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The LiDAR opportunity

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Executive summary

We take a deep-dive look at LiDAR, a sensing technology used to unlock advanced safety and autonomous driving capabilities, as well as for various non-automotive applications.

Light detection and ranging, or LiDAR for short, is a sensing method that uses laser light pulses to illuminate a scene and then calculates the time it takes for reflected light to return to the LiDAR device. In doing so, LiDAR can determine the distance of objects, image objects, and ultimately create a high-resolution 3D "point cloud" (data point rendering) of a physical setting; this point cloud is readable by computer software to perceive the surroundings within the view of the scanner.

Why the focus on LiDAR? Simply, while commercially nascent today, we see a large market opportunity emerging for LiDAR over the coming decade. LiDAR has generated significant interest in the automotive/mobility industry. Amid the rise of more advanced forms of vehicle safety and with the early commercialization of autonomous driving expected in the coming years, LiDAR has seen increased attention, as it is viewed as an enabler of these functionalities. Moreover, there is also a large market emerging for LiDAR outside of the automotive/mobility industry, with use cases in various end markets.

Yet for all the excitement that has emerged around LiDAR, we find there has been a lot of noise – it is frequently difficult to distill a clear consensus on the opportunity, product specifications, and technical landscape.

Our key take-away – while there are a wide set of risks ahead for LiDAR and appropriate expectations must be maintained, we nevertheless see a clear market opportunity.

Technical overview

A key task in evaluating the LiDAR landscape is understanding the technical dynamics. LiDAR companies offer products competing on a wide variety of metrics, and it is very easy to get lost when assessing the different approaches. Our hope is to show you that LiDAR can be understood even without a Ph.D. in silicon photonics!

The competitive landscape in the LiDAR industry is wide, and with companies offering different products, we see it as worthwhile to provide an overview on the various metrics differentiating LiDAR products. Specifically, we see two key ways to categorize the different LiDAR approaches:

- **Architectural choices:** LiDAR companies have a number of different architectural choices, with these combinations of choices and the underlying technologies determining the performance of their products. The differing architectural choices include:
  - **Wavelength** – the wavelength of light output emitted from a device, most typically 905nm vs. 1550nm on the spectrum of light waves;
  - **Continuity of light** – the continuity of light emitted, most notably the choice of Time of Flight (ToF) vs. Frequency Modulated Continuous Wave (FMCW);
  - **Scanning device** – the way in which the laser is emitted, with key choices including mechanical, microelectromechanical systems (MEMS), flash, and optical phased array (OPA); and
  - **Hardware** – the underlying components within the device, most notably the choice of silicon vs. other exotic photo-optical materials (i.e., indium gallium arsenide [InGaAs]) in the detector.

- **Specs:** The architectural choices above ultimately inform a LiDAR product's performance, which is measured in a variety of different metrics, including range, resolution, field of view, frame rate, and power consumption.

While it is easy to get lost in the many different metrics and architectural approaches, we would argue that in sum, there is no one ideal approach. Rather, different approaches offer differing functionalities – critical as there are differing use cases in the LiDAR industry with a variety of performance needs.

Market dynamics

We see a large growth path ahead for LiDAR, with opportunities in both the automotive/mobility market and the non-mobility markets, i.e., industrial, Internet of Things (IoT), smart cities, and even consumer electronics (Indeed, Apple's iPhones today use a LiDAR).

While LiDAR is mostly commercially nascent today, we forecast a ~$20bn TAM for LiDAR in mobility by 2030 (implying 67% CAGR) and a ~$19bn TAM for LiDAR in other end markets by 2030 (implying a 29% CAGR).

As it relates to the automotive/mobility industry, while there is clear opportunity for LiDAR in autonomous driving applications (which should see early forms of commercialization in the coming years), we believe the larger opportunity for LiDAR in the automotive industry is in the more scalable/high-volume advanced safety and highway autopilot use cases, where we expect inflection in the coming years.

While different LiDAR use cases may require different capabilities (whether in mobility or outside of mobility), we nevertheless note the flywheel effects created by the growth of either area unlocking economies of scale in manufacturing for the industry as a whole.

Yet to unlock a larger TAM, LiDAR must see significant cost improvements, which would enable opportunities at lower price points. We appreciate that different LiDAR applications will carry different price points and cost curves, yet what is broadly clear across LiDAR today is that LiDAR is prohibitively expensive, and cost must decline. More specifically, LiDAR average selling prices (ASPs) in the mobility industry today are in the thousands of dollars, yet we believe that a significant market size will only be unlocked when LiDAR can be available in the low/mid–hundred-dollar range.

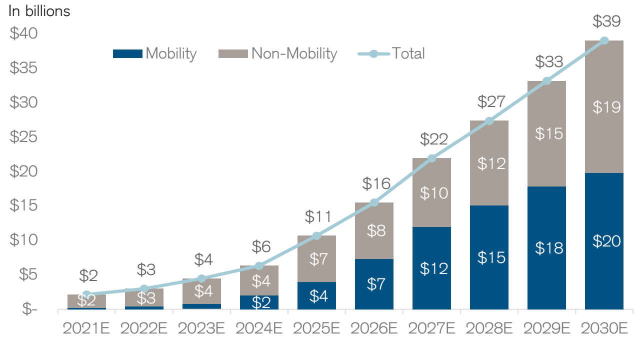
Competitive landscape

While we see a clear market opportunity ahead for LiDAR, the competitive landscape is wide. There has already been some consolidation among LiDAR companies, but we believe more is necessary. That said, with different use cases for LiDAR requiring different technical capabilities and price points, we see multiple opportunities emerging, as opposed to a winner-take-all market; however, there may be more of a competitive moat in the highway autonomy capability vs. the lower end of the market, which may be more commoditized.

Moreover, in the automotive arena, other sensors (most notably radar and camera) should be viewed as competition. Indeed, while many believe that LiDAR, radar, and camera will all be necessary in advanced safety/highway autopilot applications, and certainly in autonomous driving applications, what is unclear is the sensor configuration (i.e., the number of LiDARs, radars, and cameras).

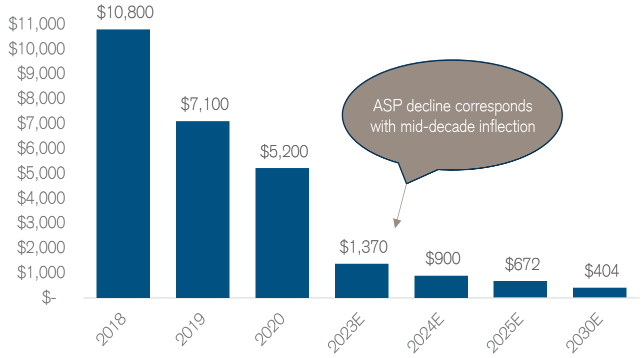
Finally, with automakers taking a more proactive approach on their advanced safety and autonomous driving capabilities, we believe the automakers themselves should be viewed as competition given the potential for insourcing.

Figure 1: Combined LiDAR TAM through 2030



Source: Company data, Credit Suisse, S&P Global

Figure 2: Mobility LiDAR average selling price weighted-average cost per unit estimates for selected years



Source: Company data, Credit Suisse

“ Wavelength is a critical metric, as it has a number of implications for LiDAR companies.

LiDAR technical overview

What is LiDAR, what does it offer, and what can it be used for?

Light detection and ranging, or LiDAR for short, is a sensing method that uses laser light pulses to illuminate a scene and then calculates the time it takes for reflected light to return to the LiDAR device. In doing so, LiDAR can determine the distance of objects, image objects, and ultimately create high-resolution 3D "point cloud" (data point rendering) of a physical setting; this point cloud is readable by computer software to perceive the surroundings within the view of the scanner.

While LiDAR is perceived as a new technology given the lack of wide commercialization, the concept for LiDAR first emerged ~90 years ago, and the first LiDAR-like system was first developed ~60 years ago. Historically, LiDAR was used for various geo-surveying exercises given its effectiveness in creating maps, but over time LiDAR has expanded its set of applications.

Most relevant to our coverage industry is the commercial usage of LiDAR within modern automotive sensor suites and LiDAR's potential role in enhancing driverless functionality in vehicles. The concept of LiDAR in the auto industry became popularized in the 2005 DARPA Grand Challenge, a US competition for autonomous vehicles, in which the winning vehicle incorporated LiDAR. Since then, the use of LiDAR in automotive applications has expanded, and with driver assist/driverless functionality increasingly being introduced in vehicles, a case has emerged for LiDAR to be more widely adopted by the automotive industry.

Moreover, LiDAR can also be used for various applications in smart cities, infrastructure, warehousing, shipping, other industrial end markets, and consumer/health; additional use cases can enhance the economics and create better scale.

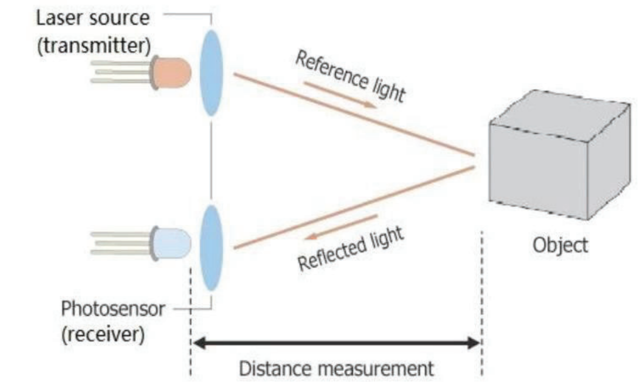
In the sections ahead, we outline the technical specs, market size, and competitive landscape in the LiDAR industry to provide a clearer picture to investors.

Figure 3: Basic features/benefits of LiDAR

Key benefits of LiDAR
- Enhanced object detection & recognition
- Point map rendering to enable perception
- High resolution & accuracy in depth perception
- Robust in low-light conditions

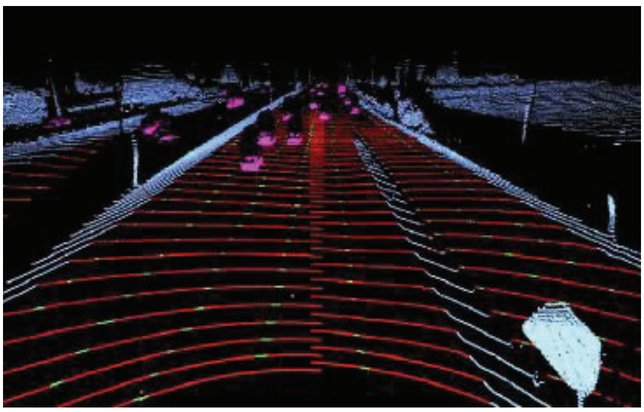
Source: Company data, Credit Suisse

Figure 4: Typical LiDAR transceiver module (Time of flight LiDAR)



Source: Hamamatsu

Figure 5: LiDAR point cloud rendering



Source: Luminar

Key metrics in evaluating LiDAR – you too can understand LiDAR without a Ph.D. in silicon photonics!

A key task in evaluating the LiDAR landscape is understanding the technical dynamics. LiDAR companies offer products competing on a wide variety of metrics, and it is very easy to get lost when assessing the different approaches. Our hope is to show you that LiDAR can be understood even without a Ph.D. in silicon photonics!

The competitive landscape in the LiDAR industry is wide, and with companies offering different products, we see it as worthwhile to provide an overview on the various metrics differentiating LiDAR products. Specifically, we see two key ways to categorize the different LiDAR approaches:

- **Architectural choices:** LiDAR companies have a number of different architectural choices, with these combinations of choices and the underlying technologies determining the performance of their products. The differing architectural choices include:
  - **Wavelength** – the wavelength of light output emitted from a device, most typically 905nm vs. 1550nm on the spectrum of light waves;
  - **Continuity of light** – the continuity of light emitted, most notably the choice of Time of Flight (ToF) vs. Frequency Modulated Continuous Wave (FMCW);
  - **Scanning device** – the way in which the laser is emitted, with key choices including mechanical, MEMS, flash, and OPA; and
  - **Hardware** – the underlying components within the device, most notably the choice of silicon vs. other exotic photo-optical materials (i.e., InGaAs) in the detector.
- **Specs:** The architectural choices above ultimately inform a LiDAR product's performance, which is measured in a variety of different metrics, including range, resolution, field of view, frame rate, and power consumption.

While it is easy to get lost in the many different metrics and architectural approaches, we would argue that in sum, there is no one ideal approach. Rather, different approaches offer differing functionalities – critical as there are differing use cases in the LiDAR industry with a variety of performance needs.

LiDAR architectural approaches

Wavelength

One of the central architectural choices in a LiDAR device is wavelength – or the wavelength of the light output from a LiDAR device. Wavelength is measured in nanometers (nm) and is typically 905nm or 1550nm, with a larger wavelength reflecting greater power.

Wavelength is a critical metric, as it has a number of implications for LiDAR companies, especially as most companies typically choose one wavelength across all offerings. Specifically, wavelength determines the photo-optical material needs for the receiver/detector, which partially drives the build-out of the required supply chain, reinforcing the stickiness of the wavelength decision.

Wavelength choice has several key implications:

- **Range/resolution:** Generally LiDAR at a higher wavelength emits more photons/uses more power as it is beyond the visible spectrum and thus not a risk to eye safety. With more photons emitted, generally better range and resolution can be achieved – key metrics in automotive applications. However, we note this relationship is not linear, as some LiDAR companies using lower wavelengths are still able to achieve higher range by relying on other architectural choices, such as the scanning approach or frequency.
- **Cost:** Generally, lower wavelength implies lower cost. 905nm has been the standard LiDAR choice, largely due to technology/component availability and lower associated costs. Specifically, 905nm LiDAR can use silicon detectors, which is a fairly economical technology and can enable an easier path to scale. Conversely, given silicon cannot respond to higher wavelengths, 1550nm must instead rely on more exotic/expensive materials for detectors, such as

Figure 6: LiDAR approach fit by end use

End use	What factors are key?	LiDAR approach that best fits use case needs
Mobility (forward-facing)	Range, Resolution, Durability	ToF Scanning, FMCW
Mobility (side-facing)	Resolution, Field of View, Cost	ToF Scanning, FMCW
Industrial	Resolution, Durability, Cost	FMCW, OPA
IoT	Field of View, Connectivity, Cost	OPA

Source: Credit Suisse

Ge (germanium), InGaAs (indium gallium arsenide), or InGaAsP (indium gallium arsenide phosphide). LiDAR companies utilizing Ge, InGaAs, or InGaAsP materials in their detectors may face a distinct cost disadvantage if they cannot obtain a reliable source for these inputs at a favorable rate as well as added potential supply risk.

- **Safety:** Generally, higher wavelengths are safer. The question on safety specifically relates to risks to the human eye. Because 905nm wavelengths fall within the visible light spectrum, these light waves can risk damage to the human eye once beyond a specific power level. However, 1550nm waves are above the light wavelength absorbed by the human eye and, therefore, pose no eye-safety risk regardless of the power level used. This allows 1550nm wavelength LiDAR devices to use power levels substantially higher than 905nm wavelength devices, allowing for greater range and resolution capability without causing safety concerns.

As to the question of the "ideal" wavelength, it is important to stress that different architectural choices will support different applications – i.e., as noted below, given both short- and long-range applications, there may be a need for both shorter- and longer-wavelength LiDAR devices. That said, for now longer wavelengths may have the lead in becoming a standard for automotive/mobility LiDAR given their longer-range capabilities – albeit assuming reliable and affordable supply of detector components at commercial scale.

While in the future LiDAR companies may eventually offer distinct products with different wavelength outputs, the participants within the industry currently tend to pick a preferred wavelength technology to leverage across their product offerings. Moreover, given the likely challenge in shifting architectures, it reinforces the notion that LiDAR companies have chosen the "right architecture/wavelength," creating both downside risk and upside potential if one approach proves to be the superior choice.

Scanning device

Also critical to distinguishing between LiDAR options is the scanning device, which is the component in a LiDAR system that directs/steers the laser beam toward the target perception object. Current scanning device approaches used within LiDAR systems include mechanical, MEMS, flash, and OPA.

- **Mechanical scanning** devices utilize tilted mirrors and/or rotation of the full scanning unit to steer the laser beam toward target perception areas. Mechanical scanning devices include those that perform complete surround spinning, appearing as the familiar dome-shaped LiDAR device on some robotaxis and are the original Time of Flight LiDAR scanning device approach. Additionally, mechanical scanning devices include those utilizing mirrors that rotate slightly, changing directions back and forth but not completely spinning.
- **Flash LiDAR** devices are a form of solid-state LiDAR that do not steer the laser beam but rather illuminate the entire measurable scene with the laser, then capture the return signal. Yet this approach struggles with range limitations, which constrains its usage in automotive realms to lower speeds and dense urban areas.

Mechanical scanning and flash LiDARs represent the more developed LiDAR scanning device methodologies, with mechanical scanning having proven to be the approach more appropriate for automotive LiDAR uses and flash scanning seeing more implementation in other LiDAR use cases.

Yet as technology progresses, solid-state scanning LiDAR (beyond flash scanning) has gained popularity in automotive/mobility LiDAR uses due to the removal of moving parts, which reduces the risk of failure and can increase the LiDAR device's ability to withstand harsh conditions while driving, such as temperature, bumpy roads, or humidity. Additionally, the simplification of the physical device into a solid-state without moving parts creates inherent cost benefits vs. mechanical scanning LiDAR. There are two approaches to solid-state scanning LiDAR — MEMS and OPA.

- **MEMS (Microelectromechanical Systems) scanning mirrors** are an increasingly popular approach expected to be key in driving cost reductions in LiDAR devices. While technically still scanning, MEMS LiDAR uses beam-steering mirrors in a miniaturized form, more suitable to harsh environments seen while driving. MEMS scanning mirrors are the most common approach within the trend toward solid-state LiDAR, representing a sort of mid-point between legacy mechanical mirror scanning and future solid-state designs.

Figure 7: Comparison of performance across scanning device methodologies

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/L
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

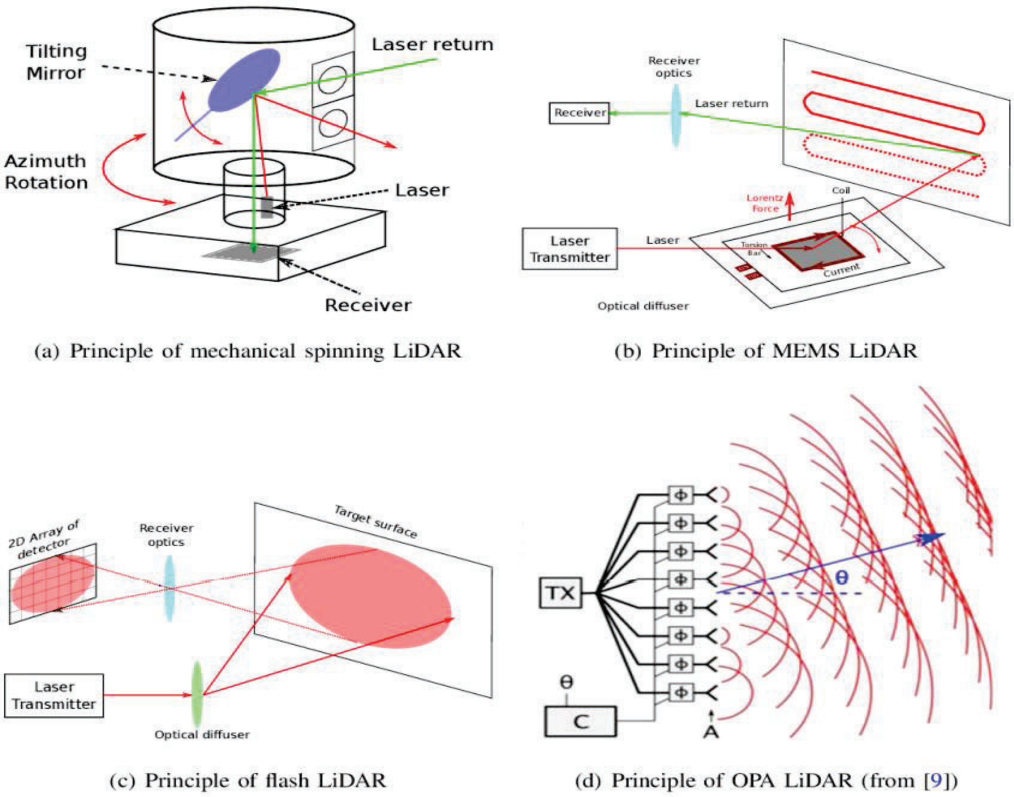
Source: ABI Research, Demystifying LiDAR: IoT and Automotive Applications, Industries, and Business Models, QTR 4 2021

Note: L=Low, M=Medium, H=High

- **OPA (Optical Phased Array) devices** use a series of phase modulators to electronically steer the laser beam in the different directions needed. OPA LiDARs are truly without moving parts and considered by some to be the ultimate goal of solid-state LiDAR. However, as of today, OPA is less technologically mature than other approaches and limited in development for commercial automotive LiDAR purposes.

Both MEMS and OPA are increasingly relevant in mobility LiDAR and may well prove to be the next standard. However, given the lack of substantial movement in the scanner to unlock width and height for the sensors, solid-state LiDAR devices are more limited in field of view and will likely require multiple scanners to achieve the appropriate perception capabilities needed in AVs.

Figure 8: Basic system designs by LiDAR methodology



Source: ABI Research, Demystifying LiDAR: IoT and Automotive Applications, Industries, and Business Models, QTR 4 2021

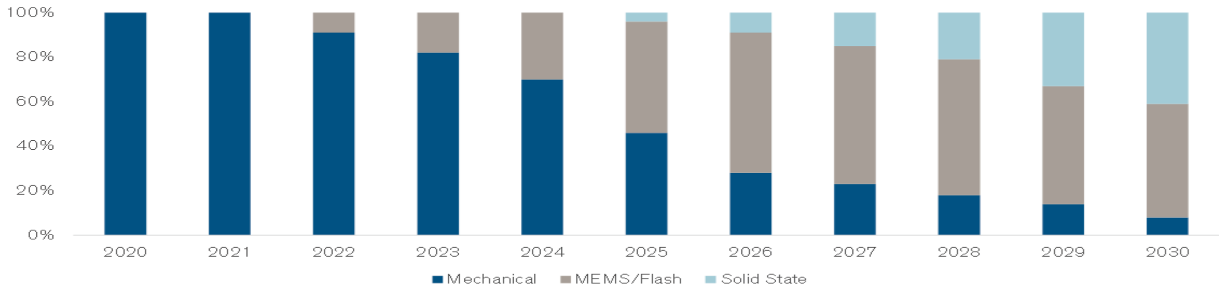
Figure 9: Approaches to scanning device methodology across the industry

Company	Aeva	Aeye	Innoviz	Luminar	Ouster	Velodyne
Scanning Methodology	FMCW MEMS	TOF MEMS	TOF MEMS	TOF Scanning Mirrors	TOF Digital Scanning and Flash	TOF Scanning and MEMS

Source: Company data

Note: TOF = Time of Flight

Figure 10: Scanning device methodology mix estimates



Source: ABI Research, Demystifying LiDAR: IoT And Automotive Applications, Industries, And Business Models, QTR 4 2021

Time of Flight vs. FMCW

Another architectural debate in LiDAR is Time of Flight vs. FMCW, with the debate between approaches centering on the continuity of light emitted.

Time of Flight LiDAR uses a series of high-power laser pulses in short time intervals. It is generally viewed as the more technologically mature approach and is the more favored approach among LiDAR companies today.

Conversely, FMCW LiDAR emits a lower-power continuous stream of light.

Advantages of FMCW LiDAR over Time of Flight include:

- **Instant velocity:** By using a continuous stream of light, FMCW is able to measure velocity – a fourth dimension, beyond the traditional three dimensions measured by LiDAR – thus making FMCW known as 4D LiDAR (as opposed to Time of Flight LiDAR, which is only 3D). The ability to measure velocity is helpful, as it provides a LiDAR system with better perception/detection capabilities (i.e., by detecting an object moving at a high speed, a LiDAR system can better understand its surroundings/plan appropriate driving behavior).
- **Better range:** FMCW LiDAR is viewed to be up to 100x more sensitive than Time of Flight[1], meaning that FMCW can detect very small amounts of light. Because FMCW is more sensitive, it can boost range and also enable sensing objects with low reflectivity (i.e., dark objects).
- **Free of interference:** FMCW is generally viewed to be free from interference/less static, such as from sunlight or other LiDAR pulses.
- **Scalability:** Long term, FMCW has a significant opportunity as a commercial solution given the ability to scale. Specifically, FMCW can use silicon photonics, in which all the photonics components for the LiDAR (i.e., laser, receiver, lens) are on a single chip. With FMCW leveraging photonics advancements from other industries and given the inherent scalability in chip manufacturing, there is a key opportunity for FMCW to scale.

We have seen key validation of FMCW, as seen in development by industry players. Nevertheless, Time of Flight currently remains the dominant approach, used by ~80% of LiDAR companies operating today, most likely due to technological maturity as well as some outstanding questions regarding performance capabilities as the technology exists today.

- **FMCW LiDAR potential has mixed reviews per industry participants:** Despite its advantages, there are critiques of FMCW, of which we find a whitepaper from LiDAR company Aeye[2] (who uses Time of Flight) providing a comprehensive summary:
  - FMCW can measure velocity simultaneously only when viewing moving objects head on (radially), not laterally. This reduces some of the benefit in functionality for FMCW's simultaneous measuring of velocity given many safety situations involve lateral movement.
  - Time of Flight can measure velocity using multiple agile scans, which makes the simultaneous velocity measurement advantage of FMCW less significant when compared to high-end Time of Flight LiDARs.
  - Processing of FMCW signals requires more disambiguation than more straightforward Time of Flight signals.
  - Certain components of FMCW LiDAR systems end up adding costs beyond what are required in Time of Flight LiDAR systems.
  - Technical gains from FMCW over Time of Flight are not robust enough to offset the supply chain and technology maturity/development advantage that Time of Flight LiDAR possesses over FMCW.

Hardware architecture

Choices on scanning and wavelength approaches discussed above have a key influence on the design of the hardware used in a LiDAR system, which underpins the primary value-add opportunity for LiDAR companies. At the most basic level, the hardware-defined architecture of a LiDAR system includes a laser emitter, a receiver/detector, and a processor, all of which play a role in both the performance of the LiDAR as well as its cost. This makes hardware architecture critical, as we see the appropriate balance of the two as a key determinate of success or failure in the industry.

Figure 11: Time of Flight vs. FMCW Comparison

Approaches to LiDAR Technology	Time of Flight LiDAR	Coherent Frequency Modulated Continuous Wave LiDAR
Measurements	(3D) Range, Azimuth, Elevation	(4D) Range, Azimuth, Elevation, Velocity
Maturity of Technology	*Medium to High*	*Low*

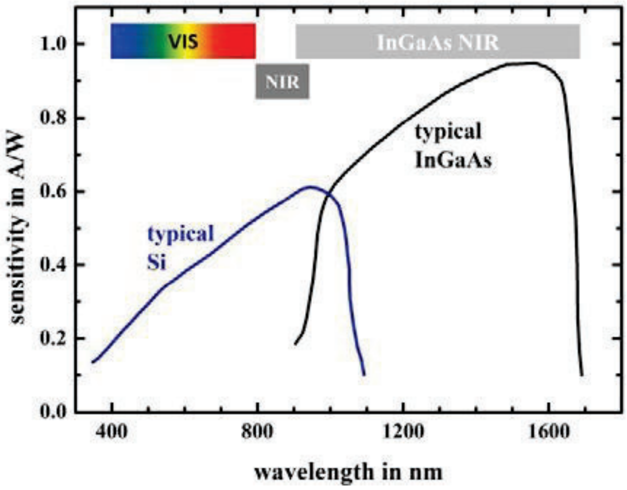
Source: Intel

[1] Smolka, Greg. "FMCW Lidar Seeks Fortune in the Autonomous Vehicle Market." *LiDAR Magazine,* 1/12/2021

[2] "Time of Flight vs. FMCW LiDAR" Aeye Technology Paper, 2021

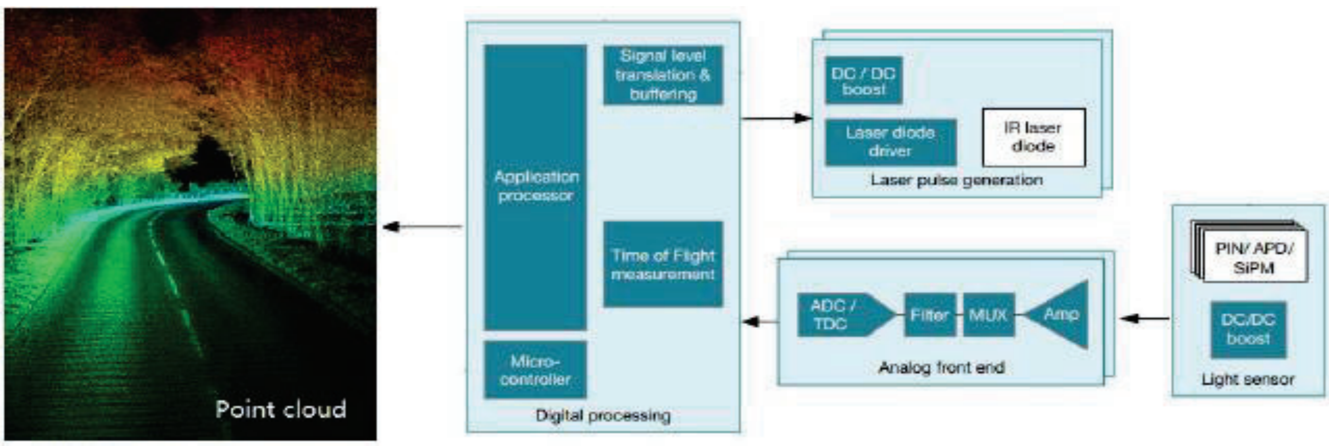
- **Laser device architectures vary among LiDAR offerings** and, while clearly critical within the system, are determined more so by the hardware choices within the rest of the system as well as the wavelength and scanning devices used. Therefore, the laser emitter component of the LiDAR hardware stack sees relatively little attention in discussion among the industry competitors. Yet there is still a range of laser architectures seen in the industry. For example, some LiDAR systems can operate with just one laser, while others may include an array of lasers, again determined by other design choices.
- **Photo-optical detector material** represents the most notable difference in hardware variations among LiDAR companies and is directly linked to wavelength choice. As discussed above, 905nm wavelength is within the range of detection by silicon photo-optical material, which is much more economical to use in the detector component technology of a LiDAR system than the more exotic photo-optical materials such as Ge, InGaAs, or InGaAsP used in the detectors of most 1550nm LiDAR systems.
- **Silicon materials unlock semiconductor-based approach:** The cost advantage enjoyed by silicon photonics over detectors leveraging exotic materials is driven by the ability of silicon-based approaches to leverage inputs, approaches, and learnings from the well-developed semiconductor industry. Further, this enables the entire hardware stack (including the processing chip, scanner/laser, and silicon detector chip) to be manufactured via the semiconductor process.
- **Vertical integration serves as an opportunity to de-risk use of less-prevalent materials:** Exotic photo-optical material LiDAR detectors start at a clear disadvantage in terms of cost and supply chain maturity/security. LiDAR companies using InGaAs, Ge, or InGaAsP materials to allow for 1550nm wavelengths acknowledge this challenge and have taken steps to de-risk the hardware stack, most notably via vertical integration.

Figure 12: Silicon vs. InGaAs photo-optical material detection performance by wavelength; silicon is more sensitive at shorter wavelengths, while InGaAs are more sensitive at longer wavelengths



Source: Vollmer, Michael & Möllmann, Klaus-Peter & Shaw, Joseph. (2015). The optics and physics of near infrared imaging.

Figure 13: LiDAR system diagram: Laser, detector, and processer combine to form point cloud rendering



Source: Texas Instruments

- **Processing chips bring the system together:** The measurements/data obtained from the receiver within the LiDAR system must be read and converted into valuable and actionable information. This takes place within a custom-built application-specific integrated circuit (ASIC), which uses algorithms to process the data (at speeds and richness levels that improve with each ASIC iteration) and then interface with the perception software stack to which the LiDAR remits its findings. Within the industry, the majority of LiDAR companies design and iterate their ASICs in-house, creating yet another form of potential competitive advantage.

Understanding the specifications

There are a number of key specs that LiDAR companies cite in defining the performance and capability of the system, of which the most critical are range, resolution, field of view, power consumption, and frame rate.

Range

Given the primary investor focus on LiDAR has been on automotive/mobility applications, it makes sense that the metric of focus for LiDAR is range. Generally, the further out a LiDAR device can accurately detect objects, the better — this is critical, as further range can unlock superior capability for autonomous driving systems to react to obstacles.

The standard suitable range for automotive applications is at least 200 meters at 10% target object reflectivity. The latter point is just as critical, as better reflectivity generally leads to higher data intensity/a better "point cloud". In general, most range measurements are quoted "10% target object reflectivity," given this provides the most reasonable and fair measure for safe detection in driving detection situations, such as pedestrians or cyclists in dark clothing.

Range can be tough to compare apples to apples across LiDAR sensors, and more range is not necessarily always desired. Some LiDAR products will offer a "maximum range," which can be in excess of 500 meters. Yet with object detection effectiveness also a key criteria (i.e., the ability to determine a moving vehicle 500 meters away), it is a reminder that a LiDAR sensor needs to be evaluated on more than just range capability.

Moreover, customers may be seeking different range capabilities for different applications, with this market dynamic prompting some LiDAR companies to offer multiple products with different ranges. For instance, in more advanced autonomous driving applications, in which a vehicle will use multiple LiDAR devices, a front-facing LiDAR (i.e., a LiDAR at the front of the vehicle) will likely require a longer range, especially to support highway driving. However, side-facing LiDARs, which detect objects adjacent to the vehicle, would not require the same range as a front-facing LiDAR focused on functioning in highways speeds. Accordingly, with range requirements varying, there is a need for a range of LiDAR products offering different capabilities, particularly when the opportunity for cost reductions exists.

Range is driven by wavelength as well as other architectural features within a LiDAR device.

Resolution

Resolution is also a critical metric in a LiDAR device, as superior resolution supports better object detection. A LiDAR device must create a sufficiently detailed resolution over a substantially large field of view to allow for proper imaging and detection.

Angular resolution is the number of measurements per 1 degree by 1 degree segment (a square degree). The primary standard for automotive-grade LiDAR in this spec is a substantial enough resolution to have no gaps between LiDAR points in the point perception output, with enough points/detail to resolve an object up to the maximum range. The "automotive/tier 1 grade" standard is typically cited as <0.1 degrees, although some systems can offer superior resolution of 0.025 degrees.

Figure 14: Automotive LiDAR standards for key specs

Key Spec	Definition / Measure	Standard for Automotive LiDAR
Range	The distance at which objects can be detected, typically tested on target object with 10% reflectivity, measured in meters (m)	200m @10% Reflectivity
Angular resolution	The number of measurements perceived by a LiDAR in a 1°x1° segment (sq. degree, °), which determines the point cloud map	<0.1°
Field of view	The horizontal and vertical range of the LiDAR scan, as emitted from the laser/scanner, measured in degrees	~100° x ~35°
Frame rate	The number of point maps captured by a LiDAR system per second, measured in frames-per-second (fps) and/or hertz (Hz)	10 to 30 Hz
Power consumption	The power required to operate a LiDAR device safely and reliably, measured in watts (w)	10 to 25 w

Source: Company data, Credit Suisse

Opportunity exists to distinguish a LiDAR device by increasing the resolution capabilities and point perception output, especially critical in uses for LiDAR requiring extreme precision, such as industrial metrology. Likewise, some cost savings could be achieved for LiDAR situations not requiring exceptionally precise results.

Resolution capability is also one of the distinguishing features of some of the scanning methodology approaches, which will likely be weighed directly against price points to determine which technical approach is the appropriate one for each LiDAR use case, especially those in which range capabilities are less important.

Field of view

Field of view is the vertical and horizontal range of the LiDAR scan, measured in degrees, as emitted from the laser/scanner. Field of view needs are dependent on the use case for the LiDAR device, with the standard for "automotive-grade" LiDAR being around/over ~100 (width) x ~35 (height) degrees.

A comprehensive example of the resolution and field of view would go as follows. For a LiDAR device with a 40-degree vertical and 120-degree horizontal field of view, and 0.1 x 0.1 degree angular resolution, the resulting point map would have 400 points vertically by 1,200 points horizontally, for a total of 480,000 data points per scan. Field–of-view demands from the original equipment manufacturers (OEMs) will be very dependent on the function of the LiDAR within the vehicle, as well as the vehicle's level of autonomy.

Field of view will also be influenced by scanning methodology, as mechanical LiDAR systems offer 360-degree rotation, unlocking substantially more measurement space than a solid-state LiDAR.

Frame rate

Frame rate measures the number of point maps captured by a LiDAR system per second. Frame rate is a key metric, as a LiDAR device must offer a fast enough frame rate. A sufficiently high frame rate enables more real-time visualization of a scene and can support faster decisions made in an automotive application. Modern LiDAR systems operate between 10 fps and 30 fps (frames-per-second) or Hz (hertz), and while most sensors currently run at 10 Hz/fps, a frame rate of >20 Hz/fps is typically desired. For context, the general consensus among researchers is that the human eye can perceive between 30 fps and 60 fps, and that most professionally produced movies are shot on film at a rate of 24 fps[3].

Frame rate is another area in which the opportunity to differentiate a LiDAR system exists, as a greater frames-per-second rate would offer enhanced data intake and corresponding perception capabilities, particularly key in high-speed situations such as highway autonomous driving.

Power consumption

Power consumption measures the power required to operate a LiDAR device safely and reliably and is typically measured in watts. Power consumption can be a limiting factor on higher-performance systems, particularly those operating at higher wavelengths.

The power consumption of the LiDAR systems currently offered in the marketplace vary substantially but will likely play a role in the selection process of OEMs when deciding which LiDAR system will integrate best into the expanding sensor suites of their vehicles. Of the flagship LiDAR products offered in the industry, most operate in a 10- to 25-watt range, with some outliers upward of that range, especially for companies using 1550nm wavelength conventions. For reference, a standard halogen headlight bulb in a vehicle is powered with around 55 watts.

In general, solid-state LiDAR systems, which can remove the scanning mechanisms, offer lower wattage consumption rates.

[3] "How Many Frames Per Second Can the Human Eye See?" *Healthline*, 10/20/2020

> “ LiDAR will be a required sensor for both high-volume vehicles and also for autonomous vehicles.

LiDAR Market Dynamics

While there are many different use cases for LiDAR, we believe the best way to evaluate LiDAR uptake is by separately considering the mobility/automotive and non-mobility end markets (i.e., industrial, IoT, etc.). Indeed, LiDAR use in each market has different performance/spec requirements as well as different pricing/volume dynamics.

While the commercial demand for LiDAR is still rather nascent (~$2bn across all use cases), we see a significant opportunity for uptake in both the mobility and non-mobility markets. We forecast a ~$20bn TAM for LiDAR in mobility by 2030 (implying a 67% CAGR), and a ~$19bn TAM for LiDAR in other end markets by 2030 (implying a 29% CAGR).

As it relates to the automotive/mobility industry, while there is clear opportunity for LiDAR in autonomous driving applications (which should see early forms of commercialization in the coming years), we believe the larger opportunity for LiDAR in the automotive industry is in the more scalable/high-volume advanced safety and highway autopilot use cases, where we expect inflection in the coming years.

While different LiDAR use cases may require different capabilities (whether in mobility or outside of mobility), we nevertheless note the flywheel effects created by the growth of either area unlocking economies of scale in manufacturing for the industry as a whole.

Yet to unlock a larger TAM, LiDAR must see significant cost improvements, which would enable opportunities at lower price points.

LiDAR in mobility

Perhaps the market where LiDAR has received the most attention is in the mobility/automotive market. Not only is LiDAR viewed as a critical sensor for advanced autonomous driving applications, but there is also a significant opportunity for LiDAR in relatively simpler driver assist functions.

Commercial demand for LiDAR in mobility is still nascent – we estimate it was only a ~$200mn market in 2021. However, given the development of LiDAR/reduction in cost, alongside increased demand for advanced driver assist features and the future opportunity for autonomous driving systems, we see an opportunity ahead for LiDAR to reach ~$20bn by 2030. Yet to unlock that TAM, LiDAR costs will need to meaningfully decline.

First, a reminder on why LiDAR is relevant for the mobility market

To understand the opportunity for LiDAR in the mobility market, it is important to understand why LiDAR will be a required sensor for both high-volume vehicles and also for autonomous vehicles.

LiDAR as part of the active safety sensor suite

Essentially all new vehicles produced in developed markets have sensors. From the most basic active safety features all the way up to the highest functioning autonomous driving capabilities, sensors provide the perception capabilities underlying these features, essentially acting as the eyes of the vehicle. LiDAR fits into this sensor stack by offering different perception capabilities than the other primary sensors in vehicles – cameras and radars.

Mass-produced vehicles today almost exclusively use cameras and radars (and to some extent, ultrasonic sensors) as their primary sensors for safety systems given the maturity of these sensors. Conversely, given LiDAR demand is still nascent in the mobility business, it is only included in a handful of mass-produced models today (i.e., Mercedes S-Class, XPeng, and NIO). However, as safety systems for mass-produced vehicles become more sophisticated with greater functionality (i.e., highway autopilot) and thus requiring greater sensor capability and redundancies, many see a need for LiDAR to be included more widely as one of the sensors in the stack.

Indeed, LiDAR offers unique spatial detection, allowing rapid measurement and understanding by an on-board computer at levels of resolution not achievable by radar technology. Likewise, LiDAR can add to the perception achieved via camera-only by elevating the sensor stack's functioning in more levels of light and deciphering an image by creating a point map of it with considerations for depth. The combination of sensors (LiDAR, radar, and camera) within the vehicle to achieve elevated perception capabilities and safety-critical redundancies is known as "sensor fusion."

LiDAR in autonomous vehicles

Moreover, in addition to the opportunity as part of the safety sensor suite, there is also an opportunity for LiDAR within autonomous vehicles (i.e., Level 4 and Level 5 capabilities).

As autonomous vehicles for now are expected to be owned and operated by fleets given the prohibitive costs, the volumes will be less than consumer-owned vehicles. Accordingly, the larger opportunity for LiDAR is likely in high-volume vehicles for consumers with increased safety capabilities.

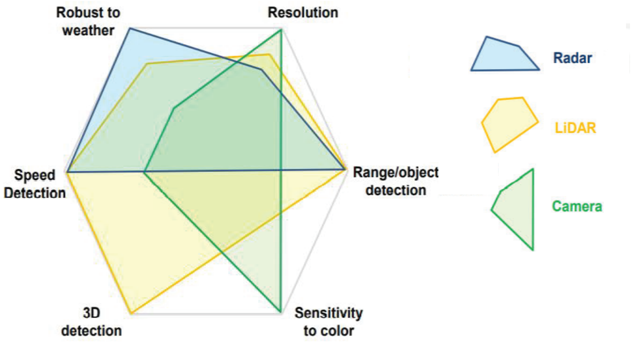
Nevertheless, given the view by most that LiDAR is a necessity in vehicles with little or no human operation and given the view that multiple LiDAR sensors will be necessary in these vehicles to provide complete coverage of surroundings, we believe there is a clear opportunity for LiDAR in autonomous vehicles as well. Moreover, given the use of high-definition (HD) maps in operating autonomous vehicles and the need to maintain these maps, LiDAR is an ideal sensor in maintaining detailed HD maps.

Figure 15: Sensor comparison description

Sensor	Benefits	Challenges
Camera	- Object detection & recognition - Read traffic signs - Perceive color - Cost-acceptable - Wide industry experience	- Indirect distance/velocity measurement - Less effective with bad weather - Poor performance in high-glare - Poor performance in low-light - Dependent on light sources
Infrared	- Object detection & recognition - Robust performance in low-light - Some industry experience - FIR no light source needed	- Similar challenges as camera - Limited industry experience - NIR additional light source needed - Relatively high-cost
Radar	- Direct distance & velocity measurement - Robust in bad weather - Robust in low-light - Cost-acceptable - Wide industry experience	- Cannot read signs - Cannot perceive color - Cannot recognize objects - Difficulty tracking large numbers of objects at high accuracy & resolution
LiDAR	- High resolution and accuracy in depth perception - Robust in low-light - Direct velocity measurement with FMCW sensors	- Less effective in bad weather - Eye safety concerns - Consistent detection of low-reflectivity objects at distance - High cost and uncertain declines - Low industry experience
Ultrasound	- Direct distance measurement - Motion detection - Cost-acceptable - Wide industry experience	- Very short range operation - Low resolution detection - Limited angular coverage

Source: S&P Global

Figure 16: AV sensor suite performance comparison



Source: Hamamatsu

Figure 17: Pedestrian avoidance test

Source: Luminar

Outlining the path of AV uptake

With the use case established for LiDAR in the different levels of safety/autonomous functionality, we now highlight our views of AV uptake. While difficult to find consistent classifications, we think it necessary to lay out definitions of AV functionality, as functionality levels are critical to LiDAR use demands.

LiDAR in L2 is limited, but opportunity exists in L3

We define any vehicles with L2 or less functionality as base active safety (i.e., adaptive cruise control, autonomous emergency braking). We don't see much opportunity for LiDAR in this market given the maturity of camera and radar sensors as well as cost limitations created by less expensive overall systems.

Yet LiDAR has an opportunity in what is more formally known as L3 or even what some refer to as L2+, which offers basic autopilot functionality; we believe there is opportunity for LiDAR to support this functionality, particularly as systems progress and take more responsibility from the human drivers. L3 (which includes what is popularly known as L2+) currently has limited uptake globally, but we expect L3 functionality to be implemented on ~30% of global volume by 2030, as it follows the typical adoption curve of automotive technologies – initially available only on premium vehicles and then expanded more widely as costs decline. More broadly, we believe L3 uptake will be significant as costs decline, as we expect it to become a key feature widely desired by consumers, given it will change the driving experience.

While we generally expect LiDAR to be adopted on L3 vehicles, we know it won't be included on all such vehicles. Tesla is currently a large operator in autopilot functionality but does not use LiDAR; thus, LiDAR use in the company's vehicles will not necessarily be a given.

Figure 18: Standard autonomous driving levels 0-5 definitions

	L0	L1	L2	L3	L4	L5
Operator	**No Automation**	**Driver Assistance**	**Partial Automation**	**Conditional Automation**	**High Automation**	**Full Automation**
Driver	In charge of all the driving	Must do all the driving, but with some basic help in some situations	Must stay fully alert even when vehicle assumes some basic tasks	Must be always ready to take over within a specified period of time when the self-driving systems are unable to continue	Can be a passenger who, with notice, can take over driving when the self-driving systems are unable to continue	No human driver required-steering wheel optional- everyone can be a passenger in an L5 vehicle
Vehicle	Responds only to inputs from the driver, but can provide warnings about the environment	Can provide basic help, such as automatic emergency braking or lane keep support	Can automatically steer, accelerate, and brake in limited situations	Can take full control over steering, acceleration, and braking under certain conditions	Can assume all driving tasks under nearly all conditions without any driver attention	In charge of all the driving and can operate in all environments without need for human intervention

Source: Industry, Society of Automotive Engineers (SAE); National Highway and Traffic Safety Administration (NHTSA)

Figure 19: Automated state of play – balancing functionality and liability

Automated Driving - Industry Defined Level 2+		Automated Driving - SAE Level 3
Driver always responsible and supervising Not limited by regulation in some countries	**Regulatory**	Driver able to completely disengage when active Regional regulatory limitations
Eyes-on, hands-off, driver ready to intervene Camera, DMS, radar, mapping, GPS information Strategic deployment but growing availability	**Technology**	Eyes-off, hands-off, intervention may be necessary Additional camera + radar, lidar, compute New technology use cases are evolving
50% of 2020 IHS Markit Autonomous Driving Consumer Survey respondents comfortable with functionality Moderate consumer education required	**Consumer**	44% of 2020 IHS Markit Autonomous Driving Consumer Survey respondents comfortable with functionality Significant consumer education required
2016+	**Timeline**	**2021+**

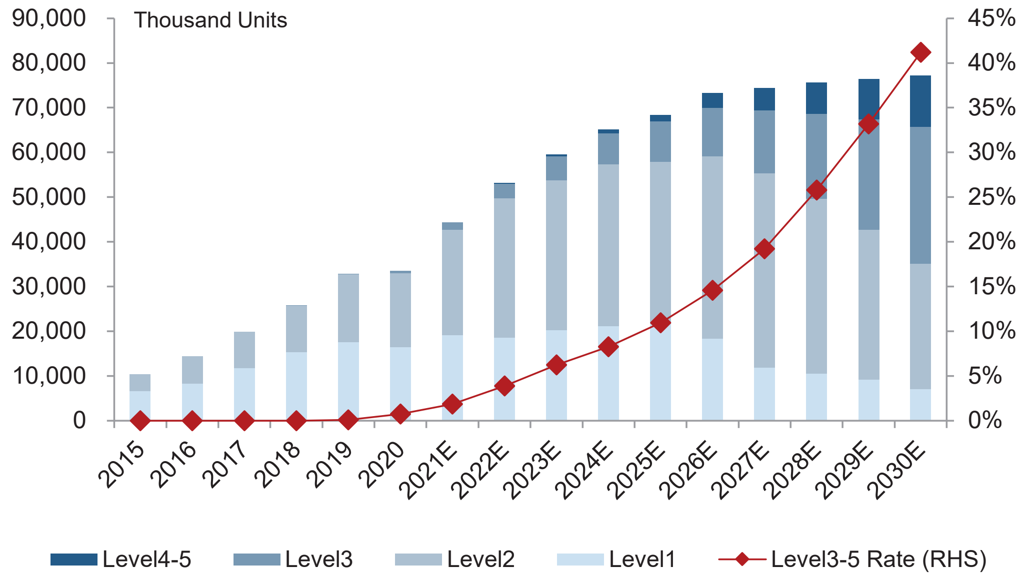
Source: S&P Global

LiDAR in L4 and L5 will likely be critical, but volume ramp will be slower

L4/L5 is a different market, representing what we have come to define as autonomous vehicles and are by and large viewed to be driverless vehicles. The only vehicles produced currently with L4/L5 capability are test vehicles, although in the coming years some OEMs have established plans for purpose-built AVs or retrofits of consumer vehicles.

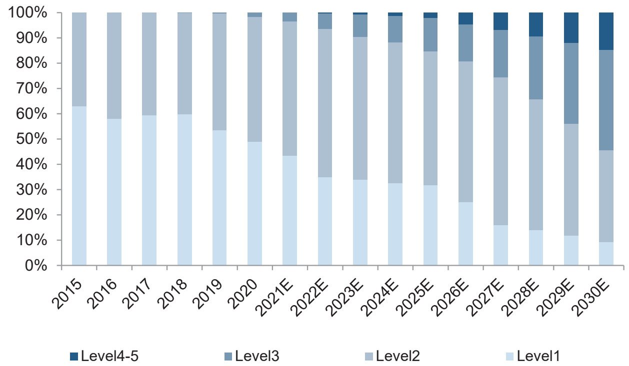
These L4/L5 vehicles are currently only planned for shared autonomous movement of people or goods given the prohibitive costs, and thus will be used in fleets. However, there is likely an opportunity later in the decade for L4 applications in vehicles for purchase by consumers. We believe L4 and L5 penetration can reach ~11% by 2030, with penetration likely to improve as the technology is validated, costs decline, and there is greater regulatory support and acceptance by society.

Figure 20: Estimates of the global autonomous vehicle market through 2030



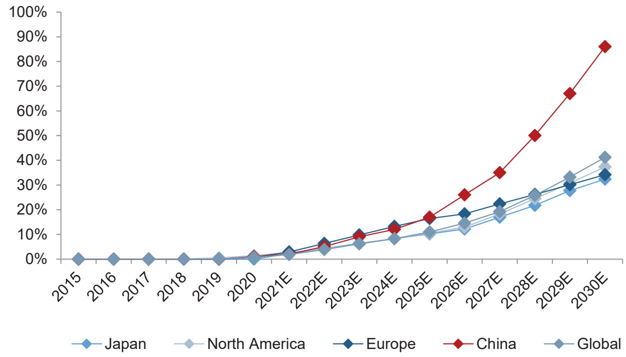
Source: Credit Suisse, S&P Global, Fuji Keizai

Figure 21: Estimates of penetration rates by autonomy level, globally



Source: Credit Suisse, S&P Global, Fuji Keizai

Figure 22: Estimates of L3 and above penetration rates, regionally



Source: Credit Suisse, S&P Global, Fuji Keizai

Sizing the LiDAR opportunities in advanced safety and autonomous applications

Given our views on the timing and uptake of autonomous driving, we now have the basis for sizing the LiDAR market opportunity ahead. In analyzing the LiDAR opportunity for advanced safety vehicles (i.e., L2+/L3 functionality) vs. more advanced autonomous functionality (L4/L5), we believe the primary opportunity ahead for LiDAR is advanced safety applications given the large potential volume, especially within the next decade.

Unpacking the methodology for understanding the LiDAR TAM in mobility

Multiple dynamics for the industry will be at play and interact with one another. Our methodology for sizing LiDAR in each segment requires:

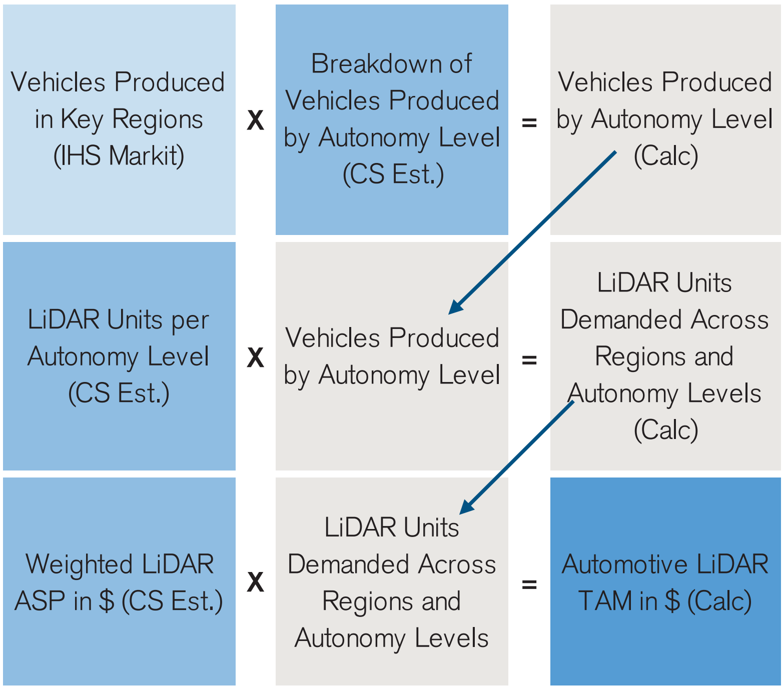
1. Understanding the volume outlook for each level of functionality (discussed in the section above),
2. An assumption on the number of LiDAR sensors per vehicle in each application,
3. Assumptions on ASP at the LiDAR unit level, considering that some LiDAR sensor prices will vary based on use case.

Sensor per vehicle assumptions

As it relates to the number of sensors per vehicle, this will vary significantly based on configurations as well as OEM-specific preferences. However, in general, conclusions can be drawn from the aggregate of OEM commentary, underpinning our views that lay out as follows:

- **L2+/L3:** As noted above, for simplicity, we consolidate L2+/L3 into one forecast, and we assume that over time on average all such vehicles will need one front-facing LiDAR unit. Of course, we appreciate that not all vehicles with such functionality will use LiDAR. However, we expect that over time L3-enabled vehicles on average will use at least one LiDAR, with weight to the latter part of the decade as OEMs will need ample sensor redundancy in L3 vehicles to ensure adequate safety as autonomous functionality expands.
- **L4/L5:** Higher-level autonomy applications are expected to offer multiple LiDAR units, with both front- and side-facing applications. AVs may have five or more LiDAR sensors, providing full 360-degree surroundings and also supporting the building/maintenance of HD maps.

Figure 23: Automotive TAM calculation walk



Source: Credit Suisse

- **L2:** Some have made the case for LiDAR in more basic active safety applications, with LiDAR providing a superior form of object detection and reducing false negatives. Yet we believe given the tight budget for safety content in L2 applications and given the maturity of camera/radar vs. the elevated cost of LiDAR, the likelihood of LiDAR uptake in these applications will be limited.

Price considerations

Lastly, also critical to our TAM calculation are the different ASP considerations.

Prices are currently high. Yet it is important to acknowledge that pricing within the mobility LiDAR industry today is not reflective of future LiDAR prices, which should decline as commercial inflection/scaling starts to emerge. Most LiDAR units sold today related to the automotive industry are for sensors used in autonomous vehicle research or other OEM testing programs, and revenue within the industry is immaterial, despite very high device ASPs. Not only is there now a lack of commercial-scale demand, but the supply chains/manufacturing capabilities must also be developed.

However, the LiDAR devices of the future, which we believe will be necessary in vehicles with L3 and higher safety/autonomous capabilities, should see benefits from scaled production, unlocking substantially lower ASPs.

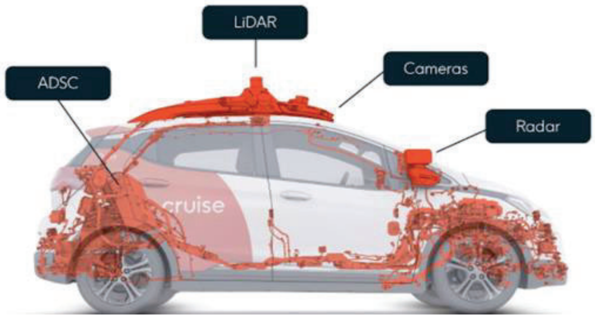
The path to price decline is critical and will depend on a variety of factors, including technological advances, material supply chains, the specifications of the LiDAR use case (i.e., high-end long-range capability vs. short-range, and robotaxi vs. advanced driver-assistance systems (ADAS), and the volume associated with series production agreements.

ASP estimates by LiDAR companies vary, but in general, most near-term ASP estimates range from $1,000 to $2,500, with reductions allowed by scaling. This could drive ASPs down to a mid-term target of ~$500, eventually reaching near commodity-level prices as low as ~$300. As prices decline, it should lead to incremental demand.

Figure 24: Sensing solutions by autonomy level

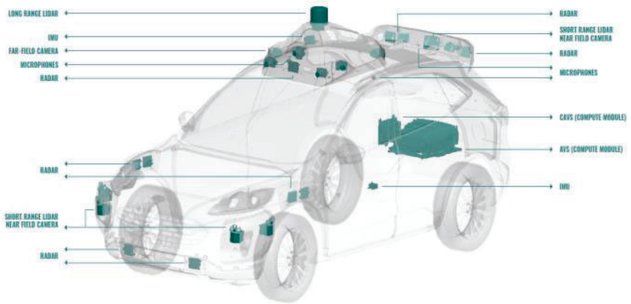
Industry Benchmarks	SAE Level 2	(Industry) Level 2+	SAE Level 3	SAE Level 4
Feature & Functionality	Eyes-on Hands-on Highway assisted driving ACC + Lane Centering	Extended eyes-on Hands-off Highway automated driving ACC + Lane Centering DFM	Eyes-off Hands-off Automated driving ACC + Lane Centering DFM	Mobility-as-a-Service Safety Driver may be needed
Market Examples (and many more not listed)	Toyota Safety Sense 2.0 Honda Sensing Audi Traffic Jam Assist	GM Super Cruise Ford Active Drive Assist Nissan ProPILOT 2.0	Honda Traffic Jam Pilot Mercedes Drive Pilot Volvo Highway Pilot	Cruise Origin Waymo One Ride-Hailing Service
Radar	5	5-7	9	17
Camera	6	7	7	18
LiDAR	0	Optional	1-5	5
Total Vehicle Sensors	**11**	**12-15**	**17-22**	**40**

Figure 25: Cruise sensor configuration (can we retain this?)



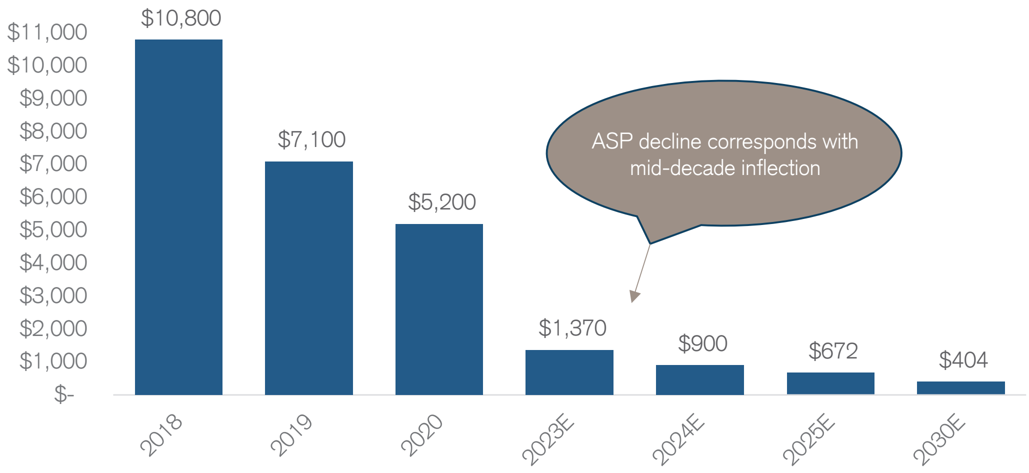
Source: Cruise

Figure 26: Argo sensor configuration (can we retain this?)



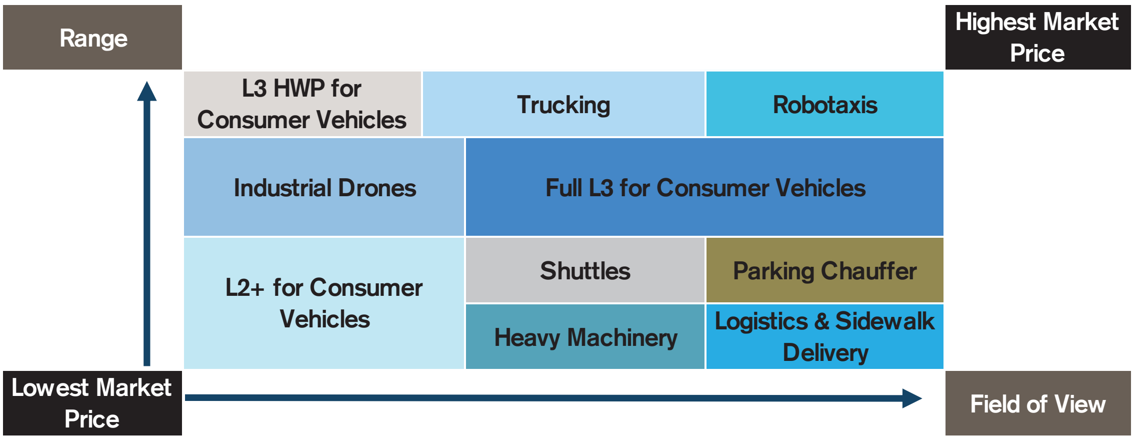
Source: Argo AI

Figure 27: Mobility LiDAR ASP historical weighted-average cost per unit amounts and CS estimates for selected years



Source: Company reports, Credit Suisse estimates

Figure 28: LiDAR requirements and price points by use case



Source: Innoviz

Figure 29: Estimated autonomous vehicle cost

	Cost non-scaled research car	Cost - early scaled ridesharing car	Comments re: cost reduction
LiDAR	$100,000	$35,000	LiDAR cost reduction
GPS System / IMU	65,000	18,000	Change from tactical grade to commercial grade
Radar	10,000	2,000	Research car requires more advanced radar; ridesharing car could see cost reduction in radar
Cameras	4,000	2,000	
Data Storage	30,000	2,000	Research car may require 100 TB harddrive; assume ridesharing car shares data storage infrastructure with other vehicles
Compute	50,000	15,000	Research car may require advanced compute, i.e. Pegasus; ridesharing car could have smaller computer, embedded GPU
Vehicle Controls	80,000	30,000	Need separate by-wire interface for research car; ridesharing car designed to support autonomous vehicle controls
Base vehicle cost	61,000	61,000	
Total	**$400,000**	**$165,000**	

Source: Company data, Credit Suisse

Note: The table above is from our prior published material in 2019. Estimates may have since changed, but it provides a directional sense of the historically high costs of LiDAR within AVs.

Software also plays a role in pricing

Software uptake rates offer a lever in LiDAR pricing, creating potential upside to ASPs. Yet we would view in LiDAR as more of a "show-me" opportunity.

On top of the core LiDAR hardware sales, LiDAR companies have also planned to offer software stacks capable of perception on top of the base hardware and sensing packages. This can create a "sticky" form of software-as-a-service (SaaS) revenue, with the exceptionally high margins known for software-driven business models. Many of the LiDAR start-ups have planned for software add-ons to generate returns on top of pure device hardware sales.

Successful software uptake from customers would certainly expand the potential upside in the revenue and gross margins of the LiDAR start-ups. Yet we are inclined to view the software sales plans as more of a "show-me" opportunity at the moment, considering recently elevated interest by OEMs toward handling more of their own software/compute needs internally.

Other TAM considerations

- **AV trucking:** Autonomous trucking is an AV application that we believe will offer a faster path to commercial scale than passenger robotaxis given a more controlled operating environment with fewer edge cases. Most indications are that LiDAR will remain a key feature on autonomous trucks once commercialization begins in 2023-24 timeframe.
- **Clear divergence in expectations:** In line with the wide range of potential outcomes for the LiDAR industry, a large disconnect exists between the TAM projections of various statistics/market data groups and those of the SPAC decks from the start-up LiDAR companies.

  Of course, some of this gap in expectations is intuitive, given one would not enter the LiDAR business without seeing larger upside for the potential of the space than most others. However, the difference also sets steep challenges for meeting financial targets set out in the SPAC decks and investor presentations should the market not expand to the forecast levels.

To unlock TAM, cost reduction and supply chain/manufacturing improvements are needed

While excitement has built on LiDAR uptake in advanced safety applications, that uptake is predicated on a clear path of cost reduction as well as broader industrialization – ample manufacturing and supply chain capabilities.

Price points are the key to expanding use case demands

Specifically, initial commercialization projects of LiDAR in advanced safety applications are likely to carry elevated dollar content per vehicle (CPV).

A $1,000+ LiDAR ASP on a premium vehicle (which is sold to consumers at elevated price points) is understandable given the large costs that such vehicles can absorb – such vehicles could have a total advanced safety system cost in excess of several thousand dollars. However, for LiDAR to be rolled out more broadly, the ASP will need to come down meaningfully, so that it can fit within the budgets of lower-priced vehicles.

Indeed, for LiDAR to eventually be rolled out more widely and standardized through models, we assume an advanced safety system would need to decline in cost to ~$1,000-2,000. Given LiDAR would be one of several sensors, it likely means LiDAR ASP would potentially need to decline to $300-500. To unlock a LiDAR ASP in the range of $300-500, it would likely require a bill of materials (BoM) of ~$100-150.

To unlock lower-priced LiDAR, cost must decline meaningfully – which would be achieved primarily through scale, manufacturing learnings, and unit-level structural hardware efficiency improvements.

The work on pricing will require support from underlying manufacturing process

In addition to the required cost improvements, the supply chain and manufacturing capabilities must be built out to ensure proper quality, i.e., automotive-grade – reflecting the rigorous sourcing standards used by automakers, as the sensor must be designed to work in extreme conditions (all the way from -40°C to 105°C) and to potentially last over the life of the vehicle (which could be 20+ years).

Figure 30: LiDAR in mobility TAM estimates

Source	Item	2025	2030
2020 SPAC company filings	Average TAM of LiDAR for ADAS, AVs, and trucks, $bn	$40	$120
	LiDAR ASP, $/unit	$1,000	N/A
Industry reports and analysis	Total estimated TAM, LiDAR for ADAS, AVs, and trucks, $bn	$11	$31
	LiDAR content/vehicle, $/vehicle	$1,361	$1,437

Source: Rangwala, Sabbir. "Lidar: Lighting the path to vehicle autonomy," SPIE.org, 3/1/2021

LiDAR companies have attempted to de-risk production scaling via partnerships with established contract manufacturers, as well as designing products for modularity and vertically integrating where appropriate. Still, LiDAR manufacturing has never taken place at mass scale, so this challenge alone will likely create a learning curve.

Further, given the manufacturing difficulties and parts shortages seen in the automotive industry (and most other manufacturing businesses) in recent years, the challenge of scaling a new technology at automotive-grade must also be considered.

The challenges on cost reduction create somewhat of a chicken and egg dilemma for LiDAR. While there is clear opportunity for LiDAR uptake on premium vehicles today given the high budgets associated with those vehicles, there is a bit of a dilemma on uptake for more basic vehicles, as LiDAR applications for more basic vehicles may only see uptake when LiDAR costs decline more meaningfully, and LiDAR costs will only decline as scale is achieved.

Lastly, we flag that in this regard, next gen LiDAR technologies such as FMCW or OPA may have a path to helping LiDAR penetration expand more widely given the use of silicon photonics and the associated benefits of scalability leveraging the well-developed semiconductor supply chain and manufacturing processes.

Figure 31: Content-per-vehicle opportunities for full sensor stack and compute power

Autonomous Functionality	Level 0/1	Level 2	Level 2+	Level 3
Addressable CPV	$275-325	$450-550	$750-1,200	$4,000-5,000
Inputs needed & corresponding price estimates	Sensing ($125-195)	Sensing ($200-225)	Sensing ($300-400)	Sensing ($1,500-2,000)
	Compute (~$150)	Compute (~$200)	Compute ($450-800)	Compute ($2,300-2,600)
	Embedded Software	Embedded Software	Multi-Domain Sensor Fusion	Signal & Power ($100-300)
			Control Algorithms	Multi-Domain Sensor Fusion
			Integration	Planning and Policy
				Control Algorithms
				Integration

Source: Aptiv

Figure 32: Expected LiDAR opportunities in internet of things markets

Subsector	Applications	Requirement
Mapping	- Drone-based mapping - Terrestrial mapping	- Long range - Range accuracy - 3D point cloud density
Security	- Critical infrastructure - Intrusion detection - Access control - Border security	- 3D perception vs. 2D cameras - Higher accuracy vs. cameras - Reduction in false alarms - Automated 24x7 operation
Smart Cities	- Retail - Airports - Enterprises - Intersections - Public venues	- Classification accuracy - No risk of capturing personally identifiable information - Lower total cost of ownership compared to cameras
Industrial Automation	- Port automation - Measurement - Warehouse automation - Mobile robots	- Long range - Robust outdoor performance - High accuracy
Smart Devices	- Consumer electronics - Consumer health	- 3D perception vs. 2D cameras - Higher accuracy vs. cameras - Small form factor - Affordable cost

Source: Company reports, Credit Suisse

LiDAR in non-mobility applications

Outside of mobility use cases for LiDAR, there is a broad range of other potential applications, some of which are relatively established even today, as well as other future opportunities as LiDAR becomes more economically feasible.

The range of LiDAR uses beyond mobility is vast

Some within the LiDAR industry expect that LiDAR devices will offer a valuable use case anywhere a camera is used and anywhere automation is sought. An example of this is in the potential role of LiDAR within consumer health/wellness devices as well as mobile electronics. With such a wide range of potential, yet somewhat uncertain uses, we find it most appropriate to apply conservatism in TAM calculations.

Varying LiDAR applications demands bespoke consideration

Over the next decade, many within the industry foresee significant levels of demand for LiDAR devices coming from smart cities/infrastructure, warehousing, robotics, commercial trucking, mining, heavy equipment/industry, and consumer electronics.

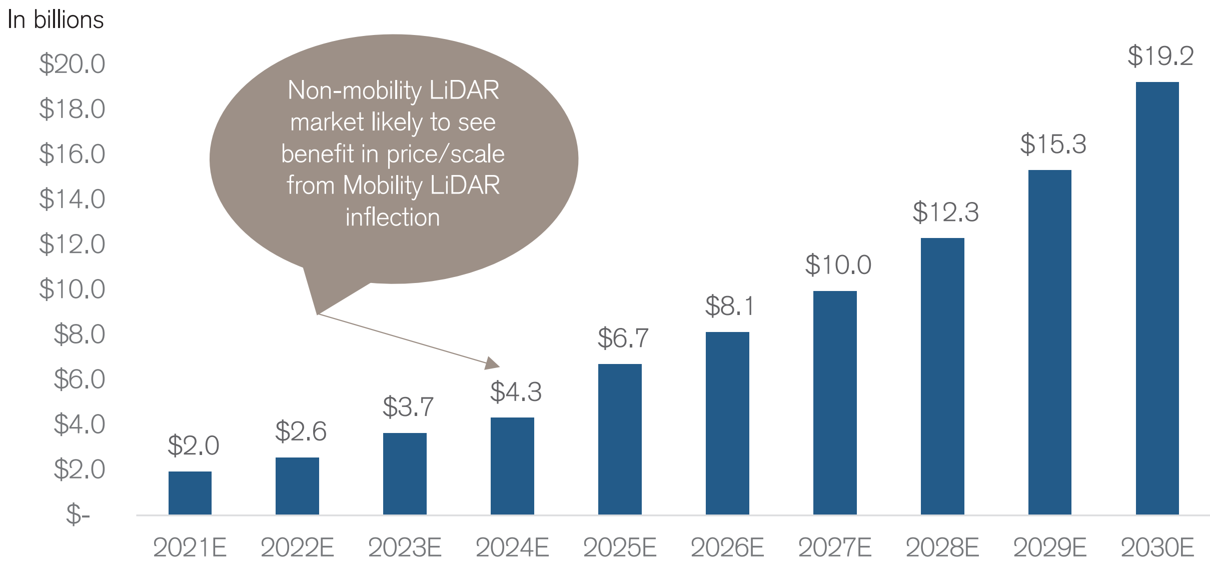
This range of end markets represents a diverse pool of demand but requires consideration for how the LiDAR opportunities will vary in each, such as spec requirements and pricing potential. As an example of how the ASP potentials will vary, and therefore must be considered independently for each demand source, consider how the ASP for LiDAR devices needed to safely give perception to a commercial AV truck will clearly be greater than that of a smart phone. This difference relates mostly to the technological demands for the devices as well as the BOMs of the products to which the LiDAR is added. An autonomous commercial truck with a $150k or greater ASP will have far more room for LiDAR spending than a $1k iPhone. This same thought exercise needs to be performed for each unique use case in order to appropriately gauge the total LiDAR TAM opportunity.

Size of the non-mobility LiDAR TAM driven by ability to reduce costs

The TAM for LiDAR should expand as price declines; therefore, reaching commercial production at scale will be critical to driving down costs.

We take particular interest as to whether or not commercial production scale manufacturing of LiDAR devices for say, autonomous driving, will create scaling/price efficiencies for production in other use cases. This is critical for two reasons: the first being that LiDAR manufacturing will likely reach commercial scale at different times for different end market use cases. The second is that a LiDAR company that can develop a technology platform that easily translates across use cases with limited retrofitting needs will instantly have a competitive advantage across its target markets. The latter of these two points would seem to provide a potentially bullish narrative for FMCW platforms that are developed on a chip leveraging the semiconductor manufacturing process, creating inherent scalability.

Figure 33: Non-mobility LiDAR use case TAMs



Source: Company data, Credit Suisse

“ LiDAR must also compete against other sensors in the automotive perception suites.

Competitive Landscape

While we see a clear market opportunity ahead for LiDAR, the competitive landscape is wide. There has already been some consolidation among LiDAR companies, but we believe more is necessary. Moreover, in the automotive arena, other sensors (most notably radar and camera) should be viewed as competition. Lastly, with automakers taking a more proactive approach on their advanced safety and autonomous driving capabilities, we believe the automakers themselves should be viewed as competition given the potential for insourcing.

LiDAR competitive landscape

A wide competitive landscape, further consolidation required

The LiDAR industry today consists of a diverse range of companies, including those that recently went public via SPAC, existing public automotive sensor/auto-tech companies, those remaining private, those now housed within OEMs and tier 1 suppliers, as well as an array of international LiDAR companies.

This wide competitive set is largely due to a sort of “gold rush” in the industry seen several years prior, where many entrants attempted to capitalize on the rise of autonomous driving. Industry consultant Gartner estimated that at one point, over 60 LiDAR companies existed[4]. The levels of development among this original group varied widely, with many simply being very distant concepts.

Yet there has since been consolidation. Amid the realization of the many challenges in achieving autonomous driving, a reset emerged on AV expectations (autonomous driving), leading to the emergence of the AV trough of disillusionment. This led to a number of LiDAR start-ups folding or pivoting to focus on more near-term or more scalable applications (i.e., L2+).

Even after this consolidation, we still see a need for further consolidation – a point corroborated by comments from industry operators, who have noted that further consolidation will likely prove necessary on the path to commercialized production. Moreover, capital availability may also force consolidation; the recent market downturn for growth stocks may have made the prospects of raising additional capital more difficult, or at least less favorable.

Yet differing value propositions create multiple opportunities

While we see a need for further consolidation, we nevertheless believe that there will still be a need for a diverse landscape, as the differing LiDAR use cases imply that there won’t be a “one size fits all”’ solution.

Most of the notable LiDAR companies differentiate their product from one another with a unique mix of technological approaches and target end markets. This creates some opportunity for value creation and may be a potential driver of future consolidation decisions. For example, a LiDAR company leveraging relatively more mature Time of Flight rotating mirror systems and targeting a more established end market, such as industrial automation or security, likely generates more value from near-term revenue than a LiDAR company working in a more long-dated field like OPA, where more value is ascribed to potential.

Further, some end markets within LiDAR appear more crowded than others, such as simple LiDAR devices for warehouse robotics, as numerous competitors may have successfully reached the technological capabilities necessary to service customer needs/safety specs.

The range of companies with a true focus on developing LiDAR capable of achieving highway autonomy is somewhat narrower, however, mostly due to the technical standards required to reach such capabilities. Therefore, it seems that the “highway autonomy capable” end of the LiDAR device market seems to offer a bit more of a competitive moat than the lower-performance end of the spectrum, where technological differentiation loses some importance relative to cost and commoditization seems to pose a greater risk.

Regional champions

It is clear that LiDAR competition is growing in all regions. Though our focus is on US-based LiDAR companies and specifically their work in the mobility arena, most of these companies operate with customers globally. Yet their focus has largely been on LiDAR applications in the US and Europe, with somewhat less focus in China. This is likely due to a different competitive landscape in China, especially amid the data-sensitive and safety-critical nature of autonomous driving, which may be a challenge for western LiDAR companies competing in China.

Several LiDAR start-ups in China have made advancements in their technology alongside US-based peers, creating a strong domestic market. Yet there is still opportunity for the western LiDAR companies to compete in China.

However, if strong local LiDAR participants dominate the market in China, this would reduce the mobility LiDAR markets available to western LiDAR operators, presenting a challenge to scaling plans.

[4] Adler, Alan. “Who will survive the coming shakeout of LiDAR suppliers?” *Freight Waves,* 10/8/2021

LiDAR must also compete against other sensors in the automotive perception suite

While we share the general industry consensus that LiDAR will be necessary in vehicles with L3 and above functionality, there will nevertheless be competition with cameras and radars to be the primary sensor in the future.

Moreover, while not a dominant view amongst automakers pursuing autonomy, Tesla has made the case for LiDAR as completely unnecessary in autonomous driving.

The case for camera and radar

LiDAR starts at somewhat of a disadvantage against camera and radar. Not only is LiDAR facing a cost disadvantage, but given it is a more commercially nascent technology that is only now starting to be incorporated on mass-produced vehicles, it still must establish a performance/durability track record, and the supply chain must also be established. Conversely, given radar and camera are more mature, in the mobility arena they offer a cost advantage, a longer track record, and more mature supply chain.

The risk of insourcing

Given our view that LiDAR is more hardware than software, we expect the majority of OEMs to outsource LiDAR; nevertheless, the risk of insourcing must also be considered. While some of the insourcing was unlocked by the industry's consolidation up until now, we also believe the desire by automakers to more widely control the value chain for key areas of the vehicle also should be viewed as a risk for LiDAR companies.

Moreover, outside of specific in-sourcing examples seen thus far, we also see it as necessary to consider OEM sourcing trends in the context of the growing value of active safety and AV content.

In the past, when the entire cost of an active safety system was just a few hundred dollars per vehicle, there was little desire to insource by OEMs, as outsourcing was much more economical. However, as the value of active safety systems has grown to $1,000 or more per vehicle, we believe OEMs will try to bring more content in-house. More broadly, we have also heard about OEMs increasingly trying to go deeper/be more proactive with their electronics supply chain – a key lesson learned from the chip shortage in 2021, when many OEMs realized the opacity of their supply chains.

More specifically, we could see OEMs dictating more of the software content in their safety systems and trying to reduce reliance on the perception software from external suppliers. To the extent uptake of perception software from LiDAR companies is more limited, that would reduce the LiDAR offering to more of a hardware solution.

Appendix

Figure 34: Key acronym glossary

ADAS	Advanced driver-assistance system	**InGaAsP**	Indium gallium arsenide phosphide
AEB	Autonomous emergency braking	**IoT**	Internet of things
ASIC	Application-specific integrated circuit	**LiDAR**	Light detection and ranging
ASP	Average Selling Price	**MEMS**	Microelectromechanical systems
BoM	Bill of materials	**NIR**	Near-infrared
FMCW	Frequency modulated continuous wave	**nm**	Nanometer
FoV	Field of View	**NRE**	Non-recurring engineering
fps	Frames per second	**OPA**	Optical phased arrays
Ge	Germanium	**SPAC**	Special purpose acquisition company
HD	High definition	**SWIR**	Short wave infrared
Hz	Hertz	**ToF**	Time of Flight
InGaAs	Indium gallium arsenide	**w**	Watts

Source: Credit Suisse

Figure 35: AV regulation developments globally

Major AV Regulatory Hallmarks around the World	
USA	Voluntary federal guidance vs. inconsistent state regulation produces a fragmented regulatory landscape
China	Strategy for Innovation and Development of Intelligent Vehicles (2020) targets wide deployment of L3 & L4 in 2025
Canada	10-year pilot program updated in 2019 centered in Ontario with emphasis on L3 automation
Japan	L4 deployment targets in 2025. Fast adoption of ALKS regulation for L3 in 2021
UK	Regulations in preparation for 2021 adoption. Deliberations on ALKS for L3 deployment are underway
France	PACTE reduces regulatory restrictions for L3 & L4 testing while LOM addresses data access and handling
Germany	Broad regulatory adoption planned for 2021 to enable L4 approvals. Ethics, data privacy is also prominent
South Korea	L4 deployment target in 2027 with early rollout by 2024. Infrastructure investment underway

Source: IHS Markit

Figure 36: NCAP and regulations

Regulations in Action - NCAP vs Mandate	
New Car Assessment Program (NCAP)	**Regulations**
Voluntary regulations	Mandatory Requirements
Identify and incentivize new technologies	Minimum requirements for all vehicles
Consumer-oriented program	Industry-oriented regulations
Often acts as a mandate market force	Multi-agency alignment often required

Source: IHS Markit

Figure 37: Growth areas supporting automated driving applications

LiDAR Sensors	HD Maps	ADAS Domain Controllers
Primarily used in L3 and L4 applications	Geo-check features for L2+ authorization	Initial growth in L2+ and L3 applications
1 to 5 or more per vehicle possible	Growth in L3-4 localization applications	High performance, lower volume in L4
Fast price declines provide growth upside	Growth via EU speed limit assist mandate	Multiple SoCs per domain controller
18% CAGR through 2030	62% CAGR through 2030	24% CAGR through 2030

Source: IHS Markit