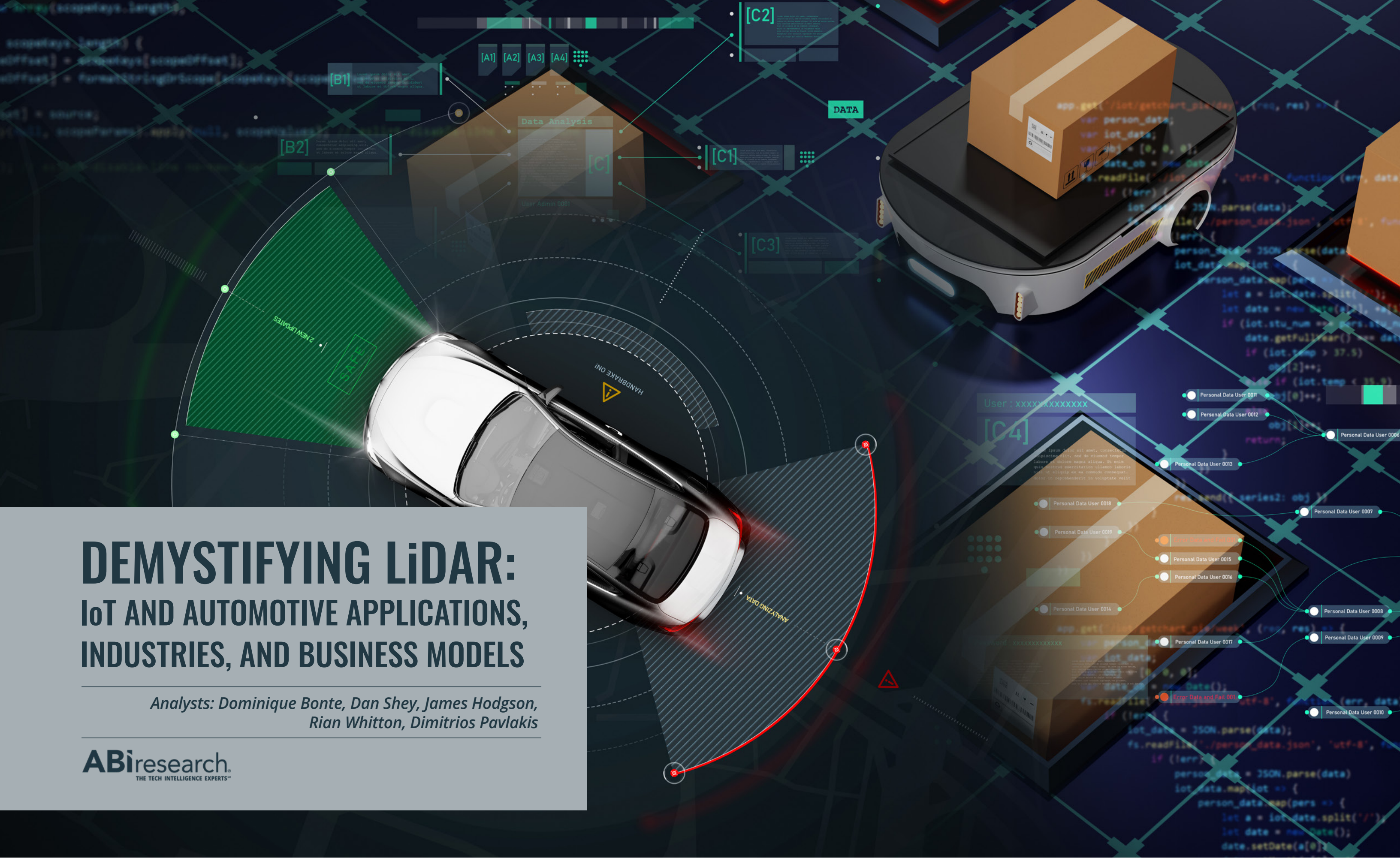

DEMYSTIFYING LiDAR:
IoT AND AUTOMOTIVE APPLICATIONS, INDUSTRIES, AND BUSINESS MODELS

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EXECUTIVE SUMMARY

INTRODUCTION

While Light Detection and Ranging (LiDAR) sensor technology was initially developed and positioned for Three-Dimensional (3D) map making, surveying, and autonomous driving (the agenda of which has now been pushed to the second half of this decade), it is now ready for deployment in several Internet of Things (IoT) markets and verticals. This coincides with technological innovation, such as the shift from mechanical to solid-state LiDAR sensors and the maturity of 3D perception software that enable the integration into and the automation of a growing number of important processes and applications. This extends the opportunity for LiDAR manufacturers to not only serve highly competitive, concentrated, and price-sensitive markets like automotive, but also several large IoT markets, such as security, smart cities, and industrial automation, characterized by a larger and more diversified end-customer base.

In this document, ABI Research demonstrates that, for this decade, the IoT market for 3D LiDAR perception is structurally highly attractive due to several key factors:

- Represents the largest total market, with a 2030 installed base of 16 million sensors *versus* 13 million for automotive, growing at a Compound Annual Growth Rate (CAGR) of 53% (2021 to 2030).
- Serves large and diversified verticals, such as security, industrial automation, smart cities, and smart spaces, with tens of thousands of potential target customers.

- Given the much higher customer dispersion *versus* the automotive industry, it enables better business models and mid-high gross margins.
- LiDAR technology is already widely adopted in applications, such as industrial automation, therefore offering a much lower market timing risk.
- The market will support between 5 and 10 quality suppliers to address the breadth of applications and industries.
- Overall, it allows for a larger profit opportunity.

At the same time, while the automotive market will represent the largest single vertical long-term opportunity, the LiDAR market for automotive is going through a number of key architecture/product stages. Therefore, the following statements apply:

- Mass market adoption in the long term will be mainly enabled by solid-state architectures due to their lower cost and reduced wear and tear compared with mechanical architectures.
- Winners will be rewarded in the second half of the decade.
- Architectural efficacy will be relevant for the second half of the decade.
- Supply chain integrity and regional economic interests will require between 5 and 10 quality worldwide suppliers. Supply chain structure will not allow a "winner-takes-all" scenario.
- Supplier economics will be challenged and mature by the end of the decade.

IoT AND AUTOMOTIVE MARKETS

Figure 1 summarizes the differences in market size, structure and dynamics between IoT markets and Automotive.

Figure 1: LiDAR Market Size and Structure

(Source: ABI Research)

MARKET SIZE AND STRUCTURE	IOT	AUTOMOTIVE
MARKET SIZE		
LiDAR installed Base in 2023 (millions)	1.09	0.144
LiDAR installed Base in 2030 (millions)	15.98	12.95
Confidence of market timing	HIGH	MEDIUM
INDUSTRY STRUCTURE		
Buyer dispersion	More than 10000	15-20
Market Maturity		
2D	HIGH	NOT APPLICABLE
3D	In process	Prospective
Supplier dispersion		
2D	5 - 10	NOT APPLICABLE
3D	5 - 10	5 - 10

This decade, the IoT market is larger than automotive. Automotive will become the largest single market beyond 2030.

Chart 1 and Chart 2 show projections for the number of LiDAR sensors (installed base) for automotive and the different IoT markets, consolidated and individually, respectively. The aggregated IoT market size will be substantially larger than automotive in the medium term with automotive catching up by 2030 and, ultimately, expected to become the largest market.

Chart 1: Installed Base LiDAR Sensors – Automotive versus IoT Segments Consolidated World Markets: 2019 to 2030

(Source: ABI Research)

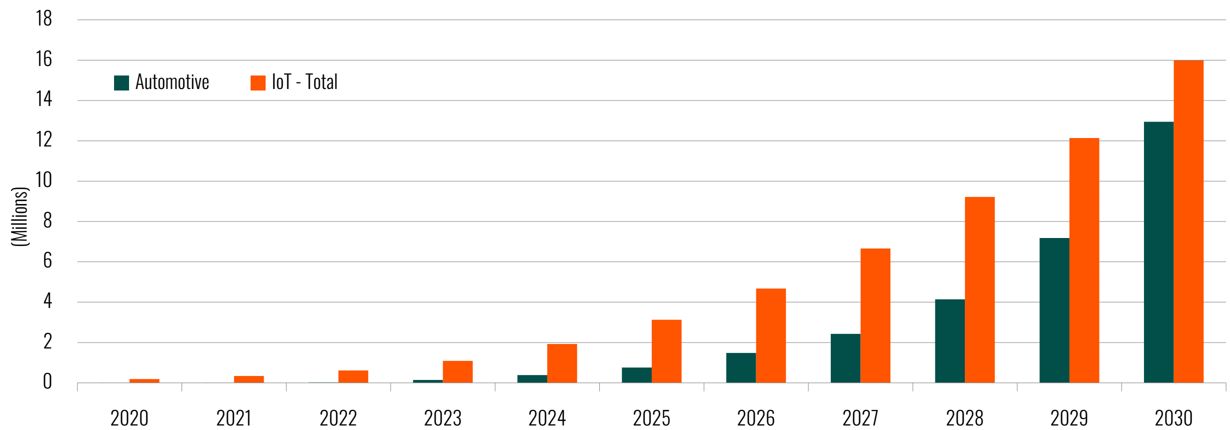
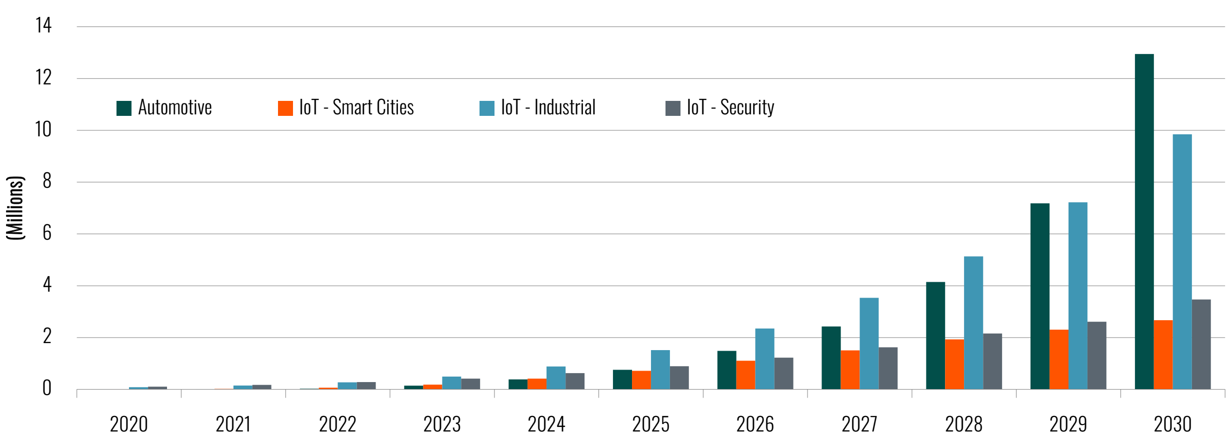


Chart 2: Installed Base LiDAR Sensors – Automotive versus IoT Segments World Markets: 2019 to 2030

(Source: ABI Research)



Within the IoT, the industrial segment will remain the largest market, followed by security and smart cities.

The IoT market provides lower customer concentration, therefore higher profitability opportunity.

The IoT market consists of very large and fast-growing segments, such as industrial automation, smart cities, and security, with an aggregate end-user base that can be counted in the tens of thousands of accounts across the globe. This contrasts with the automotive market where the top 10 Original Equipment Manufacturers (OEMs) accounted for 68% of the market as a whole (2019).

The automotive OEMs hold considerable monopsony power, with the ability of automakers to dictate prices to their suppliers only expected to increase as the LiDAR market consolidation occurs. This will have the effect of lowering the margin that LiDAR suppliers can achieve in the automotive market.

In contrast, the IoT market represents a much less concentrated ecosystem than automotive with its end-customers exercising less influential power on pricing levels and, therefore, providing an overall more level competitive environment. This, in turn, will translate to mid-high gross margin potentials for the LiDAR vendors servicing it.

The IoT market will reach mass-market faster than the automotive.

The LiDAR market will support 10 to 20 qualified vendors, with no "winner-takes-all" scenario.

Today, there are more than 100 LiDAR vendors in the market, but few with enough capital, revenue, and mature product portfolios to be able to address the significant market opportunity. Therefore, consolidation will naturally occur during this decade with ABI Research anticipating that 10 to 20 quality vendors will serve the entire IoT and automotive markets by 2030, with roughly 5 to 10 per market.

The automotive industry, for instance, rarely accepts a single-point-of-failure in the supply chain by engaging with a single technology supplier; in fact, each major OEM will typically qualify three suppliers for each high-volume design slot. This is evidenced by the major supply chain issues and long lead times that are impacting all major markets today.

Furthermore, OEMs in certain regions prefer to engage with local sensor technology developers and suppliers, increasing the number of qualified vendors. As a result, ABI Research expects that the dozens of LiDAR developers targeting the automotive industry today will eventually consolidate to a handful of suppliers, and that no single LiDAR supplier can expect to become a monopolistic supplier of LiDAR sensors to the automotive market.

IoT is a bridge to automotive.

The diverse dynamics at play allow for a complementary strategy, whereby investing in solutions targeting the IoT will enable LiDAR vendors to reap the benefits of the larger and more certain market in the earlier part of this decade, while preparing their solutions for the aggressive cost, manufacturing, and scale of automotive OEM requirements.

For instance, the industrial Autonomous Mobile Robot (AMR) market exhibits similar scaling challenges to automotive. AMRs are expected to reach an installed base of about 10 million units (by 2030). In addition to high-performance sensors, they will require manufacturing scale, a strong supply chain, and low-cost designs.

Optimizing these processes in the first half of the decade will enable manufacturers to effectively engage the automotive OEMs when they are ready to scale.

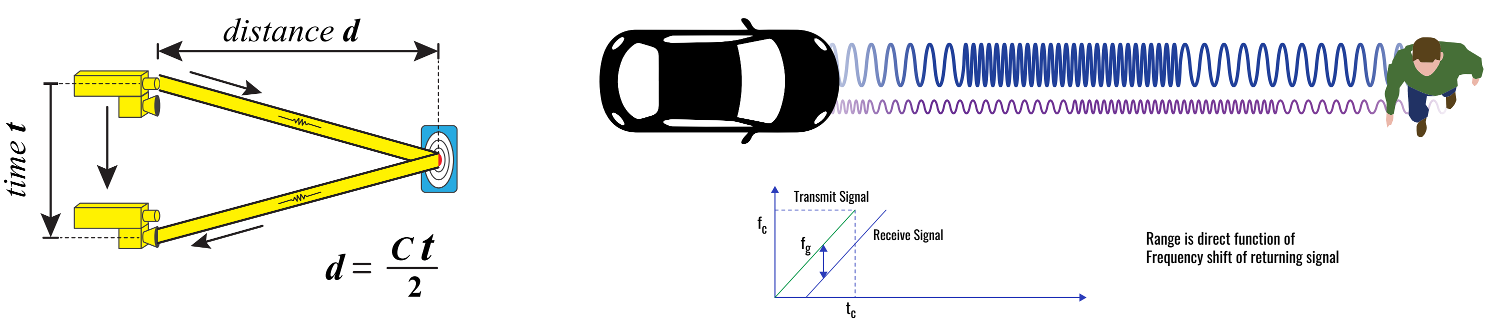
LIDAR PRINCIPLES AND TECHNOLOGIES

LIDAR PRINCIPLES

Fundamentally, LiDAR is a distance measurement device. There are two principles to measure the distance as illustrated in Figure 2. Direct detection is based on sending out laser pulses and measuring the Time-of-Flight (ToF) of the return photons. Coherent detection is based on Frequency Modulated Continuous Wave (FMCW) to provide indirect measurement of both distance and velocity (doppler effect) along the radial direction. ToF and FMCW are shown in Figure 2 and Figure 3.

Figure 2: LiDAR Principles

(Source: ABI Research)

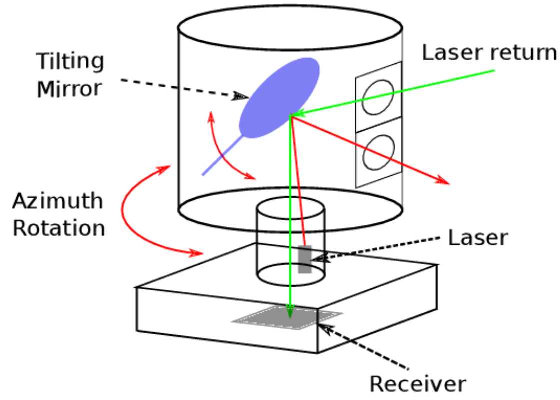


LIDAR TECHNOLOGIES

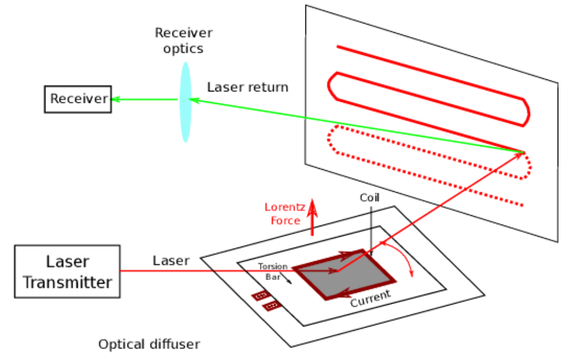
Various mechanisms are employed to expand the single point range finding to both azimuth and vertical directions and generate aggregated 3D distance measurements (point cloud). There are typically two main categories of LiDAR, classified as mechanical LiDAR and solid-state LiDAR. Mechanical LiDAR uses either macroscopic rotational transceiver construction (see (a) in Figure 3) or microscopic mirrors (see (b) in Figure 3) as in Micro-Electro-Mechanical Systems (MEMS) to scan or steer the laser beam. There are two types of solid-state LiDAR. One is flash LiDAR (see (c) in Figure 3) where the light source illuminates the whole scene and uses a Two-Dimensional (2D) detector array to capture the return signal. Despite its solid-state nature, flash LiDAR's detection range is limited due to the large amount of power required to spread out to cover the field of view, resulting in unfavorable thermal and power consumption implications. The other one is Optical Phased Array (OPA)-based electronics beam steering solid-state LiDAR (see (d) in Figure 3). OPA LiDAR steers laser beam through a series of phase modulators, where phase shifters control the optical wave-front interference, electronically steering the laser beam to different angles. This unique approach combines the solid-state characteristics with an electronic scanning mechanism.

Figure 3: LiDAR Technologies

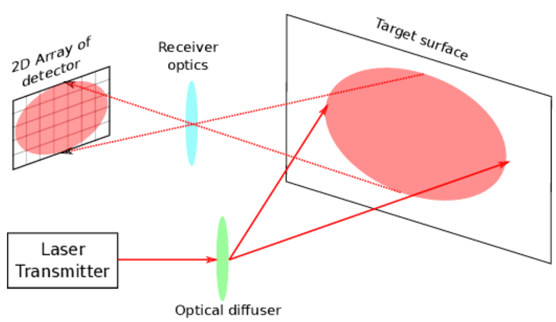
(Source: Li, You and J. Ibañez-Guzmán.)



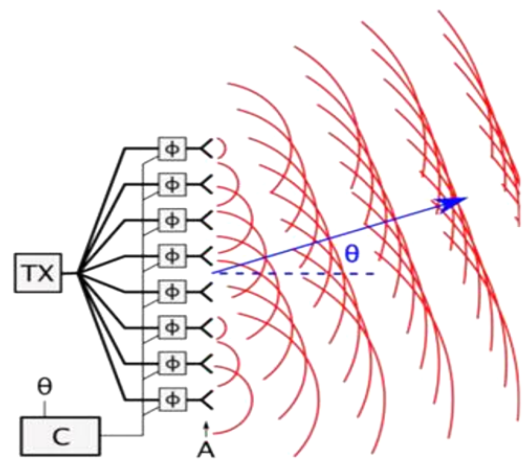
(a) Principle of mechanical spinning LiDAR



(b) Principle of MEMS LiDAR



(c) Principle of flash LiDAR



(d) Principle of OPA LiDAR (from [9])

While mechanical LiDAR is currently dominant, both in IoT and automotive (mainly in driverless concepts and trials), various forms of solid-state LiDAR will become prevalent in both automotive and IoT verticals due to their inherent cost and reliability benefits. Within industrial contexts, 3D LiDAR will gradually displace 2D LiDAR.

LIDAR VERSUS OTHER SENSORS

Table 1 provides a high-level, cross-vertical comparison between LiDAR and other types of sensors. While LiDAR has some unique advantages compared to other sensors, it will often be combined with other sensors, either for increasing reliability *via* sensor fusion in automotive, for example, or offering a wider range of applications, such as by combining them with camera sensors for biometrics applications like facial recognition in security contexts or for number plate recognition in traffic management. It is also worth noting that both High-Definition (HD) radar and Infrared (IR) are starting to be deployed in automotive and traffic management markets, for example, by FLIR, leveraging the higher robustness compared with camera sensors.

Table 1: Comparison of LiDAR versus Other Sensors
(Source: ABI Research)

SENSOR TYPE/ CAPABILITIES	COST AT SCALE	RANGE	RESOLUTION	ROBUSTNESS TO POOR WEATHER	ROBUSTNESS TO POOR LIGHTING
LiDAR	M	M/H	M/H	H	H
Camera	L	M	H	L/M	L/M
Radar	L	H	L	H	H
HD Radar	L	H	M	H	H
FIR	M	M/L	M/L	H	H

The following sections cover key use cases, including case studies, mapping of LiDAR benefits to use cases, business models, ecosystem dynamics, market opportunities, and sizing for the following key markets:

- IoT
  - Smart cities and smart spaces
  - Security
  - Industrial automation
- Automotive

SMART CITIES AND SMART SPACES

Over the past years, LiDAR has started to enable a wide range of smart cities use cases, centered around vehicle traffic and people flow tracking, monitoring, and management. While safety-related use cases, such as pedestrian detection and traffic management at intersections, are well known, COVID-19 has brought people density tracking and overall flow management to the foreground. However, crowd management has many other benefits, most importantly offering a better overall Customer Experience (CX) at retail outlets, airports, and other microcity venues through better line management, while, at the same time, providing critical information about customer behavior and attitudes for marketing purposes. Finally, LiDAR is used to survey the physical infrastructure and assets of cities to inform 3D mapping of digital twins.

OVERVIEW OF LIDAR USE CASES FOR SMART CITIES

LiDAR use cases for smart cities can be categorized according to various criteria:

- Outdoor *versus* indoor applications
- Vehicle *versus* people tracking, monitoring, and management
- Intelligent Transportation Systems (ITSs) *versus* generic smart cities applications

PUBLIC TRAFFIC MANAGEMENT AND SAFETY

Traffic management is mainly an opportunity at junctions/intersections as part of the wider ITS market with key use cases including vehicle traffic monitoring and pedestrian detection. Cities are increasingly focusing on understanding fluctuating traffic patterns and mix, as well as vulnerable road user safety. At the same time, overall traffic management is increasingly being automated *via* on machine vision solutions based on connected Artificial Intelligence (AI) sensors to enable (cooperative) Adaptive Traffic

Lights. Other ITS use cases include parking space information and management, classification for tolling, and highway speed detection and enforcement. Key examples and case studies are listed below:

- **Europe, LiDAR-Enabled Obstacle Detection at Railway Level Crossings**: Based on Cepton's Helius Smart LiDAR System.
- **France, Highway Speed Monitoring and Enforcement**: Quanergy supplying M-Series Long-Range 3D-LiDAR sensors to Parifex, which also partners with Ouster.
- **Adelaide, Lane-Based Traffic Management**: Use of Quanergy M-Series LiDAR sensors and the QORTEX DTC (Detection, Tracking, and Classification) solution to collect information about pedestrians and vehicle traffic approaching intersections.
- **Seoul, Pedestrian Safety at Schools**: 3D LiDAR-based Smart Safety School Zone solution in partnership with iCent, consisting of M-Series LiDAR sensors from Quanergy, actively monitors the movement of objects, including people and vehicle, at crosswalks to protect pedestrian safety and prevent accidents, as well as capturing vehicle traffic patterns and pedestrian numbers.
- **Pittsburg, Curb and Parking Analysis**: Partnerships between Velodyne and Kaarta to visualize urban curbside use and occupancy.
- **Reno, Nevada, Smart and Safer Transportation Infrastructure**: Velodyne partnering with the University of Reno to detect, count, and track pedestrians, cyclists, and traffic.
- **Busan, South Korea, Pedestrian and Vehicle Safety**: Solution developed based on the Quanergy MQ-8 sensor and QORTEX DTC in partnership with iCent.
- **Austin, Texas, Traffic Monitoring**: Velodyne LiDAR-based intersection traffic monitoring solution replacing inductive-loop detectors, cameras, and radars in partnership with NVIDIA Metropolis.

OUTDOOR SMART CITIES PEOPLE FLOW MANAGEMENT AND OTHER APPLICATIONS

Very much put on the map by COVID-19 for social distancing monitoring and enforcement, but also already used previously to manage pedestrians flows in crowded city centers, data can also be gathered to inform the urban planning process. Key applications include people counting and density measurements. Key examples and case studies are listed below:

- **Las Vegas, Tracking and Management of Pedestrian Flows**: Quanergy's M-Series LiDAR sensor technology powering Cisco's Smart City Connected Roadway solutions to track the flow of pedestrians and vehicles at intersections.
- **South Korea, People Counting for Tourism**: Quanergy LiDAR solution for optimizing beach operations and guaranteeing tourist safety in partnership with iCent.
- **Frankfurt Airport**: Leonardo uses LiDAR to assess weather quality, pollution, and aviation conditions.

INDOOR/OUTDOOR PEOPLE DETECTION, COUNTING, AND FLOW MANAGEMENT AT MICROCITIES

Both informed by COVID-19 restrictions and the need for better crowd flow management to minimize delays caused by lining up at a range of microcity categories, including airports, train stations, passenger ports, malls, venues, and campuses. Additionally, LiDAR tracking data provides critical data about behavior and usage patterns for marketing purposes (dwell time, line time, path, intent, and journey). Finally, LiDAR sensors are now also being used for building occupancy detection and management in terms of optimized energy management of Heating, Ventilation, and Air Conditioning (HVAC) and lighting. Key examples and case studies are listed below:

- **Miami International Airport, Real-Time Crowd Monitoring and Line Management**: Quanergy and SkyFii partnership.
- **Jackson-Medgar Wiley Evers International Airport in Jackson, Mississippi, Crowd Management at Transportation Security Administration (TSA) Security Lines and Departure and Arrival Gates**: Based on Quanergy's M-Series LiDAR-based technology combined with SkyFii's Motion Analytics Platform.
- **Quanergy and Digital Mortar Partnership, LiDAR-Based Retail Analytics**: End-to-end shoppers' journey analytics, including conversion patterns, detailed merchandising analytics, foot-traffic comparisons, forecasting, and visualizations of indoor and outdoor spaces.

BENEFITS AND UNIQUE SELLING PROPOSITIONS OF LIDAR SENSOR TECHNOLOGIES

LiDAR sensors offer the following imaging improvements over legacy sensors:

- Granularity
- Resolution
- Field of View (FOV)
- 3D information
- Robustness in adverse weather conditions, but also at night or in bright light
- Range

This enables highly accurate object detection, tracking, and classification. LiDAR sensors can be deployed for both new use cases that cannot be addressed by legacy sensors and existing applications complementing (for redundancy reasons) and/or replacing (multiple) non-LiDAR sensors. End-to-end tracking across multiple LiDAR sensors is achieved by automated identification handover, such as for tracking persons at airports from arrival in a taxi to boarding at the gate. Privacy preservation is another important benefit of LiDAR sensors compared with imaging solutions because they do not use facial recognition technologies, thus providing no Personal Identification Information (PII) risk. The matrix in Table 2 indicates which unique LiDAR features enable and/or enrich which smart cities use cases.

Table 2: LiDAR Capabilities Scoring for Smart Cities Use Cases
(Source: ABI Research)

USE CASES\FEATURES	RELIABILITY & ROBUSTNESS	RANGE	FIELD OF VIEW (FOV)	3D CLASSIFICATION ACCURACY	REDUNDANCY	PRIVACY PRESERVATION
Traffic monitoring	H	M	M	H	M	M
Pedestrian detection	H	L	M	H	L	H
Smart parking detection and payment	H	H	H	H	L	L
Speed enforcement	H	M/H	M	H	L	L
Outdoor people density tracking (COVID-19, venues, *etc.*)	H	H	H	H	L	H
Indoor people counting and tracking for COVID-19, line management, and marketing	L/M	H	H	H	L	H
Smart buildings occupancy tracking	L	M	H	H	L	H

BUSINESS MODEL ANALYSIS

For smart cities and smart spaces applications covering large areas, such as parking, airports, malls, *etc*., the business case for LiDAR can be built on the premise of substitution, with 1 LiDAR sensor capable of replacing up to 10 legacy imaging sensors. This is possible thanks to the much longer range and, therefore, broader coverage area provided by LiDAR sensors. The lower number of sensors also reduces installation, cabling, networking, and maintenance costs. The opportunity for LiDAR is attractive, even in cases where it will co-exist and be fused with other sensors. While the straight economic Return on Investment (ROI) is strong, additional business value, such as enabling increased productivity, will also be very important. For some applications, the business model is driven by the higher level of accuracy and predictable performance under various weather conditions, which are key to enabling higher safety levels.

MARKET OPPORTUNITY

LiDAR has the potential to both enable new use cases and replace existing legacy sensors for a range of applications. To gauge the size of the LiDAR market, Tables 3, 4, and 5 provide numbers and/or capacities of the key infrastructure components of smart cities, such and intersections and microcities. Capacities are directly related to the potential number of LiDAR systems that can be installed in terms of the Total Addressable Market (TAM).

Table 3 summarizes the number of signalized intersections *per region* to represent the total potential infrastructure market for *LiDAR systems* used for pedestrian detection and traffic monitoring and management at intersections. A typical intersection will be covered by two to six sensors, depending on its size.

Table 3: Signalized Intersections per Region (millions)

SIGNALIZED INTERSECTIONS	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
North America	0.34	0.34	0.35	0.35	0.35	0.36	0.36	0.36	0.37	0.37	0.37	0.37
Europe	0.38	0.39	0.39	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42	0.42
Asia-Pacific	0.52	0.53	0.54	0.55	0.56	0.57	0.59	0.60	0.61	0.62	0.63	0.65
Rest of the World	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.19	0.20	0.21	0.21	0.22
GLOBAL	1.43	1.44	1.46	1.48	1.50	1.53	1.55	1.57	1.59	1.61	1.63	1.66

TAM data are shown in Table 4 for the number of microcities per category and per region (excluding very small microcities with low technology adoption of levels).

Table 4: Number of Microcities per Category and Region 2021
(Source: ABI Research)

REGIONAL DISTRIBUTION	NORTH AMERICA	EUROPE	ASIA-PACIFIC	REST OF WORLD	GOBAL
Airports	170	128	176	62	536
Passenger Ports	8	58	36	18	120
Railway and Metro Stations	116	1290	747	168	2321
Malls	350	500	1250	250	2350
Venues	492	820	921	368	2600
Campuses	737	724	1299	259	3019
Others	308	434	1059	420	2221
Total	2181	3953	5487	1545	13166

Table 5 shows the global capacity of microcities per category, which is directly related to the potential for LiDAR systems for multiple use cases. The number of LiDAR sensors deployed per microcity category varies by type and size, from just a few sensors to hundreds for the largest microcities, such as large airports.

Table 5: Capacity per Microcity Category
World Markets: 2018 to 2030
(Source: ABI Research)

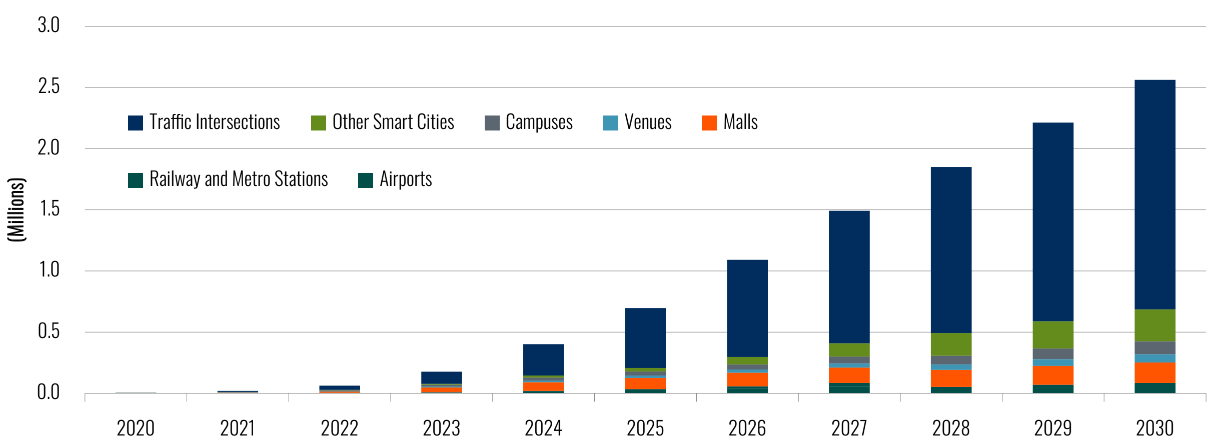
CAPACITY PER MICROCITY CATEGORY	METRIC	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Airports	(Billions of Passengers)	4.30	4.42	4.42	4.42	4.42	4.43	4.47	4.54	4.64	4.75	4.85	4.96	5.08
Passenger ports	(Billions of Passengers)	0.75	0.76	0.76	0.76	0.76	0.77	0.77	0.78	0.79	0.80	0.81	0.83	0.84
Railway and metro stations	(Billions of Passengers)	87.63	89.20	89.32	89.63	90.18	91.10	92.38	94.13	96.37	98.68	101.05	103.49	106.00
Malls	(Millions of Square Meters)	237.50	243.23	241.85	241.93	242.46	245.14	248.34	250.12	250.26	250.40	250.55	250.70	250.85
Venues	(Millions of Visitor Capacity)	92.00	93.26	93.48	94.34	96.72	99.48	102.61	106.20	110.27	114.23	118.05	121.69	125.15
Campuses	(Millions of Occupants)	80.26	81.43	81.51	81.71	82.10	82.76	83.67	84.93	86.10	87.28	88.49	89.72	90.97

The data above clearly show that the smart cities opportunity for LiDAR is fundamentally different from automotive. For instance, the number of targetable entities runs in the tens of thousands, representing a much less concentrated ecosystem than automotive, therefore exercising less influential power on pricing levels and providing an overall more level competitive environment. This, in turn, will translate to mid-high gross margin potentials for the LiDAR vendors servicing it. Procurement practices in these segments tend to follow the traditional enterprise models, with sales cycles measured in 9 to 18 months, significantly shorter than that of the automotive sector's, which typically runs in 3 to 5 years. As a consequence, this segment needs to be addressed differently in terms of the sales and marketing approach *versus* the automotive OEM market, leveraging direct and indirect channels, and, importantly, taking into account government procurement and purchasing cycles, procedures, and practices. It will also require a level of flexibility in terms of the capability of IT toolsets to customize solutions to address a wide range of requirements across the long tail of use cases and customers.

Chart 3 shows projections for the number of LiDAR sensors (installed base) for each of the smart cities categories.

Chart 3: Installed Base LiDAR Sensors by Smart City Category
World Markets: 2020 to 2030

(Source: ABI Research)



In terms of market size, the ITS market seems to be the one having reached the highest level of maturity currently, as evident from the large number of announcements from multiple LiDAR suppliers (see above). It will be the largest opportunity in the smart cities market, as is shown in Chart 3. However, microcities seem to have the biggest potential moving forward in the short term, due to the large number of applications, benefits, and use cases. The more general smart cities market, despite the recent focus on the use of LiDAR for social distancing, is still in an early phase but will become significant beyond 2025.

SECURITY APPLICATIONS

A new market entrant in the security and surveillance market, LiDAR has gained considerable technological momentum and popularity over the past few years. From enhancing security protocols and synergizing with surveillance, intruder detection, and personnel authorization technologies, to assisting governments in transportation, border control, and even social distancing protocols, LiDAR is steadily increasing its reach and penetration rate across a wide spectrum of markets worldwide. LiDAR's versatile nature allows the formation of powerful synergies with existing technological solutions ranging from monitoring operations to biometrics and behavioral analytics, security optimization and user safety, establishing itself as a valuable component of overarching security agendas for a variety of use case scenarios.

OVERVIEW OF LIDAR USE CASES FOR SECURITY APPLICATIONS

LiDAR technologies offer highly versatile security uses cases, including the following:

- Surveillance, personnel protection, access control, and border control
- Physical perimeter defense, intruder detection, and kickstarting security operations
- Crowd monitoring, flow management, and social distancing protocols

ACCESS CONTROL, BORDER CONTROL, AND SURVEILLANCE

Point-Cloud Visualization: Through the use of multiple LiDAR sensors with the capability of horizonal 360° spinning, the system can generate point-cloud visualization to provide reliable overwatch in designated areas. LiDAR point cloud can visualize physical objects and their unique contours, trajectory, velocity, and acceleration.

Access Control: During access control, authorized personnel may take advantage of the technology by having the system detect any anomalous features. The most important use case in access control is the use of LiDAR as a powerful deterrent for tailgating, providing additional security against intruders attempting to take advantage of a legitimate user's attempt to verify themselves and access secured premises.

Emerging Applications: Additionally, emerging LiDAR applications include protection of property for insider threat, hygiene, and social distancing protocols, and the safety of personnel from hazardous areas and heavy machinery. Additionally, the technology has the potential to set the foundation for the next generation of security monitoring and detection of potential biological warfare using LiDAR as the Biological Point Detection (BPD) for urban biological defense protocols.

Surveillance and Border Control: Designated areas in LiDAR system can be easily "marked" by implementers to include specific entry points in building or facilities, points of interest, or even spanning an extended perimetry that may include commercial property, border control hubs, shipyards and airports, security checkpoints and their adjoining areas, industrial settings, critical infrastructure, or even defense compounds, among many others. LiDAR can be used for a versatile range of applications, including surveillance, flow management, enhancing security systems, and defense protocols.

Case Studies:

- Quanergy provides security automation and worker protection for Korea's Shadong Port using a host of LiDAR solutions.
- Global security services company integrates Quanergy M-Series LiDAR with video-based mobile camera solution to significantly reduce false alarms.
- OPTEX implements LiDAR security and access control to Belfast Call Centers.
- Cepton's LiDAR solutions implemented in Orlando International Airport for security and crowd monitoring.

PHYSICAL PERIMETER DEFENSE, INTRUDER DETECTION, AND KICKSTARTING SECURITY OPERATIONS

Intruder Detection and Preventing Alert Fatigue: LiDAR's true strength in security applications rests in intruder detection. In the event the system detects a human intruder, an unidentified terrestrial vehicle, or even an encroaching Unmanned Aerial Vehicle (UAV), the system can assign a unique identification label to that intruder/vehicle and continuously track its trajectory and position regardless of most disruptive environmental or lightning effects. LiDAR's reliability can also prevent false alerts and, by extension, alert fatigue for security personnel.

Critical Infrastructure Perimeter Defense: Critical infrastructure is of the utmost priority for governments worldwide. LiDAR sensors can be used in critical applications, such as data centers, energy, water and utilities, nuclear facilities, and oil & gas, among many others, to provide enhanced perimeter defense with a much lower Total Cost of Ownership (TCO) compared to standard cameras. The implementation of far fewer LiDAR sensors can achieve a highly sophisticated and reliable perimeter defense, which can also provide a host of additional benefits by synergizing with existing Video Management Systems (VMSs) or any other protocol deemed necessary for that specific implementation. Note that LiDAR and other motion sensors can be quite versatile in their installations and can also be part of the hardware kit of Collaborative Robotics (cobots) and patrolling UAVs.

Kickstarting Security Operations: The system will be able to pinpoint the location of any disturbance and proceed to kickstart the security infrastructure, initiating existing perimeter defense security protocols with LiDAR being the first vital link of the security chain. In the case of a human intruder, for example, the unique ID label assigned to that particular person by the LiDAR system can activate surveillance cameras to focus on and follow them along their path, assess the severity of the situation based on computer vision and behavioral AI models, force physical access control restrictions along their way, regulate the use of smart lightning, and initiate the activation of defense drones to monitor the intruders from above.

Case Studies:

- Quanergy implements LiDAR security automation to critical infrastructure, power stations, and oil & gas.
- Quanergy implements LiDAR security across critical national entry points in South Korea.
- Knightscope and Velodyne develop LiDAR-powered security robotics geared toward intruder detection and deterrence.
- Athena partners with Quanergy to provide LiDAR security to the Indian market in critical infrastructure, electric substations, manufacturing, and oil & gas.

- Quanergy Qortex 3D perception software is integrated with Genetec and Milestone VMSs.
- Genetec provides LiDAR security monitoring to OPTEX's manufacturing facilities.
- Genetec's LiDAR and Security Center operations are implemented at Manitoba Hydro in Canada.

DATA PRIVACY, INDOOR CROWD MONITORING, AND SAFETY

Indoor and Outdoor Crowd Monitoring: Crowd monitoring and flow management are two crucial LiDAR applications in many markets, including border control (especially in airports and land borders), stadia and public events, retail, entertainment, and casinos. This concerns not only use cases aimed at optimizing user/passenger experience or line management, but also security, public safety, and well-being applications. Thus, another prominent application of LiDAR in the post COVID-19 era entails the use of the technology as part of infectious control and social distancing protocols.

Adherence to Data Security and Privacy-Related Legislation: LiDAR sensors can be used both in indoor and outdoor spaces for most standard protocols related to: social distancing, line management, people counting, and crowd analytics (constancy, dynamics, volatility, *etc*.). This versatility can be invaluable for crowd monitoring, complementing existing security and personal safety options for all indoor events. However, companies are expected to conform to an ever-increasing list of data privacy options in order to protect any PII captured with the use of traditional cameras. However, implementers will have a much easier task tackling data privacy when implementing LiDAR solutions indoors. This is because no biometric information is captured whatsoever; greatly expediting safety protocols without sacrificing speed or security, and greatly decreasing operational expenses and dependence on data filtering, anonymization, storage, and deletion, assisting companies with adhering to regulatory measures and legislation.

Case Studies:

- Velodyne provides data protection and privacy for LiDAR technologies in security applications.
- Genetec employs LiDAR sensors, data protection, and security optimization to the Santa Cruz Beach Boardwalk.

BENEFITS AND UNIQUE SELLING PROPOSITIONS

- **Reduced False Alarms**: Can accurately identify object size, velocity, and trajectory. Greatly resistant to lightning, weather, and atmospheric effects that might render standard camera surveillance utterly blind and incapable of any intelligent analytics. This, in turn, reduces costly false alarms, making the system significantly more secure.
- **TCO and ROI over Time**: Fewer LiDAR sensors required compared to standard cameras for the same coverage area with a greater FOV and decreased maintenance costs and TCO over time; popularity forces LiDAR hardware to fall in price, with increased ROI based on future trajectory and use case versatility. The ROI is further enhanced by the reduction in false alarms, because fewer resources and/or "truck rolls" are required to verify the actual presence of intruders, which is especially costly in remote and hard to access locations.
- **Anti-Spoof**: In cybersecurity, a system is as strong as its weakest link. Like cameras, LiDAR sensors can be hacked either in close proximity or remotely in various use case scenarios, ranging from access control to industrial and automotive. First, compared to cameras, LiDAR is a lot more challenging to spoof and force a non-existent obstacle or cloak another object/person in close proximity. Secondly, attempting a remote hack will come in conflict with existing ML models, which, depending on their sophistication, can learn to detect, ignore, or at least acknowledge the presence of unusual artifacts.

- **3D Visualization**: Offers 3D images through point cloud *versus* 2D from traditional cameras.
- **Real-Time Analytics**: Offers real-time data visualization and analytics, does not require post-event resource drain for security forensics analysis as standard camera footage. Note that surveillance cameras can also support real-time analytics at edge processing, but with a much higher drain of computing power and Graphics Processing Unit (GPU) requirements compared to LiDAR.
- **Efficiency and Reliability**: Does not require the computing power or software/ML requirements of computer vision.
- **Privacy Controls**: Much easier for implementers to adhere to data protection legislation because no biometric technologies are required and no PII is gathered or stored whatsoever.

Table 6: LiDAR Capabilities Scoring for Security Use Cases

(Source: ABI Research)

USE CASES\FEATURES	RELIABILITY & ROBUSTNESS	RANGE	FIELD OF VIEW (FOV)	3D CLASSIFICATION ACCURACY	REDUNDANCY	PRIVACY PRESERVATION
Intruder detection and physical perimeter defense	H	H	H	M	M	H
Access control and security for authorized personnel	H	M	M	H	M	M
Physical security synergy and orchestration	H	M/H	H	H	M	M
Human recognition and object/vehicle classification	M	M/H	M	H	L	L
Outdoor surveillance and outdoor social distancing protocols	H	H	H	H	L	H
Indoor surveillance and indoor social distancing protocols	L/M	H	H	H	L	H
Border control and public safety	L	M	H	M	L	M

BUSINESS MODEL ANALYSIS

LiDAR, Traditional Cameras, and Closed-Circuit Television (CCTV): Traditional CCTV operations and cameras make use of standard 2D models and are highly dependent on AI/ML algorithms and processing power (as well as multiple device installations) to provide real-time, 3D visualizations. In turn, the reliability of the analytics output is inherently tied to the complexity of said AI/ML algorithms in order to reliably convert standard images into a more sophisticated visualization and object tracking application. Not to mention, standard surveillance cameras are prone to lightning and weather effects that can bring any intelligence gathering processes to a grinding halt.

On the other hand, LiDAR offers a few unique value propositions. It is highly resistant to environmental conditions, allows for visualization versatility using 3D point cloud, can streamline monitoring capacity and increase scalability with a lower TCO on hardware devices (as well as software and computing power), and offers implementers customization and modular software/algorithm offerings, especially when optimized with sensor fusion and as part of a greater security agenda.

Application-Specific Contingencies: There are two features related to LiDAR visualization that implementers should keep in mind: 1) the inability to use biometrics features, such as face recognition; and 2) detecting the use of protective masks and face coverings. For starters, while both features can be applied through standard camera practices, it is imperative to note that the use of biometrics in non-critical applications is often used as a post-event analytics tool, rather than in real time. This is because real-time face recognition requires a much higher investment (*e.g.*, database management, data access and security, software, and ML tools).

Additionally, face recognition has little to no practical use during the actual intrusion instance, unless the implementer is specifically attempting to identify blacklisted individuals. While LiDAR by itself lacks the capacity to identify specific individuals, it can track down intruders with greater ease and, perhaps as importantly, do so with a much lower over TCO over time. If needed, LiDAR security services can support a sensor fusion approach with face recognition cameras to enable a state-of-the-art intrusion detection system, but with a much higher TCO and data security and analytics requirements.

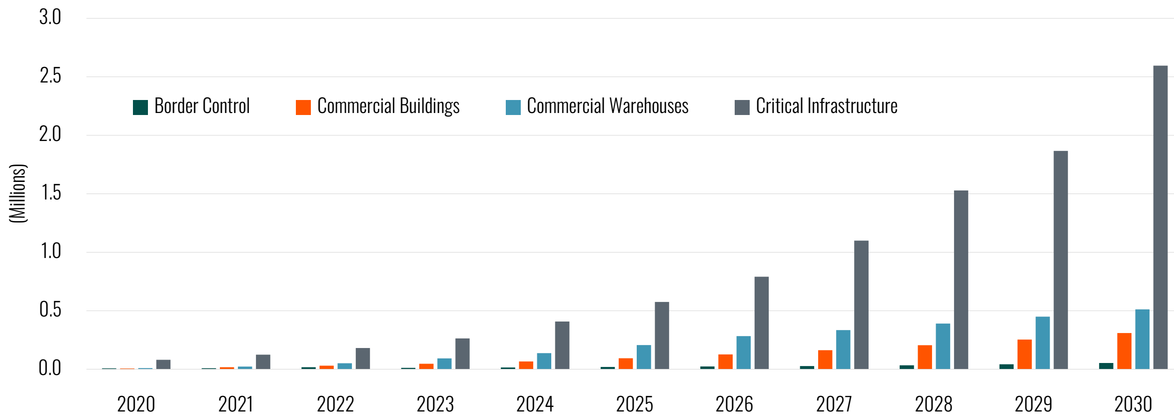
Further, the use of biometrics, cameras, and machine vision is not always the optimal choice because certain application-specific contingencies must be in place related to sensor reliability, sensing capacity, resistance to visual artifacts, and, most important of all, LiDAR's lack of face recognition, which is rated a lot higher when it comes to user privacy and data protection. LiDAR and biometrics need to be treated as complementary technologies, rather than adversarial ones because they both synergize to provide state-of-the-art security options.

SECURITY MARKET OPPORTUNITY

There is a tremendous amount of variability, fluctuation, and versatility in the overarching security market and four key categories examined in this study pertain to intruder prevention and perimeter defense, surveillance, and access control. The sub-market categories include: 1) border control, which includes airports, sea ports (passenger and cargo), and land borders; 2) commercial buildings; 3) commercial warehouses; and 4) critical infrastructure, which includes hyperscaler data centers, energy power plants, water utilities, and electric substations. LiDAR sensing technologies present three emerging opportunities for the applications under these markets: 1) sharpening the sensing capacity and technological sophistication; 2) combatting mounting perimeter security concerns; and 3) addressing the growing need for replacement of legacy equipment.

Chart 4: LiDAR Sensors Installed Base in the Total Security Market
World Markets: 2020 to 2030

(Source: ABI Research)

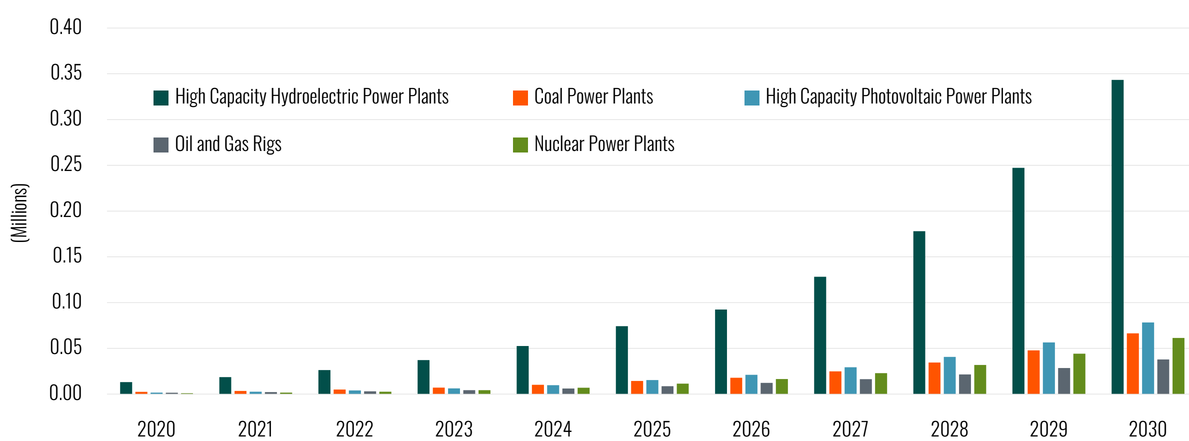


By the end of 2021, the total installed base of LiDAR in the security market is expected to stand at 124,000 sensors. By 2030, LiDAR sensors installed base for the aforementioned studied markets is expected to reach an impressive 3.4 million. The largest opportunity identified is critical infrastructure and energy, which, in total, is expected to amass the lion's share at approximately 2.6 million installed base or 74.8% of the total market for 2030. This is followed by commercial warehouses and buildings at 0.5 million and 0.3 million sensors, respectively, and finally by border control at 53,000 sensors for the same year.

Critical infrastructure and energy is broken down to 1.88 million sensors in water utilities and electric substations, 0.13 million sensors in data centers, and 0.59 million sensors in energy generation facilities (which includes nuclear, hydroelectric, oil & gas, photovoltaic, and coal power plants). While high-tier facilities like nuclear power plants are expected to hold the highest penetration rate of LiDAR technologies, it is the sheer number of facilities like hydroelectric power plants that have the potential to really drive the market forward when it comes to perimeter defense and intruder detection.

Chart 5: LiDAR Sensors Installed Base in the Energy Generation Market
World Markets: 2020 to 030

(Source: ABI Research)



The penetration rate is boosted by additional budget allocation toward physical perimeter defense initiatives as implementers become more cognizant of increased security threats that can originate on-premises. Additionally, LiDAR adoption rates will also satisfy certain key prerequisite items on the cybersecurity agenda for many organizations, as well as address the mounting concern about sabotage and espionage operations in critical infrastructure locations. Table 7 lists the total number of assets for the key security categories in critical infrastructure, water and energy.

Table 7: Total Facilities - Critical Infrastructure, Water, and Energy
World Markets: 2021
(Source: ABI Research)

CRITICAL INFRASTRUCTURE	(ACTUAL)	2021
Hyperscaler Data Centers	(Actual)	627
Water Utilities and Electrical Substations	(Actual)	133,320
Oil and Gas Rigs	(Actual)	1,237
High-Capacity Hydroelectric Power Plants	(Actual)	9,469
Coal Power Plants	(Actual)	2,151
Nuclear Power Plants	(Actual)	461
High-Capacity Photovoltaic Power Plants	(Actual)	1,313
Total	(Actual)	148,578

Other key categories include prisons, amounting to 20,187 actual facilities (2021).

LIDAR FOR INDUSTRIAL AUTOMATION

While LiDAR has accrued interest from its enablement of driverless passenger vehicles, the more immediate market opportunity for sensor-driven automation rests in the industrial material handling market. Well over a million industrial vehicles are sold to be used in factories, yards, and ports every year. Hit by labor challengers and the need to improve productivity, end users are looking to major vendors to automate forklifts, pallet stackers, towers, tuggers, and a whole range of vehicles. While such solutions previously functioned through physical infrastructure like magnetic tape or externally placed fiducial markers, onboard LiDAR and sensor fusion is quickly becoming the standard by which autonomous vehicles map out the environment, localize themselves within it, and navigate.

With the growing adoption of 3D LiDAR, robotic systems can also perceive their environment with a far higher degree of fidelity and technical redundancy than would be possible with just vision. This is opening up a market for mobile robots outside of structured environments.

OVERVIEW OF LIDAR USE CASES FOR INDUSTRIAL ROBOTICS

LiDAR use cases for industrial robotics can be categorized according to various criteria:

- 2D LiDAR for safety and obstacle detection in mobile robotics
- 2D LiDAR for stationary robotics
- 3D LiDAR for unstructured environments

2D OBSTACLE DETECTION

2D LiDAR is already widespread in the mobile robotics space. This was mainstreamed through autonomous vacuums in the consumer space, but has also taken off in the industrial material handling market. When generating 2D maps in the setup phase, LiDAR scans allow a robot to map out to a high degree of precision. They also are preferable to visual systems for detecting obstacles precisely at intermediate ranges without any lighting condition constraints. Therefore, for structured environments, they provide the requisite level of technical redundancy.

2D LiDAR, combined with the perception capabilities of vision and other integral sensors, is used for Simultaneous Localization and Mapping (SLAM) in modern day Autonomous Mobile Robots (AMRs). While cameras are important for developing perception and generating a data-rich understanding of the environment, they suffer from motion blur, poor accuracy, difficulties due to environmental factors like dust or light, and can be hamstrung by low processing speeds with expensive onboard computing architectures. Therefore, the vast majority of mobile robots not relying on external infrastructure deploy 2D LiDAR.

LIDAR FOR STATIONARY ROBOTICS

While LiDAR is generally associated with mobile robotics, it can also be deployed on stationary arms or on workstations to ensure safety. For example, collaborative robotic arms can operate at varying speeds depending on whether a person is in the immediate vicinity. Faster speeds enable faster throughput and performance, while slower speeds enable a low profile and the ability to work with humans without the need for expensive fencing.

3D LIDAR FOR UNSTRUCTURED ENVIRONMENTS

While 2D LiDAR and vision-centered sensor fusion is important, it is still limited by the following:

- **Environment**: Generally, only operates with a high level of redundancy in structured indoor environments. Cannot be applied to outdoor or rugged environments. 3D LiDAR can generate high-detail mappings of the environment in light-deficient conditions and be combined with data from vision systems. This can enable use cases involving indoor/outdoor transitions, operations in rugged or challenging environments, and greater rerouting capability for heavy vehicles. This can be evidenced by autonomous stacker developer Seegrid. Previously defined as a purely vision-based navigation solution, it acquired a small developer named Box Robotics in 2020 for the explicit purpose of integrating 3D LiDAR into its upcoming solutions.
- **Rerouting and Mobility**: Some AMRs (generally much smaller systems) can use 2D LIDAR to dynamically reroute in the case of traffic and obstacles, such as Fetch or MiR. But larger systems like automated pallet stackers and forklifts need a much higher degree of accuracy to reroute, due to their heavy payload and reduced margin of error. 3D LiDAR-enabled mapping and obstacle detection are critical to path-planning for safety critical systems. This is evidenced by the growing use of 3D LiDAR by industry leaders, such as Vecna Robotics and Waypoint Robotics.

MAPPING LIDAR

While the modern robot will require some level of sensor fusion, modern LiDAR scores highly on key criteria, especially when it comes to enabling SLAM. Below is a list of key SLAM criteria and a breakdown of the performances of various sensor categories.

- **Cost**: Total retail price of a single sensor of that technology.
- **Accuracy**: Capacity for correctly resolving two points next to each other in space.
- **Range**: The distance from the sensor at which a feature can be detected.
- **Penetration**: Capacity for a sensor to detect features and objects that are not within direct line-of-sight. This could mean that the sensor picks up reflected signals from regions not directly in front of it, or that the sensor is capable of resolving objects behind layers of visually opaque objects (*e.g.*, a wall or dense foliage).

LiDAR provides capabilities across various criteria, including the best accuracy available. This makes it the critical sensor for providing technical redundancy to mobile robotic systems.

BUSINESS MODEL FOR 3D LIDAR IN INDUSTRIAL AUTOMATION

There are a number of key industries where LiDAR will be a critical enabler to mobile automation:

- **Industrial Environments**: 3D LiDAR is critical for developing onboard capability for indoor/outdoor transitions and will enable greater rerouting capability for heavier systems.
- **Ports**: A key industrial category with limited automation. Bulk terminals deal with both liquid bulk (*e.g.*, liquified natural gas) and dry bulk (*e.g.*, coal). For grab buckets to effectively grasp the inventory, there needs to be intelligence on the parameters of the bulk and the likely safe area of operation. 3D LiDAR can provide a dense point cloud that maps out the safe area, improves the efficacy of crane-operated grab buckets, and reduces safety hazards. At the same time, 3D LiDAR is becoming a critical component for the automated forklifts that are used for material handling within the port's operations.
- **Mines**: Robots are increasingly used for mapping out the internal routes of mines. For this, robots equipped with 3D LiDAR are deployed to give a highly accurate 3D digital map of the mine. This use case is also being applied to industrial sites like ports or chemical plants. 3D LiDAR is also being deployed on equipment to help improve worker safety by providing anti-collision warnings.
- **Sidewalks**: While robot taxis have some way to go before commercialization, the smaller robots tasked with delivering small parcels and groceries in pre-defined localities are becoming much more common. While many of the smaller systems use vision and Global Positioning System (GPS) only, this significantly limits their speed and payload. Given the inevitable problems of GPS for localization in dense urban and suburban environments, only 3D LiDAR provides the technical redundancy for these systems to scale up effectively. ABI Research projects that up to 1 million robot delivery vehicles could be deployed by 2030.

ROBOTICS MARKET OPPORTUNITY

The scale of the mobile robot space is expanding greatly in the aftermath of COVID-19. This is due to:

- ***Consolidation and Commercialization of AMR Technology***: Companies like ASTI Mobile Robotics, Fetch Robotics, and MiR are being acquired by larger ecosystem vendors like ABB, Zebra, and Teradyne. What is more, the proliferation and 2D LIDAR has made barriers to entry much lower.
- **Need for Productivity Improvements and Labor Shortages**: As companies look reshore elements of the supply chain to higher-wage jurisdictions, there is a need to mitigate labor shortages and increase productivity so that such investments make sense. This has led to a huge amount of funding for industrial automation solutions. In 2021, ABI Research expects the global industry to increase revenue by 44% to more than US$30 billion.

Table 8 shows the number of significant industrial sites per category, indicating the scale of the opportunity for industrial robotics deployments.

Table 8: Number of Sites per Industrial Category

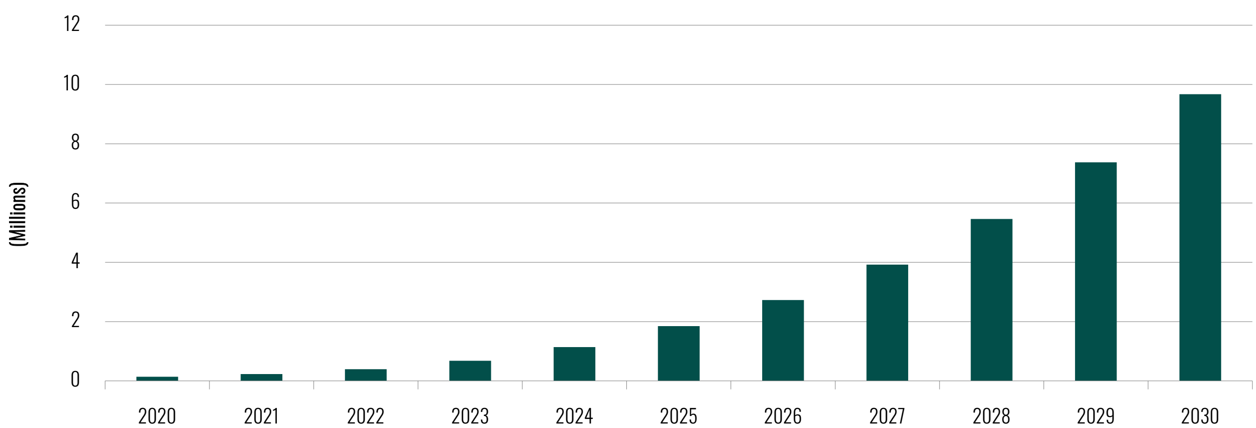
(Source: ABI Research)

INDUSTRIAL CATEGORIES	NUMBER OF SITES (2021)
Cargo ports	152
Warehouses	145,000
Manufacturing plants (>100 employees)	500,000
Total	645,152

Chart 6 shows the enormous growth in the mobile robot installed base across all markets from 2020 to 2030. The AMR market installed base will increase from 14000 in 2020 to 9.7 million in 2030. From 2020 to 2030, US$454 billion will be spent on AMRs globally.

Chart 6: AMR Installed Base
World Markets: 2020 to 2030

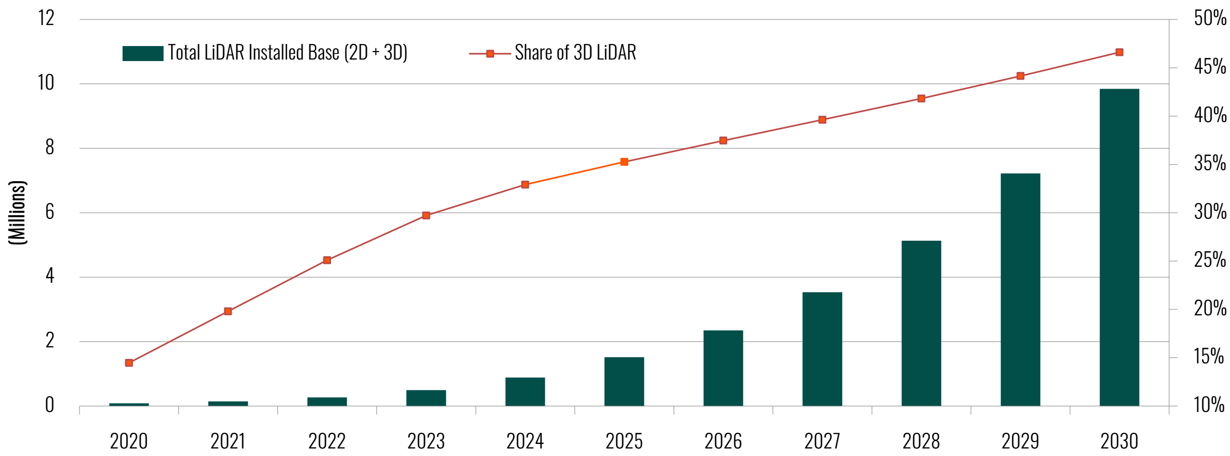
(Source: ABI Research)



A great majority of this installed base will be using some form of LiDAR sensor. Beyond the total growth, there is a large expansion in robots used in outdoor environments. Some are field environments like mines, industrial plants, ports, and farmland. Here, robots need a high level of technical redundancy and assistive perception. More than 1.2 million systems will be operating in this space by 2030. Another 1.2 million will be operating in outdoor public environments like cities. In almost all these instances, 3D LiDAR will become a default component of the overarching sensor modalities for robotic fleets. This growth in robotics portends very well for developers of 2D and 3D LiDAR solutions. Based on ABI Research's projections, the installed base for LiDAR in all commercial and industrial robotics applications increase from 83,000 sensors in 2020 to 9.8 million in 2030 with the share of 3D LIDAR sensors reaching 47% by 2030.

Chart 7: Total LiDAR Installed Base with 3D LiDAR Percentage
World Markets: 2020 to 2030

(Source: ABI Research)



LIDAR IN AUTOMOTIVE

REDUNDANCY IN HIGHLY AUTONOMOUS VEHICLE APPLICATIONS

In the automotive market, LiDAR has been positioned as a sensor to support robust perception in highly autonomous vehicle applications, particularly unsupervised autonomous driving applications that mandate a greater level of redundancy in the perception stack. These applications have yet to materialize at scale in the automotive market; however, almost every prototype or proof-of-concept for unsupervised autonomous driving features a LiDAR sensor in the perception stack.

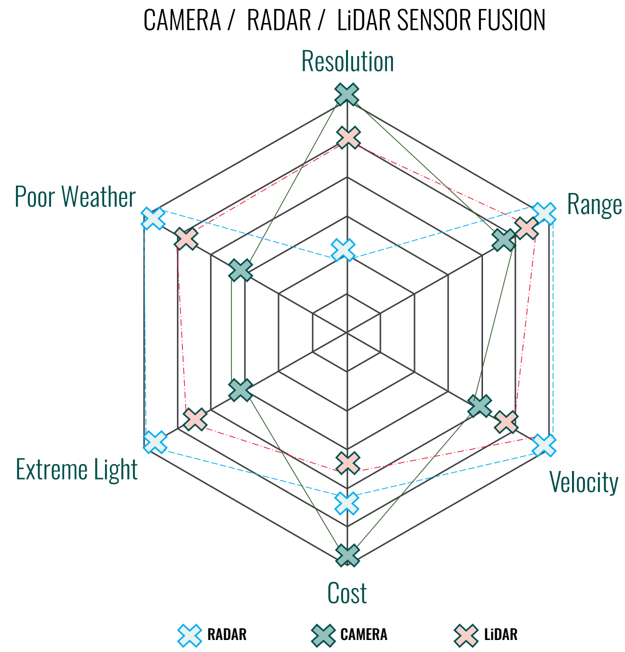
The value of LiDAR's contribution to the autonomous vehicle perception stack can be best seen in how the sensor modality's characteristics contrast and complement the *status quo* of sensor fusion today—camera and radar sensors.

LiDAR is an active ranging sensor, leveraging laser light illumination to determine distances by measuring the return time or wavelength of the reflection. This provides a method of determining distances that is orthogonal to the "structure-from-motion" techniques of cameras, and which continues to perform in poor lighting and inclement weather scenarios when cameras tend to struggle. Most LiDAR sensors slated for production in the next 3 to 5 years operate in the 100 Meter (m) to 200 m range, beyond the maximum range of many of today's Advanced Driver-Assistance Systems (ADAS) cameras.

Radar is also a ranging sensor like LiDAR. However, most automotive radar configurations deliver very poor resolution, both in the horizontal (azimuth) and vertical (elevation) dimensions. This means that while radar can detect the range and velocity of objects, it delivers no semantic insight into the road situation. In contrast, LiDAR sensors can achieve very high levels of angular resolution, well below 0.1°, allowing for obstacle identification and semantic segmentation.

Figure 4: LiDAR as a Tertiary Sensor Modality

(Source: ABI Research)



Therefore, LiDAR is ideally positioned as the perfect "third opinion" to complement the incumbent camera-radar sensor fusion in the future, and unsupervised autonomous applications that require greater redundancy. This applies to obstacle detection, collision avoidance, and navigation applications within autonomous vehicles, as well as to the mapping use case, whether that is in the form of LiDAR sensors equipped for dedicated mapping vehicles or the crowdsourcing of LiDAR sensor data from vehicles deployed in the field.

AUTOMOTIVE USE CASES

Table 9: LiDAR Capabilities Scoring for Automotive Use Cases and Applications

(Source: ABI Research)

USE CASES\FEATURES	RELIABILITY & ROBUSTNESS	RANGE	FIELD OF VIEW	3D CLASSIFICATION ACCURACY	REDUNDANCY	PRIVACY PRESERVATION
Vehicle detection and ranging	H	H	M	H	H	N/A
Pedestrian detection and ranging	M/H	M/H	M/H	M/H	H	H
Road boundary detection	H	M	M	M/H	H	N/A
HD mapping	H	H	H	H	H	H
Semantic segmentation	M	M	M	M	H	H
Velocity determination	M	M	M	N/A	M	N/A

AUTOMOTIVE LIDAR TECHNOLOGY EVOLUTION

LiDAR sensors combine range detection with scanning in order to determine elevation and azimuth, building a 3D understanding of the scene. In the early years of autonomous vehicle development, the automotive industry used the same mechanical rotating mirror scanning technology that had been successfully deployed in other applications, such as mapping and surveying. However, this scanning technology has proven difficult to scale in the automotive industry, due to the level of physical wear and tear incurred by a large, rotating mirror. Developing a mechanical LiDAR capable of a long automotive life cycle incurs greater costs, not only in the Bill of Materials (BOM), but also in additional calibration and maintenance throughout the vehicle life cycle.

The ideal solution, therefore, would be a LiDAR sensor capable of scanning without the use of any moving parts. One such approach, leveraged by LiDAR technology developers, such as Quanergy and OURS, is the use of OPA-based electronics for solid-state beam steering. Instead of a rotating mirror, this approach uses a series of phase modulators to electronically steer the beam to different angles.

With many automakers looking to deploy unsupervised autonomous vehicle applications before the widespread availability of solid-state LiDAR, digital Micro-Electromechanical System (MEMs) mirrors have been positioned as a mid-point between legacy mechanical mirrors and future solid-state designs. These LiDAR sensors also use mirrors for beam steering, but replace large rotating mirrors with digital MEMS mirrors, which have been widely adopted in several industries for many years. With solid-state sensors expected to gain traction from the second half of this decade, MEMS mirror-based designs are expected to provide an important stepping stone, reducing the physical wear and price of LiDAR over the coming years.

A final solid-state LiDAR approach is flash LiDAR, which moves away from the concept of combining range-finding beams with steering, instead preferring to use laser-illumination of the entire scene and a 2D detector array to capture the return signal. A critical weakness of flash LiDAR is the limited range, making the technology inappropriate for many perception requirements. Overtime, flash LiDAR is expected to play a supporting role to beam steering LiDAR, providing short-range detection in low-speed and dense urban environments.

Table 10: Comparison of Mechanical, MEMS, Flash, and OPA LiDAR
(Source: ABI Research)

TECHNOLOGY	COST DOWN POTENTIAL	RANGE	RESOLUTION	FOV	ROBUSTNESS
High-end mechanical LiDAR	L	H	H	H	M/L
Low-end mechanical LiDAR	M/L	M/H	M	M	M
Flash LiDAR	M	L	M	M/H	H
Solid-state OPA LiDAR	M/H	M/H	H	M/H	H
MEMS LiDAR	M/H	H	H	M/H	M/H

Table 11: Automotive LiDAR Technology Evolution
(Source: ABI Research)

PHASE I	PHASE II	PHASE III	PHASE IV
Mechanical Rotating Mirrors	**Digital MEMS/Flash**	**Solid State/OPA and FMCW**	**Solid State/OPA and FMCW**
2017 to 2022, declining afterward	2021 to 2026, declining afterward	2024 to 2027	2028 to 2030
Wide range of capabilities From 16 to 128 channels Range from 130 m to 300 m (10% targets) Resolution from 0.6° x 0.25° to 0.2° x 0.1° FOV from 130° to 360°	Broadly homogeneous technology for MEMs LiDAR Range approx. 200 m Resolution approx. 0.1° x 0.1° FOV Small form factor FOV from 90° to 130°	Range 200 m+ No moving parts Very high Mean Time Between Failure (MTBF) 1 per vehicle covering single angle	Range 200 m+ No moving parts Very high mean time between failure (MTBF) 1 per vehicle covering single angle Multiple devices per vehicle
High wear-and-tear	Medium/low wear-and-tear	No wear-and-tear	No wear-and-tear
Very low manufacturing scale (1000s units/year)	Low manufacturing scale (10,000s units/year)	Medium manufacturing scale (100,000s units/year)	High manufacturing scale (millions units/year)
Velodyne Valeo Ouster Quanergy Robosense	Velodyne Innoviz LeddarTech Robosense	Quanergy Intel Mobileye Lumotive Aurora/Blackmore/OURS	Quanergy Intel Mobileye Lumotive Aurora/Blackmore/OURS
ASP: US$70,000 to US$1,000+	ASP: US$10,000 to US$4,000 initially, falling afterward	ASP: US$2,000 to US$1,000	ASP: < US$500

AUTOMOTIVE LIDAR CASE STUDIES

AUDI A8 TRAFFIC JAM PILOT

In 2018, Audi looked to introduce the first Society of Automotive Engineers (SAE) Level 3 application to market—a conditional automation system that would enable the vehicle to pilot itself at limited speeds without constant driver supervision. Ultimately, Audi was never able to make this system fully available due to a number factors, in particular, the absence of enabling legislation. Nevertheless, when developing a perception stack to enable unsupervised operation, Audi included a scanning LiDAR supplied by Tier One supplier Valeo, based on technology developed by ibeo. Ultimately, Audi released its Traffic Jam Pilot as part of the ADAS feature suite, bringing to market the first commercial deployment of automotive 3D LiDAR.

MOBILEYE FMCW LIDAR ON CHIP

Intel/Mobileye is the market leader in automotive machine vision technologies and applications, having dominated the ADAS and active safety market with its camera-only and camera-radar sensor fusion-based systems. The company has developed a scalable architecture that relies on camera/radar sensor fusion for SAE Level 2 supervised automation applications, adding LiDAR as a tertiary sensor mode for unsupervised automation applications. Mobileye intends to use Luminar's SWIR LiDAR technologies in the next few years, before introducing its own in-house FMCW LiDAR.

INNOVIZ/BMW

In 2018, BMW announced that it would be sourcing a LiDAR from startup Innoviz to feature in the perception stack of its autonomous vehicle, originally slated to be introduced to market in 2021, which has since been delayed to 2023.

VOLVO/LUMINAR

In May 2020, Volvo announced that its SPA 2 modular autonomous vehicle architecture would feature a LiDAR sensor sourced from Luminar to enable its unsupervised Highway Autopilot application.

QUANERGY

In July 2021, Quanergy, in collaboration with ZEV, demonstrated the first OPA-based solid-state sensor at a 100 m range for 10% reflectivity of dark objects in full sunlight. It followed in October 21 by demonstrating a multi-beam sensor operating at 130 m, in collaboration with the Robotics Department of Santa Clara University's Engineering School.

AUTOMOTIVE BUSINESS MODEL ANALYSIS

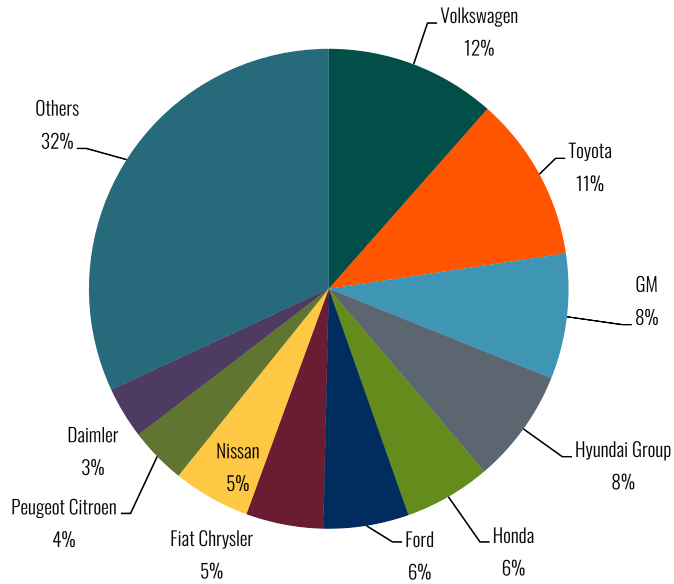
The market potential for LiDAR is tied to the market opportunity for unsupervised autonomous driving, which, in turn, has two parallel paths to market: robotaxis and autonomous passenger vehicles.

TRADITIONAL AUTOMOTIVE/PASSENGER VEHICLE

The automotive industry is defined by a highly concentrated ecosystem, featuring a limited number of OEMs, typically with a global footprint, which, in turn, rely on a limited number of Tier One integrators, and Tier Two component suppliers. The barriers of entry to the automotive market have historically proved near-insurmountable, resulting in a largely static, or even a declining number of automotive brands for consumers to choose from. While the electrification trend has allowed some new Electric Vehicle (EV) brands to break into the mainstream in recent years, the overall cost pressures of meeting the challenges of connected, automated, and electrified vehicles is driving consolidation among existing automotive brands. Examples of this consolidation trend include the recent formation of Stellantis, a newly OEM formed by the merger of PSA (Peugeot-Citroen) and FCA (Fiat-Chrysler).

Chart 8: Automotive Sales Market Share by OEM
2019

(Source: ABI Research)



In 2019, the top 10 OEMs accounted for 68% of the market as a whole. As a result, automotive OEMs hold considerable monopsony power, with the ability of automakers to dictate prices to their suppliers only expected to increase as the consolidation trend continues. This will have the effect of lowering the margin that LiDAR suppliers can achieve in the automotive market. Furthermore, the software-defined car trend is driving OEMs in the direction of hardware platformization, in which OEMs will operate a minimal number of vehicle platforms, enabling differentiation between different models at the software level. This means that each OEM will be unlikely to source LiDAR sensors from more than one or two vendors at the most, further reducing the business scope for LiDAR technology developers in the automotive space.

However, the automotive industry rarely accepts a single-point-of-failure in the supply chain by engaging with a single technology supplier. Furthermore, OEMs in certain regions prefer to engage with local sensor technology developers and suppliers, meaning that no single LiDAR supplier can expect to become a monopolistic supplier of LiDAR sensors to the automotive market. As a result, ABI Research expects that the dozens of LiDAR developers targeting the automotive industry today will eventually consolidate to a handful of suppliers.

ROBOTAXIS

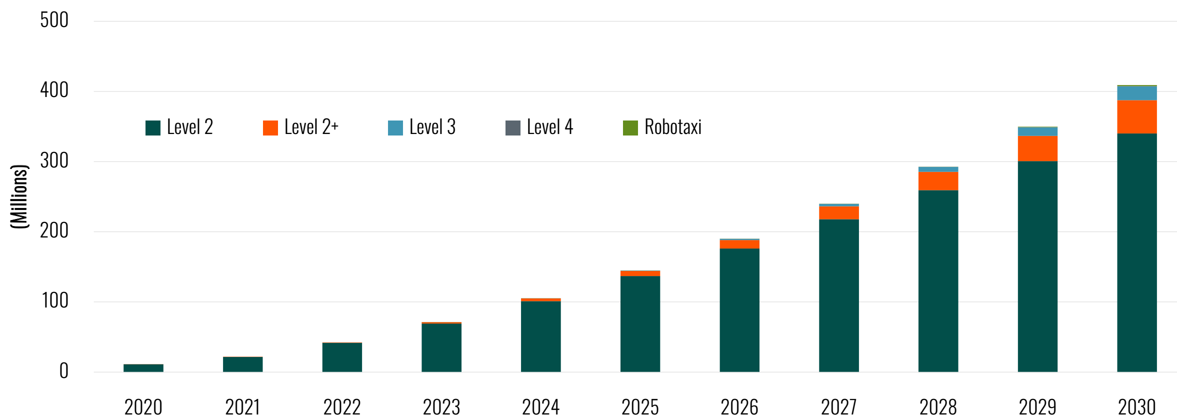
The robotaxi opportunity is a new market that has yet to achieve any scale, but is being pushed forward by both established automotive brands and new entrants to the personal mobility space. In the robotaxi market, the driverless robotaxi serves as the enabling platform for a mobility service, in which the same vehicle will serve multiple users over the course of a day. The ultimate ambition for robotaxi service operators will be to provide as many trips as possible on as few robotaxis as possible. Therefore, while the density of LiDAR sensors on robotaxis is expected to be higher (reflecting the high redundancy requirements), the volume of robotaxis is expected to be much smaller than the typical automotive passenger vehicle sales volumes.

AUTOMOTIVE MARKET OPPORTUNITY

Unsupervised autonomous vehicles (SAE Level 3 – 5) are expected to begin gaining traction from 2025 onwards, with lower levels of automation expected to dominate through to the end of the decade.

Chart 9: Autonomous Vehicle Installed Base by SAE Level
World Markets: 2020 to 2030

(Source: ABI Research)



The market opportunity for LiDAR will remain subdued until after the earnest deployment of robotaxis and Level 4 passenger models. In the meantime, small volumes of Time of Flight (ToF) Near Infrared (NIR) LiDAR will provide redundancy to camera-radar sensor fusion in Level 3 deployments.

The share of LiDAR shipments using mechanical mirror scanning technology is expected to drop rapidly following the introduction of digital MEMS mirror LiDAR. From 2025 onward, the introduction of solid-state LiDAR will also reduce the market potential for mechanical LiDAR, before taking market share from digital MEMS mirror LiDAR in the last years of the decade. From 2026, shipments of digital MEMS mirror LiDAR systems will grow at a CAGR of 60%, while solid-state LiDAR shipments will outpace that, with a CAGR of 163% over the same period. By that point, the maturity of low-end mechanical LiDAR is expected to result in a low Average Selling Price (ASP), making the technology attractive for SAE Level 3 applications in cost-sensitive vehicle segments. Overall, however, mechanical LiDAR is expected to fall rapidly from over 70% of LiDAR shipments in 2024, to less than 6% by 2030. To put matters into perspective, Charts 10 and 11 show the evolution of the installed base of the various LiDAR types and the relative shares of shipments of the various LiDAR technologies in automotive, respectively.

Chart 10: Installed Base of Automotive LiDAR Sensors
World Markets: 2020 to 2030

(Source: ABI Research)

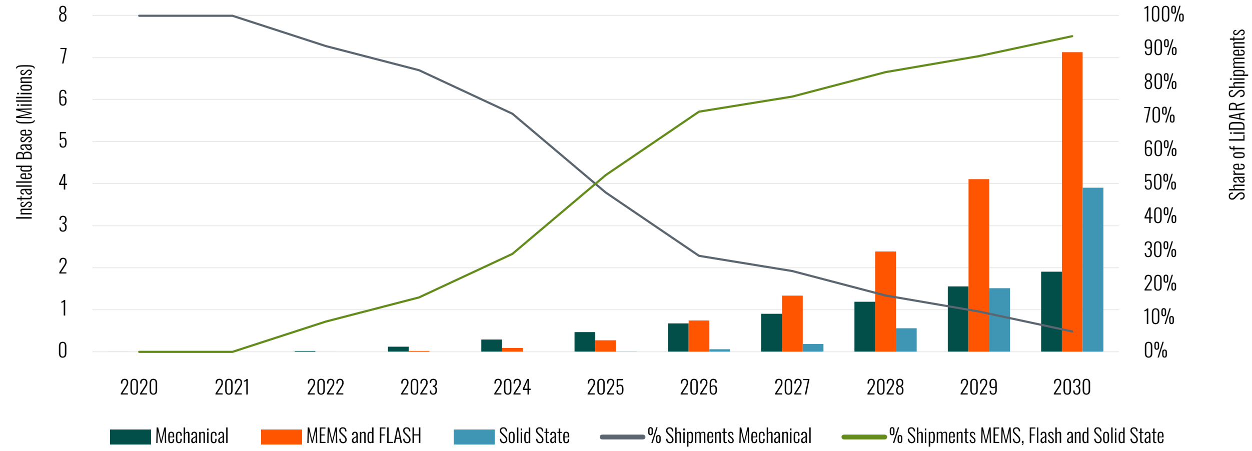
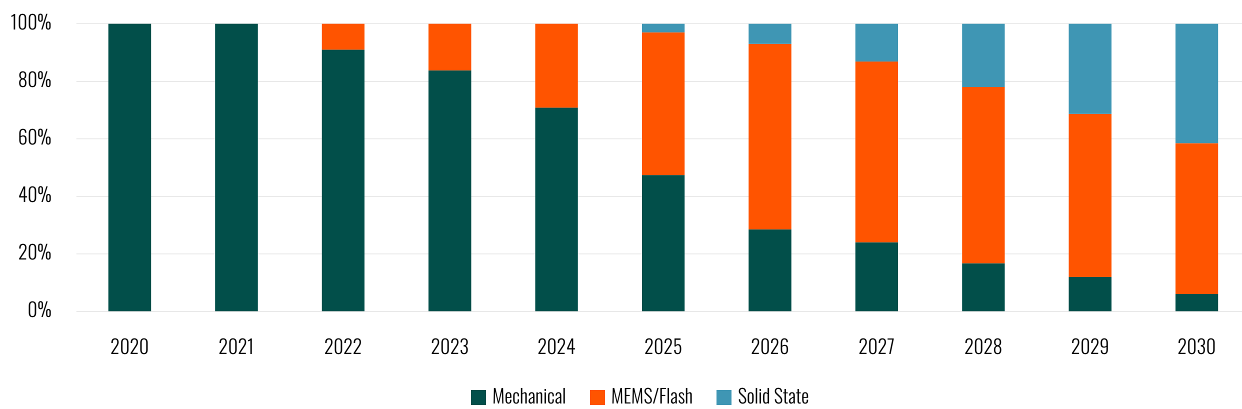


Chart 11: Relative Shares of Shipments of the Various LiDAR Technologies in Automotive
World Markets: 2020 to 2030

(Source: ABI Research)



SUMMARY AND CONCLUSIONS

It is now increasingly becoming clear that LiDAR offers features, benefits, and capabilities that are well suited for a broader set of additional uses cases across multiple verticals. In particular, LiDAR's accuracy, long range, privacy preservation, redundancy, and robust operation in adverse conditions, makes it a desirable and, in many cases, a must-have sensor to add to systems and solutions. High-profile opportunities include traffic monitoring and management, people flow management at airports, and other types of microcities, surveillance, intrusion detection, border control, and warehouse and supply chain automation across the industrial, smart city, and security markets.

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