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Autonomous Vehicles

Automotive LiDAR: Rounding Out the ADAS and Autonomous Driving Sensor Suite

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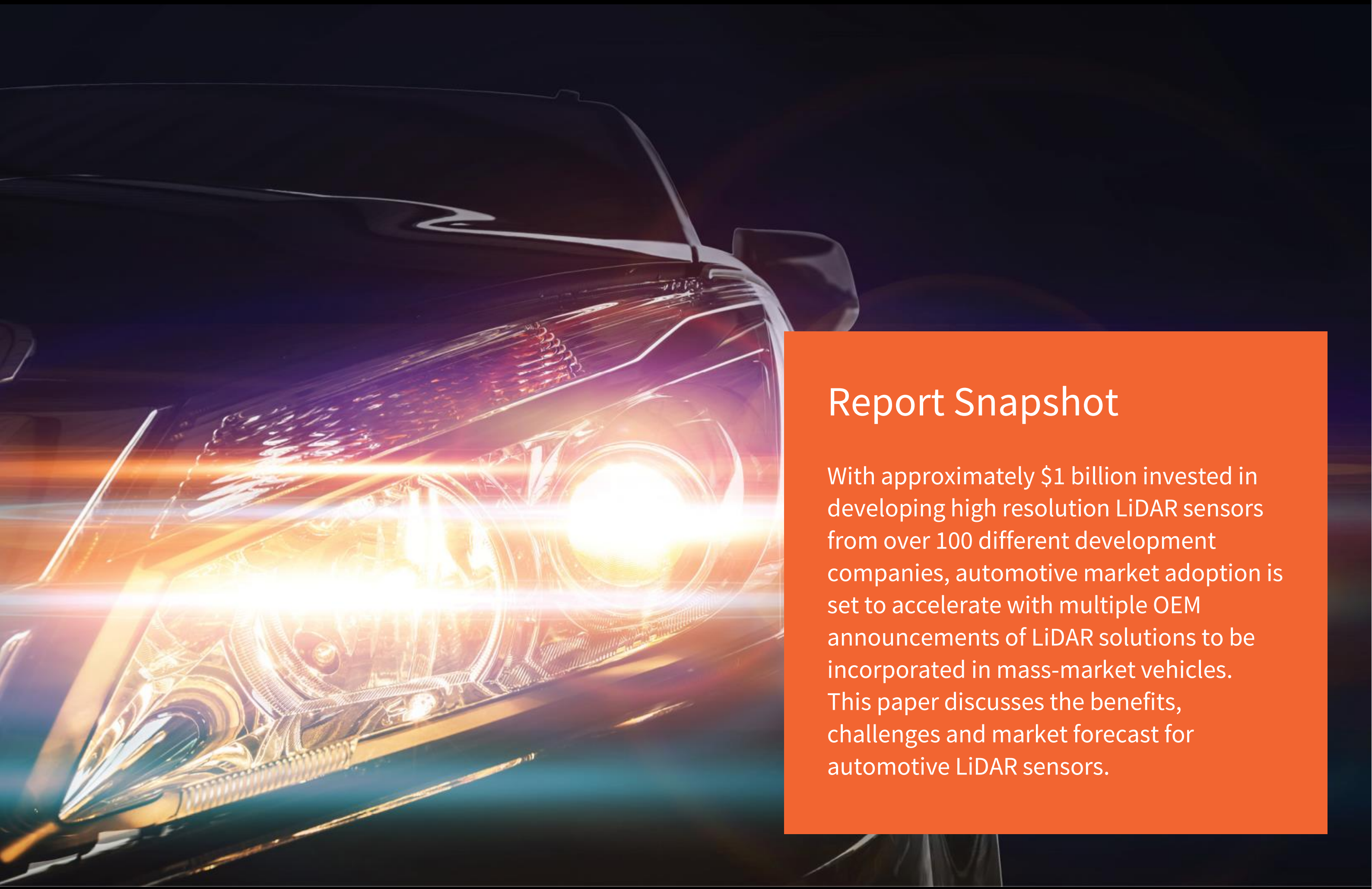

Report Snapshot

With approximately $1 billion invested in developing high resolution LiDAR sensors from over 100 different development companies, automotive market adoption is set to accelerate with multiple OEM announcements of LiDAR solutions to be incorporated in mass-market vehicles. This paper discusses the benefits, challenges and market forecast for automotive LiDAR sensors.

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1. Executive Summary

Automotive LiDAR (Light Distance And Ranging) sensors promise to complete the suite of sensors required for highly automated driving solutions. A variety of sensors are used to provide environmental (including object detection and tracking) and localization perception inputs for advanced driver assist systems (ADAS) and automated driving route planning and vehicle control. Typical sensors used for autonomous driving include ultrasonic, camera, RADAR and LiDAR.

Exhibit 1.1 Automotive ADAS Sensor Comparison

Sensor Type	Cost	Weather Sensitivity	Low Light Performance	Range	Resolution	Sensor Size
Ultrasonic	Very low	Low	Good	Short	Low	Small
Camera	Low	Medium	Poor	Medium Low <100m	High	Small
RADAR	Medium	Low	Good	Long 200m+	Medium	Medium
LiDAR	High	Medium	Good	Long 200-300m+	High	Large

Source: Strategy Analytics

Typical ADAS systems today rely on Camera and RADAR inputs for features such as auto emergency braking (AEB). As more automated features such as lane keeping assist systems (LKAS) and dynamic driving assistance technologies such as traffic jam assist and highway pilot/chauffeur systems are implemented, LiDAR inputs will augment Camera and RADAR sensor inputs. Laser ranging is used to determine the distance from the sensor to the object. When combined with directions determined by the same sensing unit, the 3D position of each point becomes part of a scanned 'point cloud'. The ability to detect objects such as pedestrians, cyclists, and vehicles in high resolution from short to long distances makes LiDAR an attractive solution to round out an automated vehicle's sensor suite.

Key benefits of LiDAR sensors include:

- Accurate distance/depth and velocity measurement
- Spatial resolution - high resolution 3D object characterization
- 200+ meter range
- Wide Field of View (FoV) and Angular Resolution for azimuth and elevation

To support the high resolution sensing requirements for future autonomous driving applications, market projections project growing demand growth for LiDARs.

As a result, over one billion dollars has been invested in up to 100 different companies developing high resolution LiDAR sensors using a wide range of new technologies, from different laser diodes, scanning methods, integrated chipsets, receiver technologies and more.

- In some cases, OEMs and Tier 1 vendors have invested in more than one developer where different technologies suit certain sensing applications or to hedge against one developer failing to enter the market.

- Technology companies such as Alphabet/Google/Waymo, and Mobileye have announced that the firms will market in-house LiDAR solutions.

- Some investors are also technology partners or suppliers to the LiDAR developer.

- As it becomes more challenging to commercialize fully-autonomous driving systems (SAE L4 & L5), OEM investments are shifting the demand for high resolution LiDARs to high performance ADAS and semi-autonomous driving applications (SAE L2 & L3) .

Exhibit 1.2 Automotive LiDAR Investors

LiDAR Developer (or supplier)	Notable Investors
Aeva	Volkswagen
AEye	Airbus, Continental, General Motors, Hella, Intel, LG Electronics, SK Hynix, Subaru
Baraja	Sequoia Capital (also investing in Zoox)
Blackmore	BMW (previous), Toyota (previous)
Blickfeld	Continental, Fluxunit (OSRAM)
Cepton	Koito
Hesai	Baidu, Microsoft, ON Semi
Innoviz	Aptiv, Magna, Naver, Samsung ,Softbank
Innovusion	NIO
LeddarTech	Aptiv, Marelli, OSRAM
Luminar	Daimler Trucks, Gores Group, Volvo Cars
Ouster	Constellation, Cox Enterprises
Quanergy	Aptiv, Daimler, Samsung
RoboSense	BAIC, Cainiao (Alibaba), SAIC
SOS Lab	Mando
TetraVue	Bosch, Foxconn, Samsung
TriLumina (VCSEL supplier)	Caterpillar, DENSO
Velodyne	Baidu, Ford, Graf Industrial, Nikon

Source: Strategy Analytics

LiDAR has historically been disadvantaged because of high cost, reduced performance in heavy rain or snow, and would still require sensor fusion with other types of sensors, such as cameras, in order to function within a "sensing solution," as some LiDAR players call themselves. Advances in technology and production efficiencies have reduced the high costs of LiDAR and automakers have begun to incorporate the technology into its suite of ADAS sensors.

- There is often a trade-off between what performance can be achieved against low power consumption (limiting cost and sensor module size from the resulting thermal management requirements), size, weight, processor and receiver photodiode capabilities (with related laser pulse rates) and crosstalk with other light sources.
- LiDAR is extremely challenging to develop because it needs tight cooperation between different sensing domains, as changes in one domain affect other domains, and that the sensor itself is complicated to develop.
- LiDAR has a high compute need for the high data rate image processing of the 3D point cloud, consisting of om over 1 million data points per second – significantly more than camera and RADAR sensors.
    - LiDAR 3D point cloud data processing is performed in steps of pre-processing data by removing un-needed data, filtering relevant data and division of the point cloud into segments and finally features are identified and classified.
- Furthermore, the LiDAR design has to be amenable to commercial requirements for mass production and be made affordable. A platform design has been used by some developers to leverage demand in other industry sectors.

2. Importance of Automotive Ecosystem Partners

Because LiDAR development is dependent on the technical assistance in so many different sensing domains, the partnership of many other companies is critical to the potential success of the resulting sensor module. Typically, LiDAR start-ups have partnered with an established Tier 1 supplier to bring the technology to mass-market, high volume vehicle production.

- Developing high resolution LiDARs have been more challenging than with other types of sensors, due to the complexity and immaturity of new technology concepts required to overcome a number of issues, such as ambient light (also known as noise).

- Because of the complexity in LiDARs and the high cost of development, partnerships must be formed with other companies, especially with the automotive Tier 1 vendors that would provide valuable experience and expertise in validating sensors to automotive standards and commercializing sensors for mass production.

- The unique position of the Tier 1 vendors that also develop their own sensor technology can discern which of the new technology concepts can meet automotive requirements. Start-up LiDAR developers often come with a “religious fervor” in promoting their technology concepts, but not with the necessary experience and technology agnostic approach of a Tier 1 vendor.

LiDAR is extremely challenging to develop because it needs tight cooperation between different sensing domains, as changes in one domain affect other domains, and that the sensor is complicated to develop. Expertise is needed in:

- Optical (lasers, receivers, beam steering)

- Silicon MEMS micro-mirror, point cloud data processing and memory applications

- Electronics (feedback controls and ensure quality in them)

- Thermal management

- Package integration a qualified, automotive quality sensor

With the various domains in the sensor, the ability for the LiDAR developer to work with its various partners is also a critical factor in its potential success.

Tier 1 vendors hold a critical position in the development of LiDAR sensors. Because of their experience in supplying auto makers, they can discern what new technologies are capable of meeting the requirements and standards in the automotive sector. In high resolution LiDARs, some technology concepts have matured and have gone into production, while new concepts promising high performance will require further development before they reach maturity at a later stage.

Exhibit 2.1 Automotive LiDAR Ecosystem Partners

LiDAR Developer (or supplier)	Partner	Activity
Aeva	ZF, Continental	Tier 1 Manufacture
AEye	Aisin, LG Electronics	Tier 1 Integration
AEye	ANSYS, Hella Aglaia, Intvo	Software (simulation) & Machine Learning
AEye	Infineon	Processor
AEye	OmniVision, ON Semi, Teledyne, e2v	Image Sensor (sensor fusion; ToF)
AEye	OSRAM	Laser Diode
Blickfeld	SensL (ON Semiconductor)	Photodetector (SiPM, SPAD)
Blickfeld	Xilinx	Processor
Cepton	Koito	Tier 1 Integration (headlight module)
DENSO	TriLumina	Laser Diode (VCSEL)
IBEO (ZF)	ams	Transmitter and Laser Diode (VCSEL)
IBEO (ZF)	ZF	Tier 1 Manufacture
Innoviz	Aptiv, Harman (Samsung), Hirain, Magna	Tier 1 Integration
Innoviz	Magna	ECU Manufacture (package Innoviz receivers, mirrors and Maui ASIC)
LeddarTech	Aptiv, Marelli, Valeo	Tier 1 integration
LeddarTech	Faurecia-Clarion	Tier 1 Manufacture
LeddarTech	Renesas, Texas Instruments	Processor
LeddarTech	SensL (ON Semiconductor), First Sensor	Photodetector
LeddarTech	STMicroelectronics	MEMS Micro Mirror
LeddarTech	TriLumina	Laser Diode (VCSEL)
Luminar	DENSO	Tier 1 Manufacture
Ouster	Xilinx	Image processor
Quanergy	Daimler, Geely	OEM
Quanergy	Harman (Samsung), Sensata	Tier 1 Integration
RoboSense	Cainiao (Alibaba), JD.com, Meituan, Zhen Robotics	OEM (autonomous delivery vehicle)
RoboSense	Horizon Robotics	Software (machine learning)
RoboSense	Xilinx	Processor (FPGA)
SiLC	Varroc	Tier 1 Integration (headlight module)
SOS Lab	PHIX	ASIC design
SOS Lab	Mando	Tier 1 Manufacture
Velodyne	Apex.ai, Deepen AI	Xilinx image processing
Velodyne	AutonomouStuff	Tier 1 Integration
Velodyne	EPC	Laser Driver (GaN)
Waymo	EPC	Laser Driver (GaN)
XenomatiX	Cosworth, Marelli	Tier 1 Integration
XenomatiX	Smart Me Up (Marelli)	Software (machine learning)
ZVISION	Xilinx	Processor

Source: Strategy Analytics

Strategy Analytics is seeing the emergence of a new class of higher performance and resolution LiDAR units. These will also have a higher selling price than the existing, simpler LiDARs that were used for low level ADAS functions such as automatic emergency braking (AEB) solutions. The low resolution & performance LiDAR solutions are being replaced by camera-based systems. The new high resolution LiDAR sensors could also see multiple sensors fitted per vehicle and will be used to support automated driving applications.

- The first of these high resolution LiDAR sensors is the Valeo/Ibeo SCALA unit fitted initially to the Audi A8, and now to other Audi models including the A6, A&, Q7 Q8 and e-tron.
- As seen in Exhibit 3.1 below, numerous OEM high resolution LiDAR launches are expected through 2021 through 2025.

3. ASIC vs. FPGA LiDAR Processing

Real-time processing of the LiDAR point cloud that can include over 1 million data points per second requires a high level of compute to accelerate point cloud deep learning algorithms. LiDAR 3D point cloud data processing is performed in steps of pre-processing data by removing un-needed data, filtering relevant data and division of the point cloud into segments and finally features are identified and classified.

LiDAR system developers must balance the trade-offs between using an application specific integrated circuit (ASIC) or a (Field Programmable Gate Arrays) FPGA. Currently, most ASICs employed are focused on the analog photonics and not the digital signal processing :

- NRE - one-time cost to research, design, develop and test a new product or product enhancement.
- Performance and Power Consumption – Power budget vs. chip performance
- Time to market
- Cost
- Silicon Package size

There are generalizations and inaccuracies widely cited when referring to automotive ASICs and FPGAs that need to be revisited and, in many cases, removed from the definition of each solution. It is encouraged that the silicon vendor is queried before selecting an ASIC or FPGA for LiDAR applications as many of these generalizations and inaccuracies and can be addressed.

Some of these generalizations include:

- **ASIC Generalizations**: (optimized performance, power efficiency, long development timeframe/slow time-to-market, low customizability)
- **FPGA Generalizations**: (too expensive, high power consumption, not optimized to applications, limited developer resources, only used in research/test vehicles, not suitable for mass production)

3.1 FPGA-Based Solutions

FPGAs and FPGA-based MPSoCs (Multi-processor Systems-on-Chip) benefit from a parallel processing architecture, unlike the serial architectures in CPUs and GPUs. The flexibility of FPGAs makes it suitable for applications and devices that need to be modified and upgraded frequently as opposed to ASICs that are better suited to permanent applications.

- FPGAs offer flexibility and differentiation, and adaptability along with low latency and high throughput along with fast time to market timeframes. Flexibility and adaptability are important in the LiDAR field as performance, standards and algorithms powering ADAS and autonomous systems are constantly changing. FPGAs for example can be configured and re-configured to balance power efficiency with performance requirements.
- FPGAs can offer both the additional performance and processing efficiency that AI applications need – including LiDAR point cloud processing, as well as enabling programmability that lends well to system flexibility, hardware re-use and lower development cost.
    - FPGAs are an attractive choice, especially when perception algorithms are still being developed as chips can be customized as the algorithm is developed and avoid the potential of an expensive redesign of an ASIC solution.
- Early implementations of FPGAs have been as accelerator devices to augment the performance of CPU-based SoCs. However, FPGAs are increasingly becoming the lead processing device in MPSoCs.

FPGAs have evolved from basic programmable logic to complex SoC devices that contain multiple embedded processors, compute engines, memory and interfaces - all while being power efficient.

Examples of different classes of FPGAs, using Xilinx solutions as example are as follows:

- FPGA: Artix-7 family, Kintex-7 family
- SoC: Zynq-7000 family
- MPSoC - Zynq UltraScale+ MPSoC
- RFSoC - Zynq UltraScale+ RFSoC

3.2 ASIC Solutions

Many developers have developed ASICs (Application Specific Integrated Circuits) as a means of raising integration and reducing cost and power consumption. A typical ASIC solution tends to higher efficiency, a smaller die size, as well as lower power consumption than GPUs and FPGAs. LiDAR developers must also weigh the long development cycle of ASICs and their lack of flexibility.

An ASIC a silicon solution that serves the specific purpose for which it has been designed and cannot be reprogrammed or modified to perform another function or execute another application. ASICs are designed to be used for a specific function – and that specific function only.

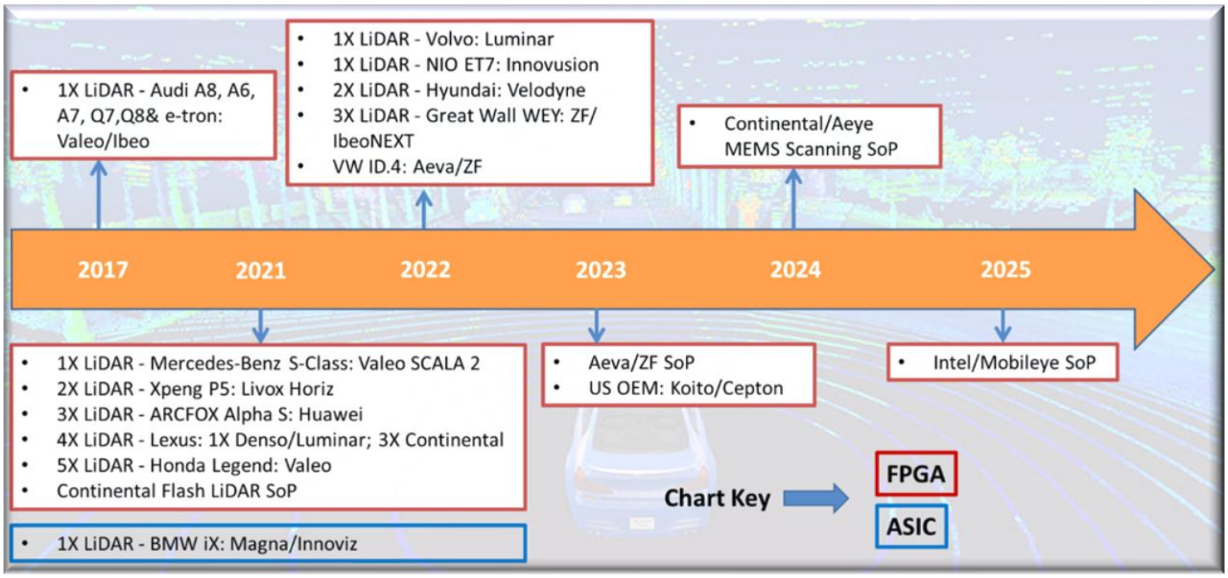
As a feature matures, and volumes increase an ASIC can be developed to reduce costs and power consumption. Designing and building a purpose-built ASIC for a specific function is not without potential pitfalls as they cannot be reprogrammed and require ongoing NRE investments. Design teams with specialized knowledge are needed to design, test, validate and build an ASIC potentially adding costs and months of development time to the overall project.

An ASIC is typically:

- Suited for a mass-market, high volume design specifically suited to design needs.
- More energy efficient than FPGA's
- More cost effective when used in high volume applications – the cost per unit of an ASIC is typically lower than a FPGA.
- Much smaller package size than FPGAs

Due to its inherent design flexibility allowing engineers to change the circuitry within an FPGA to respond to fluid design and performance requirements of automotive LiDAR systems . As seen in Timeline below, FPGA solutions make up the majority of automotive production LiDAR processing applications as compared to ASIC-based designs.

Exhibit 3.1 Automotive LiDAR Production Timeline



Source: Strategy Analytics

Innoviz is the only major LiDAR company to achieve a design win for a production vehicle that has also designed key LiDAR system components in-house such as the MEMS module, silicon detectors and the signal processing ASIC named Maui. BMW will incorporate the Innoviz LiDAR technology with Tier 1 supplier Magna providing the integrated system solution. Innoviz claims that designing critical components in-house rather than using off-the-shelf commodity components provides for protectable and sustainable technology differentiation from LiDAR competitors or alternative technologies. Innoviz believes one of the significant barriers to entry for automotive LiDAR are the processes and know-how to manufacture a compact and intricate sensing product in high volumes.

The Innoviz 16 nm Maui signal processing ASIC.

- Controls the firing of laser light pulses that reflect off objects in the scene and return to be collected by the detectors;
- Receives and processes the analog signals from the above-mentioned detectors and creates the point-cloud that is streamed out of the LiDAR; and
- Includes the logic that controls the MEMS mirrors to maintain the correct scanning pattern, which is configurable by SW, and maintains synchronization among the individual mirrors which is important for the performance of the LiDAR.
- Maui includes technology to filter noise such as ambient light and extract the signal which is vital to LiDAR performance.

- Maui also includes hardware and CPU cores that address the functional safety and ISO26262 needs of a system that must comply with the safety goals of autonomous vehicles.
  - Source: https://sec.report/Document/0001193125-21-006347/

4. LiDAR Forecast

The increased resolution sensing required in autonomous driving applications correlates with the demand for high resolution LiDARs.

- Each year, Strategy Analytics publishes its Autonomous Vehicles and Sensors Market Scenarios report. For autonomous driving applications, from semi-autonomous SAE Level 3 to fully-autonomous Levels 4 and 5, high resolution LiDARs are required.
- At present, only these LiDARs have the centimeter resolution that can detect the position of objects, such as curb stones, and can recognize objects, such as pedestrians. Whereas imaging RADARs do not have the resolution capable to compete with LiDARs (RADAR angular resolution at 1° versus 0.1° in LiDARs) and that Mobileye's "VIDAR" concept has only just got off the ground.
- However, regulatory clearance for Level 3 applications on public highways has been slow, with Japan and, recently, Germany and Europe, allowing such semi-autonomous driving systems to be fitted on new light vehicles by auto makers.

4.1 High Resolution LiDARs

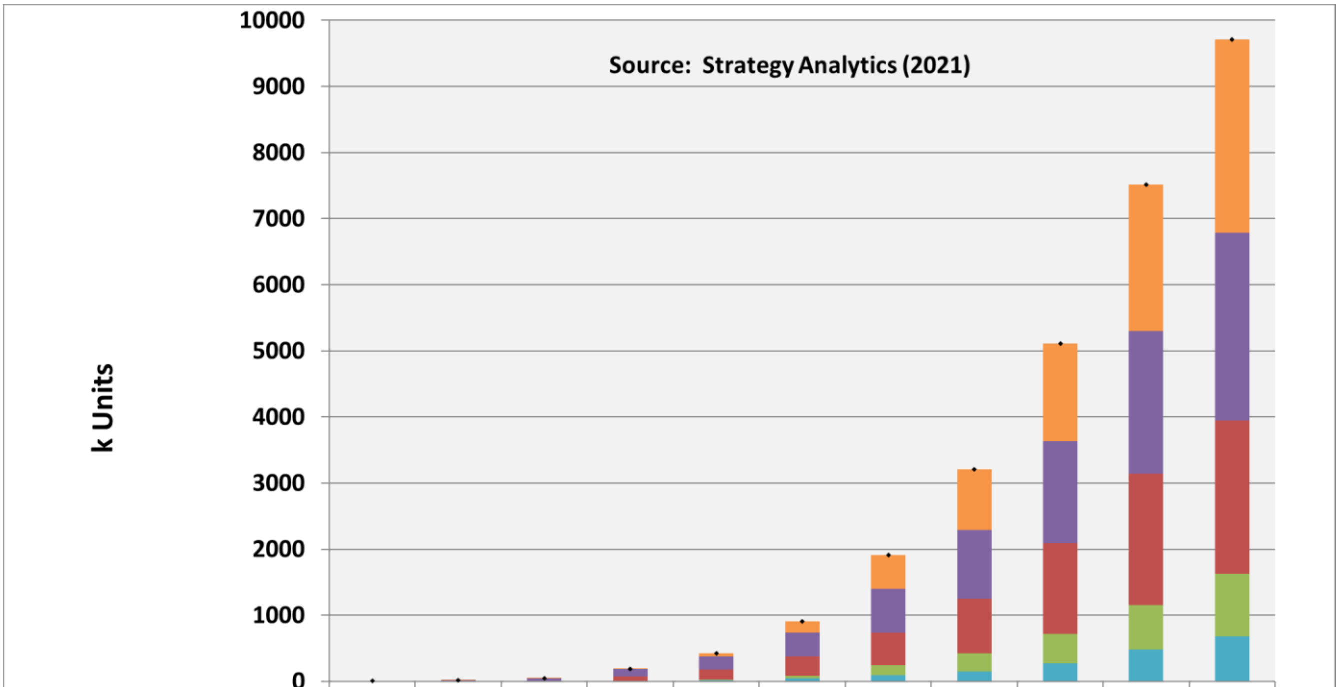
Please note that this sensor forecast for high resolution LiDARs only includes fitments to new light vehicles below 6 tons gross vehicle weight and not retro-fitments for autonomous test vehicles and not for autonomous last-mile shuttles and cargo handling vehicles that operate off the public highway

As it becomes more challenging to commercialize fully-autonomous driving systems and that OEM investments are being withdrawn, the demand for high resolution LiDARs is shifting towards ADAS and semi-autonomous driving applications. Only recently have SAE Level 3 applications gained clearance from regulatory authorities. Therefore, the deployment of high resolution LiDARs has been delayed until now. Only when new technology concepts gain automotive qualification, industry acceptance and maturity will they enter service with new LiDARs in the future.

- All LiDARs are deployed in Distance Warning applications, particularly for autonomous cruise control.

- Looking at the LiDAR market by where the end-vehicle is manufactured shows the importance of the European market – which accounts for most of the demand at present, Exhibit 4.1.
- LiDARs fitted to light vehicles manufactured in China are expected to grow from 2% of unit demand in 2014 to 30% by 2028.

Exhibit 4.1 High Resolution LiDAR Demand Forecast



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
China	0	0	1	3	47	173	507	920	1,477	2,215	2,918
Europe	5	15	46	114	197	363	665	1,037	1,542	2,162	2,844
NAFTA	0	0	1	60	154	287	495	823	1,371	1,984	2,315
Japan	0	0	0	10	5	40	145	274	446	671	947
South Korea	0	0	0	1	20	46	98	151	272	479	677
Emerging Market Regions	0	0	0	0	0	0	0	1	2	4	6
TOTAL	5	15	48	188	423	909	1,910	3,205	5,111	7,513	9,707

Source: Strategy Analytics

5. Conclusions

- Automotive LiDAR (Light Distance And Ranging) sensors promise to complete the suite of sensors required for highly automated driving solutions.
- As a result, around $1B has been invested in up to 100 different companies developing high resolution LiDAR sensors using a wide range of new technologies, from different laser diodes, scanning methods, integrated chipsets, receiver technologies and more.
- High resolution LiDAR has entered the automotive market, the first of these is the Valeo/Ibeo SCALA unit fitted initially to the Audi A8, and now to other Audi models. Numerous high resolution LiDAR OEM production launches are expected through 2021 through 2025.
- Automotive light vehicle high resolution LiDAR will grow from under 50,000 units in 2020 to over 9.7 million units in 2028.
- FPGA-based LiDAR solutions are already being sold in the automotive market

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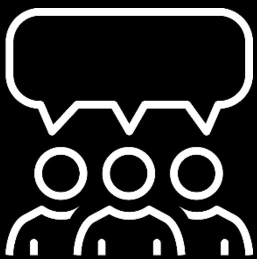

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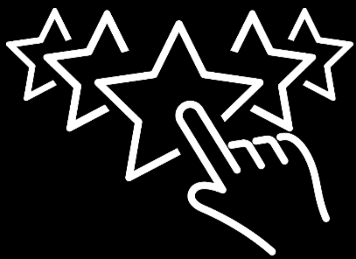

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