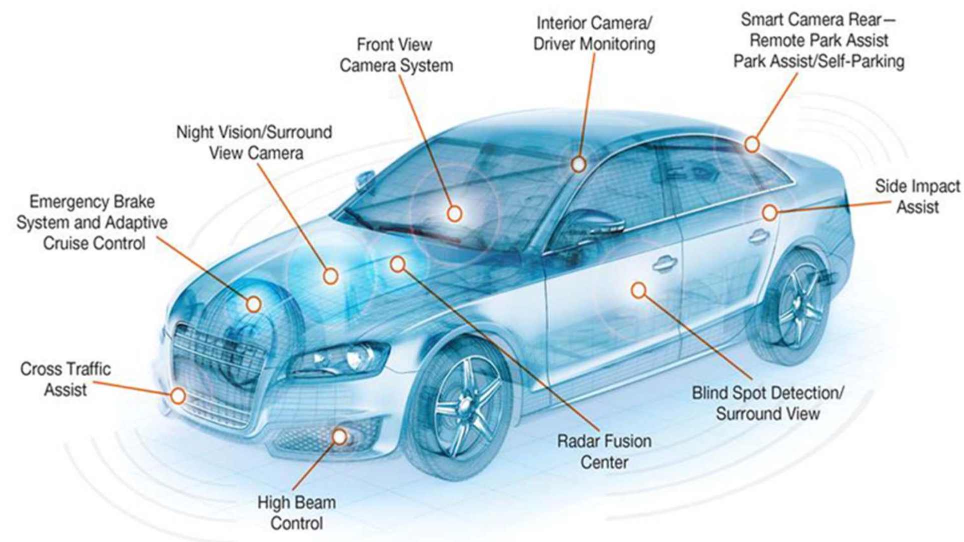


Figure 8. Figure 11(a) and (b). Advanced Driver Assistance Systems (ADAS) Application Example [6]

The advent of autonomous 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 9.

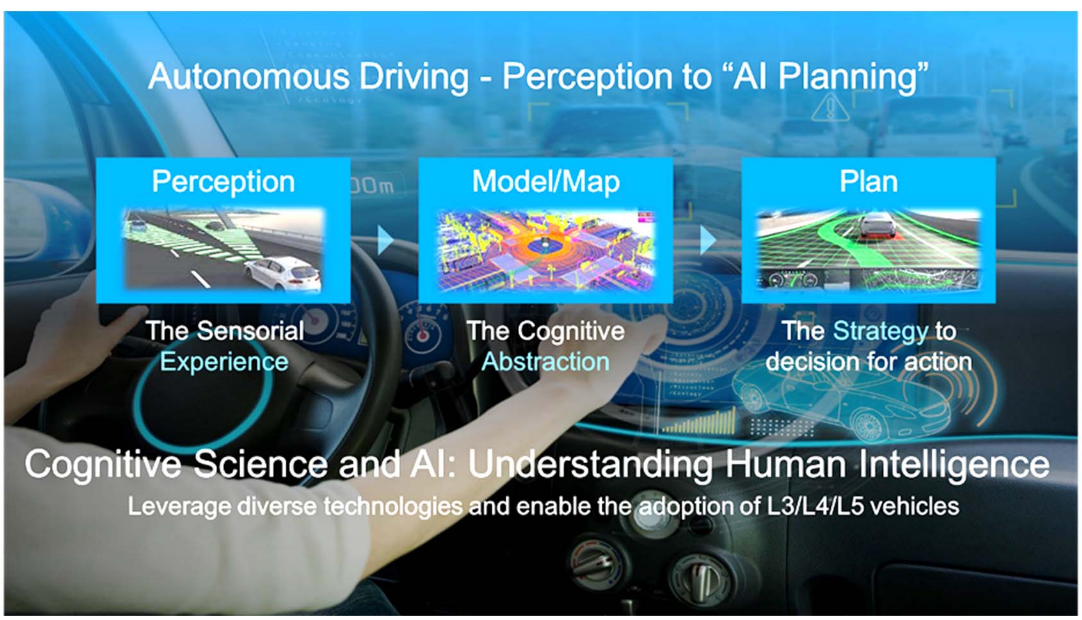


Figure 9. Autonomous Driving - Perception to "AI Planning"

The U.S. NHTSA (National Highway Transportation Safety Administration) [7] has segmented autonomous driving into distinct levels depending on the human interaction needed – from Level 0 (No automation) to Level 5 (Full automation), illustrated in Figure 10. Each of the levels has implications for sensor technologies and fusion, as a myriad of traditional and new sensing devices such as 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), and 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. The sensing requirements in autonomous cars are shown in Figure 11.

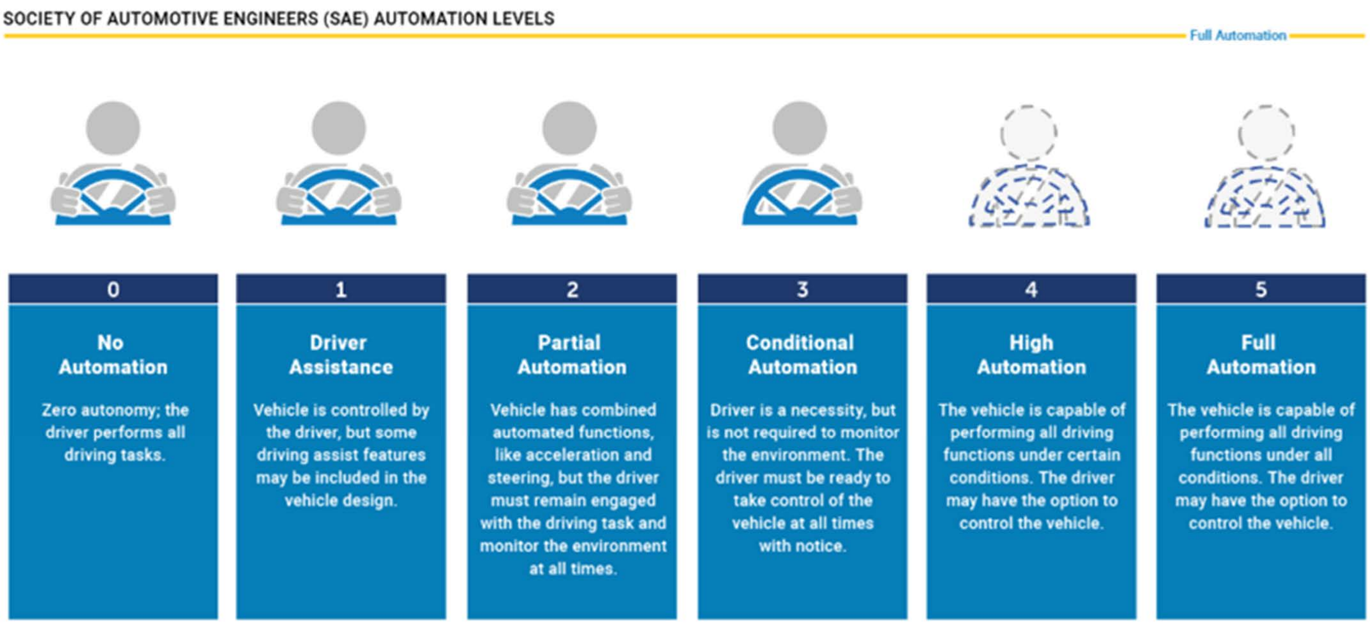


Figure 10. Autonomous Driving Levels

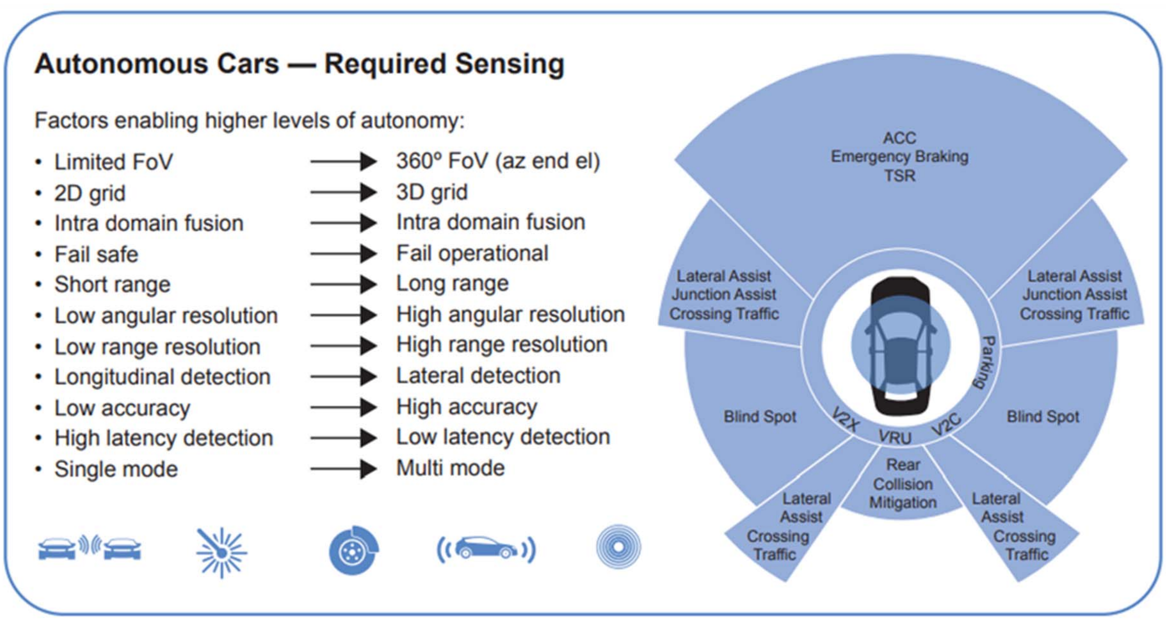


Figure 11. Autonomous Cars - Required Sensing

4.1 Camera

Cameras are image-capture 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 review, trends and roadmaps for camera-based automotive sensors will be addressed in the next revision of this Roadmap.

4.2 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 automobiles for Radar technology 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 24GHz mono-pulse radar to transmit while 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 a 24GHz frequency for transmission. Soon, the limitations of bandwidth at 24GHz 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 make decisions.

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) pHEMT (pseudomorphic High-Electron-Mobility-Transistors) MMIC (Monolithic Microwave Integrated Circuits) technology which enabled the integration of VCO (Voltage Control Oscillators), 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 communication 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 60GHz (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 Silicon technology development, through miniaturization, high volume and low cost that this industry-standard technology platform offered, greatly accelerated automotive radar deployment into the mainstream. Thus, higher frequency radar gained traction, and 77-81GHz mmWave radar became the industry norm for automotive safety applications as it allowed the utilization of a wide bandwidth Frequency Modulated Cyclic Wave scheme [8] that improved accuracy while increasing bandwidth. As radar proliferation increases, attention to packaging technologies to enable more complex radar techniques is also evolving.

4.2.1 Radar Technology and Applications

Radar sensors can be classified per their operating distance ranges: Short Range Radar (SRR) for the 0.2 to 30m range, Medium Range Radar (MRR) in the 30-80m range, and Long Range Radar (LRR) for the 80m to 200m+ range. Long range radar is used in Adaptive Cruise Control (ACC) and highway Automatic Emergency Braking Systems (AEBS) while short range radar is deployed for Blindside 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 through 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 13.

Current technology costs make Lidar (Section 4.3 below) a niche platform and not yet 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.) from 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 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.

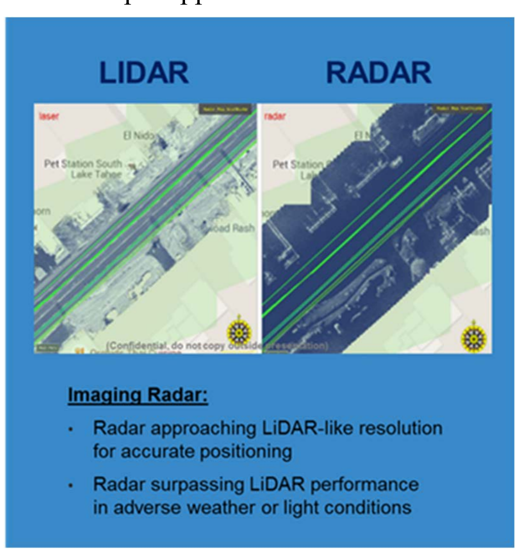


Figure 13. Lidar vs. Radar Resolution

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 24GHz radar frequency for the 76-81GHz 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 [9] – 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 provides 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 x M receive antennas from only N physical transmit and M physical receive antennas, as shown in Figure 14.

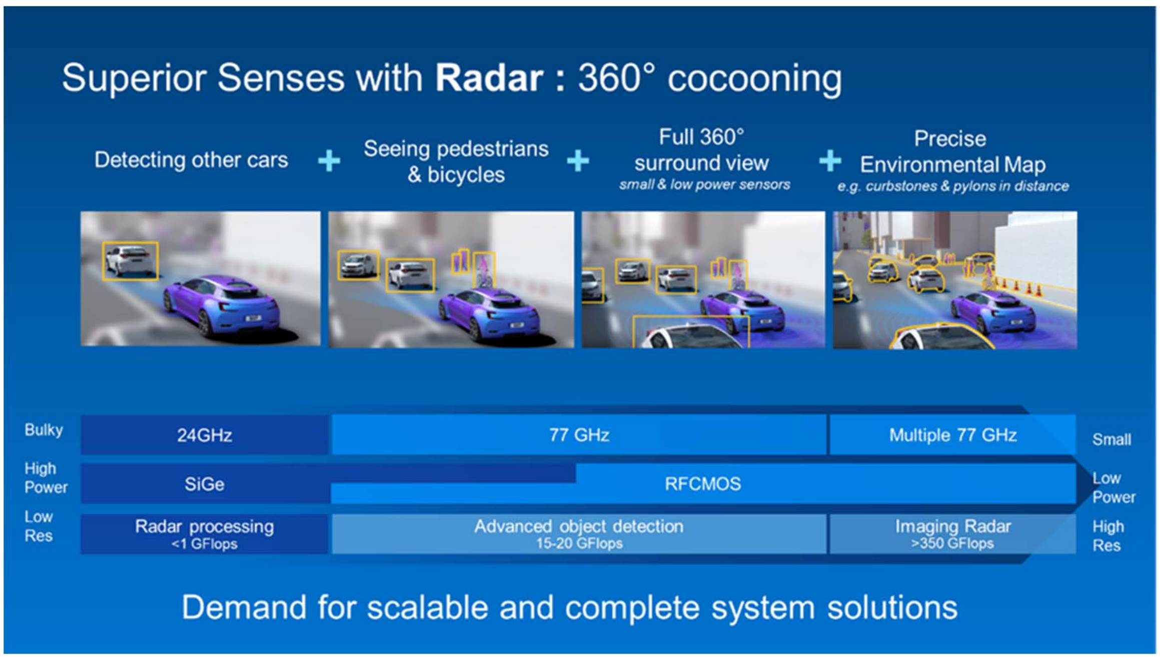


Figure 14. Superior Sensing with Radar

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 angular 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.

4.2.2 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) [10] mandates are expected to establish and enforce stringent safety rating requirements in 2020 for advanced 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, inattention, 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 in shown in Figure 15.

Figure 15. 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 stars" 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 bring L3 autonomous driving into 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.

4.2.3 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 unit combining transmit and receive functions and include analog functions, or it can be a separate chip for each function.

4.2.4 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 materials for both. Radiation loss is frequency-dependent, increasing with increasing frequency, and also inversely proportional to the material's dielectric constant (D_k). The thickness of the dielectric stack is also important, especially for waveguide launcher packages – the lower D_k 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.

4.2.5 Package Platform

Radar sensors for the 77GHz 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, 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 77GHz. These requirements will only get more challenging as the industry evolves further, from 77GHz to 120-140 GHz frequency ranges for specific applications. This is shown in Figure 16.

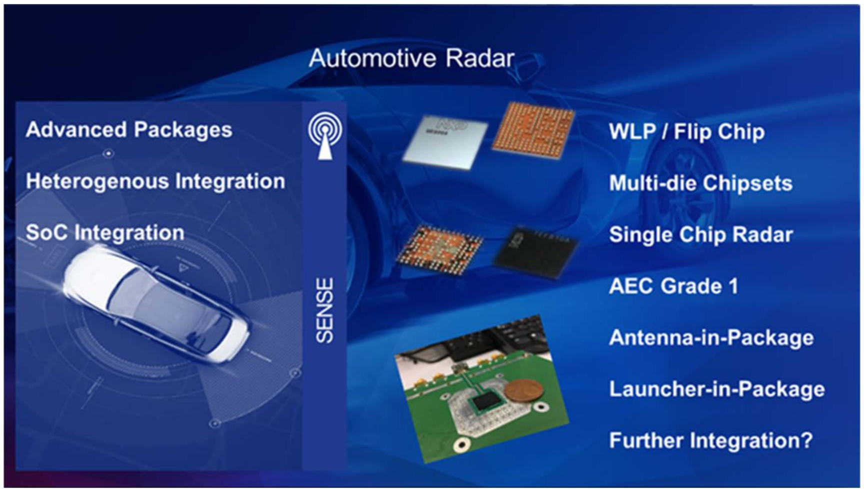


Figure 16. Automotive Radar Packaging Trends

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 (Figure 17). Integration of different board elements into the package leading to larger die with more power and thermal requirements are 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 for the antenna, making it suitable for short- to medium-range radar applications.

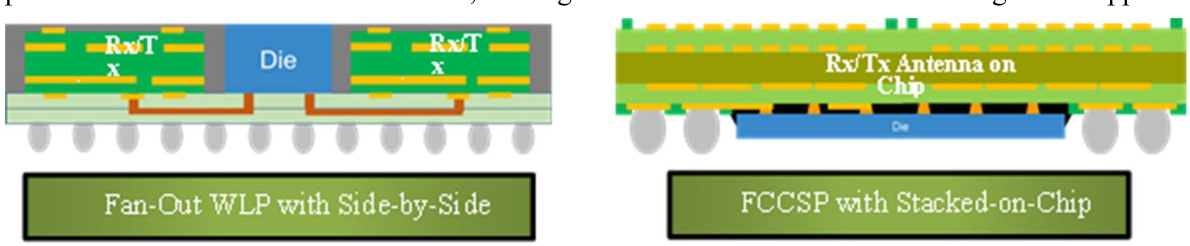


Figure 17. Automotive Radar - Current Package Technologies

4.2.6 Materials Requirements [11]

1. **Dielectric constant, D_k**: More than low dielectric constant, a critical need is a consistent D_k, as variations will cause variations in phase angle of the 77GHz frequency RF signal that decreases circuit performance. Thus, tolerance of the material's D_k is an important factor and contributes to the design D_k (as extracted from circuit performance).
2. **Dissipation factor, D_f**: This property is another key contributor to the design D_k. Low-loss circuit performance requires not only a low dissipation factor, but also a stable dissipation factor with a very narrow tolerance window for D_f 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.
3. **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 77GHz 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. TCD_k and TCD_f (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 D_k and D_f – the variation in D_k and D_f due to moisture absorption has the same impact of variability of D_k and D_f over the required frequency range and is detrimental to 77GHz circuit performance.

4. **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.

4.2.7 Design Rules

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

1. **Design rule reliability**: The design rules roadmap that governs flip-chip and wafer-level packaging (FCCSP, eWLB, etc.) are constructed for the most part for 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, as the glass transition temperature for the substrate dielectric should be above the operating range to avoid signal hysteresis and loss.
2. **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, as 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 18. Ensuring Product Quality - An Integrated Platform

4.2.8 Technology Integration

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

While current applications for automotive radar are well-served by the 76-81GHz spectrum (76-77GHz for LRR and 77-81GHz for MRR and SRR applications), the march towards machine learning and artificial intelligence has spurred development towards 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 140GHz radar as a niche solution for applications requiring high precision. 140GHz RF frequency leads to sub-2.5mm signal wavelength, enabling range accuracy of better than 15mm with 10GHz of bandwidth for specific short-range radar applications. 140GHz radar is an excellent choice of technology for in-car vital sign monitoring systems, to detect acute health hazards in time to prevent accidents. It can also overcome barriers like cloth to monitor 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 (Figure 19). 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.

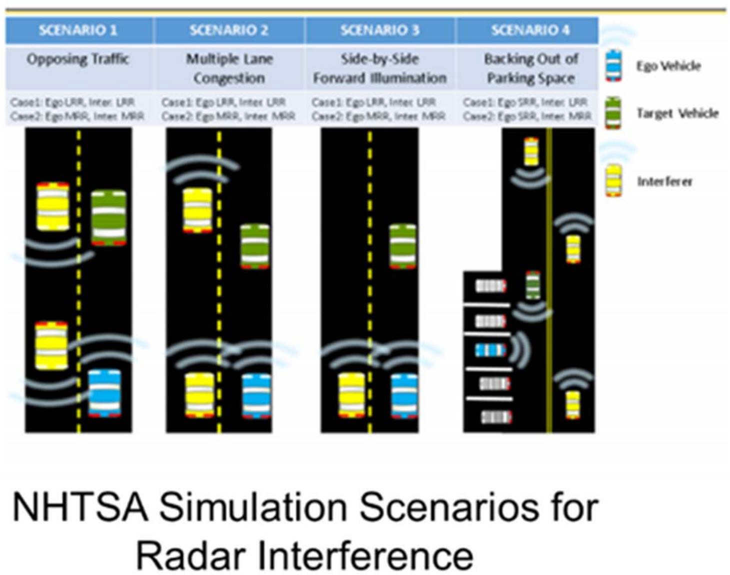


Figure 19. Radar Interference Scenarios

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 lab 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, as 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 devices 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 rather than the current 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.

One such enhancement is having the ability to design the antenna as part of the package, 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 higher performance that long-range radar requires. This is shown in Figure 20.

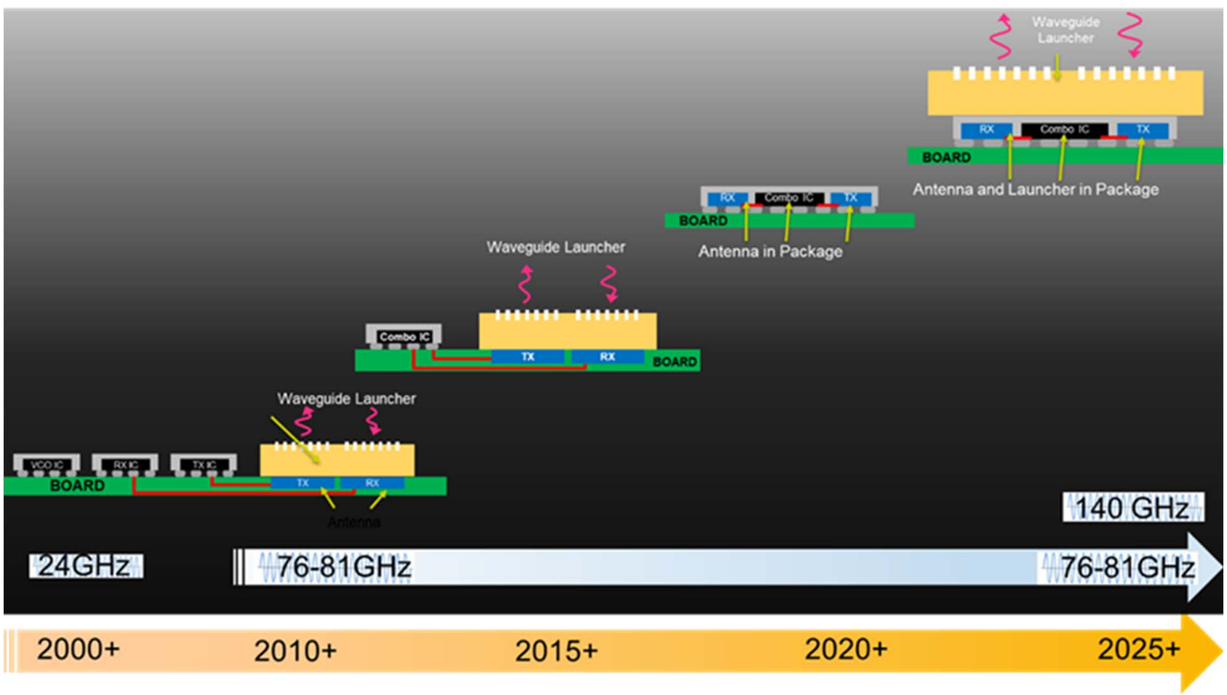


Figure 20. RF Frequency Evolution and Radar Module Evolution

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, and 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 in 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 like 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, mm Wave RF performance will need to be evaluated against conventional wafer-level packaging or flip-chip packaging.

4.2.9 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, TCD_k 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 as 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.

4.3 Lidar

Lidar (Light Detection And Ranging), is a technology for detecting and measuring distance to a target using a laser. Distance is estimated, for example, via timing the difference between transmitted and reflected signals. State-of-the-art lidars send millions of laser pulses around the car to create an accurate and detailed 3D representation of an environment.

The typical components (Figure 21) of a LiDAR system are:

A. **Laser Range Finding System**, comprised of 1) the laser transmitter, capturing target details that the laser encounters; 2) the photodetector, which receives the returned laser photons through the optics and an electronic signal after processing; 3) the optics, for transmission and reception; and 4) signal processing electronics, which calculate the distance between the laser source and the reflecting surface, based on the received signal.
B. **Scanning System**, comprised of a beam-steering system and laser source that will steer laser beams at different azimuths and vertical angles, which the LiDAR system uses to illuminate and scan its Field-of-View (FoV).

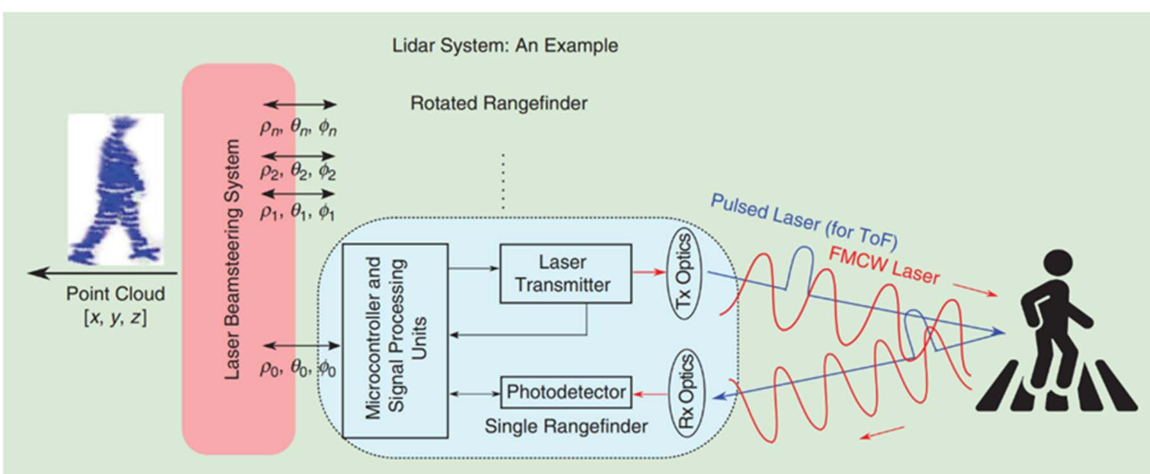


Figure 21. LiDAR System Components: a) Laser Beam steering system (Laser source), b) Microcontroller and Signal Processing Units, c) Laser Transmitter, d) Laser Receiver [12]

SAE's 6-level taxonomy was created in 2014 (Level 0 – no ADAS, to Level 5 – complete autonomy) to establish a clear definition of various abilities required for Advanced Driver Assist Systems. At each level, the automotive industry has enabled new technologies while driving costs of the new technology down. Levels 0-2 primarily deal with "Driver Assist" Systems such as Automatic Emergency Braking, Lane Keeping Warning, etc. There is a significant leap from Level 2 to Level 3, which requires an active "Driver Alert" and "Hand-back" control to a human driver. This transition required more than conventional camera and radar system and needs complex digital imaging radar and potentially lidar systems as well.

Due to prohibitive costs for the end-consumer as well as the need for substantially more computing power to handle and fuse huge volumes of data that come from multiple sensors suite and actuator that have redundancies built-in, automotive OEMs have focused on “Level 2+” systems – technology that adds safety features that are required by Global Safety Mandates but always keep the driver in the loop without removing control from the driver.

To enable completely autonomous driving that Level 3 and Level 4 transitions enable, the consensus is that a variety of sensors are needed – camera, radar and lidar being the principal elements that form the core of perception for high-level autonomy. These sensors are complemented by V2X, GPS, IMU, etc., that taken together, enable the vision of a car as a cocoon of sensors on the road interacting with other car cocoons with no human intervention. While camera and radar are de-facto automotive standard sensors, lidar technology is experiencing rapid advances that bring both the cost and form-factor of lidar down – advances that will enable introduction to the mass automotive market.

4.3.1 Lidar Technology Elements

The building blocks of a LiDAR module comprise, as mentioned earlier, a scanning system and a laser range finding system. The scanning system consists of a driver, laser source and optics that, taken together, illuminate the scene in front of the vehicle. The laser range-finding system consists of a photodetector and optics for detection, an ASIC module for processing the captured signal and feedback key parameters to the emitter system, as well as a data processing and control module that fuses sensor data, analyzes and filters the information, maps it locally and globally on a GPS, and sends control signals for the various actuator units that make up the powertrain, braking and driving experience.

Scanning System			
Laser source / Emitter: Laser Diodes			
EELs (Edge Emitting Lasers)		**VCSELs (Vertical Cavity Surface Emitting Lasers)**	
Better suited for discrete elements		Better suited for manufacturing as arrays	
Range : ~500m		Range ~ 300m	
Beam Steering			
Mechanical	**MEMS**	**Flash**	**Optical Phased Arrays**
High Signal to Noise ration over wide Field of View	Near Solid state technology using Si fabrication technology	Solid state technology used for autonomous landing spacecraft	True solid state lidar
Mechanical moving parts	Some moving parts	No moving parts	No moving components
Bulky Module	Smaller modules at lower cost	Limted detecting range and FoV	No commercial product

Laser range finding System			
Detector Technique			
Direct Detection		**Coherent Detection**	
Pulsed Lasers		Frequency Modulated Cyclic Wave (FMCW) Lasers	
Time of Flight (ToF) direct measurements		Indirect measurement of distance using the Doppler Effect	
Simple structure and signal processing methods		Require high quality laser generators with long coherent distances	
Max. range limited due to eye safety requirements		Uses less emitted power for illumination allowing extension of FoV	
Photo Detector			
P-i-n Photodiodes	**Avalanche Photo Diode (APD)**	**Single Photon Avalanche Diode (SPAD)**	**Silicon Photon Multiplier (Si-PM)**
Lower SNR than APDs	Si-based APD's are sensitive through visible spectral region to ~1000nm wavelength (NIR)	Higher gain than APDs allowing detection of extremely weak light over long distance	Provides information on the magnitude of an instantaneous photon flux
	InGaAs APD's needed for wavelengths to 1700nm	CMOS technology enables an integrated array of photodiodes on one chip	

Figure 22. Scanning and Laser Range Finding System Technology Options

Dozens of startups, tier-1s and car OEMs are working on a cheap, compact and robust lidar, resulting in what can only be described as a "Gold Rush". Despite the original challenges of early lidars, it is still a more efficient technology at providing the 3D point cloud than its alternatives. On the other hand, the unbridled innovation in lidar technology has also led to deep fragmentation of the development of its various elements in the scanning and laser range-finding systems (Figure 22).

The microcontroller, signal processing and control elements are more conventionally available silicon technologies and architectures, albeit with greater requirements on compute power and data processing. Prototype modules combining different elements above have been demonstrated by multiple firms engaged in lidar development. Figure 23 and Figure 24 provides a snapshot of some of the variety available in the lidar industry today.

		Mechanical Spinning	MEMS	Flash	OPA	Undisclosed
ToF lidar	NIR	Velodyne, IBEO, Valeo, Ouster,* Hesai, and Robosense	Innoviz Robosense	Continental Xenomatix	Quanergy	
	SWIR	Luminar	AEye and Hesai	Argo* (Princeton Lightwave)		
FMCW lidar					Cruise (Strobe)	Aurora (Blackmore, 1,550 nm)

*The manufacturers that utilize single-photon Geiger-mode SPAD as a photodetector.

Figure 23. Representative LiDAR Manufacturers and Adopted Technology [12]

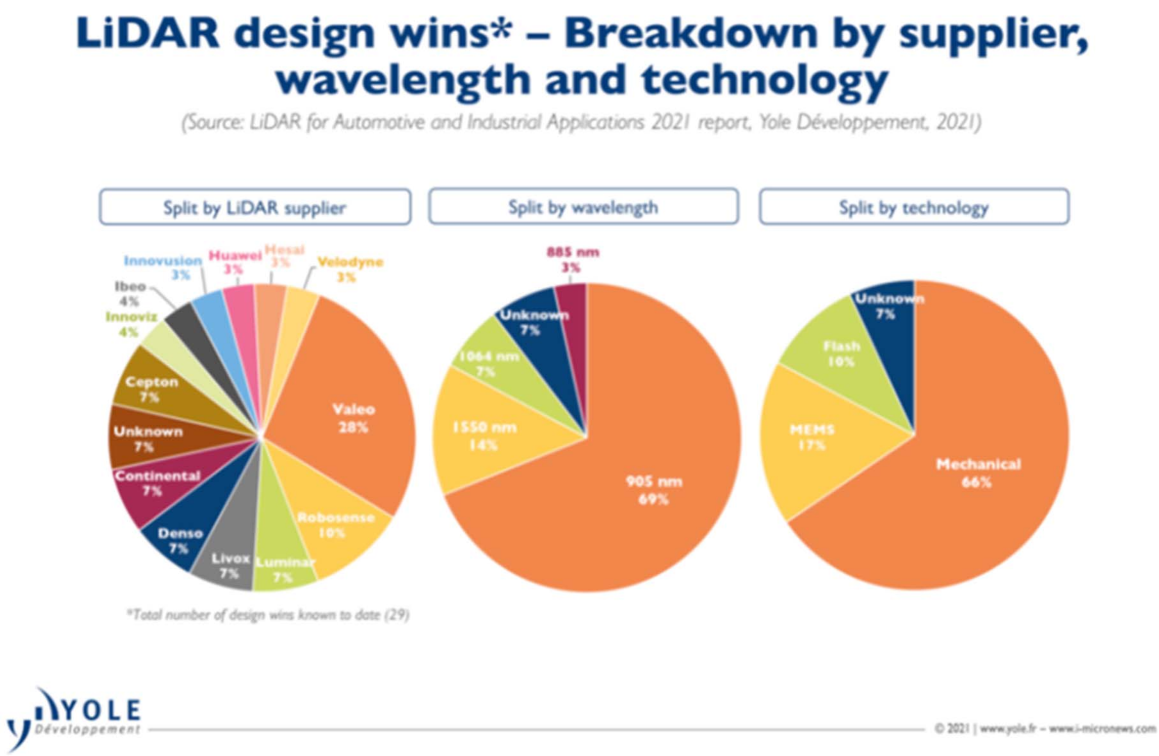


Figure 24. LiDAR Design Wins by Wavelength of Laser and Technology of Beam Steering [13]

4.3.2 Lidar Package Technology

Just as for many other technologies in their infancy, pioneer lidars had to rely on off-the-shelf discrete parts and were primarily mechanical lidars with moving parts (e.g., Velodyne HDL-64E) and high assembly cost. Since then, technology has evolved to now use solid state lidars – those with no moving parts. On the one hand, it underwent a gradual evolution, e.g., in the form of integration of lasers and receivers into arrays, multiple ADCs and preprocessing into SoCs, and so on. At the same time, revolutionary leaps led to adoption of solid-state beam-steering, FMCW principle and focal-plane array (camera-like) flash lidar, etc.

Individual components of a lidar module such as photo detectors, diodes, MEMS devices, etc. are available commercially as packaged products today for established markets in the automotive industry. Hence, packaging technology incorporated into these products such as molded cavity structures, ceramic substrates, through-hole laser packages, wire bond, flip chip packages, etc. can be adapted and applied to develop unique lidar solutions.

The combination of silicon microprocessing, laser measurement techniques, and photo detector technologies obviously leads to heterogenous technologies that will have to be combined at the package or PCB level to achieve optimum performance characteristics. Thus, the decision points will revolve around the degree of heterogenous integration on the package and the combination of multiple Silicon-in-Package chips on a PCB. These choices will be driven by performance requirements. For example, integration of a photo detector and an ASIC can be packaged as a SiP chipset and then integrated with a DSP chip on the PCB [14]. Combining them on a SiP architecture provides inherent benefits in lowering the distance that a signal needs to traverse and hence improves sensitivity and aperture ratio. Having a monolithic SoC approach, while providing better speed of detection, suffers from low NIR sensitivity.

The availability of MEMS solutions for automotive sensors (motion, pressure) provides an established pathway for lidar packaging development through molded cavity packages – either in laminate or wirebonded lead frames. These solutions have the added advantage of having demonstrated AEC Q100/Q106 reliability requirements.

While conventional packaging platforms offer a heterogenous integration path for lidar module development, there still remain several technology challenges and fundamental developments to enable highly efficient and cost-effective lidar solutions. The entire materials set of a package is primarily optimized for electrical performance while providing a reliable, hermetic solution to guard against dust, moisture and other environmental factors. In addition to the above, a lidar package should also have well-defined and understood optical properties.

Laminate substrates, die attach films, mold compounds, lids, etc. have to be characterized for optical quality. For example, a deep understanding of transparency of a die-attach film at different wavelengths will be required for developing low-cost package solutions for short-range lidar. Materials suppliers are working on these individual aspects – characterizing the properties through the process flow in the assembly factory and lifetime is critical.

At least one semiconductor packaging materials supplier, Kyocera, has indicated support for lidar products through their existing solutions in adjacent markets such as CMOS image sensors (Figure 25). Each one of the components requires different thermal, electrical and mechanical requirements and are currently discrete components integrated on a board.

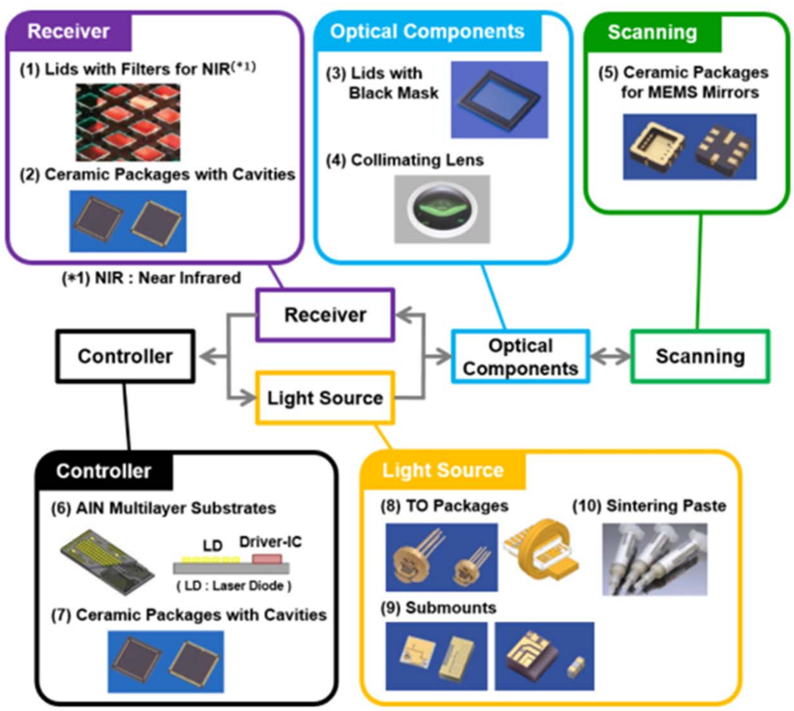


Figure 25. Potential Package Components for a LiDAR Module [15]

Another example of heterogenous integration for LiDAR can be found in the work of the University of Berkeley's Integrated Photonics Lab where active III-V photonic components and Silicon photonic circuits are integrated with CMOS electronic circuits using a Through-Silicon-Via (TSV) construction in the package (Figure 26).

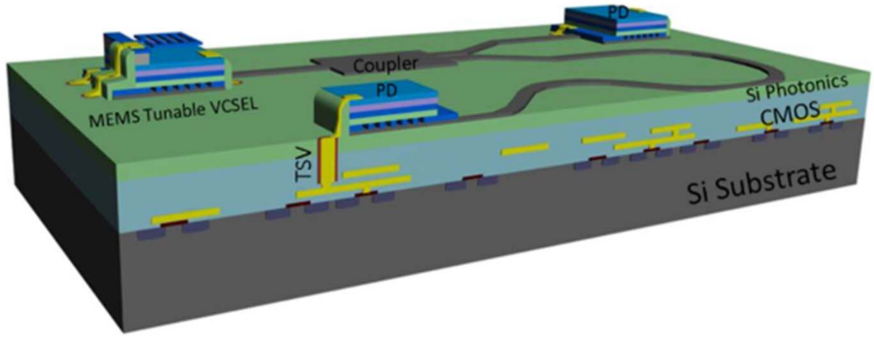


Figure 26. Example of MEMS-Electronic-Photonic Heterogenous Integration [16]

Given the fragmented nature of early-stage innovation, where the first solid state lidar products for autonomous driving are being prototyped in the market, there are multiple pathways for development with little clarity on the eventual high-volume manufacturing roadmap. All variations, however, will involve heterogenous integration at the package level and PCB level because it offers the optimum balance between module size, reliability, performance and cost.

4.3.3 Materials and Technology Integration Requirements

Typical lidar performance metrics that can be impacted by packaging technology are:

1. **Wavelength of Laser**: Near-InfraRed (NIR) is preferred for safety reasons, and the package materials should ideally have excellent NIR sensitivity.
2. **Optical performance**: Waveguide losses, grating coupler efficiency for antenna solutions.
3. **Thermal performance**: Heat dissipation is a serious concern requiring precise chip-package-board codesign. The laser emission and antenna circuitry restrict cooling options to only one side (typically the backside of the package) while having higher average and peak power requirements compared to a typical 3-5W mobile applications processor for a smart phone.
4. **Electrical performance**: Low inductance is a priority for ToF applications in the detectable range. Reducing package electrical losses is critical for beam quality and high Signal-to-Noise ratio.
5. **Thermal crosstalk**: Some technology elements, such as OPA (Optical Phased Array) implementations, will need to resolve thermal crosstalk amongst adjacent phase shifters, since it leads to optical interference phase conditions. This may require longer spacing between phase shifters for thermal isolation, which will increase cost and footprint.

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

6. *Figure 27. LiDAR Detector Package Roadmap Example*

There are several other important parameters in a lidar system that will need optimizing for electrical, optical, reliability, assembly yield and manufacturing performance. Given the breadth of use cases and specific lidar technologies that address them, the requirements will necessarily be different for different combinations of photo detectors, measurement techniques, laser sources, wavelengths, beam steering, processing and control. The requirements, though, will all require design co-ordination amongst SoC, photonics and package designers and board designers to achieve optimum performance in a heterogeneously integrated module. One potential roadmap for LiDAR package technology is shown in Figure 27.

4.3.4 Summary

The nascent automotive lidar market is expected to grow exponentially with 40-50% of total lidar revenue coming from ADAS applications as shown in Figure 28.

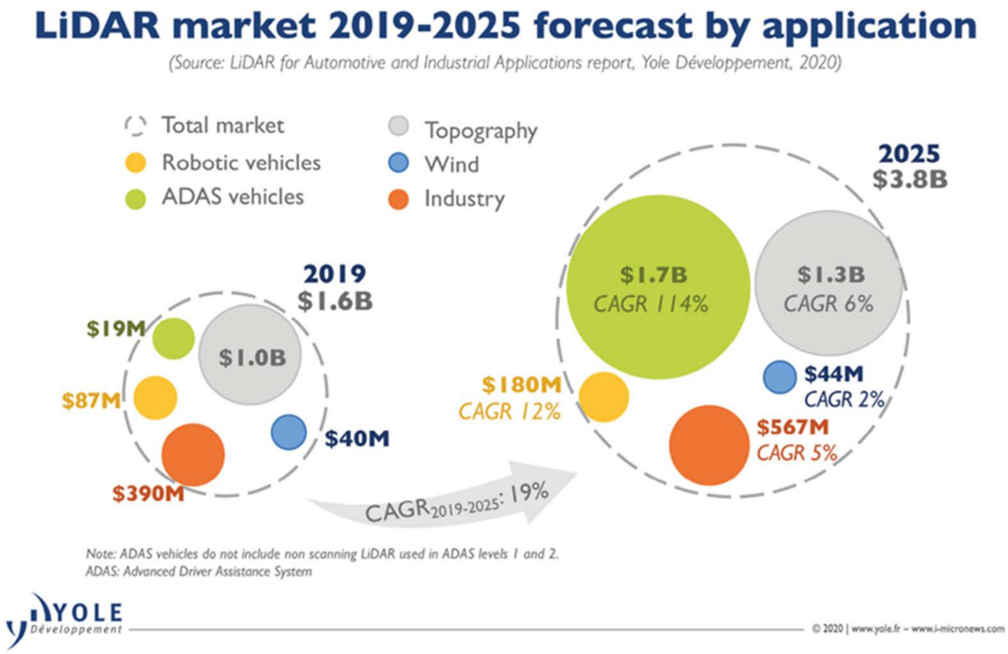


Figure 28. LiDAR Market Forecast (~40% ADAS in 2025), [17]

This growth in ADAS lidar will need packaging materials and technology development to integrate dissimilar Si CMOS, Si photonics, III-V devices as well as discrete optical and electrical components in a cost-competitive package that reduces the lidar module cost to $200-$1000 – this will drive the mass adoption envisaged for Level 3 and Level 4 autonomous driving.

4.3 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 29. 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 30.

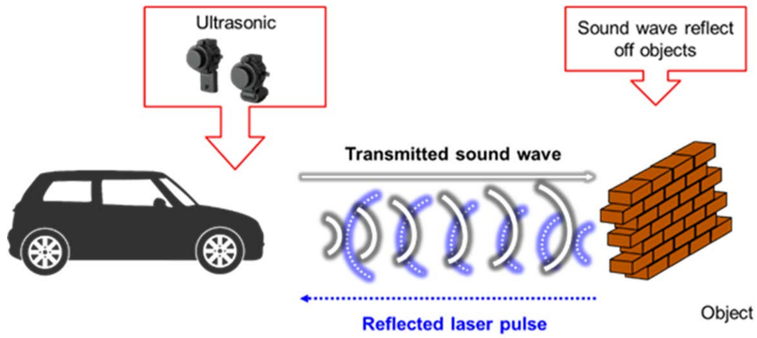


Figure 29. Definition of Ultrasonic Sensors

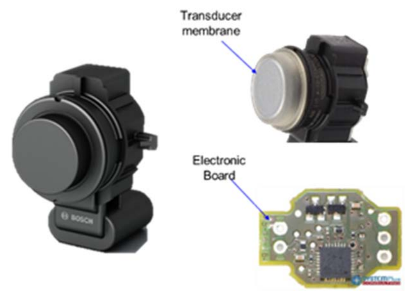


Figure 30. An Example of Ultrasonic Sensor; Courtesy: Bosch.

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 use 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.

5. Data Processing for Autonomous, ADAS, Infotainment and Connectivity

5.1 Trends in ADAS, AD and Infotainment Computing

With the increasing electrification and automation of automobiles, the role of semiconductors in the automotive market is becoming critical, and it is one of the fastest growing segments in the semiconductor industry. Automobiles are rapidly evolving from "mechanical devices" or platforms to "electronic devices" or platforms, with electronics hardware content expected to account for about a third of the total cost of the entire vehicle. This transformation of the auto industry is driven by three key vectors: 1) emergence of autonomous driving, 2) secure, high-speed communications and infotainment, and 3) expected transition from combustion engine technology to all-electric vehicles. In this section we will primarily focus on vectors 1 and 2. The technology advances and megatrends in autonomous driving (AD), advanced driver assistance systems (ADAS), digital experience, connectivity, electrification, and shared mobility will transform in-vehicle compute and software architecture requirements over the next decade.

While it is very difficult to predict market dynamics and business models of transformation from human-driven vehicles to self-driving vehicles, it is expected this transformation will certainly lead to new business opportunities. Figure 31 shows three broad segments that are bound to evolve. With increasing automation over the next 5-10 years, achieving L4-L5 automation is a certainty. The traditional market of owning a car will continue with a self-driving option, but at the same time it is expected that Transportation as a Service (TaaS, also referred to as Mobility as a Service, MaaS) will evolve significantly as these services become more and more reliable, efficient, and cost effective. The next generation of users, instead of owning a vehicle, may choose to rely more on an auto fleet to help them get around. This is already happening in big cities, with the advent of Uber/Lyft options. Another trend complementing automation is content delivery and overall user experience in the vehicle. Occupants of such self-driving vehicles will expect them to have efficient, secure and high-bandwidth connectivity for business or entertainment purposes. The requirements and demands for the infotainment segment will hence evolving rapidly.

Figure 31. The Evolving Market in the Auto Industry

These disruptive trends in the auto industry require very high compute power, memory, and low-latency and excellent network connectivity with high reliability and quality requirements. Overall, it represents a ~$70B TAM opportunity and is one the fastest-growing segments for the semiconductor industry.

Let's take a moment to look at the definition and requirements for various levels of autonomy. Figure 32 shows L1 to L5 level of autonomy as defined by the Society of Automotive Engineers. Compute requirements significantly increase going from L3 to L5 as the level of automation increases.

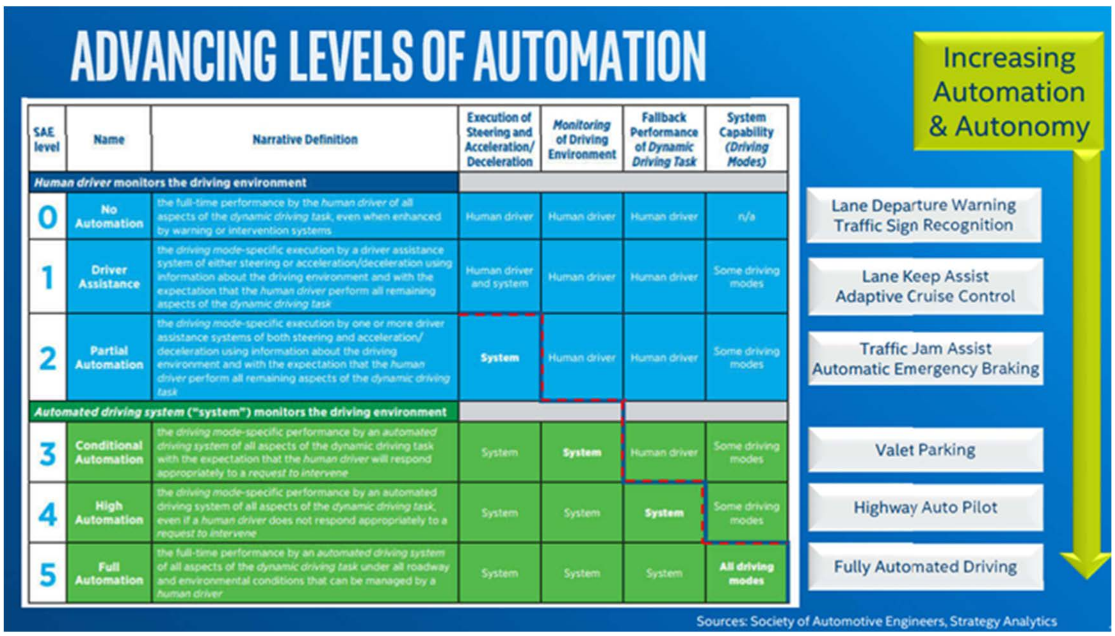


Figure 32. Advancing Levels of Automation Driving Computing Needs

These requirements drive the automotive electrical and electronic in-vehicle architectures towards centralization and consolidation of systems, starting with centralized domain controllers and eventually expanding to cross-domain vehicle computers with a periphery of zone controllers. Today's in-car compute functionality is distributed amongst several electronic compute units; these features will be consolidated in a central cross-domain high-performance compute system with centralized functionality. The consolidated system will rely on zone controllers as gateways that consolidate input and output functionality for a subset of functions in an area within the vehicle. In this new environment, software features are becoming the key to differentiating the offerings of automotive compute suppliers. It will initially deploy in premium vehicle lines.

Chip design comes with a large investment ranging in the 100's of millions of dollars, domain and performance dependent. This poses a challenge to the automotive semiconductor industry, which traditionally offers dedicated portfolios that depend on long life-cycles with relatively static demand and high volumes. This status quo is challenged on two fronts: On one side of the equation, personal mobile devices' ability to screen-mirror poses a challenge to the incumbent infotainment SW and HW stack providers, ultimately commoditizing their solutions into this space. On the other side, automotive electronics content continues to grow rapidly, in support of the fundamental changes in the driver experience. Features like ADAS continue to advance and proliferate across vehicle lines. The value per ADAS compute system and its supporting sensors is going up as the performance requirements are continually increasing for accuracy and improved performance. For OEM manufacturers, it is believed that software stacks will largely determine the value and will create product differentiation across product SKUs. OEMs will increasingly work directly with semiconductor and software companies to drive innovation, as their brand value is tightly coupled to the SW-derived user experience. It is clear that in the future, a vehicle will look more like a server on wheels, with similar compute, memory and low-latency network demands. What will distinguish different brands will be the software stacks and customization that individual OEMs will drive on relatively open-source hardware systems.

Automotive players must make corresponding adjustments to product definition and development organizations. The ADAS Use Case requires a more complex software development under strong governmental regulations. The Connected and Digital Experience requires a continuous cycle of software refresh with updated and new features supported with new connectivity to service-oriented back-ends and in-car data-centric high-performance compute. New shared-mobility business models will require end-to-end mobility platforms connecting vehicle availability to city transportation networks and infrastructure.

To accelerate the deployment of these higher user experiences in the vehicle, it is necessary to reduce the complexity of development and refresh cycles. Horizontal technology stacks are required. This technology transition will increase reuse of software components. In parallel, ideally, as in other industries such as consumer compute, infrastructure and networking, standardization practices will greatly accelerate reuse and cost reduction of the HW and SW stacks.

The simultaneous changes to the industry require the automotive ecosystem to adopt a scalable and flexible platform for vehicle compute and software. Automotive players that achieve the necessary modifications to their development process will be able to tap into new valuations and monetization possibilities. In this pursuit, there is substantial risk of failure, as it requires new expertise and approaches to compute and software rearchitecting that is still new for incumbent automotive players.

This is a prime time for semiconductor companies to help with innovations, prioritizing those that reduce architectural complexity and effectively allow the application developers to decouple SW development from HW architecture in support of services-oriented solutions.

5.1.1 ADAS to AD Transformation

The legacy approach for deploying ADAS features is smart-sensor based, due to the easy overlay integration to pre-existing vehicle architectures. The smart sensors process the raw data before transferring its conclusions to the ADAS ECU. This simplified deployment approach has allowed ADAS features in entry-level vehicles. The reduced scope of this functionality is considerably less expensive than a centralized vehicle architecture.

For the foreseeable future, as ADAS deployments continue to evolve, several vehicle architectures will co-exist. This will be the case even within different vehicle platforms from a single OEM. Over time, these architectures will converge into domain- and zone-compute systems.

Currently deployed ADAS systems are largely full-vertical solutions that allow car manufacturers to offer the higher-end features without the R&D efforts for in-house development. A number of the premium and EV OEMs have embarked on full ownership of these vertical ADAS solutions, requiring open platforms to support in-house ownership of the full stack. The deployment of $L2^+$ centralized ADAS systems will take time among larger OEMs as they carry the cost of sustaining legacy vehicle platforms with sensor-based ADAS infrastructure. The ADAS higher-end features will be easier to deploy by smaller OEMs. We will see larger OEMs deploy higher-end $L2^+$ features in new electric vehicle lines, since they will have the opportunity to shed legacy vehicle platforms.

At the intersection of ADAS and infotainment systems, a natural trend is to leverage the higher-performing infotainment system to fulfill entry-level ADAS requirements. Some of the earliest ADAS features to be deployed to the infotainment domain controller are Driver Monitoring Systems, Occupant Monitoring Systems, and surround-view cameras.

Front camera systems used for lower-end ADAS L1 features are reused in combination with surround sensors to achieve L2 levels of ADAS. As the ADAS capabilities increase, resolution of cameras and sensors goes up and result in more complex sensor suite configurations. These sensors' higher bandwidth allows for deeper vision perception and are processed in a centralized system with AI acceleration. The AI accelerator processes the sensor data and produces object information shared with the next stage in compute. Higher end $L2^+$ systems centralize sensor fusion to support the necessary surround view of the world. This higher-featured system would not be possible with smart sensors, as the overall compute would suffer from the sensor-based compute partitioning. $L2^+$ ADAS systems have significantly higher computing requirements than the ADAS entry-level systems.

A few examples of ADAS compute offerings:

- Nvidia's ADAS offering ranges from 30 TOPS with Xavier to 254 TOPS with Orin, while their next-generation SoC has been published to target 1000 TOPS.

- Tesla's in-house HW platform for AD aimed at L2^{+} features two FSD SoCs aggregating to 144 TOPS while its predecessor was capable of 21 TOPS.
- Qualcomm's ADAS Platform ranges from 30 TOPS to 700 TOPS.

5.1.1.1 Road to Autonomy: AD Architecture

While there are multiple roads to achieve L4-L5 autonomy, there are some basic ingredients that are required. Figure 33 divides these ingredients into 5 buckets, namely compute power, performance per watt per dollar, functional safety, sensors and sensor fusion, and standardization.

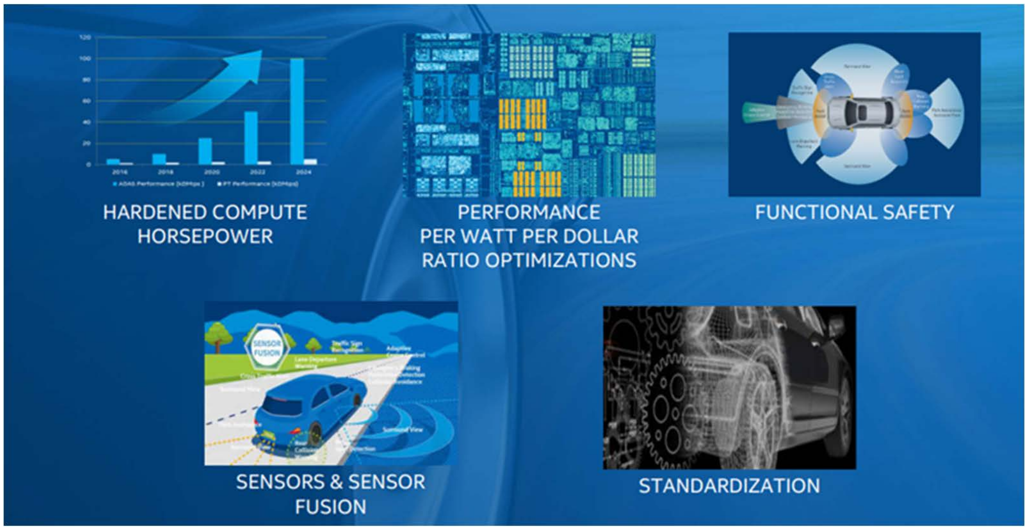


Figure 33. Key Ingredients for L4-L5 Driving

These are critical segments that requires focus in terms of specific hardware/software development for automotive segments; however, it is equally important to develop standards that allow various component suppliers to design to those requirements. Without such cohesive efforts across the auto industry, bringing these technologies at affordable cost to allow mass adoption may remain elusive.

The backbone of a self-driving vehicle in terms of functional building blocks can be divided into four broad areas, namely Acquisition, Perception, Cognition and Action. The Acquisition is primarily sensors that measure and observe the surroundings; Perception/Cognition is translation of the measured data to an actionable item; and then finally doing the Action such as braking, turning, accelerating, etc. While each of these functional blocks has unique challenges, it is Perception/Cognition that is the most computationally intensive and time-sensitive; this is a latency-sensitive block. Figure 34 shows pictorially these functional blocks.

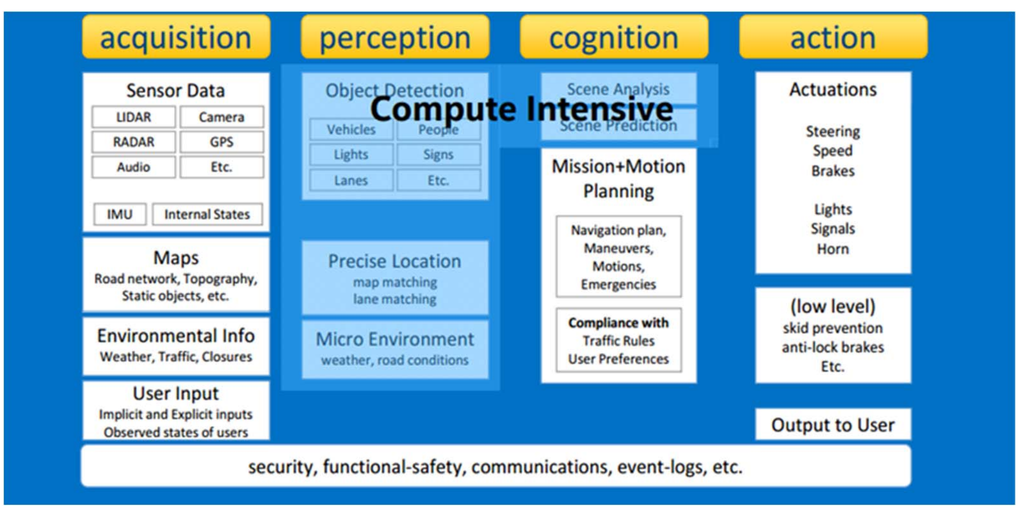


Figure 34. Functional Blocks for Self Driving Vehicle

The overall compute, memory and connectivity function must deliver some key performance metric categories. While it is always difficult to define clear KPIs for an emerging and dynamic market such as ADAS, based on some of the studies conducted by Waymo, UMich, ME, one can break down the key metrics into six categories:

1. **Performance at low latency**: end-to-end latency <100ms; humans response time varies; however it is believed to be an average of 600ms. Self-driving vehicle latency should deliver significant improvement if one is to improve performance.
2. **Performance Predictability**: tail latency numbers (99.99%) should meet or exceed 100ms requirements.
3. **Storage requirements**: localization requires HD maps, which are likely to be stored on the vehicle itself rather than relying on cloud/over-air transmission. Estimates range from 40-50TB of storage requirements.
4. **Thermal Power**: package and system thermal management to ensure seamless functioning of compute elements and also minimize impact on vehicle performance.
5. **Power budget**: efficient computation is required to minimize power; this can impact vehicle fuel efficiency significantly.
6. **High quality**, reliability and availability.

As one can imagine, the compute element in the vehicle must take inputs from all the sensors (such as camera, lidar, radar), analyze the data, locate the vehicle and define next path/action items. This must be achieved with extremely high reliability and with overall latency of less than 100ms. This is expected to not only drive the overall compute requirements, but it also puts strict requirements on sensors, network and associated software stack-up to optimize performance while delivering high reliability. The amount of compute power required depends on the quality and quantity of input data, software stacks (AI/ML algorithms), security requirements, etc.; while the metric is not clear at this time, it is certain that compute and bandwidth requirements will continue to increase many-fold from L1 to L5 (Figure 35). One must also pay close attention to the overall thermal/power budget while delivering the performance required by these vehicles.

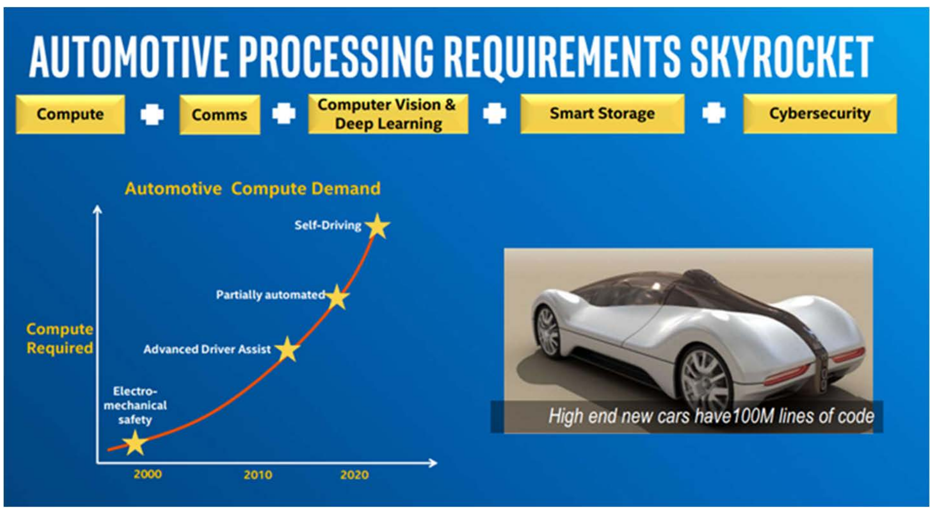


Figure 35. Compute Requirements

5.1.2 Infotainment

End users have higher expectations of the in-vehicle user experience due to the fast refresh of technology in consumer devices like smartphones and tablets. Consumers expect a seamless experience from their personal devices and smart appliances from the home to the vehicle. On top of the already available in-vehicle multi-display and 3D graphics content, this trend has accelerated the development of features such as personalization, AI-based personal assistants, voice recognition, transparent over-the-air feature refreshes, video streaming and gaming. The deployment of these features drives hardware and software complexity, driving new compute architectures for infotainment.

As OEMs seek ways to simplify their in-vehicle infrastructure and deploy scalable new infotainment features across their vehicle lines, ECU consolidation helps simplify compute systems, decrease weight and power, and enable open platforms in support of greater connectivity of data to services. The new software-defined digital cockpit integrates head-unit and cluster functionality, and in some cases low-level ADAS features like driver monitoring systems. This consolidation in hardware requires a new software approach to support the range of applications in the increasingly complex cross-domain digital cockpit. It requires a single platform capable of continuous refreshes while able to preserve the integrity of the mixed-criticality domains. The need to separate safety from non-safety related applications hosted in a single SoC, while preserving performance, drives virtualization down to the hardware.

A new generation of high-performance, heterogeneous SoCs is required to enable the open platforms for the software-defined digital cockpit. High-performance pixel processing and automotive-level robustness with mixed-criticality hardware-level partitioning are the minimum requirements for this domain. Domain consolidation will initially require up-front investments for all ecosystem players, but will over time reduce the total cost of ownership through lower power, weight, and a more agile software lifecycle. This evolution threatens to reduce the revenue for infotainment system providers, forcing suppliers to enhance their offerings to remain viable with improved 3D graphics, additional camera, audio, and video processing for new user experience feature innovations. The consolidation trend is underway, but the ecosystem is challenged to overcome the safety and security challenges of this cross-domain functionality to remain competitive.

5.1.3 Package Technology and AD Requirements

In order to understand the implication of packaging technology requirements for the AD market, one has to first understand the broader packaging technology trends in the semiconductor industry. In the past few decades, the semiconductor industry has witnessed explosive growth across multiple market segments, driven by consumer demand for products that deliver user experiences and by the need for increased compute capability for processing an increasing amount of data. This growth is primarily enabled by silicon technology node scaling at a fixed cadence. In a traditional sense, the role of electronics packaging is to serve as a bridge between silicon and the computing system, providing space transformation between the dimensionally fine interconnect features on the silicon and the significantly coarser interconnect features on the system board (Figure 36). Additionally, the package serves a number of other functions, such as providing mechanical protection to the fragile silicon, facilitating power delivery to and power removal from the semiconductor device, and the transmission of high-bandwidth signals to and from the silicon. Packaging technologies evolved primarily to maintain scaling cadence with silicon nodes, evolving from wire-bond to flip-chip technologies and from ceramic substrates to organic to meet increasing demand for I/O count and performance demands of semiconductor-based products.

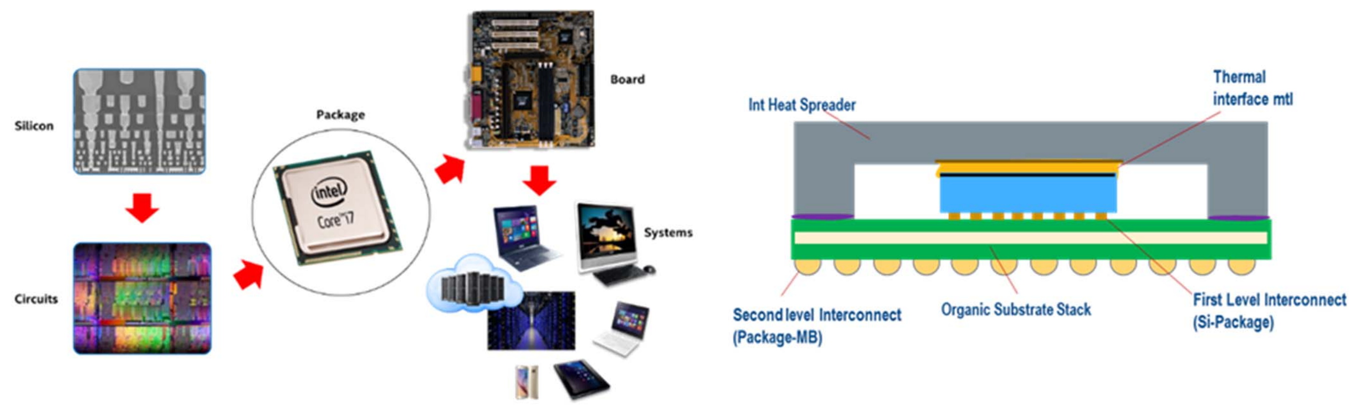


Figure 36. Traditional Role of Packaging serve as a bridge between Si and the System board; A typical cross-section of FCxGA package is shown with evolution of Die-Substrate Interconnect with Moore's Law.

In recent years there has been strong and increasing demand for package-level heterogeneous integration, essentially driven by four primary reasons: 1) Increasing demand for integration of dissimilar Si-technologies/IP blocks on the package to meet end-product requirements; 2) Need to provide interconnect technologies at low power, low latency and at higher bandwidth connectivity to deliver SIP performance that is similar to a monolithic die; 3) Improved time to market using the chiplet approach; and 4) the need to build-in yield resiliency with respect to the introduction of advanced Si-technology nodes. These vectors are driving significant advances in packaging technologies and drive strong demand for advanced packaging technologies such as EMIB, Foveros, CoWoS, Info_oS, FOCoS, etc. With the advent of advanced packaging offerings, the mainstream products (typically data-centric products, server, laptop, desktop) are being constructed with multiple chiplets connected together at extremely tight interconnect pitches to optimize product performance and silicon area. The expectation in the ADAS market segment is no different. In the following section, we will describe implications of global trends in package technologies, and their impact on the AD market segment.

5.1.3.1 Role of Advance Package Technology in AD Market

Heterogeneous packaging technologies can be broadly classified into two categories, i.e., 2D and 3D technologies. In the 2D packaging technology, dies are mounted on an organic multi-laminate substrate with lateral connections between the dies as shown in Figure 37. In 3D technologies, the dies are stacked on top of each other to provide vertical connection between the two entities, and the die complex is then mounted on an organic multi-laminate substrate as shown in Figure 38. Multi-Chip Package (MCP), and Fanout embedded bridge or EMIB technology, fall in the 2D category, while active (example: Intel's Foveros) or passive (example: TSMC's CoWoS) Si-Interposer based packaging falls in the 3D category.

Figure 37. Examples of 2D package technologies; Die to Die connection is lateral

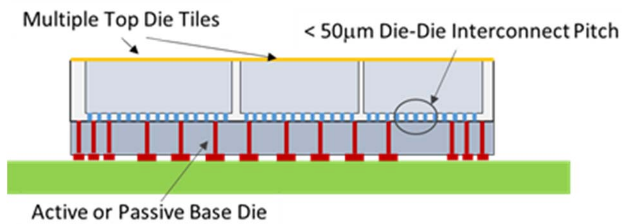


Figure 38. 3D packaging technologies: Foveros or passive Si Interposer based; Die to Die connection is vertical + lateral.

While traditional MCP fan-out packaging technologies are currently mainstream with significant volume of product built, the demand for advanced packaging technologies based on EMIB, fan-out, embedded bridge, and Si-interposer is increasing rapidly as product complexities with die-disaggregation and desire to use mixed Si-node technologies grows. It is expected that over the next decade or so, these advanced packaging technologies will become mainstream. Figure 39 shows the evolution of package technology trends driven by high performance computing and AI/ML product demands. These heterogeneous packaging technologies allow product architects increased freedom to optimize product performance, reduce cost and improve TTM.

A future vehicle will be like having a server on wheels, with similar requirements in terms of compute power, latency and thermal dissipation. Integration of various silicon products on the package using 2.5D/3D package architectures is well into development today, with mass adoption of these technologies expected over the next 5-10 years, driven by main-stream product segments. For autonomous driving to truly proliferate across the range of price points and not just be limited to the high-end luxury vehicle, delivering performance at a reasonable cost is of paramount importance. This implies that building SOC for the AD market will likely rely on similar chiplet architecture, leveraging IP or chiplet re-use and invoking advance packaging technologies for integration (Figure 40).

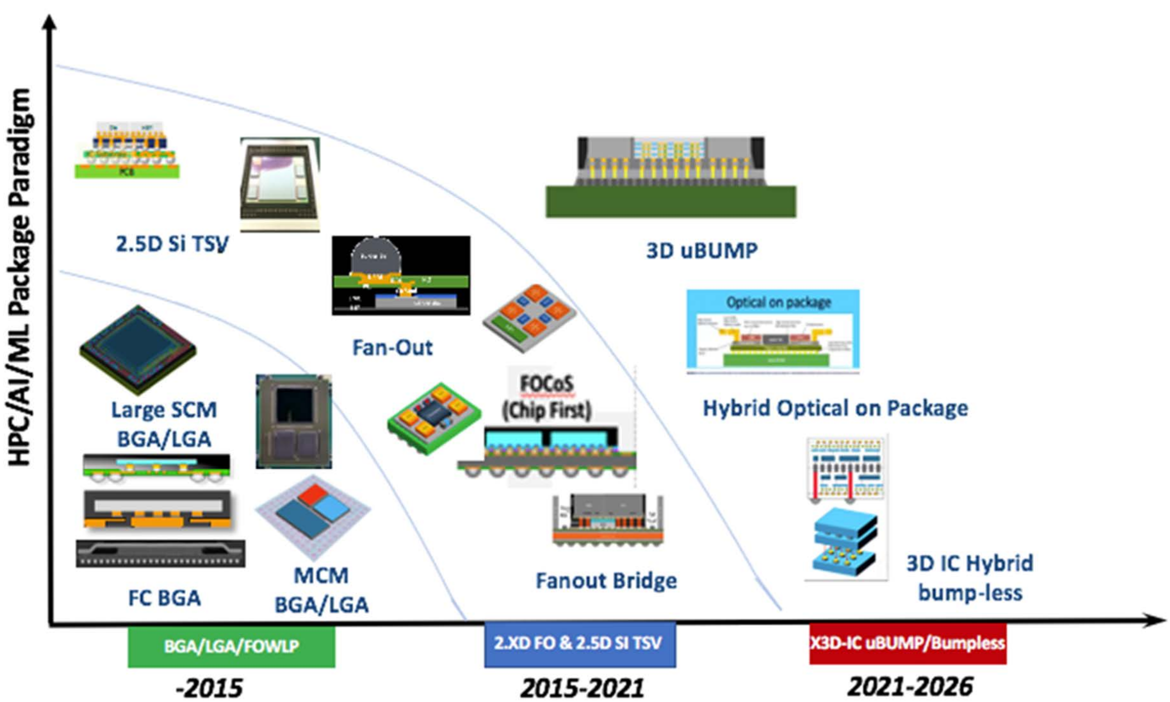


Figure 39. Evolution of heterogeneous packaging technologies from MCP/Fan-out to advanced packaging technologies such as EMIB, Fanout bridge, Si-interposer. (Courtesy: ASE)

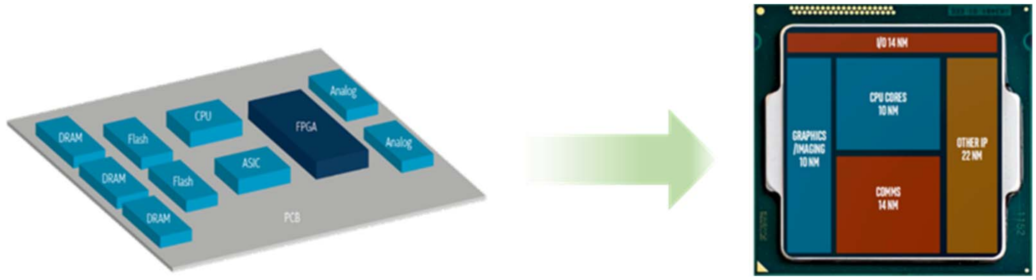


Figure 40. Board level to package level integration; higher bandwidth at low latency and power, integration of different IP blocks to deliver functionality

Key figures of merit (FOMs) for packaging technologies can be divided into two broad categories; the first category includes performance-based FOMs such as interconnect densities, D2D I/O power, off-package I/O scalability, power delivery schemes and cooling capabilities; while the second category includes manufacturability, yields, cost and reliability. Packaging technologies must continue to improve on these FOMs to ensure they continue to meet current and future product requirements. However, it is equally important for a product engineer to understand the trade-offs between these two categories in order to deliver a viable product that meets the product landing zone in terms of performance and cost – for example, re-using the chiplet or IP across market segments (aka traditional server market to AD market) to reduce cost of development and improve time to market; it is however critical that these chiplets/IP blocks are designed upfront to meet the entire range of reliability requirements. At the same time, advanced packaging technologies need to be developed, including design rules, materials, process conditions and metrologies to meet AD reliability requirements including DPM goals. We will discuss this more in the reliability section.

5.1.3.2 Smaller System Level Footprints

Smaller foot print requirement will be strongly driven by AD markets; this is expected to be unique requirement for this market segment primarily driven by available weight/space constraints in a vehicle; Smaller system foot print will drive smaller package foot print; balancing product functionality at tighter package foot prints drives higher silicon to package area ratios, which brings some unique challenges in developing assembly process at package and MB levels, scaling board and substrate DRs such as BGA pitch, pad, line/space to allow breakout/fanout, innovative materials to continue to deliver high reliability and high yielding processes (Figure 41).

Figure 41. Smaller System Footprints through Advanced SiP and Module Integration

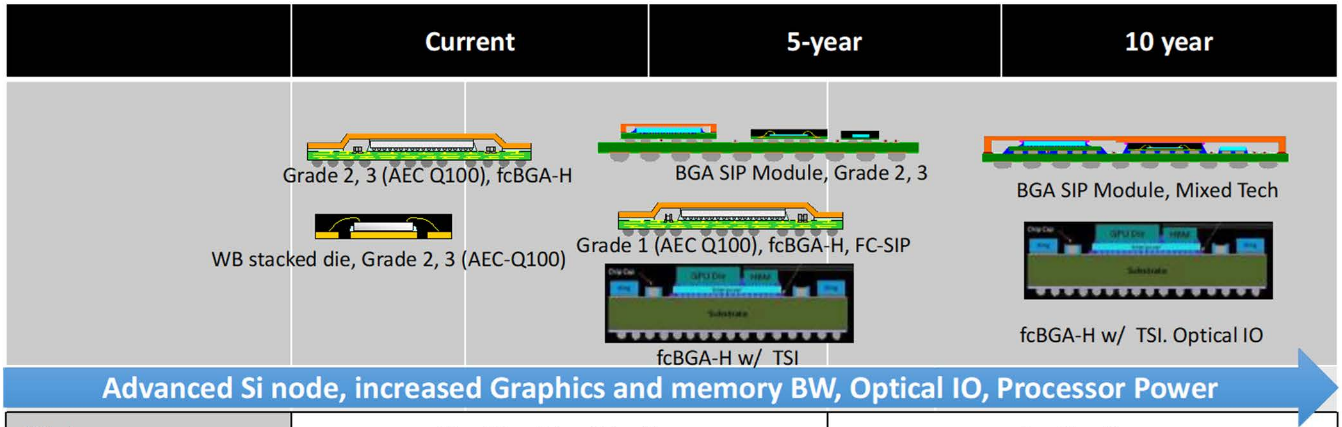
5.1.3.3 Processor Roadmap

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 42, 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 differs from 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 lower-performance MCUs will continue to be there for off-loading mission-critical functions.

- Broader utilization of AI/ML advanced packaging solutions should proliferate into automotive processors due to similar requirements on processing rates, highest communication rates (low latencies and bandwidth) and highest capacities.



Si Node	40nm/28nm/14nm/10nm/7nm		5nm/3nm/2nm
Interface Speed (parallel), opto	High end 128 bit (32bit X 4 channels) → Massive parallelism Mid-end 64 bit (32bit X2 channel)		
Bump pitch	150um/130um/110um		<100um
Mounting structure	PCB Attach		SIP/Module
Reliability	AEC Q100 Grade 3/2/1	AEC Q100 Grade 2/1 AEC Q006 Grade 1	AEC Q100 Grade 1 AEC Q-104 for SIP
Safety	ASIL-B	ASIL-D?	

Figure 42. Automotive Processor Roadmap

5.1.3.4 Thermal Management

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 performance, driving high TDP, while on other hand these products will be subjected to harsh environmental conditions with T_{amb} significantly higher in comparison to their traditional use conditions (aka: cloud/server); Figure 43 shows a comparison of thermal boundary conditions between typical server or client products versus the automotive environment. Typically for Client/Server, T_{amb} ~40-45C, which gives thermal headroom of 60-65C (with Tj_{max} ~105C); however in the AD segment, T_{amb} estimates range from 75-80C, thus giving thermal headroom of less than 50C (with Tj_{max} ~125C). Furthermore, any additional power consumed for system cooling purposes takes 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 challenge for package- as well as system-level thermals. One needs not only to innovative high-conductivity thermal interface materials, but these are also strong requirements to co-optimize the system layout to ensure thermal constraints are resolved successfully.

- For Client/Server Market: Tamb ~40-45C
  Tja budget (thermal headroom): 60-65C (assuming Tj: 105C)
- AD/IVI Market: Tamb ~ 75-80C
  Tja budget (thermal headroom): 45-50 C (assuming Tj: 125C)

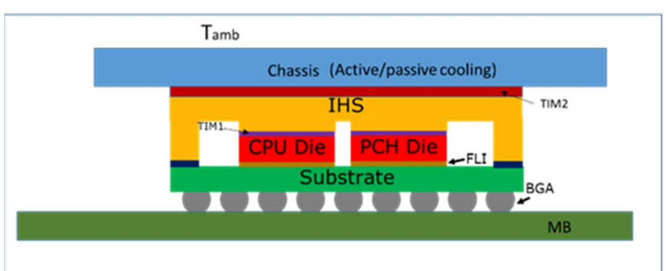


Figure 43. Thermal Boundary Condition Comparison - Client/Server vs. Automotive

5.1.4 Delivering AD 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 44 highlights the qualitative comparison of AEC-Q100 Grade qualification requirements (Grade 3 to Grade 0, with Grade 0 requirements being most stringent) against the current capability of packaging technologies ranging from low I/O count QFN, QFPs, to FCBGA to current state-of-the-art packaging technologies such as 2.5D/3D/SIP. The intention of Figure 44 is to highlight the key gaps for higher functional packaging technologies to meet higher reliability standards driven by AD markets. Significant investments and R&D efforts are required to optimize design, materials and assembly/test processes to deliver higher-functionality packaging technologies at reliability levels governed by AEC-Q standards.

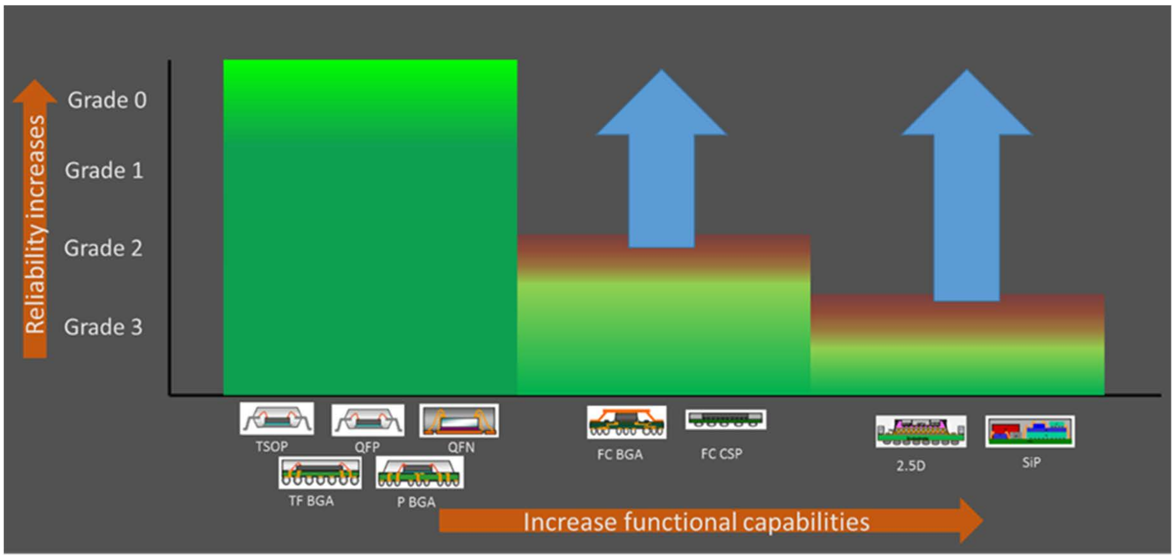


Figure 44. Role of Reliability Requirements and Functional Capabilities

There are a wide range of quality and reliability failures one can encounter in packaging. Figure 45 shows a few examples of these failure modes. High-level failure mechanisms can be differentiated into two categories; 1) time-zero fails that happen at the end of assembly; and 2) wear-out driven failures that are seen during product life cycles. Time "0" failures typical impact product yields and it is imperative to eliminate these fails; for example, Figure 45 under the "Yield" title shows white bumps (white color is a result of acoustic measurement technique) which represent delamination in Low-k ILD layers in Silicon backend processing, and is the result of Silicon-package interaction during assembly processes. A good understanding of these failure modes and mechanisms can eliminate this failure mode. In examples of wearout mechanisms, shown in Figure 45 under the "Reliability" title, one needs to develop a detailed understanding of the failure mechanism, but it is equally important to develop reliability models to project if these failure modes are risks to the product under a real-use conditions. Appropriate accelerated tests need to be developed to quantify the DPM risks for products. Quality is also a critical category of fails that are measured at the end of line before shipping the product to the end customer. While these fails can be considered subjective or cosmetic in nature, sometimes they contribute significantly toward the DPMs. For example, Figure 45 under the title "Quality" shows scratching on the silicon during assembly/test operations; while these lead to non-functional fails in the product, customers tend to reject these units. Developing appropriate metrologies to screen out sub-par quality product is critical to meet product DPM goals.

In general, reliability risks increase with increasing die size, as shown in Figure 46. With increasing die size, thermo-mechanical stress increases in the package, and as a result, risk of wearout-driven failures increases. Figure 46 shows an example of such wearout failures. The interface between Si and the package (commonly referred as first-level interconnect) can lead to fatigue failures in underfills, solder bumps or solder resist films typically laminated on top of a package substrate.

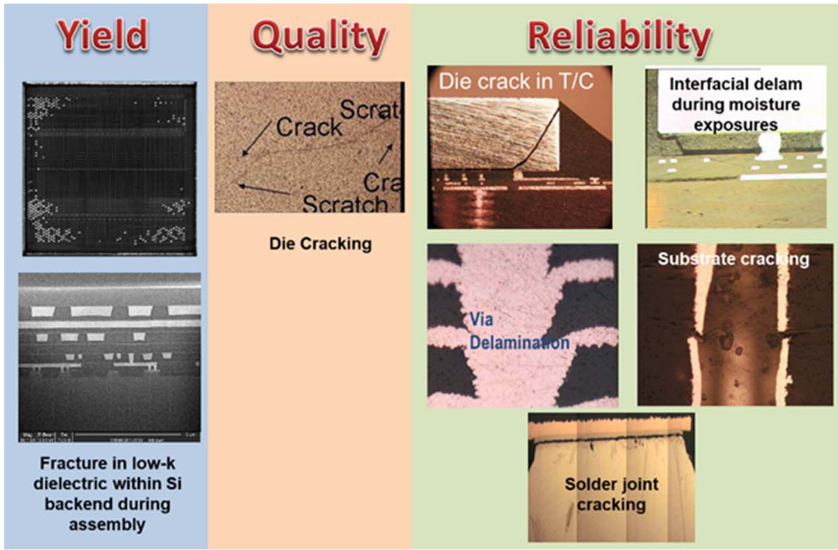


Figure 45. Range of Quality and Reliability Failures

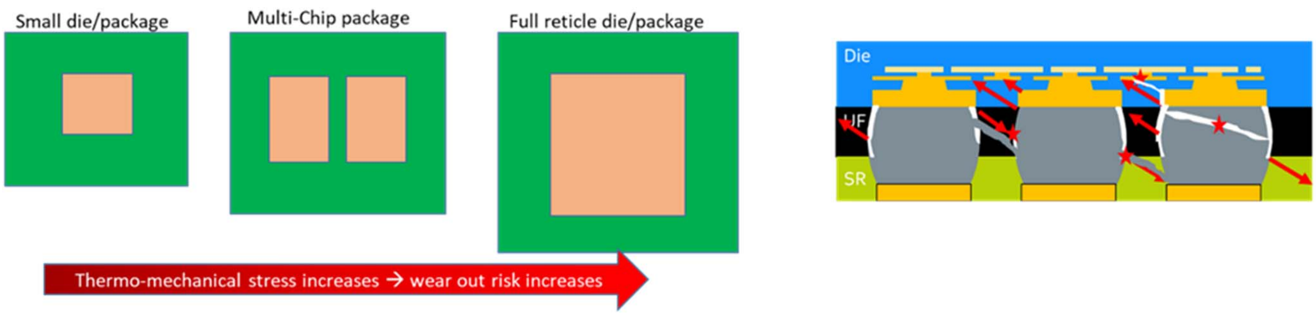


Figure 46. Reliability Risk and Die Size

Eliminating such failures requires package architecture optimization to reduce thermo-mechanical stress, but also drives new materials with higher fracture toughness and appropriate design rules such as non-critical or redundant bump assignments at high-stress locations, which certainly has significant impact on SoC/IP floorplans.

While focus is needed to invent/develop materials/processes to meet the high-temperature, harsh environment conditions and high usage life requirements for these markets, another critical aspect that needs attention is understanding the real-use conditions 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 for these conditions, rather than blindly chasing some standards-based requirements.

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 physical presence of drivers, but rather are expected to operate closer to 18-24 hrs/day.

Given that ADAS is a fledgling concept, the usage models or mission profiles are ill-defined at best. This implies that following AECQ* standards 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 across 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 ~10000 hrs in life is now expected to operate for ~30000 hrs over 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) governing 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 desired reliability. Finally, given the fact that higher performance at lower power and smaller footprint generally requires use of the latest technology (silicon or package), thorough characterization of that latest technology to ensure no latent failure mode lurks to provide zero defects is not easy.

Finally, given that a higher performance/power ratio and smaller footprint generally requires use of the latest technology for products, thorough characterization of that technology (silicon or package) is paramount to ensure no new and latent failure modes exist if a zero-defect mindset is to prevail. This is generally not practical given the lack of maturity of new processes early-on and a lack of early, high volume 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 47, typical consumer electronics 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 the 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 old, 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.

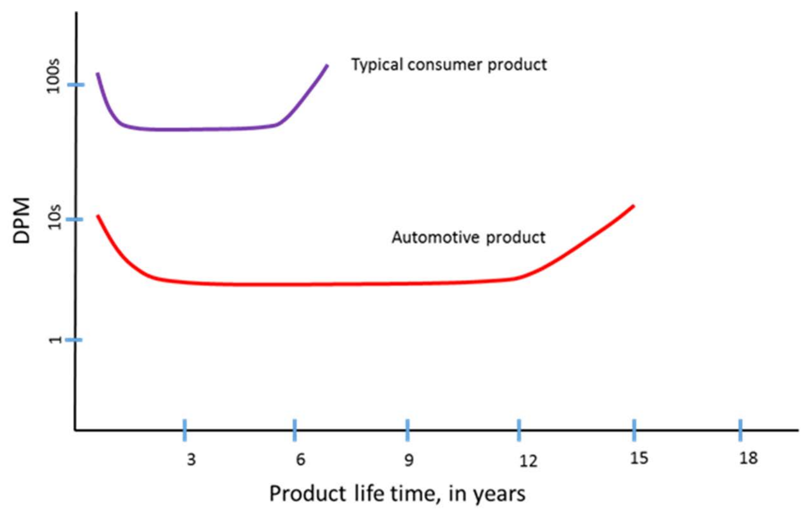


Figure 47. Quality Requirements for Different Market Segments

6. Vehicle Electrification

Electrical components, such as battery, on-board charger, inverter, and motor, are predominant in evaluations of the performance and the electrification level of the vehicles. Figure 48 shows the fundamental schematic of those important components, each of which has different functions, including energy storage, energy transfer, and energy harvesting. To better predict the current status or the trend of these components, a roadmap including the target parameters at different stages has been made.

6.1. Inverter (DC-AC to motor)

A Roadmap from the U.S. Department of Energy (DoE) has listed key targets for traction motor and Power Electronics Inverter Module (PIM) of the electric drive system for the years 2020 and 2025 [19] and is shown in Table 1 and Table 2.

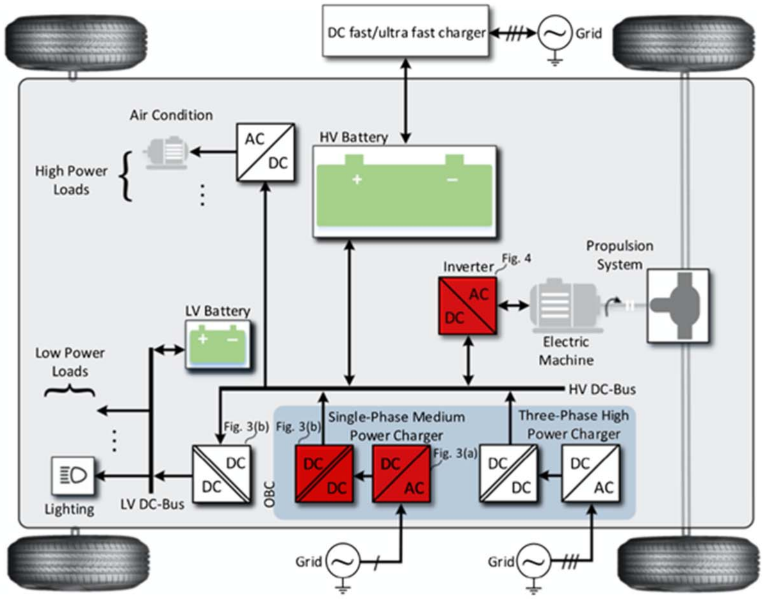


Figure 48. Overview of the electric power system in EV/HEV [18].

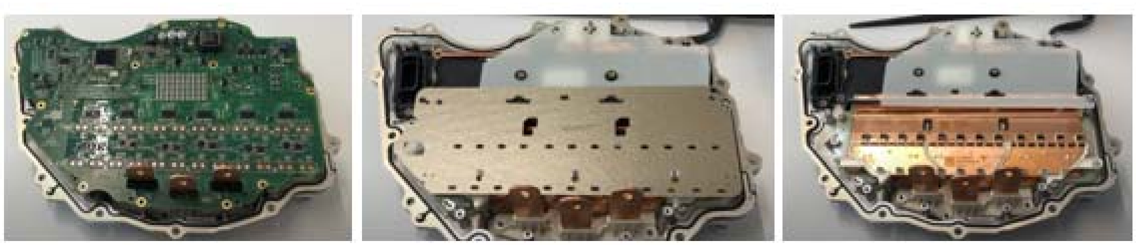
Table 1. DOE Targets for Traction Motor and PIM

DOE Targets	**Cost ($/kW)**		**Power Density (kW/L)**	
	2020	2025	2020	2025
Traction Motor	4.9	3.3	5.7	50
PIM	3.3	2.70	13.4	100

Table 2. DOE Targets for Key Electric Specifications

Peak Power (kW)	200
Continuous Power (kW)	110
Battery Operation Voltage (Vdc)	850-1100
Voltage Rating (V)	1200
Maximum Device Current (A)	200
Maximum Current (A)	800
Switching Frequency (kHz)	30-50
Maximum Efficiency	>98
Power Factor	>0.6

A video of the Tesla Model 3 inverter teardown is available (https://www.youtube.com/watch?v=fj4KBVgJsGA):



(a) (b) (c)

Figure 49. (a) 1st layer: control and gate drive board; (b) 2nd layer: isolation and insulation between control board and inverter power line; (c) 3rd layer: SiC inverter power line.

Tesla Inverter expanded view [20] and teardown [21] are shown in Figure 50.

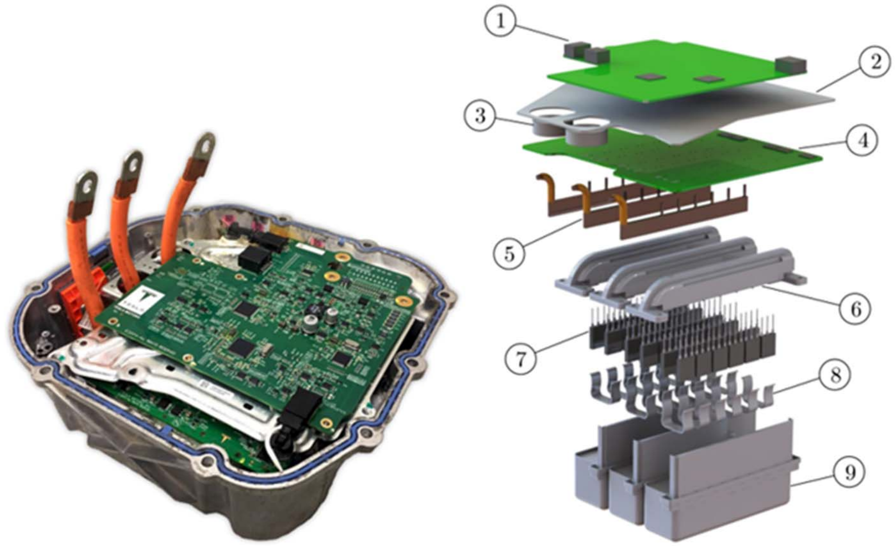


Figure 50. Left: Model S dual motor rear drive unit inverter. Right: Tesla Model S inverter components: (1) Control board, (2) Aluminum shield, (3) Phase current sensor ferrite ring, (4) Gate drive board, (5) Phase busbars, (6) Heat sinks, (7) TO-247 package IGBTs, (8) IGBT clips, (9) DC-link capacitors.

6.1.1. Global Safety Mandates

Electric powertrains and inverters are safety-critical components (ISO 26262 [22]) that require comprehensive, automated testing at the power level.

6.1.2. Packaging Technology

6.1.2.1. Current Technology

In order to achieve all the requirements for commercial automotive power modules (Figure 51, Figure 52), industries have developed several solutions which have been used in these products. For instance, Hitachi has added heatsinks to both sides of the module with special pin-fins optimized by a genetic algorithm that can efficiently improve the heat dissipation. Delphi Technologies used flip-chip soldering techniques to improve the current distribution. Featured with a SiC-based switch rated at 650V and Ni/Au plated metal stack as the replacement for wire bonds, the next-generation Delphi inverter module can power up to 1200V and 500A_{RMS}. Toyota is working with Denso to develop a card-like formfactor power module with high modularity by using a half-bridge configuration with two IGBT diodes in each module. This small-and-thin formfactor has enabled a very low resistance and parasitic inductance, lowering the conduction loss without suffering switching loss. To enhance thermal management in the super-small die size, Continental aggressively removes the conventional copper baseplate and thermal grease, which are replaced with a CTE-matched AlSiC. The power module manufactured by Mitsubishi Electric is also highlighted for applying a direct lead bond (DLB) and thermally conductive electrically isolated layer (TCIL), improving the power and thermal capability and reducing the internal inductance and resistance. Nissan Leaf is another entry-level automotive product, and it has a small formfactor power module with the implementation of die-Cu/Mo buffer plate-busbar direct-soldering. Also, the removal of ceramic substrate, baseplate, and the circuit pattern board and the addition of silicon-based "special fillers" have improved thermal conduction and electrical insulation. The details of these commercially available products are listed in Table 3.

6.1.2.2. Future Trends

From the above discussion about the current commercially available power modules, there is still a strong demand to further improve the performance ratings, such as thermal management, power rating, reliability, and switching characteristics. New packaging forms are one kind of solution to continue upgrading performance (Figure 53). Basically, they can be categorized as system integration, PCB embedded technology, press-pack packaging, and high-complexity 3D packaging. The pros and cons of these packaging forms are shown in Table 4.

Table 3. Details of Some Commercially Available Products

Suppliers	**Examples of EVs**	**Module Configuration and Maximum Ratings**	**Die Interconnection and Die-Attach**	**Substrate, Baseplate Assembly, and Encapsulation**	**Cooling**
Hitachi	Cadillac CT6 plug-in hybrid (General Motors), S500 and S550 plug-in hybrids (Mercedes Benz), e-tron (Audi) Volt extended-range EV (Chevrolet)	Half-bridge IGBT, 700V, 325Arms Single IGBT, 430V, 325Arms	Cu lead frame soldering Flip-chip soldering	Isolation sheet, removal of the baseplate and thermal grease, resin Direct substrate cooling, CTE-matched ceramic substrates	Double-sided with integrated and optimized pin fins Double-sided
Delphi	Unknown	Single SiC MOSFET, 650V, 285Arms	Ni/Au plated metal stack for top-side soldering or sintering	Unknown	Double-sided
Toyota and Denso	Toyota	Half-bridge IGBT, 650V, 180Arms	Flip-chip soldering on a surface electrode	Isolation sheet	Double-sided
Continental	I-PACE (Jaguar), Range Rover Sport Plug-In Hybrid	Half-bridge IGBT, 450V, 650Arms	Double-sided sintering	AlN DBC ceramics, removal of the baseplate and thermal grease	Single-sided, AlSiC heatsink
STMicroelectronics	Tesla Model 3	Single SiC MOSFET, 650V, 100Arms	Cu ribbon bonding, silver sintering	Unknown	Single-sided pin fins
Mitsubishi Electric	Honda Insight Unknown	Half-bridge J-series TPM IGBT, 600V, 300Arms 6-in-1 J1-series IGBT family, 650V to 1200V, 200Arms to 1000Arms	Al wire bonding, Cu DLB Al wire bonding, Cu DLB	TCIL, direct substrate, cooling, resin Isolation layer, removal of thermal grease	Single-sided Single-sided with optimized and integrated pin fins
Infineon	Renault Zoe, BMW i3, Volkswagen group	6-in-1 HybridPACK IGBT family, 650V to 750V, 200Arms to 800Arms	Cu wire bonding, diffusion soldering	Different substrate-to-baseplate solder joints	Single-sided pin fins or double-sided
Nissan	Nissan Leaf EV	Custom-made IGBT, 600V, 340Arms	Wire bonding, buffer plate	Isolation sheet replacing of the ceramic substrate, baseplate and the circuit pattern board	Single-sided
Fuji Electric	Honda Accord Unknown	Boost+6-in-1; 700V, 124kW High bridge All-SiC; 1200V; 25A to 400A	Wire bonding Cu pins with flexible board	No baseplate Thick Cu blocks with Si3N4 sheet; no baseplate	Straight fins direct cooling Single-sided

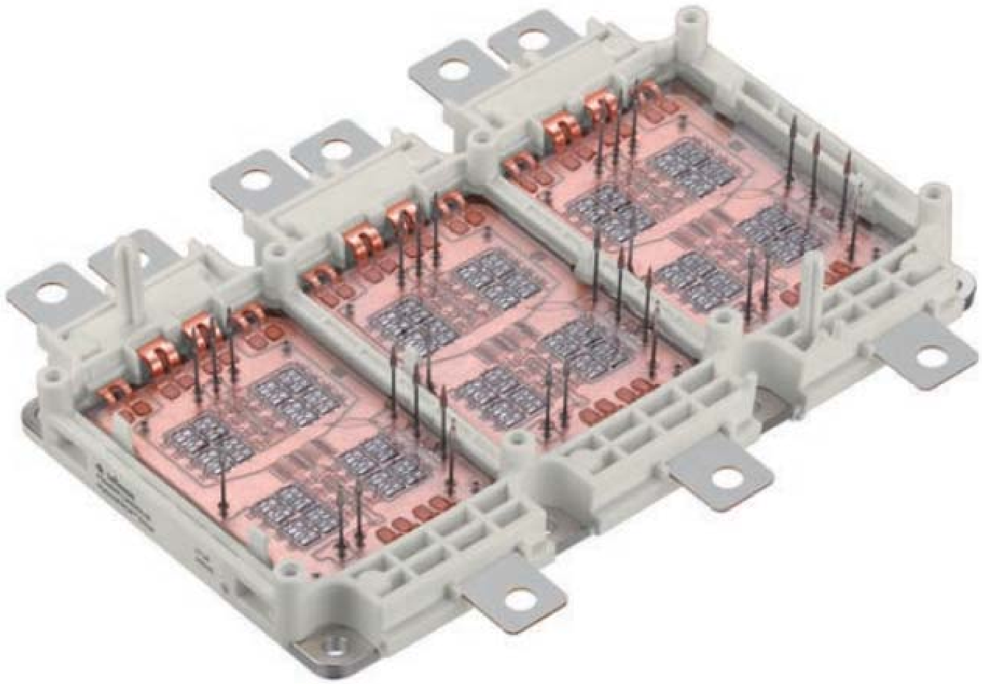


Figure 51. HybridPACK Drive Package - Power Module Example [23]

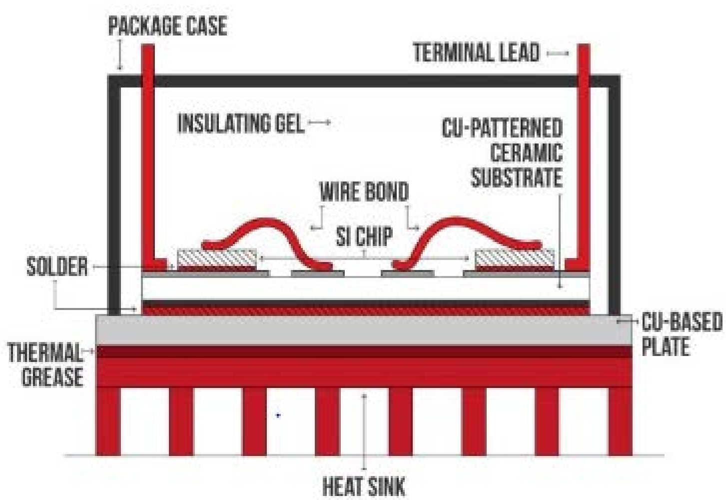


Figure 52. Cross-sectional Construction Power Module [24]

Table 4. Pros and Cons of Different Package Forms

Concept	Advantages	Challenges
System integration	Reduced system complexity, parasitic inductance and resistance; improved power density, and system reliability.	Increased difficulty in manufacture and thermal management.
PCB embedded packaging	Convenience for system integration; reduced parasitic inductance and resistance; improved power density, system-level reliability; reduced cost	Lower maximum operation temperature; lower bonding strength between layers
Press-pack packaging	Reduced system complexity, cost; improved joint reliability, manufacturability and ease of assembly; higher modularity.	Pressure sensitivity; contact resistance of thermal and electrical conduction.
High complexity 3D packaging	Convenience for system integration; improved power density; additional heat dissipation paths; higher modularity.	Increased system complexity, difficulty in manufacture and assembly.

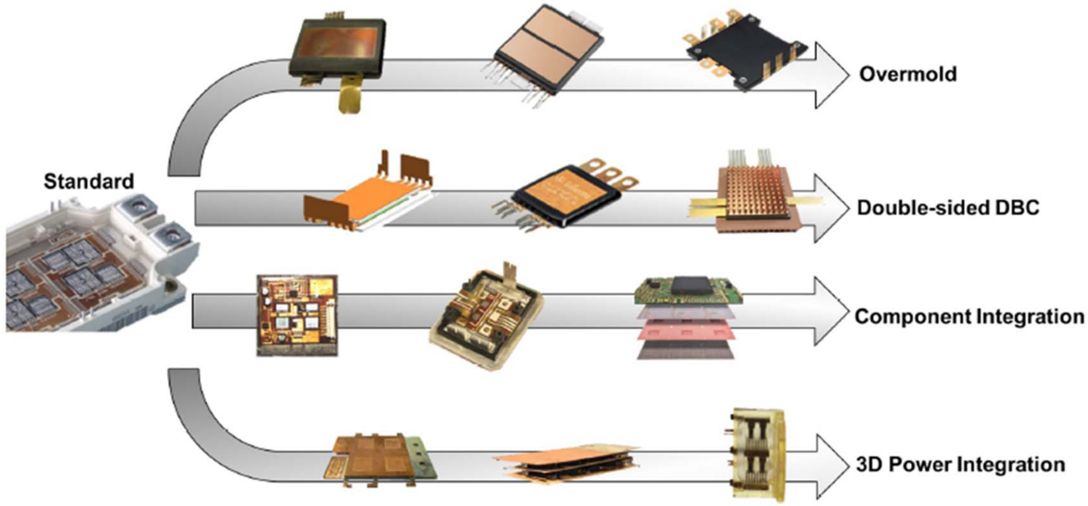


Figure 53. Advances in Package Structures [25]

6.1.3. Materials Requirements

Compared with other applications, the working condition for the automotive application is harsher. For example, the operational temperature ranges from -40C to 150C because of the climate variance based on the user's location. Also, the vibration induced by road conditions and the traction system is a big challenge to the components used in the inverter. The materials requirements will be discussed in the category of different components of the whole inverter module.

6.1.3.1. Semiconductor Die Materials

First of all, the requirements of the switch material, which is the core of the inverter, includes the bandgap energy, electron mobility, breakdown voltage, thermal conductivity, and maximum operating temperature. Currently, wide bandgap (WBG) materials such as SiC and GaN show great potential to replace the conventional Si material. The properties comparison is shown in Figure 54.

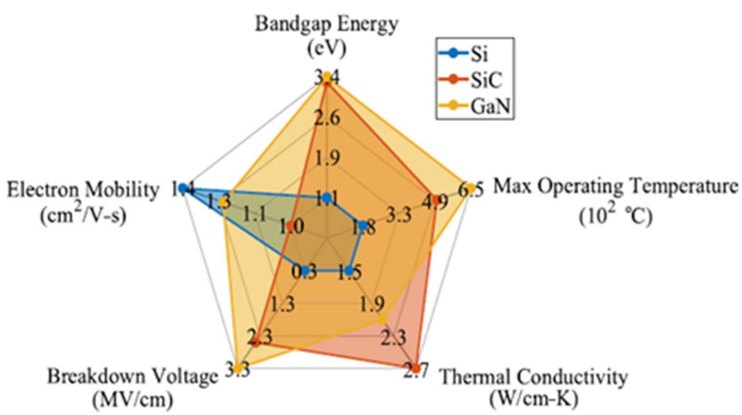


Figure 54. Comparison of Three Semiconductor Die Materials [26]

6.1.3.2. Die Attachment and Interconnection Materials

Second, for the die attachment and interconnection function, which provides the electrical connection between substrate and devices, and also acts as a physical mounting layer, properties such as melting temperature, thermal conductivity, and coefficient of thermal expansion (CTE) should be considered. At the same time, mechanical properties, such as peel strength, tensile strength, shear strength, high flexural strength, and fracture toughness can determine the mechanical reliability of the bonding layer and the die attachment.

For example, various kinds of soldering/bonding materials have been investigated and each of them show pros and cons: nano-silver sintering has been widely used because of its high melting temperature and mature process, while a Ni_3Sn_4-composed die-bonded interface requires even lower process cost although the melting temperature is lower than nano-silver material. Also, other Cu-Sn intermetallic compounds (IMCs) show a very high melting temperature; however, the process cost is a drawback.

6.1.3.3. Substrate Materials

Basically, the substrate is an electrical isolation layer in the middle with conductive layers on both sides (top and bottom). Currently, the most commonly used materials are DBC (a ceramic material) with Cu for the two conductive layers. Other materials that have been investigated or are commercially used are Silicon Nitride (Si_3N_4), Aluminum Nitride (AlN), Aluminum oxide (Al_2O_3), and Beryllium oxide (BeO) for the insulation layer, and aluminum for the conductive layer, respectively.

6.1.3.3. Baseplate and Heatsink Materials

The baseplate is the connection part between the substrate and the heatsink, so it is required to provide a high thermal conductivity and good mechanical properties (matched CTE). Conventionally, AlSiC or Cu are widely used, but the high CTE has significantly increased the mechanical instability at high temperature. Recently, in order to decrease the CTE, some metal-matrix composite materials have been investigated, such as W-Cu, Mo-Cu, and Cu-Mo-Cu. Tuning the composition ratio can change the CTE effectively.

6.1.3.4. Encapsulation Materials

Basically, the encapsulation materials are desired to be high-temperature endurable (high Tg), but they also come with a high CTE, suggesting a trade-off has to be made for most of the conventional materials. Recent research shows that polymer with metal-oxide fillers, such as Al_2O_3 and ZrW_2O_4, can achieve the high Tg and low CTE.

6.1.4. Design Considerations

Power module design considerations are shown in Table 5.

Table 5. Primary Design Considerations of Module Packaging

Design considerations	**Details**
Size	Volume, weight, power density, energy density.
Electrical performance	Current rating, voltage rating, switching frequency range, power loss, electrical insulation, electromagnetic interference (EMI).
Thermal management	Temperature distribution, thermal resistance (Rth), heat capacity, coefficient of thermal.
Mechanical strength	Thermal stress distribution, material properties (tensile strength, flexural strength, peel strength, etc.), external shock and vibration.
Reliability and fatigue	Joints failure, crack propagation, delamination, lifetime under temperature and power cycling.
Manufacturability and assembly	Manufacture procedure, process temperature and pressure, external connections.

6.1.5 Inverter Product and Module Performance

Key specifications of electric vehicles have been profiled in Table 7 [27]:

6.2. Charger (AC/DC) – Onboard and Charging Infrastructure

6.2.1 Charger Technology and Applications

The charging systems of EVs can be categorized into three levels, as shown in Table 6.

Table 6. Levels of Charging Systems

Categories	**Level 1 charging**	**Level 2 charging**	**Level 3 charging (DC fast charging)**
Typical power rating	1.2-1.4 kW	3.3-6.6 kW (single-phase) 22 kW (three-phase)	50 kW or more
On-board/off-board	On-board	On-board	Off-board

The on-board chargers (OBC) are located on the vehicles. Since the space on the vehicle is constrained, the power density requirement for OBC is high. Based on DoE's Electrical and Electronics Technical Team Roadmap (2017), the power density for OBC should reach at least 4.6 kW/L by 2025.

For off-board chargers (DC fast chargers), the power density requirement is not defined since the charging infrastructure is located in open space. The growth of this charging infrastructure is fast. The typical power levels of the charging stations are 50 kW, 150 kW and 350 kW. The manufacturers for the 350 kW DC fast chargers include ABB, Tritium, Efacec, etc. ABB's Terra High Power Gen III charger is considered to be the state-of-the-art 350 kW DC fast charger. The maximum charging power is 350 kW with 500 A output current. The maximum charging voltage reaches 920 Vdc. The efficiency reaches 94% at full load.

Table 7. Specifications of Commercially Available Traction Inverters

Vehicle	EV Type	Motor Type	Power (kW or kVA)	DC Link Voltage (V)	VPD (kW/L)	GPD (kW/kg or kVA/kg)	Device	Cooling Methodology
Jaguar I-Pace 2019	BEV	PMSynRM	300*kW	500	32.68	36.45	Si IGBT	Water-Glycol
Nissan Leaf 2019	BEV	PMSynRM	140*kW	450	4.21*	12.55	Si IGBT	Water-Glycol
Tesla M3 2018	BEV	PMSynRM IM	344*kW	430	27.4*	7.51**	SiC MOSFET	Water-Glycol
Chevy Bolt 2017	BEV	PMSynRM	153kVA	350	19.61*	15.93*	Si IGBT	Water-Glycol
Toyota Pirus 2016	PHEV	PMSynRM	162.2*kW	600	11.5	16.7	Si IGBT	-
Audi e-tron 2016	PHEV	IM, IM	75*kW	600	9.375	7.5	Si IGBT	Double Sided WEG
BMW i3 2016	BEV	PMSynRM	125	355	9.375	14.1	Si IGBT	-
Chevy Volt 2016	PHEV	PMSynRM	180*	360	17.3*	21.7**	Si IGBT	Double Sided WEG
Cadillac CT6 2016	PHEV	IPMSM	215*	360	23*	16.5**	Si IGBT	Double Sided WEG
Tesla S 2015	BEV	-	320*kW	430	47-50*	52-55*	Si IGBT	-
Honda Accord 2014	HEV	IPMSM	-	700	-	-	Si IGBT	-
Chevy Spark 2014	BEV	PMSM	140*kVA	350	10.68*	10.29**	Si IGBT	-
Toyota Camry 2013	HEV	PMSynRM	-	650	11.5	12.7	Si IGBT	WEG
Nissan Leaf 2012	BEV	PMSynRM	80kW	375	7.1	4.97	Si IGBT	-
Sonata HSG 2012	HEV	PMSM	23kW	270	7.3	6.9	Si IGBT	Ethylene Glycol
Toyota Pirus 2010	HEV	IPMSM	-	650	5.9	6.9	Si IGBT	Water-Glycol
Lexus 2008	HEV	IPMSM	-	650	10.6	7.7	Si IGBT	Double Sided WEG
Toyota Camry 2007	HEV	IPMSM	70kW (Peak)	650	11.7	9.3	Si IGBT	Water-Glycol
Honda Accord 2006	HEV	IPMSM	12kW	-	2.4	2.9	Si IGBT	Air cooled Heat Sink
Toyota Pirus 2007	HEV	IPMSM	50kW	500	3.8	4.5	Si IGBT	Water-Glycol

6.2.2 Global Safety Mandates

The requirements for charging devices or systems intended to reduce the risk of electric shock to the user in grounded or isolated circuits for charging EVs are covered in the standard for personnel protection systems for EV supply circuits. Table 8 summarizes some of the applicable technical codes and standards that address safety directly relating to EVs [28].

An isolation need is present in all functions of the EV including the high-voltage battery, dc-dc converter, inverter for driving the electric motor, and also for the charger module connected to the grid. Therefore, the key component in the interface between the existing electrical system and the EV is the transformer. With on-board or off-board chargers, the EV body must be connected to the earth during charging. When the charger has no electrical separation, isolation monitoring is essential, and the battery must be isolated [29].

Non-isolated dc-dc converters generally have advantages of simple structure, high efficiency, high reliability, low cost, size, weight, etc. However, the non-isolated dc–dc converter stage of the low-frequency approach provides no galvanic isolation. Thus, a line-frequency transformer is needed which galvanically isolates the batteries from the grid. In combination with the line-frequency transformer, this charging station approach results in a large and expensive system mainly because of the required magnetic materials. To reduce the amount of magnetic material and decrease the total volume requirements of the charging station, the operating switching frequency must be increased and the galvanic isolation integrated into the dc-dc stage. The result is a filter with a higher power density. Both the volume and weight are reduced.

Table 8. Technical Codes and Standards

Document Name	Document Title/Section
SAE J-2344	Guidelines for electric Vehicle Safety
SAE J-2464	EV/HEV Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
SAE J-2910	Design and Test of Hybrid Electric Trucks and Buses for Electrical Safety
SAE J-2929	EV/HEV propulsion Battery System Safety Standard – Lithium -based Rechargeable Cells
UL 2202	Safety of EV Charging System Equipment
UL 2231	Safety of Personal Protection Systems for EV Supply Circuits
UL 225a	Safety of Plugs, Receptacles, and Couplers for EVs
NFPA 70E	Electrical Safety in the Workplace
NFPA 70	National Electrical Code (NEC); Article 220, Branch Circuit, Feeder and Service Calculations; Article 625, Electric Vehicle Charging Systems; Article
DIN V VDE V 0510-11	Safety Requirements for secondary batteries and battery installations – Part 11
ISO 6469-1:2009 (IEC)	Electrically propelled road vehicles – Safety specifications – Part 1: On-board rechargeable energy storage system (RESS)
ISO 6469-2:2009 (IEC)	Electrically propelled road vehicles – Safety specifications – Part 2: Vehicle operational safety means and protection against failures
ISO 6469-3:2001 (IEC)	Electric Vehicles – Safety specifications – Part 3: Protection of persons against electric hazards
IEC TC 69:	Safety and charger infrastructure*
IEC TCs 64	Electrical installations & protection electric shock

The requirements for devices or systems intended to reduce the risk of electric shock to the user in grounded or isolated circuits for charging EVs are covered in the standard for personnel protection systems for EV supply circuits.

6.2.3 Packaging Technology/Integration

For level-1 and level-2 OBC, discrete power semiconductors have dominated. However, power modules can be employed for higher-power OBC. The driving circuits can be integrated into the same package as the power semiconductor. Such integrated power semiconductors have already come into the market. Texas Instruments, Navitas Semiconductor and ST Semiconductor are all selling integrated GaN power semiconductors.

For DC fast chargers, since the power rating is significantly higher, high-current power modules are preferred. The conventional IGBT power modules are cost-effective; however, the switching frequency is typically limited to around 20 kHz. Pure SiC MOSFET power modules are not widely adopted by the industry. One attractive strategy is the Si/SiC hybrid power modules. The main switch contains a Si IGBT and a unit-paralleled SiC Schottky diode, which can effectively balance the loss and cost. Such Si/SiC hybrid power modules are already employed in commercial PV inverters. Infineon Technology is the major semiconductor manufacturer to provide such power modules.

6.2.4 Key Performance Metrics

Based on the U.S. DoE's Electrical and Electronics Technical Team Roadmap, cost, specific power, power density and efficiency are four key performances for EV on-board chargers. The current status and targets for 2025 are listed in Table 9. Some of the charger products, with their module performance, are listed in Table 10.

Table 9. On-Board Charger Targets

On-Board Charger Targets	2020	2025
Cost, \$/kW	50	35
Specific power, kW/kg	3	4
Power density, kW/L	3.5	4.6
Efficiency	97%	98%

Table 10. Charger Products and Module Performance

Product	Battery Type and Energy	All-Electric Range	Connector Type	Level 1 Charging		Level 2 Charging		DC Fast Charging	
				Demand	Charge Time	Demand	Charge Time	Demand	Charge Time
Toyota Pirus PHEV (2012)	Li-ion 4.4kWh	14 miles	SAE J1772	1.4kW (120V)	3 hours	3.8kW (240V)	2.5 hours	N/A	N/A
Chevrolet Volt PHEV	Li-ion 16kWh	40 miles	SAE J1772	0.96-1.4kW	3 hours	3.8kW	2-3 hours	N/A	N/A
Mitsubishi i-MiEV EV	Li-ion 16kWh	96 miles	SAE J1772	1.5kW	3 hours	3kW	14 hours	50kW	30 min
Nissan Leaf EV	Li-ion 24kWh	100 miles	SAE J1772 JARI/TEPCO	1.8kW	3 hours	3.3kW	6-8 hours	50+kW	15-30 min
Tesla Roadster	Li-ion 53kWh	245 miles	SAE J1772	1.8kW	3 hours	9.6-16.8kW	4-12 hours	N/A	N/A

7. Reliability

7.1 Impact of Megatrends on Automotive

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

- **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). Soon under the engine hood we will have heterogeneously integrated devices such as high-performance GPUs or CPUs, or small-footprint devices such as QFN, CSP, WLP, that will have significantly higher power dissipation. Even for standard ICs it is expected that the load profile will change from what is happening now – the temperature might be higher, and device might be activated more often. In order to keep the temperature below the threshold limit, a new cooling solution is needed.
- **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 electric powertrains. Consequently, operational time will significantly increase from roughly 9,000 hours (today) towards 50,000 hours and even up to 130,000h within a time frame of 15 years (including the charging time for the HV/EV and connectivity – update over the air). Long-time use may decrease the number of large temperature cycles per day; however, it will keep devices at higher temperature for a significantly longer time. This might lead to new, not yet investigated failure modes. The challenge is that for these new use case scenarios, and the introduction of new materials and interconnection technologies in a harsh environment, new failure modes can be expected.
- **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 an all-purpose vehicle [31]. 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 [32]. For their new business models, availability of the cars will be one of the major concerns.

- **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.

See also the reliability discussions in Chapter 24 of this Roadmap.

7.2 State of the Art

The current reliability practice in automotive electronics is based on the reliability physics (RP) approach. The design of the controllers considers the anticipated field loads in order to allow 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., materials 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.

7.3 Anticipated Challenges

Model-based engineering plays a major role during the development of automotive electronics. It is the methodology that allows development of complex electronic devices and control units in the most optimum way. Along the entire supply chain, simulation-driven design (Figure 55) is a widely accepted methodology. This modeling approach is composed of four stages:

- Virtual Design of Experiments [33] – at this stage, either an analytical solution or a FEM-based simulation is executed to analyze the designed device or system and identify what are the most significant parameters and recommended materials.
- Materials characterization and modeling [34], considering any process-dependent behavior shown by most of the organic materials, is a mandatory step for achieving quantitatively correct results.
- At the later design stages, multi-domain and multi-scale simulations are used [35]. The typical ECU might have up to 7000 devices. In order to quantitatively predict the stress state, we have to run multi-

domain simulations coupling the electrical with the thermal and the thermo-mechanical domains. At the same time, the simulations require a global/local approach for precise determination of the critical degradation state for the specific design elements and for estimating the resulting lifetime correctly.

- The final stage of the simulation-driven design is validation [36]. There are many different techniques used, among which the most important are thermography, optical deformation measurements, strain measurements using strain gages, and stress measurements using piezoresistive stress sensors. After successful validation, design decisions can safely be finalized based on the simulation results, which can be obtained much faster than by experimental tests.

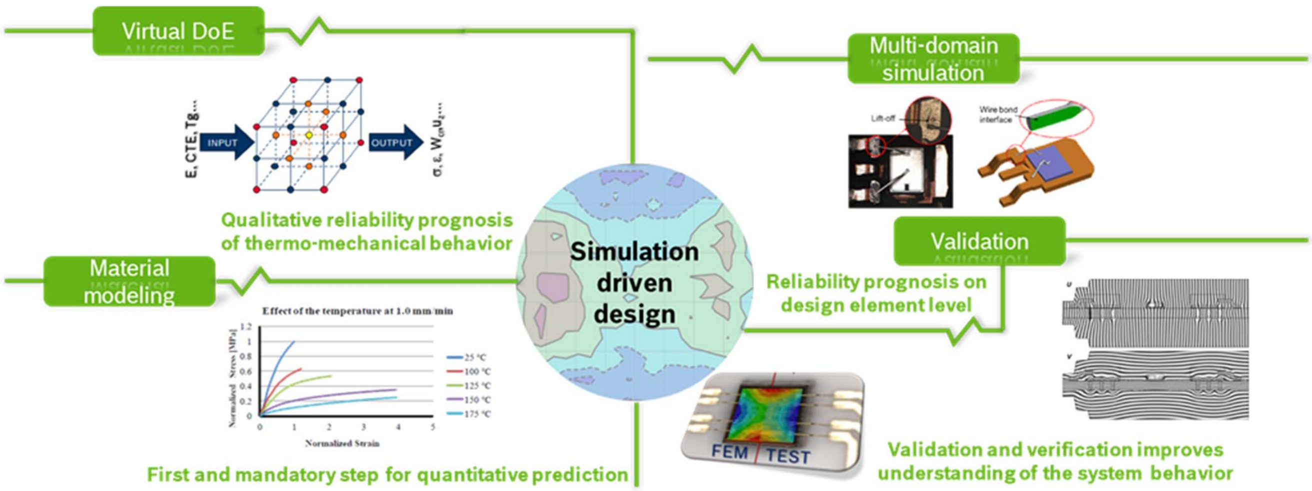


Figure 55. Simulation Driven Design – From Concept Phase to Robust Design

A new emerging methodology in model-based engineering is the digital twin (Figure 56). We define a digital twin as the instantiated model (numerical, analytical, hybrid) of a specific asset or device, which is deployed (in the cloud or on an edge device) and connected to the physical device. The connection may be established through sensors installed at the device or other sources collecting specific information (e.g., control units, weather forecasts, devices nearby, etc.), delivering a continuous data stream fed into the model as boundary condition or as reference values.

For heterogenous devices and systems, digital twining is the methodology that will lead to a better understanding of the parameters having direct effect on the performance and lifetime of the electronic devices and systems. The digital twins enable following the history of almost all HIR devices starting from their production, through reliability and qualification phases, the various use cases and service modes during service in the field until the device end of life. Besides technical aspects, the digital twin will be the main driver for the industry in respect to business development strategies . However, a lot of effort is still required. Details regarding technical challenges are discussed in the Modeling and Simulation chapter of the HIR roadmap.

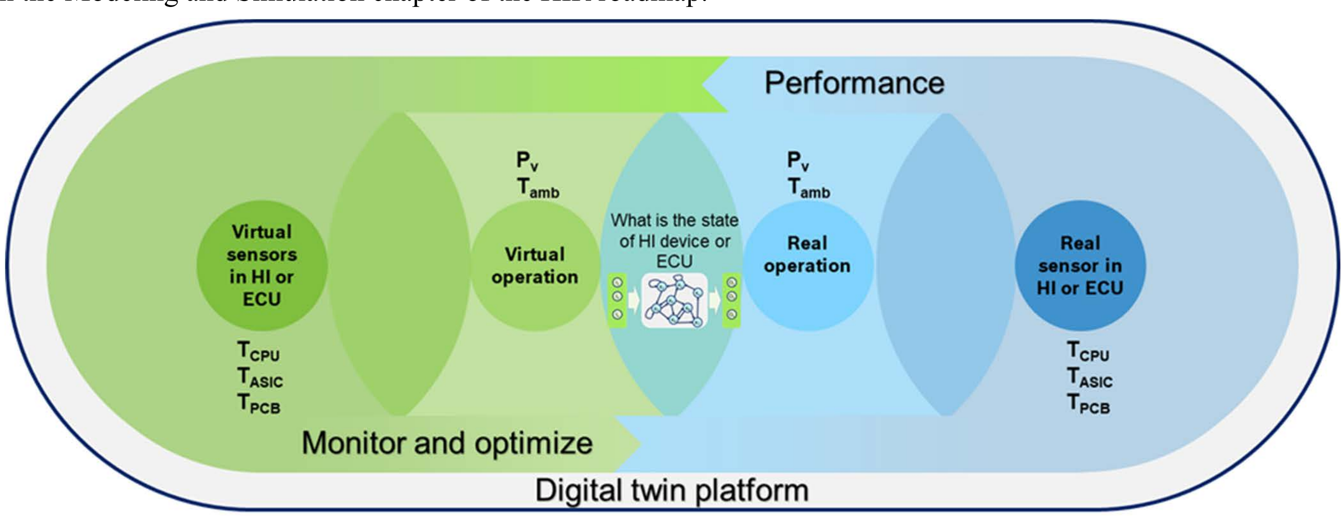


Figure 56. General Concept of Implementation of the Digital Twin for a Heterogeneously Integrated Electronic Device or Control Unit

Integration of the digital twin is still a challenge. Over the next few years, collaboration between research institutes and industry will drive these developments. The large amount of necessary data generated by the sensors can easily sum up to several GB per day. This amount cannot be transferred to the cloud directly. Instead, the digital twin capability will be integrated right into the ECUs (local digital twin). It will gather all information about the usage, pre-evaluate it locally and briefly inform the central ECU about the health status. If degradations are detected, the in-car central analytics SW will be activated for estimating the remaining useful life and perhaps suggest introduction of mitigation measures. At the car level, additional data evaluation will be done before packages of compressed information are sent to the cloud services. In the cloud, there will be a comprehensive digital twin that can be continuously improved through the various information from the fleet. This is used for updating the individual local digital twins in the cars/ECUs/devices and for updating the degradation database of the fleet. Figure 57 depicts schematically the future PHM architecture with edge/cloud digital twins.

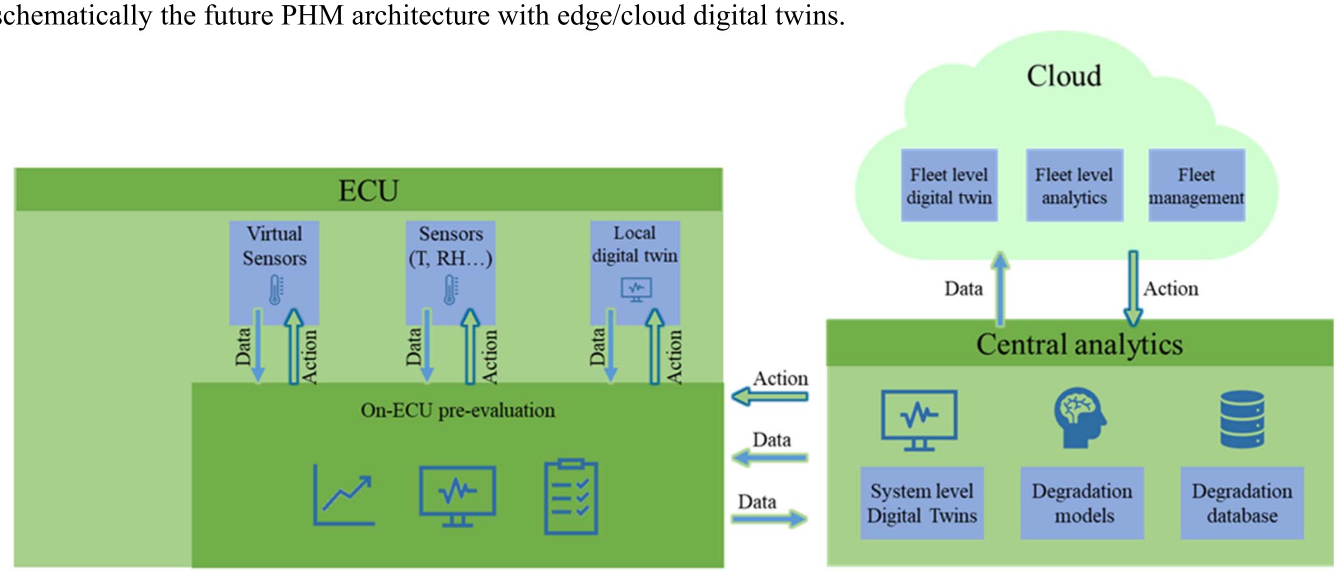


Figure 57. PHM Architecture with Edge/Cloud Digital Twin Solution [37]

Model-based engineering and the digital twin will be key enablers for reducing the costs of reliability assessment, shortening the qualification time and enabling new, data-driven business models. The following actions are required to achieve these ambitious plans:

- Development of the metamodels and reduced models (MOR) or compact models for data exchange across the 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 materials characterization and modeling techniques for advanced materials, such as encapsulants, thermal interface materials, adhesives, sealants, new joint materials, etc., including toughness of the interfaces. This is especially needed for the mm-wave technologies.
- Implementation of artificial intelligence (AI)/machine learning (ML) algorithms in the design and optimization process.
- Implementation of machine learning for thermo-mechanical compact models required for digital twins.
- Training and validation strategies for digital twins.
- Standardization and implementation of a virtual pre-qualification of electronic devices and systems utilizing this model-based approach.

7.4 Prognostics and Health Management

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 reliability physics (RP) 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 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 propagation of defects. They can be derived from the RP or from DD approaches. The RP 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, RP 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 58), to support five destinations of methodology research:

- Developing the required infrastructure, sensors, and electronics hardware.
- Studying and characterizing the failure mode and mechanism effect by thorough analyses (FMEA) for both RP and DD approaches.
- Providing appropriate solutions to data acquisition, management, and secure data transfer.
- Performing the data fusion for reaching 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.

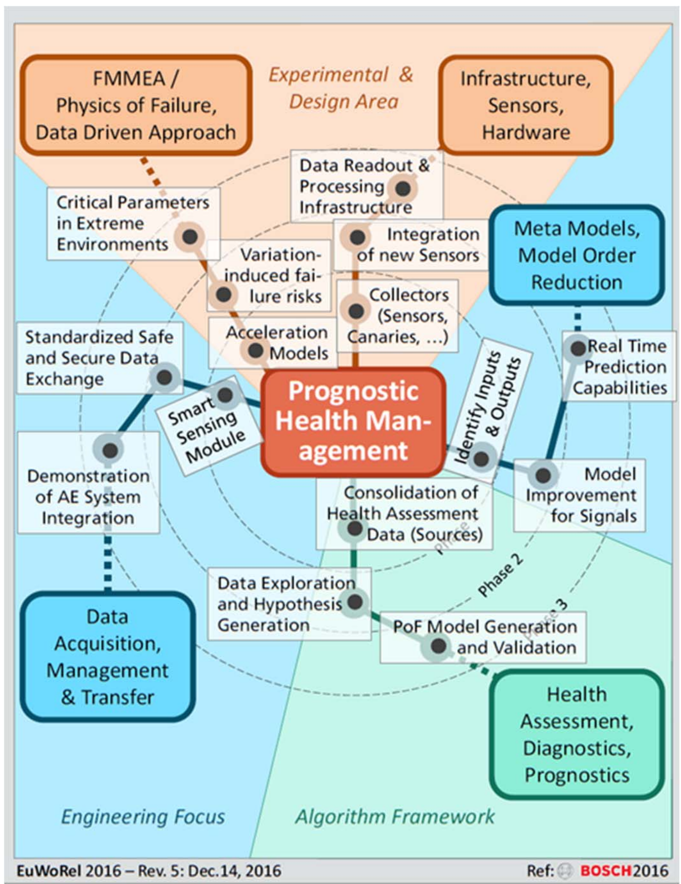


Figure 58. PHM Methodology Metro Map [32]

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 materials supplier is at the bottom of the supply chain, then the information flow is through the chip/packaging/system developer to the OEM.

In the future, due to the complexity of the system and interactions between different components of the system, development of 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.

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

- The data-driven approach requires:
  - Application of available sensors or implementation of new sensors 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.
- Main research activities for the RP 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 algorithms for deducing compact models and digital twins for 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 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 autonomous driving, will be based on 3rd generation smart systems [33] and cyber-physical systems. There is an urgent need to define new standards for reliability assessment and qualification criteria, which will account for the complexity of these systems including advanced packaging (SiP, PoP). Especially important is defining the responsibility for the specific design elements. Here the suppliers will require significantly more detailed information about the loading conditions in real field applications. The package/board/system interaction will play a major role.

7.5 New qualification Criteria/Test – standardized description of field condition on design element level

The stress-driven approach has been applied for qualification of microelectronics devices for many decades. This methodology is simple and straightforward: one takes a representative sample from (future) production lines, executes a standard set of accelerated life tests at fixed conditions for a specified duration, and afterwards every part is electrically tested; the requirement is that no fails shall occur. In this approach, it is assumed that when the device has passed all of the accelerated life tests, it will be capable of meeting its application mission.

A mission profile is a collection of relevant environmental and functional loads that the device will be exposed to during its full life cycle. Already in 2013, the Automotive Electronic Council (AEC) had defined a method applying the stress test-driven approach in cases of more severe mission profiles. This is described in an appendix to well known standards AEC-Q100 (for ICs) and AEC-Q101 (for discretes), better known as "Appendix 7". In this appendix, a flow chart gives guidance: it starts with the application mission profile and may lead to the conclusion to do an accelerated life test longer and/or at more severe or at different acceleration conditions for these extended mission profiles.

This mission profile concept has become accepted, but recent developments in the area of electrical vehicles and in the near future for autonomous vehicles, have led to not only a large number but also to extremely demanding mission profiles. Further elongating accelerated life test durations or applying harsher test conditions with at the end zero-fail tolerance is no longer appropriate; qualification times are becoming very long with an increased risk of over or wrongly accelerated failure mechanisms.

The constantly growing number of mission profiles downstream in the automotive supply chain is a complicating factor. Already-qualified devices for one mission profile may need re-qualification for another mission profile. Therefore, most importantly, mission profiles need to be standardized.

To limit qualification throughput times, combining the mentioned stress-driven with the failure mode-driven approach using Physics of Fail (PoF) and Physics of Degradation (PoD) is the way forward. Assessing the degradation of a population of devices during an accelerated life test, and using physical and empirical aging models supported by device simulations to predict reliability, will allow keeping the qualification phase to an acceptable length. Degradation responses to be used are electrical parameter shift and their changing distribution during the accelerated life tests, e.g., as a result of hot carrier injection or biased temperature instability in ICs, or quantifiable physical parameters like crack length or corrosion area that grow over time. One can use this method to extrapolate the degradation to an accelerated life test duration that would cover the extended mission profile, to explore the capability and robustness margin. It also allows for validating predictive modeling results that are already available in the early development phase, e.g., to optimize the device and package design as well as the materials used.

7.6 Reliability across the Supply Chain – from wafer (chip) to system of systems (CPI, sub-system to system)

An aspect that needs further understanding in the future is the reliability along the supply chain. This includes aspects from wafer production, chip production, as well as packaging and system production. Tracking of production data along the value chain from wafer to system needs to be further considered. We need to study to what extent monitored data from different parts of complex systems will be necessary to exchange. Topics of major importance will be:

- Digitalization for monitoring processes during production in the different domains
- Understanding to what extend exchange of data will be needed
- Standardization will play an increasing role
- Model-based prequalification

Confidentiality challenges need to be considered. This includes different chip technologies, but also package technologies. Different CTEs of the many different materials interfaces need to be understood. Already today tracking of production data along the value chain shows examples that data from front-end production, which are at certain limits/weaknesses, can have impact at the back-end. Design for manufacturability and reliability will become more important, to gain ´required inputs for simulation models. Process weaknesses in front-end production can cause problems during certain subsequent package production processes.

For heterogeneous integration, where many different chips will be integrated, potentially with a mix of III/V technologies, challenges in the different domains can be expected. This can include stability of chip BEOL contacts or different metal finishes. For example, GaN chip technologies typically apply final gold contacts, whereas standard silicon technology uses Al as final contact metallization. Another example is the finish of discrete passive components, which typically have matte Sn-based, but also Ni-, or Cu-based finishes. Thus, discrete passives cannot be simply implemented with chips that typically have aluminum-based finishes. Careful adjustment for system-in-package solutions is required. Cu pillar micro-bumps with a CTE of 17 ppm/K might create much stress in a silicon-based device (CTE in the range of 3 ppm/K). Soft BEOL materials need to be made stable enough for stresses introduced by different package materials. In the future, more modeling and simulation including virtual prototyping will be needed to tackle the challenges along the value chain to allow reliable heterogeneous integration. It will be interesting to see how today's fabless companies will tackle the area of heterogeneous integration with respect to meeting reliability targets.

8. 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 for these technologies.

9. Cross References to other HIR chapters [39]

Many of the discussions related to radar and lidar include key technologies that are reviewed in detail in Chapter 11, MEMS and Sensors. The processor technologies covered in section 5 include utilization of system in package technologies also addresses in Chapter 21: SiP and Module System Integration. Finally, the reader is advised to consult Chapter 10, Integrated Power Electronics, for more detailed information on power packaging. This automotive chapter and the newly formed Chapter 24 on Reliability are in continuing collaboration . The chapter will be further enhanced in conjunction with the supply chain team which covers a critical aspect for semiconductors overall and with even more importance for automotive in view of the stringent qualification and change notification requirements.

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